The Ecosystems Center

2003 Annual Report

Marine Biological Laboratory

Woods Hole, Massachusetts

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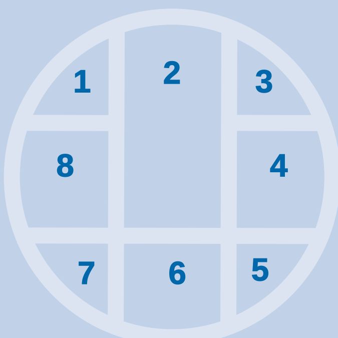

1. The mushroom, *Laccaria* sp., growing on the tundra near the Arctic Long-Term Ecological Research (LTER) site at Toolik Lake. Center scientists study the symbiotic relationship between mycorrhizal fungi such as these and Arctic plants. (John Hobbie)

2. Research assistants take lake water samples for nutrient analysis at the Arctic LTER site at Toolik Lake. The Brooks Range is in the background. (Marcus Gay)

3. Christie Haupert prepares to add a stable isotope nitrogen-15 tracer to an Amazonian pasture stream. The Brazil streams researchers conducted nitrogen-15 additions in order to determine how stream size influences the biogeochemistry of nitrogen in pasture stream channels. (Chris Neill)

4. Samantha Lampert, summer research assistant from Colorado College, measures the conductivity of pasture stream samples in a laboratory located on the cattle ranch Nova Vida in Brazil. (Chris Neill)

5. Fall foliage of the Alpine bearberry (*Arctostaphylos alpina*) on the Alaskan tundra. (Marcus Gay)

6. Bonnie Keeler tests water samples in Sweeney Creek as it flows into the Rowley River, Plum Island LTER. (Bruce Peterson)

7. Summer interns Alex Breslav of Pennsylvania State University and Joe Powers of Michigan Technological University label tundra with nitrogen-15 to monitor its fate in the Imnaviat Creek watershed at the Arctic LTER. (Yuriko Yano)

8. Carrie McCalley, Paul Overduin of the University of Alaska, Fairbanks, and Erica Stieve dig snow out of a weir at Imnavait Creek for early season runoff measurements. (Yuriko Yano)

Printed on recycled paper using soybean-based ink.

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Erica Stieve

Introduction to The Ecosystems Center

Near the Arctic Long-Term Ecological Research site at Toolik Lake, Alaska.

The Ecosystems Center was founded in 1975 as a year-round research program of the Marine Biological Laboratory (MBL). Its mission is to investigate the structure and functioning of ecological systems and to predict their response to changing environmental conditions, to apply the resulting knowledge to the preservation and management of natural resources, and to educate both future scientists and concerned citizens.

The center operates as a collegial association of scientists under the leadership of co-directors John Hobbie and Jerry Melillo. Because the complex nature of modern ecosystems research requires a multidisciplinary and collaborative approach, center scientists work together on projects, as well as with investigators from other centers at the MBL and from other institutions, combining expertise from a wide range of disciplines. Together, they conduct research to answer a variety of questions at field sites ranging from Arctic Alaska, Sweden and Russia to Brazil, and from the temperate forests of New England to the estuaries of the eastern United States.

- At the Arctic Long-Term Ecological Research site at Toolik Lake in the foothills region of Alaska's North Slope, Ecosystems Center scientists study the effect of warmer temperatures on Arctic ecosystems. Will an increase in the depth of thaw in the permafrost make more nutrients available to plants? Will these nutrients flow into streams and lakes and affect the aquatic food web?

- At the Plum Island Ecosystem LTER site in northern Massachusetts, researchers ask how changes in rural land use and urban development affect the flow of nutrients and organic matter into New England estuaries. How will they alter the food web in coastal waters? What happens to the production of commercially valuable fish as a result?

- In Brazil, scientists investigate the degree to which the clearing of tropical forests in the western Amazon changes the amount of greenhouse gases such as carbon dioxide and nitrous oxide that are released into the atmosphere. What will the effect be on global climate? How will change in temperature and atmospheric gas concentrations affect the productivity of forests? What effect does the clearing of forest for pasture have on tropical streams ecosystems?

- In Boston Harbor, researchers measure the transfer of nitrogen from the sediments to the water column. How long will it take the harbor to recover from decades of sewage addition?

- On the continental shelf and slope of the East Coast, scientists study the chemical composition of dissolved organic matter in marine environments. How does it affect our understanding of how and why carbon is stored?

- Studies by center scientists have shown increased freshwater discharge from the Arctic rivers in Eurasia. If ocean circulation is affected, how might the climate in western Europe change?

- On Martha's Vineyard, researchers conduct experiments that use controlled burning to restore coastal sandplain ecosystems. How much will beneficial processes such as groundwater recharge and nitrogen retention increase in restored ecosystems? Will it restore diversity in plant and animal species?

• At the Harvard Forest LTER in central Massachusetts and at the Abisko Scientific Research Station in Sweden, scientists use soil-warming experiments to assess how forests would respond to climate warming. How much carbon might be released as temperatures increase? How will warming affect the cycling of critical plant nutrients such as nitrogen? Will changes in nitrogen cycling affect carbon storage in plants?

• In virtually all areas of study at The Ecosystems Center, scientists use mathematical models to simulate ecosystem structure and function and to make predictions. Over the next 100 years, will Arctic ecosystems store or release more carbon? In the year 2101, what is the projected deforestation in a coastal New England watershed?

• Computer models at the center are also used to ask questions about effects of future changes in climate, carbon dioxide and ozone on vegetation productivity and carbon storage world-wide. These models are run at a spatial scale of half degree of latitude and half degree of longitude.

The Ecosystems Center staff currently includes 11 principal investigators and 48 research and administrative staff members. The annual operating budget for 2003 was $9.4 million. Although research programs are funded primarily by grants from federal and state agencies, additional support for research and education comes from private foundations, corporations and individual donors.

Facilities at The Ecosystems Center include mass spectrometers for stable isotope analysis, chemical analytical laboratories and experimental chambers. Center staff also makes extensive use of the DNA sequencing facilities at the MBL's Josephine Bay Paul Center for Comparative Molecular Biology and Evolution.

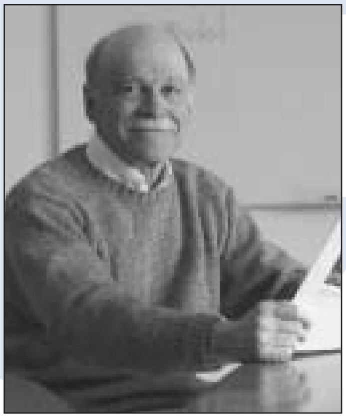
In 2003, the MBL and Brown University established a joint Graduate Program in Biological and Environmental Sciences. Ecosystems Center scientists will hold formal appointments at Brown, and graduate students will conduct research at both institutions. Brown has also joined the Semester in Environmental Science (SES) consortium, allowing Brown students to enroll in SES, the Ecosystems Center's undergraduate educational venture. The SES program, launched in the fall of 1997, brings undergraduates from a consortium of 60 liberal arts colleges and universities to the MBL campus for an intensive introduction to environmental sciences from the perspective of ecosystem ecology.

COREY LAWRENCE

Sam Kelsey, Chuck Hopkinson and Jane Tucker taking sediment cores at the Parker River, part of the Plum Island LTER in northern Massachusetts.

One of the important reasons for conducting basic research in ecology is the development of a sound foundation for environmental policy and management. Center scientists are actively involved in the application of scientific knowledge to the solution of environmental problems in a variety of ways, including briefing federal and state legislators and administrators, advising resource managers and serving on committees responsible for formulating policy and coordinating research. Researchers also work with non-governmental organizations and government agencies on assessing the impact of development on ecosystems or evaluating the success of various approaches to resource management.

Reaching Out, Reaching Up:
The Brown/MBL Education and Research Partnership


TOM KLEINDINST

John Hobbie


TOM KLEINDINST

Jerry Melillo

In the fall of 2003, the Marine Biological Laboratory formally joined with Brown University in nearby Providence, Rhode Island, in an education and research partnership. This new relationship, developed with lightning speed for an academic venture, opens new horizons for both institutions and promises to be a landmark event for The Ecosystems Center. The implications of the partnership are numerous and positive for the center.

Graduate student education is a cornerstone of the new Brown/MBL partnership and offers a special opportunity to The Ecosystems Center. Since the center's founding, its scientists have periodically mentored graduate students from U.S. and foreign universities during the research phase of their studies. With Brown, we now have the opportunity to be involved in all parts of a comprehensive graduate program in the environmental sciences that includes training in theory, techniques, experimental design, data analysis and synthesis, the writing of scientific papers, and grantsmanship. These commitments bring many benefits as well. Center scientists involved in the partnership will have formal appointments at Brown. The students will leaven our intellectual bread by challenging our ideas, approaches and interpretations, and our Brown colleagues will show us new ways of thinking and doing.

A second dimension of the education partnership with Brown focuses on undergraduates. Brown has a long tradition of excellence in undergraduate education, and The Ecosystems Center takes great pride in its own undergraduate education program, the Semester in Environmental Science (SES). Brown has become a formal member of the SES consortium of 60 colleges and universities across the country from which we draw our students. The SES program is now listed in the Brown course catalogue as an opportunity available to Brown upperclassmen and to students from other colleges and universities who have "special student" status at Brown. In addition, center scientists will team with Brown faculty to teach advanced-level courses either on the Brown campus or through distance-learning technologies to minimize travel between Woods Hole and Providence.

The potential for new research partnerships between Brown and center scientists is very exciting. We are already exploring collaborations in several areas including coastal zone science and management and global environmental change. The narrow ribbons of land and water ecosystems along the continents, the coastal zones, provide the world's people with many goods and services. The rivers, estuaries and marine waters of the coastal zone provide us with commercial fisheries, shipping, aquaculture, mineral resources, recreation of all sorts, natural habitats for diverse plant and animal life, nutrient cycling and much more. The uplands along the coast are the home and workplace of more than half of the world's population. In the United States, for example, 53 percent of our total population lives in the coastal zone and this percentage is expected to increase dramatically in the coming decades.

This large and growing population pressure in coastal areas is responsible for many of the current stresses on coastal resources. The United States Environmental Protection Agency has estimated that some form of pollution or habitat degradation has impaired nearly 40 percent of the nation's surveyed estuaries. Between 30 and 40 percent of shellfish-growing waters in the nation's estuaries cannot be harvested each year, primarily due to bacterial contamination from urban and agricultural runoff and septic systems. Public health is at risk in the coastal zone as is the health of the plants and animals of this vital region.

We cannot allow the destruction of the coastal zone to continue. We need to use state-of-the-art natural and social science techniques to understand how the linked coastal zone ecosystems (uplands, rivers, estuaries and coastal marine waters) work, why and how humans are impairing the functions of these linked systems, the consequences of the impairments, and how we fix what we have broken. These essential tasks will require a new partnership between natural and social scientists to think together in a geo-referenced context; that is, to think about specific places and all of their unique issues. This will deepen our understanding of the problems and allow us to shape sets of culturally, economically and institutionally relevant solutions to guide the policy process.

To work effectively on global-scale issues such as climate change, we have to bring the human dimension into earth system research. As with the coastal zone issue, global-scale issues require us to foster the development of interdisciplinary teams of natural and social scientists – ecologists, geologists, chemists, mathematicians, computer scientists, visualization specialists, economists, political scientists, scholars in the areas of population studies, urban studies, public health and so on. An interdisciplinary approach will allow us to sharpen questions while at the same time making them more holistic.

Brown faculty and Ecosystems Center scientists have begun to consider possible topics to initiate our collaborative, interdisciplinary research. Quantification of humanity's impact on the environment has been a topic of interest to both natural and social scientists as part of their larger dialogue on the transition to sustainable use of the Earth system. One powerful integrative index of humanity's impact on the environment is the fraction of global net primary production used by the world's people. The Earth's annual net primary production (NPP) is the amount of plant material generated during a year through the process of photosynthesis.

Since the mid-1980s, several estimates have been made of the fraction of the land-based NPP that is used by humans. The extant estimates for this human-appropriated NPP, or HANPP, cluster around 30 percent of the total, although the uncertainties are large.

To date, the estimates have been at the global scale. While these highly aggregated HANPP estimates have been important for informing general discussions on sustainability, they have had little effect on environmental management and planning that is done most effectively at regional and sub-regional scales. It is now time to develop HANPP estimates at finer levels of resolution so that they can be used in the debate about future pathways of development. The question is – are we ready to take up this challenge?

We think the answer is yes. Using a combination of geographically specific data of various kinds, geographic-information-systems technology, simulation modeling and visualization techniques available now, an interdisciplinary team of scholars should be able to produce much more geographically detailed pictures of current NPP and HANPP, with the HANPP considered from both the demand and supply perspectives. Further, we should be able to build scenarios to explore possible futures for the relationship between NPP and HANPP. The scenarios could combine projected changes in population, consumption levels, technologies, and trade patterns, with changes in land use and climate to permit integrated assessments for examining alternative pathways toward sustainable development. These alternative pathways could then be the basis for rich explorations of the kinds of institutions needed to achieve the desired ends in different parts of the world.

As the Brown/MBL partnership matures, we will add more topics to our list for research collaborations and explore new education ventures. While many of the details about the new partnership remain to be worked out, The Ecosystems Center sees exciting new opportunities on the horizon that will bring positive change to our efforts in research and education, and serve society through scholarship.

Jerry Melillo
John Hobbie
Co-directors, The Ecosystems Center

Research Articles: An Overview

The research articles in this year's report focus on two major themes at the center – climate change and the interactions between the cycles of carbon and nitrogen. Two of the articles link these themes.

Over the past century the world has gotten warmer and the global water cycle has intensified. Since the mid-1800s, the global average temperature has warmed by about 1°F (about 0.6°C). The Northern Hemisphere average temperature at the end of the 20th century was almost 1.5°F (about 0.9°C) warmer than during the few centuries prior to the Industrial Revolution. The observed magnitude, pattern, and timing of the global warming indicate that rising concentrations of carbon dioxide (CO_2) and other greenhouse gases caused by human activities are in large part responsible. During the past 100 years, there have also been changes in the global water cycle associated with the warming. In many parts of the Northern Hemisphere, the annual amount of total precipitation (rain plus snow) has increased.

PHOTO COURTESY OF MAX HOLMES

Max Holmes and Jim McClelland with Russian colleagues on the Ob River.

The article titled "Causes of Increasing River Discharge from Eurasia to the Arctic Ocean," describes the work of center scientists Bruce Peterson, Jim McClelland, and Max Holmes with Marc Stieglitz from Georgia Institute of Technology, exploring the mechanisms responsible for the observed long-term

Looking south to the Brooks Range from Toolik Field Station.

increases in Eurasian river discharge. Among the mechanisms they consider is the observed intensification of the water cycle in this region. They argue that increased precipitation may be driving the increased freshwater input to the Arctic Ocean. The article examines the potential importance of this increased input to ocean circulation and future climate.

Increases in atmospheric carbon dioxide not only lead to climate change, they can also have a direct effect on plant growth and carbon storage in land ecosystems. Ecological theory, supported by several recent field experiments, suggests that in mid- and high-latitude ecosystems, plant and whole-ecosystem responses to elevated levels of carbon dioxide are partly controlled by the availability of nitrogen. Ed Rastetter and Gus Shaver of the center, Steve Perakis of the United States Geological Survey, and Gören Ågren of the Swedish Agricultural University are carrying out a process-based modeling study to explore this carbon-nitrogen interaction in new ways. They focused on the degree to which the magnitude and form of nitrogen losses from terrestrial ecosystems might constrain the capacity of land ecosystems to store the carbon in plant tissues and in soils, thereby removing carbon dioxide from the atmosphere. Their analysis also considers how global warming might affect nitrogen cycling and carbon storage.

Besides being affected by warming and carbon dioxide concentration increases, carbon-

ADRIAN GREEN

nitrogen interactions in land ecosystems are affected by increases in nitrogen inputs in rain and snow. These increases are primarily associated with the burning of fossil fuels and the use of nitrogen fertilizers in agriculture. In industrial regions of the mid-latitudes, these nitrogen inputs have increased dramatically, going from a few kilograms of nitrogen per hectare before the Industrial Revolution to as much as 80 to 100 kilograms per hectare currently. The team of Paul Steudler, Al Chan and Jerry Melillo from the center, along with John Aber from the University of New Hampshire, Colleen Cavanaugh from Harvard University and Jay Gulledge from the University of Louisville focused on the ways increased nitrogen inputs are affecting long-term trends in methane (CH_4) consumption by forest soil microorganisms. They found that long-term nitrogen additions dramatically reduced methane consumption on forest plots in central Massachusetts. Because methane is a powerful greenhouse gas, this carbon-nitrogen interaction has important implications for the climate system, and these are discussed in the article.

The results of another long-term nitrogen fertilization experiment, this one in the Arctic tundra of Alaska, provide new insights into controls on carbon storage in high-latitude soils. Center scientist Gus Shaver, Michelle Mack and Ted Schuur of the University of Florida, and Syndonia Bret-Harte and Terry Chapin of the University of Alaska found that 20 years of nitrogen fertilization have resulted in decreases in carbon stocks in the organic mat at the surface of the tundra soils. They argue that this may be evidence that decomposition in these soils is limited by nitrogen availability. Until now, they had hypothesized that carbon availability to microbes was the primary controller of decomposition in these Arctic soils. The article considers the implications of this new insight in analyzing the role of tundra ecosystems in the global carbon cycle in climate change.

The final article reports on center scientist John Hobbie and his son, Erik Hobbie of the University of New Hampshire, who used shifts in the ratios of two stable isotopes of nitrogen in plants and fungi along with other ecosystem-level data to explore, in a quantitative way, the symbiotic relationship between Arctic plants and mycorrhizal fungi. More specifically, they present a new approach for estimating the role fungi play in supplying nitrogen to the plants, and what the carbon costs are to the plants for this "service." While the approach was developed for Arctic ecosystems, it should be useful for the study of plant-mycorrhizal fungi relations in other ecosystems and may lead to a quantitative measure of plant use of organic nitrogen of the soil.

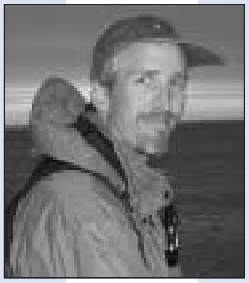
JON BENSTEAD

Atigun Gorge in the Brooks Range.

Causes of Increasing River Discharge from Eurasia to the Arctic Ocean

MAX HOLMES

Bruce Peterson, Anya Suslova and Alexander Zhulidov on the Lena River.



JIM MCCLELLAND

Max Holmes

MAX HOLMES

Jim McClelland

The amount of freshwater flowing into the Arctic Ocean has been steadily increasing for most of the past century. Because the Arctic is an important component of the global climate system, this trend has the potential to profoundly alter global ocean circulation. Under the current hydrological system, water at the ocean's surface around Greenland becomes chilled (therefore more dense), sinks to ocean floor and is replaced by warmer surface water from farther south. The process is called North Atlantic Deep Water (NADW) formation and it is a primary control of ocean circulation in the Atlantic basin and indeed globally.

Ecosystems Center scientists recently quantified the long-term increase in river discharge during the last century from Eurasia to the Arctic Ocean. River water reaching the Arctic Ocean from the six largest rivers (Figure 1) increased by about 128 cubic kilometers per year over the baseline from 1936 to 1999. (One cubic kilometer (km^3) equals one trillion liters, or an area about the size of the state of Virginia, covered to a depth of 10 centimeters.) If this pattern continues, the addition of freshwater, which is less dense than sea water, could slow or even halt NADW formation within this century and have a major impact on regional and global climate.

Ecosystems Center scientists Bruce Peterson, Jim McClelland, and Max Holmes are now working in collaboration with Marc Stieglitz of Georgia Institute of Technology to identify the mechanisms behind these long-term increases in Eurasian Arctic river discharge. Researchers have suggested four potential mechanisms that would have very different implications for future discharge: 1) increased transport of moist air as a result of a warmer climate, 2) hydroelectric dams, 3) permafrost thawing, and 4) forest fires. By ruling out some of these scenarios, the team can place some limits on projections of river discharge in the future – giving modelers greater confidence in their predictions for ocean circulation.

Based upon scenarios from global climate models, the movement of moist air from lower to higher latitudes will increase in a warming climate. Warm air holds more moisture than cold air; atmospheric circulation moves warm, moist air from the tropics to the poles, where the moisture meets colder air and becomes precipitation in the form of rain and snow. As the Earth heats up, due to global warming, there will be an even greater transport of moisture, thus more precipitation in the Arctic. Precipitation data from that region, however, are so limited that it is difficult to confirm whether this mechanism is mainly responsible for the observed upward trend in discharge.

Another possible explanation that Peterson and colleagues have considered is hydroelectric dams, which exert a major influence on watershed storage and flow regimes. Russia began building major hydroelectric dams (greater than 1 cubic kilometer-reservoir capacity) in the watersheds of the largest Eurasian Arctic rivers in the mid 1950s. There are now three major dams in the Ob watershed, eight in the Yenisey watershed, one in the Lena watershed, and one in the Kolyma watershed (Figure 1).

Records at gauging stations revealed that operation of dams has dramatically changed the seasonality of discharge, reducing discharge in spring and summer and increasing it in the winter months. Dam effects cannot, however, account for the long-term increase in annual discharge. In fact, overall, dams have slowed the increase in discharge relative to what it would have been without dams (Figure 2). The fate of the missing water is unclear. One possibility is increased groundwater storage. Another possibility is that more water is evaporating from reservoir surfaces or agricultural fields.

Permafrost thaw is another obvious source for the increased discharge. In the Northern Hemisphere, the upper 20 meters of permafrost contain 11,000-37,000 km^3 of frozen water, much of this in the Eurasian Arctic. This volume far exceeds the excess 4160 km^3 of river water delivered to the Arctic Ocean between 1936 and 1999, but on closer examination, the permafrost thaw could not have supplied this quantity of water.

How much permafrost would have to thaw to supply the observed increase in discharge? The discharge on average increased each year by 2 km^3 of water. Each year the thaw must supply 2 km^3 more than the year before so that by 1999, the top 4 meters of permafrost would need to be thawed (Figure 3). Widespread changes in thaw of this magnitude would be easily measured, yet such changes have not been observed. Additionally, if permafrost were a major source of the increase, then watersheds with the most permafrost would show the largest increase in runoff. No such pattern is apparent. In fact, the watershed showing the second largest change in runoff (Severnaya Dvina) has no permafrost. Some other mechanism must be at work.

Widespread forest fires could increase river discharge by destroying vegetation. Living plants actively take up ground water and release it through their leaves. Loss of vegetation causes a decrease in this evapotranspiration, allowing a greater proportion of precipitation to reach river channels. As the forest recovers, however, this effect diminishes.

There are 620 million hectares of boreal forest in Russia, so large sustained increases in fires could substantially increase river discharge. From observing fires elsewhere, researchers know that the increase in stream discharge is large in the first year after a fire, declining quickly at first and then more gradually. Peterson and his colleagues assumed that

Figure 1. Map showing the six largest river systems draining into the Arctic Ocean from Eurasia. Numbers identify the locations of major dams (reservoir capacity greater than 1 km^3).

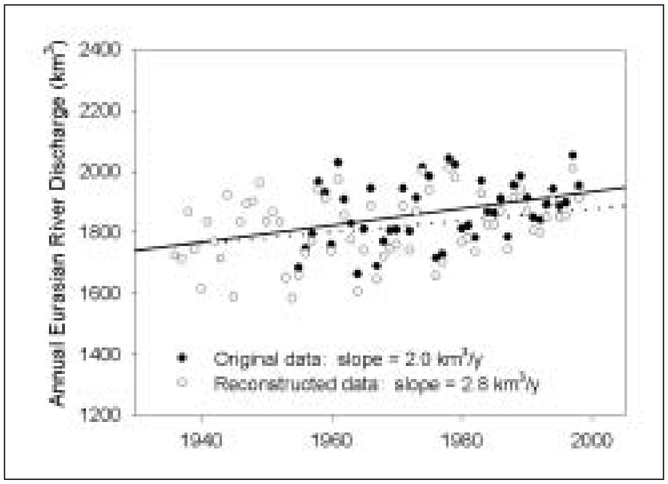


Figure 2. Combined annual discharge from the six largest Eurasian Arctic rivers versus time for measured discharge records (solid circles, dotted line), and for records that have been reconstructed to remove the influence of dams on discharge (open circles, solid line).

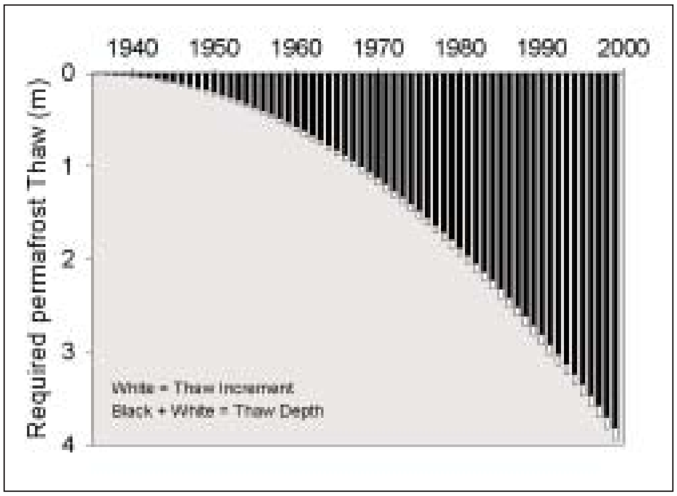


Figure 3. Permafrost thaw required to generate the observed long-term increase in Eurasian Arctic river discharge, assuming that all permafrost is equally susceptible to thaw, and all water in thawed permafrost is converted to river discharge. This scenario reflects the minimum amount of permafrost thaw that would have been required. The white bars show the annual thaw increment, and the black and white bars together show the depth at which thawing would have had to occur.

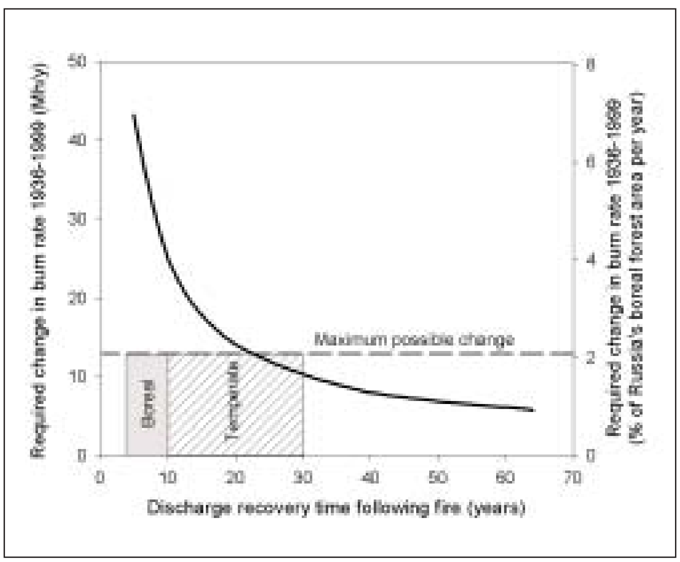


Figure 4. Changes in burn rates of Russian boreal forest that would have been required to produce the observed increase in Eurasian Arctic river discharge between 1936 and 1999. Values are plotted as a function of discharge recovery time.

discharge for the Eurasian rivers would increase by two-thirds in the first year and decline quickly. Based on that model, they found that by 1999 an extra 6 million to 43 million hectares (depending on length of recovery time) would have to burn each year to account for the extra water (Figure 4).

These rates amount to burning an additional 1 to 7 percent of Russia's boreal forest area each year. The upper end of this range is clearly unrealistic because Russia's forests are presently burning at a rate of only 1 to 2 percent per year and changes in burn rates must be less than total present rates. The lower end of this range corresponds with longer recovery times, on the order of 25 to 30 years. In temperate forests recovery can sometimes take this long, but three to 10 years is a typical range for boreal forests like these. Given these short recovery times, it is very unlikely that forest fires can have produced the 64-year trend of increasing discharge found in the records.

The long-term increase in Eurasian Arctic river discharge between 1936 and 1999 cannot be explained by the effects of dams, permafrost thaw, or increases in fires. The net effect of dams has been to slow the increase in discharge. Both thawing of permafrost and increased fires may have contributed to the increase in discharge, but neither can be considered a major cause of the long-term trend. The most plausible and robust mechanism is amplification of the global hydrologic cycle as predicted by climate models. In particular, increased transport of moisture in the atmosphere from tropical to Arctic latitudes in a warming climate provides the best explanation for the observed increase in discharge. It also provides little hope of stemming the flow in the near future.

Understanding where carbon is stored and how fast it can be sequestered is one of the major obstacles to predicting how increasing levels of carbon dioxide (CO_2) in the atmosphere will affect ecosystems – and how ecosystems affect climate. Several early experiments suggested that trees and plants tend to grow faster under high carbon dioxide conditions and could therefore absorb much of the carbon dioxide emitted by the burning of fossil fuels. However, carbon dioxide is not the only factor that limits plant growth, so Ecosystems Center scientists Ed Rastetter and Gus Shaver, in collaboration with Steve Perakis of the United States Geological Survey in Corvallis, Oregon, and Göran Ågren of the Swedish Agricultural University in Uppsala, Sweden, undertook a study of how nitrogen losses from terrestrial ecosystems might constrain the ecosystem's capacity to remove carbon dioxide from the atmosphere and store carbon in plant tissues and in soils.

In ecosystems, nitrogen takes many forms. Small, inorganic molecules such as ammonium and nitrate, as well as some small organic molecules, are readily available to plants and microorganisms. Larger molecules of organic nitrogen can be difficult for microorganisms to break down and are therefore not easily available to support plant growth. The researchers used a computer model to examine whether the ability to remove carbon dioxide from the atmosphere and store it as biomass depends upon which form of nitrogen dominates the loss from terrestrial ecosystems.

Surprisingly little is known about the forms of nitrogen leaving terrestrial ecosystems. Estimates of the amount of unavailable nitrogen leaving ecosystems range from less than 20 percent to over 95 percent of total nitrogen losses. Rastetter and his colleagues postulated that if most of the nitrogen losses were in an unavailable form, then the long-term potential for sequestering carbon dioxide from the atmosphere in these ecosystems would be low. Their reasoning is easy to follow from the perspective of an ecosystem initially in balance with just as much nitrogen entering the ecosystem in rainfall and nitrogen fixation as is leaving in both available and unavailable forms.

TOM KLEINDINST

Ed Rastetter

If carbon dioxide in the atmosphere increases, the photosynthetic rate of plants will also increase, but the increased photosynthetic rate cannot be maintained unless the plants can also acquire more nitrogen from the soil. Plants can accomplish this by increasing the number and activity of roots (and associated microorganisms), but this depletes the concentration of available nitrogen in the soil. With less available nitrogen in the soil, less gets washed away by rainwater and more nitrogen remains in the system to support plant growth.

In addition, higher productivity by plants results in more litter (leaves and other plant debris), which falls to the ground and increases the supply of fresh organic matter to the soil microorganisms. In the process of decomposing this fresh organic matter, the microorganisms also take up available forms of nitrogen from the soil, thereby further depleting the amount of nitrogen that can be washed away in rainwater. Because less nitrogen is lost, it accumulates in the ecosystem, which in turn enables carbon to be sequestered in both plant tissues and in soil organic matter.

The ability to sequester nitrogen, and hence carbon, in this way depends upon the ability of plants and microorganisms to curtail nitrogen losses by increasing their rates of nitrogen uptake. However, the plants and microorganisms can only prevent losses of available nitrogen. If most of the nitrogen lost from an ecosystem is in an unavailable form, then very little nitrogen and carbon can be sequestered by this mechanism. On the other hand, if most of the nitrogen lost from the ecosystem is in an available form, then the potential to retain nitrogen and carbon by this mechanism should be high.

To test these ideas, Rastetter and his colleagues modified the Multiple-Element Limitation model (or MEL for short) to include losses of both available and unavailable forms of nitrogen. This model is designed to simulate the interactions between the carbon and nitro-

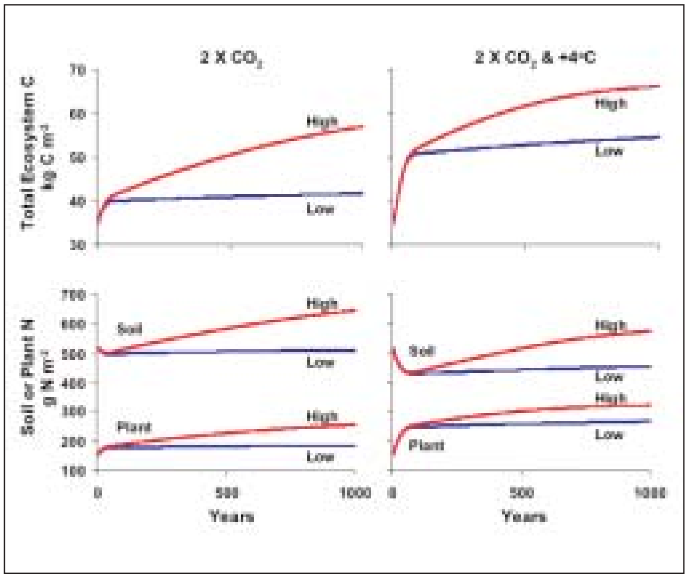


Figure: Responses of terrestrial ecosystems to elevated carbon dioxide and to elevated carbon dioxide (CO_2) with warming. "High" indicates systems with nitrogen losses composed of more readily available forms of the nutrient. "Low" indicates that nitrogen losses were composed mainly of less available forms. Early responses are dominated by a net redistribution of nitrogen from soils to plants and do not differ between the two types of ecosystem. Over the long term, a larger net accumulation of nitrogen results in more carbon being sequestered in the ecosystem with a high ratio of available to unavailable nitrogen losses than in the ecosystem with a lower ratio.

gen cycles in terrestrial ecosystems and has been used in the past to understand the relationships between carbon storage and the movement of nitrogen through ecosystems. The researchers ran simulations of ecosystems responses under two sets of climatic conditions and two sets of soil conditions. They applied a doubling of atmospheric carbon dioxide concentration with no change in temperature and a doubling of carbon dioxide concentration combined with a 4° C increase in temperature to systems with a high (5:1) and a low (1:5) ratio of available to unavailable nitrogen losses (Figure 1).

The simulations indicate that the ratio of available to unavailable nitrogen losses has little effect on the responses to elevated carbon dioxide and warming for about 60 years. However, after 60 years the effects are substantial. The dramatic difference between the short-term and long-term responses results from very different mechanisms.

During the first 60 years, the redistribution of nitrogen already in the ecosystem fuels carbon sequestration. When carbon dioxide initially increases, plants compete more effectively for nitrogen and more nitrogen ends up in the plants and less in soil organic matter. Because the ratio of carbon to nitrogen in woody plants is about six times the ratio in soil organic matter, the ecosystem as a whole stores more carbon. In addition, the plants grow more wood, which further increases the amount of carbon per unit nitrogen they store, and they produce more litter, which increases the carbon per unit nitrogen stored in the soil.

After 60 years, the cumulative effects of small nitrogen losses over time begin to show up. Nitrogen cycles within a system much faster than it is lost from the system, so differences in the loss rate take a while to make their effects known. The ecosystems with a low ratio of available to unavailable nitrogen losses tend to lose more nitrogen in the long run, because they cannot conserve nitrogen that is not readily available. Over a 1,000-year simulation, the ecosystem with nitrogen losses that were more available sequestered about nine times as much nitrogen as the ecosystem that was losing mainly recalcitrant nitrogen. This increase in ecosystem nitrogen resulted in about three times as much carbon being stored in the ecosystem with a higher ratio of available to unavailable nitrogen losses.

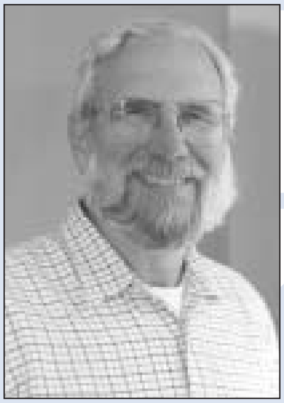
Warming, in concert with elevated carbon dioxide, enhances the early redistribution of nitrogen from soils to plants. Warming increases the rates of all metabolic processes, but most importantly in this context, it increases the rate of nitrogen release from the soil organic matter. This release of soil nitrogen is the major bottleneck limiting productivity in most terrestrial ecosystems. Thus, by stimulating this release, warming allows the plants to take full advantage of the elevated carbon dioxide to increase production and sequester carbon. The redistribution of nitrogen within the ecosystem therefore has a stronger effect with warming than without. The relative contribution of curtailing nitrogen losses is commensurately smaller. Thus, over a 1,000-year simulation that included warming, the effect of nitrogen availability was much smaller than in the simulation that did not include warming. The ecosystem losing a greater proportion of highly-available nitrogen sequestered about four times as much nitrogen as the ecosystem losing a greater proportion of unavailable nitrogen.

Not much is known about the form, rates, or control of nitrogen losses from terrestrial ecosystems. These simulations suggest that developing a better understanding of nitrogen losses will shed light on the processes that regulate ecosystem productivity and response to changes in atmospheric carbon dioxide and climate. Perhaps the most important role of simulation studies like this one is to focus future research efforts. Other Ecosystems Center researchers have already stepped up efforts to determine the forms of nitrogen leaving terrestrial ecosystems, their availability to plants and microorganisms, and their effects on ecosystem carbon sequestration. But modeling studies also serve as a reminder that the cumulative effects of small changes can exert far greater influence over centuries than can be observed in experiments that last only years or decades.

BETH BERNHARDT

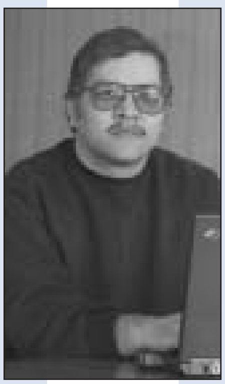
A student in the Semester in Environmental Science program surveys the cedar swamp to estimate the percentage of *Sphagnum* moss cover.

Forest Soil Methane Consumers Vulnerable to Increasing Nitrogen: Implications for Global Change



TOM KLEINDINST

Paul Steudler



TOM KLEINDINST

Al Chan

Not all greenhouse gasses are created equal. In the atmosphere, methane (CH_4) traps heat far more effectively than carbon dioxide (CO_2), the most common greenhouse gas. Although its concentration in the atmosphere is less than 1 percent of carbon dioxide, it is such a potent greenhouse gas that it will have 21 times more effect on the warming over the next century than will carbon dioxide.

Methane concentrations in the atmosphere depend strongly on soil biological processes that produce or consume the gas. The major sources of methane are natural wetlands, rice cultivation, domestic animals and biomass burning. On balance, temperate forest soils usually consume more methane than they produce, tending to counteract the accumulation of methane in the atmosphere. However, disturbances to these systems may result in reduced methane consumption, allowing atmospheric concentrations to grow.

Increased nitrogen (N) availability from human agricultural and industrial activity can disrupt methane consumption in several ways. In experiments, methane consumption of forest, grassland and agricultural soils declines when the associated plants receive extra nitrogen. Changes in soil nitrogen availability may also directly affect microbial communities that consume methane throughout the soil column. The activity of these communities is sensitive to soil nitrogen additions such as fertilization or atmospheric deposition. Researchers regularly observe decreases in the rates of methane consumption shortly after nitrogen addition and such changes often persist for many decades after additions have been discontinued. Hence, the sensitivity of atmospheric methane oxidizers to human activities that increase nitrogen inputs likely has accelerated the rate of methane accumulation in the atmosphere.

A joint project of Ecosystems Center scientists Paul Steudler, Al Chan and Jerry Melillo, John Aber of the University of New Hampshire, Colleen Cavanaugh of Harvard University and Jay Gulledge of the University of Louisville is examining how the addition of nitrogen affects the capacity of forest soils to consume atmospheric methane. Control and fertilized plots used in this work are part of a long-term nitrogen addition experiment located at the Harvard Forest Long-Term Ecological Research site in central Massachusetts. This forest receives about 8 kilograms of nitrogen per hectare per year (kg N/ha/yr) from precipitation, a relatively low level for the northeastern United States. Control plots receive no additional nitrogen. One set of plots receives nitrogen additions of 50 kg N/ha, (referred to as Low N plots) similar to what is observed in regions of moderate to high atmospheric nitrogen deposition. The other set, High N plots, receive additions of 150 kg/N/ha that exceeds levels currently seen even in regions of high nitrogen pollution.

The experiment, begun in 1988, takes place at two sites, a stand of mixed hardwood that is at least 50 years old and a red pine plantation of 62 years. This study documents in a controlled experiment the timing and magnitude of the changes that occur when moderate to high levels of nitrogen are added to a low N deposition forest. Over the past 15 years, researchers from The Ecosystems Center and collaborating institutions have intensely studied the sites, giving Steudler and colleagues access to a rich data set to help interpret their findings on methane consumption.

In the field, they measured rates of methane consumption using small chambers placed over the soil surface for 20 minutes. Concentrations of methane were also measured just above the litter layer and at 5, 10, 20-centimeter depths in the soil below the litter layer using small stainless steel tubes that were sealed at one end and equipped with a two-way stopcock at the other end. Small, 2-millimeter holes located above the sealed end allowed soil air to diffuse into the tubes.

Over the sampling period, methane consumption rates were always less in the nitrogen-treated plots than in the controls (Figure 1). In untreated plots, methane consumption rose in May or June and stayed high throughout the

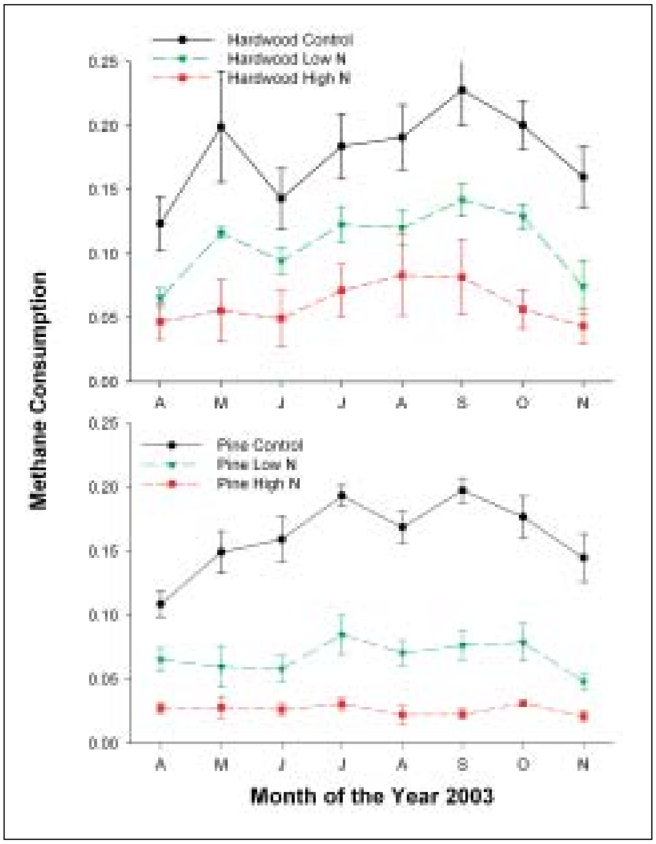


Figure 1. Monthly methane consumption rates as milligrams of methane carbon per square meter per hour. In both pine and hardwoods plots, nitrogen additions reduce total methane consumption and decrease seasonal peaks. Bars indicate variability among samples; sample size = 3.

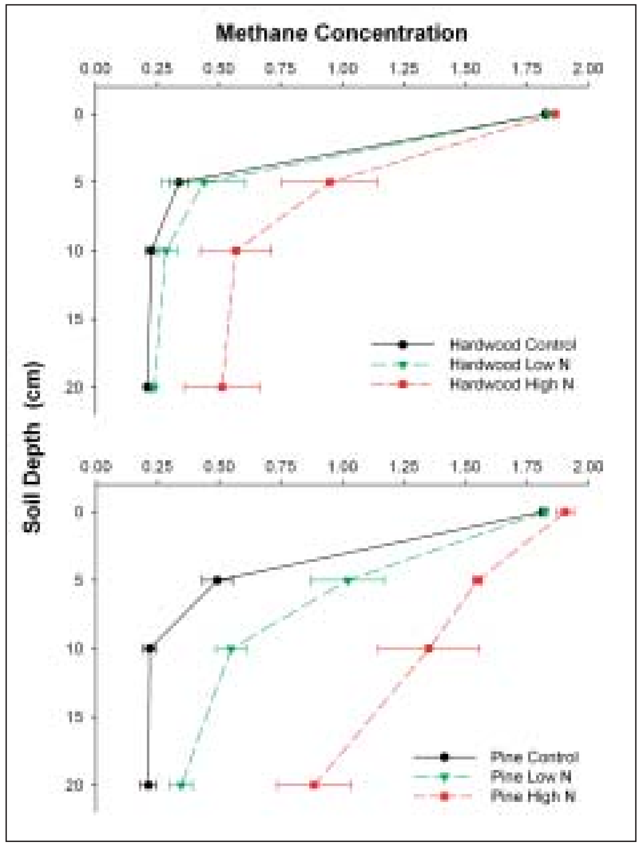


Figure 2. Methane concentration (measured in parts per million by volume) declines with soil depth in all treatments, but the nitrogen-treated plots exhibit greater concentrations at depth than controls. This suggests that nitrogen additions reduce methane consumption throughout the soil profile. These samples were collected in September, but are typical of patterns seen at other times of year. Bars indicate variability among samples; sample size = 3.

growing season. In contrast, nitrogen-treated plots, especially on the pine site, showed little seasonal increase and their year-round rates were also much lower than in untreated soils.

By measuring changes in methane concentration at the soil surface and at different depths within the soil, the researchers hoped to determine what mechanism was responsible for slowing methane consumption and how long lasting the changes might be. Greater methane concentrations in the soil profiles of the nitrogen-treated plots reflect a decrease in methane consumption rates. The depth profiles (Figure 2) shed some light on the mechanisms responsible for these changes. Higher methane concentrations in deeper soils indicate that the microbial community has been altered so that it is not capable of consuming as much methane as the controls. The number of methane-consuming microbes may have decreased or the population may have shifted toward species that use methane incidentally, rather than as a main

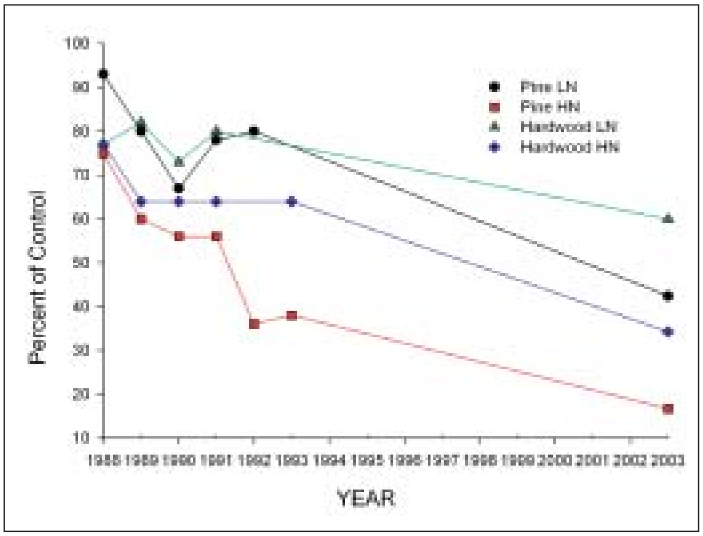


Figure 3. Trends in soil methane consumption at the Harvard Forest LTER nitrogen addition experiment. Methane consumption in low and high nitrogen plots is shown as a percentage of consumption in control plots. Both low N and high N treatments exhibit declining consumption over time.

source of carbon. Steudler and his colleagues are working on additional field and laboratory experiments that will help them distinguish among these and other possible explanations.

In 2003, the nitrogen-induced decrease in methane consumption was even larger than in 1992 and 1993 (Figure 3). Soil microbes in the high N pine plot consumed only 17 percent of the amount consumed in control plots, while the rate in the low N plot was reduced to 42 percent of the rate in the controls. The pattern in the hardwood plots was similar, with consumption in high and low N plots reduced to 34 percent and 60 percent of the control, respectively.

These findings help explain the low methane consumption rates measured in other forests in the United States and Europe that have received moderate to high nitrogen deposition for decades. These results also have important long-term implications for the methane consumption capacity of temperate forest soils in general. It appears that even moderate levels of nitrogen deposition may diminish the potential for these soils to slow the future growth in atmospheric methane, effectively weakening one of the natural brakes on this especially potent greenhouse gas.

Carbon Balance of Nitrogen-limited Tundra Ecosystems: Long-Term Results Confound Predictions Once Again!

After fertilizing the Alaskan tundra with nitrogen and phosphorus for 20 years and watching the plants grow ever bigger and more productive (Figure 1), Gus Shaver and his colleagues expected to find that the amount of organic matter in soils had also increased as a result of the increased deposition of leaf litter and other plant materials in fertilized plots.

Instead, they found that the layer of carbon-rich soil had grown thinner and less dense over the two decades of fertilizer addition.

The work, carried out by Gus Shaver of The Ecosystems Center and colleagues Michelle Mack and Ted Schuur of the University of Florida and Syndonia Bret-Harte and Terry Chapin of the University of Alaska, Fairbanks, clearly illustrates the pitfalls of solely relying on short-term studies to predict changes in slowly responding ecosystems. It also demonstrates the necessity of a reciprocal relationship between models and on-the-ground experiments.

Researchers at the center have shown repeatedly that fertilizer addition to tundra leads to dramatic increases in plant growth and photosynthesis, which means that carbon and organic matter inputs to the ecosystem are also increased. For example, in five previous harvests of one long-running experiment over the 20 years from 1981 to 2000, fertilizer addition approximately doubled the amount of new plant matter produced each year. In 2000, the same pattern was evident in plant productivity (Figure 2), yet soil carbon stocks and the carbon content for the whole ecosystem had decreased by about 20 percent (Figure 3).

Based on their understanding of decomposition in these soils, the researchers had expected that the new organic matter would decompose slowly and carbon would accumulate in the soil; simulation models, based on the same understanding, came to the same conclusions. When their measurements, in repeated samplings of two different long-term fertilizer experiments, showed losses rather than gains in soil carbon, Shaver and colleagues found they had to rethink both their understanding of what limits decomposition in these systems and the simulations that had grown out of that understanding.

One fact that became obvious only when a complete inventory of vegetation and soils was made is that, although the changes in primary production and plant biomass are very striking and clearly important (Figures 1, 2), the long-term increases in plant carbon content are tiny in comparison to the much larger soil carbon stocks (Figure 3). Primary production in unfertilized tundra adds about 150 grams of carbon per meter squared to the ecosystem each year (300 grams in fertilized tundra). These new carbon inputs compare to 7 to 9 kilograms of carbon per square meter already stored in tundra soils. The effects of the fertilizer on those large amounts of existing soil carbon are more important than effects on new carbon inputs.

TOM KLEINDINST

Gus Shaver

The new results shed light on both the functioning of tundra ecosystems and the long-term effects of environmental change on carbon exchange with the atmosphere. The fact that fertilizer addition increased carbon losses from tundra soils suggests that nutrient (probably nitrogen) availability, rather than carbon availability, limits decomposition. This is causing the research team to reexamine the literature and data on decomposition in tundra soils (most of

GUS SHAVER

Figure 1. Long-term fertilization experiments in their tenth year of treatment (1999) at Toolik Lake, Alaska. Unfertilized tundra is in the immediate foreground and the distant background. The dense stand of shrubby dwarf birch in the middle distance is the fertilized plot. Plastic greenhouses and shade frames in the background are additional shading and warming treatments, part of the Long-Term Ecological Research project.

it based on short-term studies lasting 1-3 years) with a fresh eye. Future plans include a range of experimental studies designed to determine how the initial chemical makeup of the organic matter interacts with soil temperature, moisture, and nutrient availability to determine carbon losses in decomposition.

Changes in the structure of soil invertebrate and microbial communities may also help explain the unpredicted increase in decomposition. Another colleague, John Moore of the University of Northern Colorado, has shown that fertilizer addition to wet and moist tundra caused a shift in the soil food web from one dominated by fungi to one based on bacteria. At present, the researchers can only speculate about the possible effect of this change in community structure on soil carbon balance.

Finally, the fact that decomposition increases more than productivity increases when nutrient availability is high casts doubt on past predictions of tundra response to climate change. According to previous models, higher productivity in a warmer climate would, in the long run, lead to increased carbon accumulation in both plants and soils; this would remove carbon dioxide (CO_2) from the air and is thus a negative feedback on carbon dioxide accumulation in the atmosphere. These long-term experimental results, however, suggest the opposite, indicating carbon net losses despite higher productivity, and therefore a positive feedback on atmospheric carbon dioxide increases.

Clearly, if simulation models are to be of any use in predicting long-term effects of environmental change on carbon balance of ecosystems, the mechanisms in the models need to be right. Long-term, whole-system experiments are a particularly effective way of illuminating the interactions and overall controls of major ecosystem processes like primary production and decomposition. One significant drawback of these experiments, though, is that researchers have used relatively drastic manipulations to induce major changes in both process rates and vegetation and soil community structure. The amount of nitrogen added in this experiment, for example, is at least 4-6 times the annual nitrogen uptake requirement of the vegetation in unfertilized tundra, a change that is unlikely to occur under any reasonable scenario of climate change or increased nutrient deposition. The next step is to use more subtle manipulations, such as low-level fertilizer addition and greenhouse warming experiments to increase nutrient turnover, to simulate situations more similar to actual or predicted environmental changes. This new round of experiments, some currently under way and some in the planning stages, will provide more realistic tests of model predictions based on an improved understanding of mechanisms.

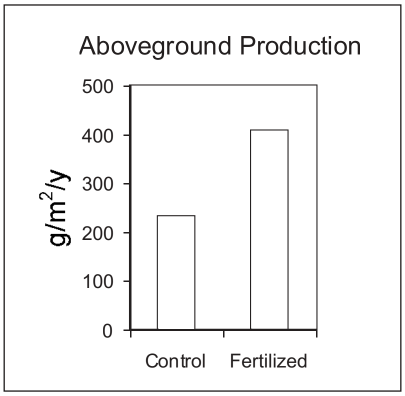


Figure 2. Aboveground production (not including root production) of new plant biomass in control and fertilized tundra at Toolik Lake in 2000. These plots were similar to those shown in Figure 1 but about 1 km to the east. In 2000 they were in their 20th year of fertilizer treatment.

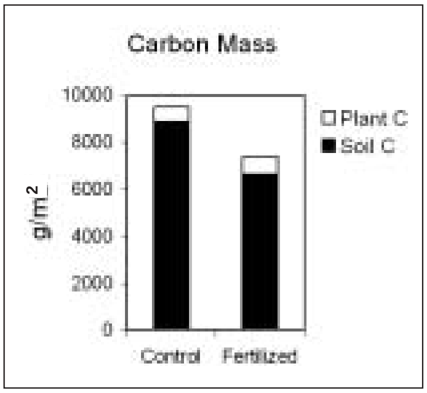


Figure 3. Mass of carbon (C) in plants and soils of control and fertilized plots at Toolik Lake in the summer of 2000, after 20 years of fertilizer addition. The C mass in plants includes not only the new plant material (produced during the current year) shown in Figure 2 but also old, perennial tissues such as woody stems. The soil C mass includes both the amount of C in the upper organic mat and the C in mineral soil within the annually thawed "active layer " that lies beneath the organic mat above the permafrost that underlies the entire system.

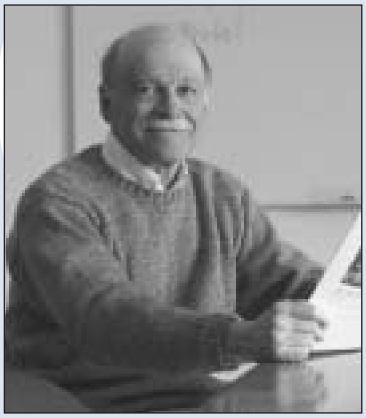
Mushrooms, found in fields and forests world-wide, are the fruiting bodies of certain fungi that consist of a network of microscopic threads, called hyphae. These fungi obtain energy and nutrients by breaking down soil organic matter, the remnants of plants and animals. Some species of mushrooms are symbiotic, living in a mutually beneficial association with the roots of many types of plants. Together, the roots and fungi are called mycorrhizae. The fungi obtain sugars from the plant roots and, in return, provide nitrogen and phosphorus to the plant. Although most of the plants in the world are mycorrhizal, little is known about how important the symbiosis is in providing the nutrients that are in short supply for the growth of the plants. In particular, the transfer of nitrogen has been difficult to measure.

John Hobbie of The Ecosystems Center and his son, Erik Hobbie of the University of New Hampshire, have investigated nitrogen movement from the soil to the plants in the Arctic tundra of the Long-Term Ecological Research project at Toolik Lake. Erik and colleagues have developed a model of how mycorrhizal symbiosis works in boreal (northern) and other forests; John has collected samples to test the model in the well-studied tussock tundra.

The new approach makes use of the natural abundance of ^{15}N. This is one of the two stable (non-radioactive) isotopes of nitrogen. The lighter isotope, ^{14}N, makes up most of the nitrogen on earth. The ratios of $^{15}N/^{14}N$ in soils and plants are expressed relative to the ratios of $^{15}N/^{14}N$ in atmospheric nitrogen gas and are reported in parts per thousand. This is known as $\delta^{15}N$. In biological and physical reactions the ^{15}N is used more slowly than ^{14}N because of its heavier mass. Thus, the nitrogen-containing compounds produced by these reactions will contain less ^{15}N (lower $\delta^{15}N$) than what remains behind.

By combining field data with model calculations, the team was able to assess what fraction of the plants' nitrogen came from the fungal association and what part was gathered directly by plant roots.

The model to be tested suggests that the hyphae take up nitrogen from the soil in the form of ammonium (NH_4^+) and amino acids. Inside the hyphae, the nitrogen compounds undergo a biochemical rearrangement into several amino acids that are subsequently transferred to the plant roots. Because the molecules containing ^{15}N form new amino acids more slowly than those containing ^{14}N, the amino acids that are transferred to the plants are depleted in ^{15}N while the nitrogen-containing compounds that remain in the hyphae are enriched in ^{15}N. Independent estimates of this change in abundance place it at about 8-10 parts per thousand (‰.) The result is that there are three pools of nitrogen, each with a different concentration of ^{15}N. These are the soil ^{15}N, the ^{15}N in the fungi, which is measured in the fruiting bodies (mushrooms) (Figure 1), and the ^{15}N in plants.


TOM KLEINDINST

John Hobbie

At the Toolik Lake research site, the natural abundance of ^{15}N has been measured in the soil, plants, and fungi. Some of the plants, such as sedges, have values of 2 to 3‰. They are not mycorrhizal and the model does not deal with them. The model applies to ecto- and ericoid-mycorrhizal plants, which include willow (*Salix)*, birch (*Betula*), and species of *Vaccinium* (blueberry and cranberry); they have a $\delta^{15}N$ of -3 to -7 and contribute around 70 percent of the primary production at this site, according to Gus Shaver of The Ecosystems Center.


ALISON HOBBIE

Erik Hobbie

To test the model, the researchers chose three values that encompass the range of $\delta^{15}N$ in soils: 0, 1, and 2‰. The $\delta^{15}N$ measured in the mushrooms is 6 to 8‰ except for one species (*Laccaria*) that cannot break down proteins, so they used a value of 7‰ for mycorrhizal fungi. To represent the nitrogen that ends up in plants, they chose a typical mycorrhizal plant with a $\delta^{15}N$ of -5‰.

Based on the $\delta^{15}N$ of plants, soil and fungi, the model (Figure 2) apportions the ^{15}N into that transferred into the plant and that remaining in the hyphae. Knowing the $\delta^{15}N$ of the

JOHN HOBBIE

Figure 1. ***Laccaria*** **sp. at Toolik Lake research site.**

JERRY LOOMER

John Hobbie removes cellulose disks from the tundra. Disks were incubated in the soil for seven weeks to collect fungi.

plant and the amount of ^{15}N taken up, the researchers were able to calculate the percent of the total plant N contributed by the mycorrhizae. This is 50 to 86 percent – the range reflects the uncertainty of the $\delta^{15}N$ of the soil.

The last step in the calculations goes beyond the model and translates the percent of the total plant nitrogen into the actual quantities of nitrogen moving through the fungi and into the plants, 0.4 to 0.7 grams of nitrogen per square meter (g N/m^2) (Figure 3). This was possible because the annual productivity of these plants has been measured by Shaver and his co-workers as equivalent to 0.8 g N/m^2.

The researchers were also able to calculate how much carbon the plants donated to their symbiotic partners, because they had measured a carbon to nitrogen ratio of 10 in the fungi. They found that the fungi use 5 to 16 percent of the plant's photosynthate (carbon generated by photosynthesis) in return for providing 50 to 86 percent of the plant's nitrogen. The mycorrhizal symbiosis is not only present but vital to the plant's growth.

The application of the model at the Toolik site successfully accounted for the depletion of the $\delta^{15}N$ in the plant leaves as well as for the enhancement of the $\delta^{15}N$ in the mycorrhizal fungi. The conclusions are ecologically reasonable.

Based on the results of this model and knowledge of other nitrogen flows in this system, John and Erik Hobbie concluded that the mycorrhizal association provided the majority of the nitrogen in the mycorrhizal plants at the Toolik Lake site. The relationships evident there allow them to suggest mechanisms that would explain changes in the natural abundance of ^{15}N at other experimental sites. For example, there are a number of long-term experiments underway across the United States and Europe that double the carbon dioxide concentration over a plot or portion of a forest. In these experiments, plant foliage generally exhibits depletion of the $\delta^{15}N$ but fungal ^{15}N is rarely measured. One plausible explanation is that plants, faced with abundant carbon but short on nitrogen, rapidly increase carbon flow to their roots and mycorrhizal fungi. The results are more growth of mycorrhizal fungi, an increase in the amount of nitrogen depleted in ^{15}N going to the plants, and a decrease in the $\delta^{15}N$ of the plants. This model can be an effective tool for teasing out the relationships between mycorrhizal plants and fungi, but only when they exhibit strong differences in their natural abundance of ^{15}N. It is fortunate then, that the depletion of plant $\delta^{15}N$ is common in nitrogen-limited plant communities throughout the world, particularly in Arctic, boreal, and temperate forests. This approach will be successful for analysis of the nitrogen cycle in all these systems but only when soil, plant, and fungal $\delta^{15}N$ values are all measured. As researchers in these systems begin collecting and analyzing mushrooms, as well as plant and soil samples, ecologists will be able to discern patterns in nitrogen and carbon usage that had previously been hidden.

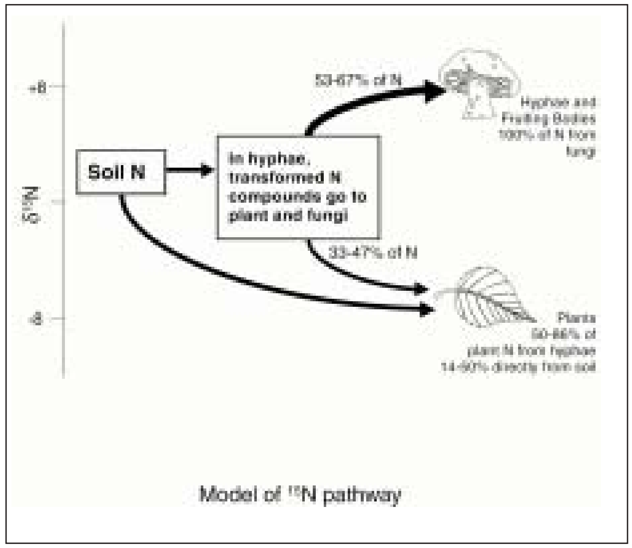


Figure 2. Model of the ^{15}N pathway at the tundra site. Nitrogen in the soil, which may have a $\delta^{15}N$ of 0, 1 or 2, is taken up into the fungal hyphae, where ^{14}N is converted to amino acids faster than ^{15}N. The nitrogen passed on to the plant as amino acids therefore contains less ^{15}N. From the ratios of ^{15}N to ^{14}N in plants and fungal fruiting bodies, it is possible to calculate that the plant received 33-47% of the N while the hyphae and fruiting bodies retained 53-67%. Of the N in the plant, 50-86% comes from the fungal hyphae and 14-50% is drawn directly from the soil nitrogen pool.

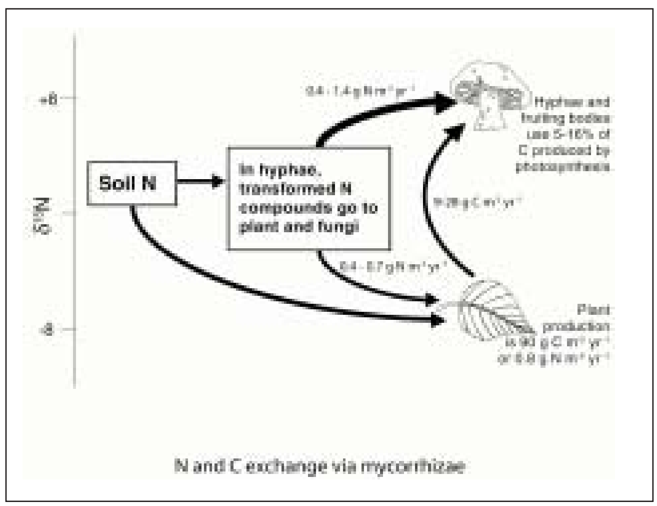


Figure 3. Nitrogen and carbon exchange via mycorrhizae, estimated from the $\delta^{15}N$ and from plant biomass production. From LTER and other data, nitrogen is incorporated into plant biomass at a rate of 0.8 g N per square meter per year. Based on the model (Fig. 2), fungal hyphae take up 0.44-1.4 g N per square meter per year. If the ratio of fungal C:N is 10 and fungi incorporate 50% of the C they receive through the hyphae, then 9-28 grams of carbon per square meter per year move from plants to fungi. This represents 5-16% of the carbon photosynthesized by plants.

Semester in Environmental Science:

Hands-on Approach is Key to Learning about Ecosystems

TOM KLEINDINST

Ken Foreman, SES Associate Director

The Ecosystems Center's Semester in Environmental Science was offered for the seventh time in 2003. Nineteen undergraduates participated in the fall semester program, representing 14 of the 60 colleges and universities within the MBL Consortium in Environmental Science.

Members of the consortium agree to grant credit to their students who successfully complete the SES curriculum. A notable addition to the consortium in 2003 was Brown University, which will grant credit not only to their own students who complete the SES program, but also to students from non-affiliated colleges and universities who are accepted into the program. This effectively opens the program to qualified students from any college or university in the nation.

TOM KLEINDINST

Dixie Berthel

The SES program provides undergraduates with a unique opportunity to work with center scientists to study biogeochemistry and ecology in freshwater ponds, estuaries and forests on Cape Cod. These local ecosystems are affected by nutrient overloading, urbanization and land-use change, invasions of exotic species, and climate change - issues of global significance that make these ecosystems excellent natural teaching laboratories.

The goal of SES is to help train the next generation of environmental leaders. SES is not simply a program in marine biology or terrestrial ecology, but integrates and contrasts ecosystems structure and processes across the landscape. Lectures are given by the center's research scientists. Students learn to think critically about scientific information and environmental issues by analyzing and interpreting data they collect for themselves in a diverse array of ecosystems on Cape Cod. SES provides a way for undergraduates to become exposed to and engaged in ecosystem research during the formative stages of their education. Students aspiring to become policy makers and environmental advocates leave SES equipped to understand complex issues.

Students in SES spend about 20 hours each week in the field and lab, and take core courses in aquatic and terrestrial ecosystems science, an elective, and a science-writing seminar. During the last third of the semester, students conduct an independent research project under the guidance of center research scientists.

Teaching by means of a hands-on approach is central to the SES experience, and so it is with the electives that the students take. In both electives offered in 2003, Mathematical Modeling in Ecosystems, taught by Ed Rastetter, and Microbial Methods in Ecology, taught by Joe Vallino, students learn techniques and methods by performing them in a series of laboratories.

"I've learned a lot here, both about myself as a scientist and about ecosystems science…I can think of no better way to synthesize and apply years of courses than this…I'm amazed at how much you've been able to do for all of us to make this a wonderful experience."

Melanie Hayn
(SES '03, Cornell University '04)

In the Microbial Methods course, students work with techniques such as epifluorescence microscopy for bacterial abundance, radioisotopic tracers for bacterial productivity, fluorescent substrates for extracellular enzyme activity, and use molecular probes to assess species diversity. Students learn that the development and application of new methods lead to advances in understanding microbes. For instance, the application of epifluorescence microscopy and radioisotopic tracers led microbial ecologists to realize that the number of microorganisms and their growth rate were many orders of magnitude higher than was previously thought.

Early in the semester, students travel to Little Sippewissett Marsh in Falmouth, where they collect marine sediments to construct a self-contained, miniature ecosystem, known as a Winogradsky Column, which they use throughout the course to study microbial communities. Students study the metabolic processes of both production and respiration that are the result of microbial activity in ecosystems. These include sulfide oxidation, nitrification, and sulfate and nitrate reduction. Students measure consumption of electron acceptors (e.g., nitrate and sulfate) and production of reduced end products, such as a sulfite, by bacteria in these systems.

Focusing on system-level understanding using the Winogradsky Column is key to the elective. Often microbial processes are studied in isolation. This course, however, emphasizes the coordination of the entire microbial consortium, since the products of one group of microorganisms often serve as food to another group of microorganisms. Although different microorganisms conduct different reactions, the overall microbial community is tightly coordinated and efficiently recycles elements on a global scale. Without these microbial communities, higher life forms on our planet would not be possible.

In the Mathematical Modeling elective, students learn to build dynamic simulation models of the ecosystems they have been studying in the core course. They then use their computer models to analyze questions like "How will ecosystems respond to global warming?" or "How do competing species respond to increased carbon dioxide or nitrogen pollution?"

These models are typically based on a mass-balance analysis of each of the components of an ecosystem. For example, a model's components might include nutrients in organic matter, algae that take up the nutrients during photosynthesis, and zooplankton that consume the algae. The mass-balance analysis is analogous to assessing the monetary balance of a bank account: the rate of change of mass equals the inputs (deposits) minus the outputs (withdrawals). The ecosystem components are then linked together by the flow of materials like carbon or nitrogen from one component to another. The final model takes the form of a system of interdependent mass-balance equations, one for each ecosystem component.

The center's connection with SES students does not stop when the semester ends. Many SES students have expanded their independent research projects into senior honors theses with center scientists as co-advisors. To date, The

"My experience in Woods Hole was a big part of what influenced me to continue my education… It was amazing to live in a community of scientists… The SES program is truly a unique opportunity for undergraduates, combining classes, research and community."

Lynn Diener, Ph.D. Candidate, University of Wisconsin (SES '97, Bard '99)

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Hampshire College
Harvey Mudd College
Haverford College
Hendrix College
Kenyon College
Lafayette College
Lawrence University
Lynchburg College
Macalester College
Mary Washington College
Middlebury College
Millsaps College
Morehouse College
Mt. Holyoke College
Randolph-Macon Woman's College
Rhodes College
Ripon College
Rollins College
Sarah Lawrence College
Skidmore College
Southwestern University
Spelman College
Trinity College (CT)
Trinity University, (TX)
University of Richmond
University of the South, Sewanee
Vassar College
Wabash University
Washington and Lee University
Wellesley College
Wesleyan University
Wheaton College
Williams College
Worcester Polytechnic Institute

Semester in Environmental Science Distinguished Scientist Seminar Series 2003

September

5 Pedro Sanchez, The Earth Institute, Columbia University "Eliminating hunger in Africa: What needs to be done?"

26 Jackie Grebmeier, University of Tennessee "Benthic processes in the Arctic Ocean: Temporal/spatial variability and global change."

October

17 Don Anderson, Woods Hole Oceanographic Institution "Red tides and harmful algal blooms (HABs): The global problem and a regional case study in the Gulf of Maine."

November

21 Ann Bartuska, The Nature Conservancy "Abating the threat of invasive species: Putting science to work in public policy."

CAITLIN HICKS

Marselle Alexander of Bates College takes pore water samples in a white cedar swamp in Woods Hole. Marselle's final project, "The role of *Sphagnum* in the acid-base chemistry of bog waters" won the MBL Associates' prize for excellence at the public symposium at semesters' end.

Ecosystems Center has hired 22 SES graduates as summer research assistants, interns in the National Science Foundation's Research Experience for Undergraduates program, teaching assistants or full-time research assistants.

Nearly 40 percent of SES graduates are currently enrolled in graduate or professional training programs in environmentally related fields. Three-quarters of SES alumni remain involved in careers dedicated to environmental advocacy, research or policy.

The major source of funding for the Semester in Environmental Science has been the Andrew W. Mellon Foundation, which contributed $500,000 in 2003. Also this year, the SES program received grants of $250,000 from the C.V. Starr Foundation, $25,000 from the Harold Whitworth Pierce Foundation, $12,500 from the Environmental Data Research Institute and $5000 from the Blum-Kovler Foundation. These grants, as well as past support from the Davis Educational Foundation, The Burroughs Wellcome Fund and the Charles E. Culpeper, Catherine Filene-Shouse, and Worthington Family Foundations, are much appreciated. Generous contributions from individuals, including the Sears and Osterhout families and the Bill and Phoebe Speck Fund have provided significant support for scholarships.

I still view my experience at SES as one of the most valuable of my undergraduate career. It has provided me with a much more complete understanding of the complex relationships of the planet's ecosystems. I am constantly referring to the knowledge I obtained while I was in Woods Hole.

Kyle Schwabenauer,
Pollution Control Engineer
(SES '98, Allegheny College '00)

The Ecosystems Center's education activities are varied. In addition to teaching the Semester in Environmental Science and actively participating in the Brown-MBL Graduate Program in Biological and Environmental Sciences, center scientists serve as adjunct professors, guest lecturers and members of doctoral committees at a number of colleges and universities. Senior staff members supervise postdoctoral scientists at the center and undergraduate interns at remote research sites. Visiting scientists and students come to work on projects, some for a week or two and some for a year or more. Staff members work with elementary and secondary school students, serving as mentors and judges in local science fairs.

Student Research Opportunities

With funding from the National Science Foundation, many college students participated in the Research Experience for Undergraduates (REU) program in 2003, working with Ecosystems Center scientists at field research sites.

Julie Allen, a student at Michigan State University, spent the summer at the Arctic Long-Term Ecological Research (LTER) site at Toolik Lake, Alaska, where she examined the effects of temperature change on primary production in Arctic lake systems. Also at Toolik Lake, Joseph Bartlett of the University of Vermont worked with Linda Deegan and Jon Benstead on a study of the effects of phosphorus fertilization on growth of Arctic grayling. Another University of Vermont student, Nathaniel Morse, worked on a project that measured oxygen balance in Arctic streams.

Under Gus Shaver's direction, Alex Breslav of Pennsylvania State University set up a project at the Toolik Lake LTER site to determine the relationship between light levels and nitrogen fixation in the tundra. Brooke Kaye of Cornell University also worked with Gus on an experiment that examined how gross ecosystem productivity varied along a topographic sequence at Imnaviat Creek in Alaska. Joe Powers of Michigan Technological University designed a project to study soil moisture probe calibration in organic layers of Arctic tundra.

With Anne Giblin, Lyndon Valicenti of the University of California at Santa Barbara looked at water column fixation in the Arctic lakes. Back on Cape Cod, Trisha Thoms of Colorado College worked with Anne on her Boston University Marine Program REU project at West Falmouth Harbor.

At the Plum Island Ecosystem LTER site, Aislinn Agnew, a student at Gordon College, carried out an REU project on the growth of different salt marsh invertebrates on four common marsh plants. With Chuck Hopkinson and Vin Valentine, Jason Cavatorta of Amherst College studied marsh sedimentation patterns along the Parker and Rowley Rivers. Morgan Johnston of Pennsylvania State University investigated the importance of metabolism in salt marsh pond development within the Plum Island Sound estuary.

Chris Freeman of Connecticut College completed a project with Heather Haas and Linda Deegan at Plum Island on trophic support of fish in salt marsh habitats. Matthew Holden, an REU from Clark University, worked at the Plum Island site to digitize maps of land cover from 1951. Joshua Hopp of Washington and Jefferson College studied the distribution of benthic chlorophyll in salt marsh tidal creeks.

At the Harvard Forest LTER, Heidi Lux was mentor for a Dartmouth College student, Margaret Graham, who studied soil respiration and soil carbon pools at the forest. On Martha's Vineyard, Chris Neill worked with two undergraduate interns, Talia Chalew of the University of Maryland and Rebecca Hale of Hampshire College, on the sandplain restoration project.

Schoolyard Long-Term Ecological Research (LTER) Projects

Both the Arctic LTER and Plum Island LTER projects received supplemental funding from the National Science Foundation to develop educational activities at or near their sites.

The Schoolyard Project of the Arctic LTER at Toolik Lake is based in Barrow, Alaska, 250 miles to the northwest of Toolik, since there is no community near Toolik. The program is designed for Barrow students, who are mostly Native Iñupiat Eskimo, in kindergarten through


LAURIE CHIASSON

Heidi Lux

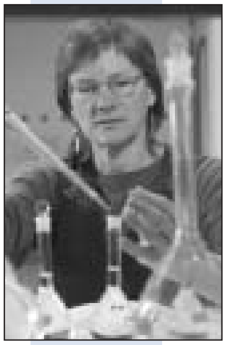

TOM KLEINDINST

Vinton Valentine


PHOTO COURTESY OF AIMLEE LADERMAN

Aimlee Laderman

grade 12, their teachers, and local residents. It consists of two activities, a field experiment to demonstrate the effects on tundra vegetation of warmer air and soil temperatures and "Schoolyard Saturday," a weekly series of lectures and field demonstrations by visiting and resident scientists. The program is administered by the Barrow Arctic Science Consortium, with input from retired Arctic scientist Jerry Brown of Woods Hole, who was instrumental in developing the Barrow project.


TOM KLEINDINST

Pat Micks


HEIDI WILCOX

Jon Benstead

In 2003, a gift from BP Exploration Alaska helped fund a trip for three Barrow High School students and their science teacher to Toolik Lake Field Station, where they were able to see the Arctic LTER's tundra warming experiments. Also, an automatic weather station was installed for year-round observations at the Barrow greenhouse site. Forty sessions of the Schoolyard Saturday lecture series were held; total attendance for the year was approximately 1,300 students and adults. In August, Heidi Wilcox from The Ecosystems Center visited Barrow and set up an experimental site at a small lake on the Barrow Environmental Observatory for students to use in 2004.


JIM LAUNDRE

Yuriko Yano

In 2003, the Plum Island LTER Schoolyard program and Massachusetts Audubon Society's Salt Marsh Science project expanded their partnership. Thanks to funds contributed by the Schoolyard LTER and others, Mass Audubon provided ongoing support for 42 teachers in 10 schools enabling them to teach field protocols and complementary classroom lessons. The Schoolyard LTER also helped to support two Mass Audubon educators provide classroom and field support for more than 1,500 students in the towns of Newburyport, Newbury, Rowley, Salisbury, Ipswich, Salem, Danvers, Gloucester, and East Boston.

Science Education in the Community

Many members of The Ecosystems Center staff judged community science fairs or assisted students with their science fair projects.

Hap Garritt, Michele Bahr, Gus Shaver and Jane Tucker judged the Falmouth Academy science fair and Michele and Marshall Otter were judges at the Falmouth Public Schools Science Fair. Marshall also judged projects at the Massachusetts State Science Fair at the Massachusetts Institute of Technology.

Debbie Scanlon served as the center's liaison with the Woods Hole Science and Technology Education Partnership (WHSTEP), a collaboration of scientific institutions, schools and businesses that supports science and technology education. WHSTEP coordinates a program with the Lawrence School, Falmouth's junior high, to bring scientists to the school to advise students on their science projects. Laura Broughton, Ben Felzer, Pat Micks, Sam Kelsey, Heidi Wilcox and Michele Bahr were mentors in 2003.

Chris Neill continued to write his column on natural history for the *Falmouth Enterprise.*

Science Journalism Program/Arctic Ecology and Modeling Course

The Ecosystems Center participates each year in the MBL's Science Journalism Program. Journalists attend lectures and a laboratory session in June in Woods Hole, co-directed by Ken Foreman and Chris Neill with help from Sam Kelsey. This year, two of the journalists, Amanda Onion of ABCnews.com and Nicola Jones of *New Scientist* magazine, also traveled to Alaska in August to take part in Arctic Ecology and Modeling, an MBL summer course that was part of a National Science Foundation BioComplexity research project. The course, organized by John Hobbie and Debbie Scanlon, was designed to educate students about the Arctic environment and demonstrate the relationship between data collection and quantitative modeling.

After two days of lectures and demonstrations at the University of Alaska, Fairbanks (UAF), and the Bonanza Creek Long-Term Ecological Research (LTER) site, John Hobbie and Dave McGuire of UAF drove the class along the 400-mile northern section of the Dalton Highway from Fairbanks to Prudhoe Bay. They stopped along the route to discuss the ecology of the region, and stayed at the Toolik Lake LTER site for several days. At Toolik, scientists there gave talks on hydrological and terrestrial modeling, geology of the Brooks Range, biogeochemistry and nutrients. Field trips were taken to Atigun Gorge and Slope Mountain as well as to the terrestrial and aquatic experimental sites at Toolik.

In addition to the science writers, there were seven other participants in the class. Three were teachers: Jerry Loomer, a high school science teacher from Rapid City, South Dakota; Jerri-Lynn Hollyfield, an elementary school teacher from Birmingham, Alabama, and Richard Sperduto, a teacher and facilities manager at Falmouth Academy. Two students were recent college graduates investigating a future in environmental research: Elizabeth Deliso from the Rocky Mountain Biological Laboratory in Crested Butte, Colorado, and Jennifer Salotto of Beth Israel/Deaconness Medical Center of Boston. There was one master's candidate, Annika Mosier of the University of Nevada, and a professional geologist, Alice Stieve of the Savannah River Site in South Carolina.

Semester in Environmental Science

Most members of The Ecosystems Center staff were involved with the Semester in Environmental Science program in 2003. John Hobbie served as SES director, Ken Foreman as the program's associate director, and Dixie Berthel as administrative assistant. Teaching assistants were Pat Micks, Bonnie Kwiatkowski, Marcus Gay, Ian Washbourne, Jen Bowen, Leslie Graham and Becky Karasack. Ed Rastetter taught the elective course in mathematical modeling and Joe Vallino taught the microbial methods elective. John, Ed, Ken, Linda Deegan, Anne Giblin, Chuck Hopkinson, Jerry Melillo, Gus Shaver, Chris Neill and Bruce Peterson gave lectures for the core aquatic and terrestrial courses. Retired Yale University scientist Aimlee Laderman provided students with expert advice on white cedar swamps, the subject of several students' final research projects. Other staff members were involved in an unofficial status, helping students with field work, lab assignments or independent study.


TOM KLEINDINST

Qianlai Zhuang

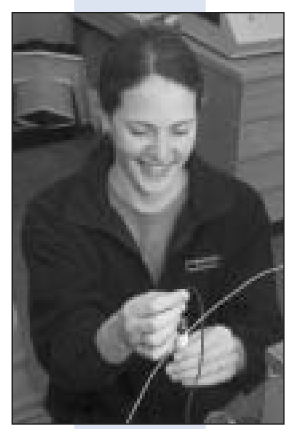
Postdoctoral Scientists

Laura Broughton came to The Ecosystems Center in 2002 to work with Gus Shaver. She has a National Science Foundation Microbial Biology Fellowship to investigate the effects of climate change on the soil microbial community in Arctic systems. Laura received her doctorate in 2001 from Michigan State University, where she studied with Kay Gross at the Kellogg Biological Station. Her dissertation research investigated former agricultural fields and effects of plant communities on soil microbes. At the center, she is studying the effects of warming and fertilization treatments on differences in soil microbial community composition and processes among tundra types at the Arctic LTER site in Toolik Lake, Alaska.


JON BENSTEAD

Chris Crockett

Jon Benstead received his doctorate from the University of Georgia in 2001, where he worked with Cathy Pringle at the Institute of Ecology. His dissertation research examined the consequences of catchment deforestation for stream ecosystems in eastern Madagascar. Since arriving at the center in 2002, he has been working with Linda Deegan and Bruce Peterson on responses of small Arctic streams to nutrient enrichment and the controlling factors in population trends and growth of Arctic grayling.


TOM KLEINDINST

Emily Gaines

Al Chan joined the center in 2002. He received his doctorate in 2000 from the Department of Microbiology at Iowa State University and did his research at The National

Brown-MBL Graduate Program

DEBBIE SCANLON

Marshall Otter discusses the evolution of preparation techniques used in stable isotope analysis with Brown University's Warren Prell, geology professor, and Tom Dean, deputy provost.

The Brown University-Marine Biological Laboratory Graduate Program in Biological and Environmental Sciences was established this year, providing exciting opportunities and benefits for both institutions. Ecosystems Center co-director Jerry Melillo led the MBL effort to develop the partnership.

Students in the joint Brown-MBL graduate program will work with scientists at both institutions and conduct research in either institution's laboratories.

MBL affiliation is a cornerstone of Brown's new Environmental Change Initiative, a multidisciplinary research and education program designed to address complex global environmental issues. Building on Brown's collective strengths in ecology and evolutionary biology, environmental science, economics, geological sciences, sociology and international policy, the Environmental Change Initiative will draw upon MBL's research, education and training programs.

The Brown-MBL partnership will also provide opportunities for faculty exchange and collaborative research, establishing joint multidisciplinary, multi-investigator projects that will take advantage of both institutions' resources.

"Developing a joint graduate program like this one is a major outcome of a recent strategic planning process designed to chart the future of the laboratory," said MBL Director William Speck. "This is an exciting venture that will enhance the MBL's research and educational programs."

"This match is perfect," said Mark Bertness, professor of biology at Brown. "At Brown, for example, we have excellent evolutionary biologists, while MBL has an outstanding phylogenetics program. Brown has expertise in community ecology and MBL has the world's best ecosystems science group. We're complementary."

Brown has become a member of the consortium of the Semester in Environmental Science, The Ecosystems Center's undergraduate program. Student enrollment in both graduate and undergraduate programs will be offered for the fall semester of 2004.

Soil Tilth Laboratory in Ames, Iowa, working with Timothy Parkin. His research focused on the controls of methane cycling in soils. Al is working with Paul Steudler on the Atmospheric Methane Oxidizers in Soil project, investigating the short- and long-term effects of nitrogen deposition on methane oxidation in temperate forests and how they relate to the physiological and molecular diversity of atmospheric methane oxidizers. Al is also the creator and webmaster of Microbes.info, a resource for finding information on microbiology topics.

Vinton Valentine came to The Ecosystems Center this year to work with Chuck Hopkinson. He received his doctoral degree from the University of Delaware, where he studied with Vic Klemas at the Center for Remote Sensing in the Graduate College of Marine Studies. In his dissertation research, he used remote sensing and GIS technologies to investigate the displacement and spatial structure of the scrub-shrub/emergent wetland ecotone along tidal rivers as a result of sea-level change and human impacts. At the Plum Island Ecosystem LTER site, Vin is analyzing creek network patterns to develop indicators of condition and stability for tidal marshes facing sea-level rise and other stressors.

Yuriko Yano joined The Ecosystems Center in 2002 after receiving her doctorate from the Department of Forest Science at Oregon State University in 2002. Currently, she works with Gus Shaver, Anne Giblin and Ed Rastetter on nitrogen cycling and turnover in an Arctic watershed at Toolik Lake, Alaska. The main focus of her research is to determine how nitrogen is retained in soil and/or transported in hydrological flows within the watershed.

Qianlai Zhuang joined the center in 2001 to work with Jerry Melillo in the Terrestrial Ecosystem Model (TEM) group. He completed his doctorate that same year at the Institute of Arctic Biology and Department of Biology and Wildlife of the University of Alaska in Fairbanks, where he studied with David McGuire. In his dissertation research, he investigated the effects of changes in permafrost on carbon dynamics in high-latitude ecosystems. He also examined interactions among permafrost changes, water dynamics and fire for their effect on carbon dynamics. Since he came to The Ecosystems Center, Qianlai has been working on both a biocomplexity project and a land-use and land-cover change project. His research focuses on the dynamics of soil methane emission and consumption and their feedbacks between terrestrial ecosystems and climate.

Heather Haas received her doctorate in 2001 from the Department of Oceanography at Louisiana State University under the guidance of Richard Shaw and Kenneth Rose. In her dissertation research she used statistical and simulation modeling to examine brown shrimp population dynamics in the northern Gulf of Mexico. Heather joined The Ecosystems Center staff in 2002 to investigate higher trophic levels at the Plum Island LTER site. She works with Linda Deegan to study habitat preference patterns of mummichog fish.

Zhenwen Wan came to The Ecosystems Center in 2002 after two months in Alaska, where he received a visiting scientist award from the International Arctic Research Center, Japanese Frontier Research System for Global Change, to develop a physical-biogeochemical coupled plankton ecosystem model. He received his doctorate in 1999 from the Institute of Oceanology, Chinese Academy of Sciences. His dissertation research focused on the development of a plankton ecosystem model and the study of ecological dynamics in Jiaozhou Bay, China. Following that, he worked as an assistant research scientist in the First Institute of Oceanography, SOA, China. He works with Joe Vallino, Bruce Peterson and Linda Deegan, modeling biogeochemical processes of Arctic streams.

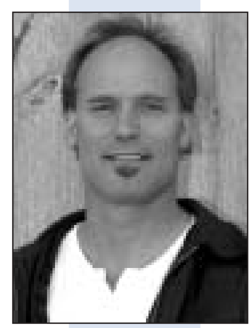
Michael Williams came to The Ecosystems Center in 2000 after two years in Brazil, where he received a visiting scientist award from the Foundation for Research and Development to study precipitation and river chemistry of the Piracicaba River basin and an NSF International Research Fellow Award to study relationships between land use and water quality in the Amazon basin. He received his doctorate in 1997 from the University of California at Santa


TOM KLEINDINST

Chuck Hopkinson


TOM KLEINDINST

Ben Felzer


CINDY VALLINO

Joe Vallino

JON BENSTEAD

Heidi Wilcox

Barbara. His dissertation research focused on the effects of prescribed burning and drought on exports of solute from mixed-conifer catchments and their sources in the Sierra Nevada. At the center, he has worked with Chuck Hopkinson, Ed Rastetter and Joe Vallino on land use, water quality and in-stream processing of nitrogen in the Ipswich River basin on the northeast Massachusetts coast. Mike left the center in February to assume a joint appointment as research scientist at the University of Maryland and Cornell University.

Martin Sommerkorn joined The Ecosystems

PHOTO COURTESY OF JERRY LOOMER

BioComplexity Class

SHARON BROUGHTON

Laura Broughton

Center in 2000 to work with Ed Rastetter on controls on belowground carbon and nutrient dynamics in tundra systems. He completed his doctorate in 1998 at the University of Kiel, Germany, where he studied with Ludger Kappen at the Institute for Polar Ecology. For his dissertation, he examined spatial patterns and controls on carbon dioxide fluxes in Siberian tundra systems. Martin also completed postdoctoral work on the coupling of net primary productivity and methane emissions in wetlands with Torben Christensen in Lund, Sweden, and came to The Ecosystems Center from the National Research Center for Environment and Health in Munich, Germany. At the center, he conducted and coordinated an experiment using the carbon-14 isotope as a tracer at the Arctic LTER site at Toolik Lake, Alaska. Martin moved to Aberdeen, Scotland, in June to become a research scientist at the Macaulay Institute.

Byron Crump joined The Ecosystems Center in 1999 after completing his doctorate in biological oceanography at the University of Washington, where he studied with John Baross. His dissertation described the microbial ecology of the Columbia River estuary, focusing on the abundance, activity and community structure of bacteria and on the relationships between bacterial activity and the physical and chemical aspects of turbidity in the estuary. He worked with John Hobbie at the LTER sites in Massachusetts and Alaska, studying changes in microbial activity and community composition. In April, Byron accepted a position as assistant professor at the University of Maryland.

Mary Booth joined The Ecosystems Center in 2001 after completing her dissertation in ecology at Utah State University, where she worked with Martyn Caldwell and John Stark. Her dissertation research focused on changes in water and nitrogen cycles associated with invasions of annual grasses in the Great Basin. At the Arctic LTER at Toolik Lake, Alaska, she worked with Gus Shaver to examine controls on the processing and retention of inorganic nitrogen in soil organic matter at different stages of decomposition. Mary left the center in August to begin a postdoctoral fellowship at Lamont-Doherty Earth Observatory, Columbia University.

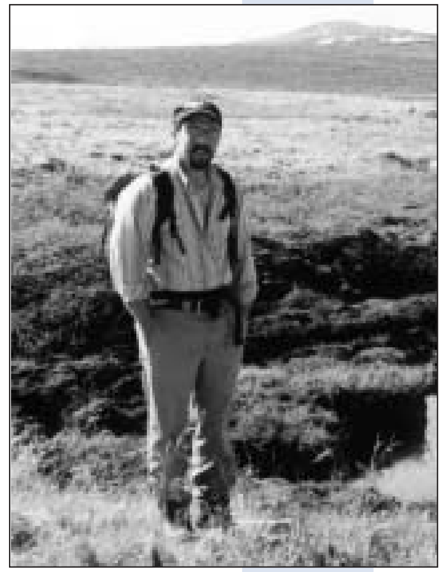
Diane Sanzone joined the center in 2001 after completing her doctorate at the Institute of Ecology, University of Georgia, where she worked with Judith Meyer. Her dissertation work focused on the transfer of nutrients and organisms from aquatic to terrestrial ecosystems and their effect on consumers in eight different terrestrial biomes. While completing her doctorate, Diane spent a year in Iceland as a Fulbright Scholar studying nitrogen dynamics in Arctic rivers. At the center, she worked with Bruce Peterson at the Toolik Lake LTER site on questions related to food-web dynamics and nutrient spiraling in Arctic streams. In September, Diane became Arctic Network Coordinator for the National Park Service in Fairbanks, Alaska.

Heather Rueth came to The Ecosystems Center in 2001 after completing her doctorate in ecology at Colorado State University, where she worked with Jill Baron of the Natural Resource Ecology Laboratory. Her dissertation addressed alpine forest responses to nitrogen deposition in Northern Colorado, focusing on changes in nitrogen biogeochemical processes with increased nitrogen availability. Heather worked with Gus Shaver and the International Tundra Experiment (ITEX) group to develop a biogeochemical sampling protocol to be used throughout the ITEX network of 25 sites and was involved with the Northeastern Ecosystem Research Cooperative-Nitrogen (NERC-N) Synthesis group studying the response of forest ecosystems to elevated nitrogen deposition. In August, Heather joined the faculty at Grand Valley State University in Michigan as an assistant professor.

Solange Filoso also joined the center in 2001 after two years at the University of São Paulo in Brazil, where she studied the effects of land use changes and other human activities on the export of nitrogen in tropical rivers. She received her doctorate in 1996 at the University of California at Santa Barbara under the guidance of John Melack. Her dissertation research was on the importance of throughfall and atmospheric deposition on the biogeochemistry of the Negro River, the largest tributary of the Amazon River. At the center, she worked with Chuck Hopkinson, Ed Rastetter and Joe Vallino on the simulation of nitrogen processing and transport in the Ipswich River basin, using a hydrochemical model. Solange left the center this year to accept a position as a postdoctoral associate at Cornell University.

Adjunct Scientists

Paul Colinvaux, an adjunct scientist at the center, came from the Smithsonian Tropical Research Institute in Panama. He is professor emeritus at Ohio State University. His paleoecological research reconstructs environmental histories from data such as sub-fossil pollen in lake sediments. His current research, funded through NSF in collaboration with Lawrence Livermore National Laboratory and Lamont-Doherty Earth Observatory, is to test whether tree-rings of the tropical tree *Hymanaea courbaril* from Panama and Brazil can be used as climate indicators.


JOHN HOBBIE

Neil Bettez

Robert Howarth, an adjunct scientist at the center, returned to Cornell University this summer, after an 18-month leave of absence that he spent at The Ecosystems Center. While at the center, Bob continued his work on nitrogen fixation in tropical forests and coastal marine ecosystems and was instrumental in organizing conferences on the subject throughout the world. In April, he received the Lindeman Award for outstanding ecologist from the University of Minnesota. He was also appointed director of the North American Nitrogen Center, part of the new International Nitrogen Initiative. In September, Bob was keynote speaker at a briefing before a joint meeting of the House Oceans Caucus and the House Committee on Science, U.S. House of Representatives in Washington, D.C.


PHOTO COURTESY OF FRANK BOWLES

Frank Bowles, Joanna Bergström, Ted Melillo

Visiting Scientists and Scholars

Zoe Cardon of the University of Connecticut spent her fall sabbatical leave at The Ecosystems Center working with Ed Rastetter to develop a new mathematical model of biogeochemical function around plant roots. The


COURTESY OF ED RASTETTER

Zoe Cardon

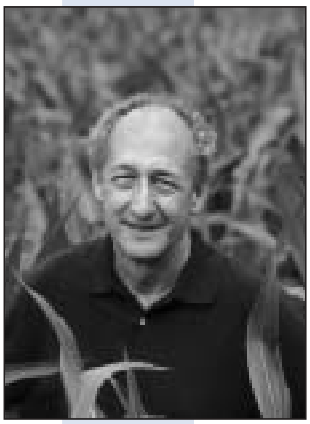
model will be used to examine the effects of water movement toward roots, carbon release from roots, and microbial and protozoan community interactions near roots on nutrient uptake by plants.

Jim Galloway of the University of Virginia returned to The Ecosystems Center for the summer, having spent a year here as visiting scientist in 2002. While at the center, he completed work on a revised global nitrogen budget that is now in press in *Biogeochemistry*. He also worked extensively with scientists from The Ecosystems Center and the Woods Hole Research Center on the development of the International Nitrogen Initiative.

Neil Bettez, a former research assistant on the Arctic LTER, returned to The Ecosystems Center during the summer to conduct research with Bob Howarth and Roxanne Marino. Neil is studying for his Ph.D. at Cornell University. Ketil Koop-Jakobsen came to work on a Ph.D. at Boston University Marine Program under the direction of Anne Giblin, who is a BUMP adjunct professor. Bente Foereid of The Macaulay Institute in Aberdeen, Scotland, worked with Ed Rastetter, and Raquel Machas of University of Algarve in Portugal did research with Bruce Peterson.

ANNE GIBLIN

Ian Washbourne



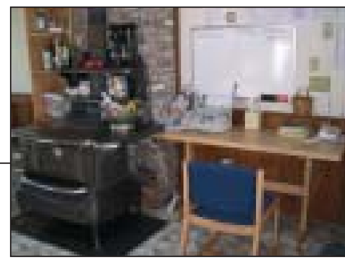
TOM COGILL

Jim Galloway

ANNE GIBLIN

Ketil Koop-Jakobsen

With the MBL's purchase in 2003 of a five-acre farm on Route 1 in Newbury, Massachusetts, the Plum Island Long-Term Ecological Research project expanded its field camp facilities at the research site. Marshview Farm consists of a double house capable of accommodating 12, a large barn and several smaller outbuildings. The basement of the house was renovated to provide laboratory facilities for sample processing and analysis. With a planning grant from the National Science Foundation, plans are underway to renovate the barn to accommodate additional housing, storage, laboratory and meeting needs. The farm supplements a smaller field camp with marsh and water access at Batchelder's Landing in Rowley, which the MBL rents from the Essex County Greenbelt Association.



Clockwise from top:
Large backyard provides ample space to store boats and vehicles and to dry nets.
Front and rear views of farmhouse.
Christian Picard in the newly renovated basement of the house, which provides much needed space for sample processing and analysis.
Three-level barn presently used for storage.
One of two kitchens in the farmhouse, which has six bedrooms, offices/study areas and recreational rooms.
(Photos by Mike Johnson and Bonnie Keeler.)

Ecosystems Center Events and Activities in 2003

U.S. Postmaster General John E. Potter and John Hobbie stand in front of the Arctic Tundra commemorative postage stamp at the first-day-of-issue ceremony in Fairbanks in July. John Hobbie served as one of the scientific consultants on the project, the fifth in the U.S. Postal Service's "Nature of America" series.

Elections and Promotions

Jerry Melillo was elected president of the Ecological Society of America (ESA) and will begin his term in August 2004. Gus Shaver was elected ESA's vice president for science; his three-year term also starts in August. The 8,100-member organization was founded in 1915 to promote the science of ecology.

Adrian Green

In 2003, Anne Giblin and Linda Deegan were promoted to the position of senior scientist. Anne received her Ph.D. from the Boston University Marine Program and joined The Ecosystems Center in 1983 after a postdoctoral fellowship at the Woods Hole Oceanographic Institution. Linda came to the center in 1989 from the University of Massachusetts, Amherst, where she was an assistant professor in the Department of Forestry and Wildlife Management. She received her Ph.D. from Louisiana State University.

Roxanne Marino was appointed senior research associate at Cornell's Department of Ecology and Evolutionary Biology. She continues her part-time appointment as staff scientist at The Ecosystems Center.

Center Review

In 2003, the MBL's strategic planning committee recommended periodic reviews of all year-round centers. Accordingly, a group of scientists visited The Ecosystems Center in October for a two-day review of the center's programs, achievements and goals. The team of Mary Firestone of the University of California, Berkeley, Donald Boesch of the University of Maryland Center for Environmental Studies, Hugh Ducklow of the Virginia Institute of Marine Science, Harold Mooney of Stanford University and Ronald Prinn of Massachusetts Institute of Technology met with center scientists and staff and MBL Director William Speck. In its final report, the review committee commended the center for its collaborative, multidisciplinary approach, and emphasized that this sort of interaction is unique among academic and scientific institutions.

In the News

Center scientists and their research projects were the subjects of media coverage in 2003. MBL Science Journalism Fellows from ABCNews.com, *Audubon Magazine* and the *Palm Beach Post* reported on Arctic research from the Long-Term Ecological Research (LTER) site at Toolik Lake, Alaska, and the Public Broadcasting Service's show, Scientific American Frontiers, filmed part of its production, "Hot Times in Alaska," there in August. The show is scheduled for broadcast in summer 2004. *The Boston Globe North* and the *Newburyport Daily News* featured Plum Island LTER scientists in stories about the center's new Marshview Farm Field Station. The *Pittsburgh Post-Gazette* interviewed adjunct scientist Paul Colinvaux about his paleoecological research on species diversity in the Amazon. *The Cape Cod Times* quoted John Hobbie in an article about the need for patience in long-term research, and Ben Felzer wrote an op-ed piece on global warming for that newspaper. The MBL's alliance with Brown University was well covered by Providence media, and prompted a *Providence Journal* editorial calling the partnership the "New Marine-Science Power."

International Conferences

Ed Rastetter traveled to La Selva, Costa Rica, in January to meet with other scientists to design a project to conduct intensive sampling at 40 locations in the canopy of a tropical rain forest within La Selva.

Jerry Melillo completed the second year of his second term as president of Scientific Committee On Problems of the Environment (SCOPE) and in February, helped to organize a SCOPE-sponsored workshop on the carbon cycle, held in Ubatuba, Brazil. Jerry also organized a United Nations Environment Programme - SCOPE workshop on Emerging Environmental Issues in Paris in October.

Gus Shaver and Jerry Melillo attended a Swedish Research Council workshop on developing international collaboration in Arctic research in Abisko, Sweden, in September.

In October, John Hobbie traveled to Silkeborg, Denmark, to attend the Northern Lakes (NORLAKE) Symposium, sponsored by the Scandinavian nations. He reported on the conclusions that he and other authors have reached in the freshwater chapter of the book under preparation, *Arctic Climate Impact Assessment*.

In November, Paul Steudler and Jerry Melillo attended a Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) workshop on agroecosystems in the Amazon Basin in Brasilia, Brazil, co-organized by Jerry. At that meeting, Paul Steudler presented a paper that he wrote with Jerry and others on their research on pasture sites in the Amazon Basin.

Also in November, Paul, Jerry, Chris Neill and Christie Haupert attended the LBA's Science Meeting in Fortaleza, Brazil. Chris made two presentations, "Soil nitrogen transformations and soil solution fluxes following clearing of Amazonian tropical forest for pasture" and "Key connections in Amazon stream corridors: Using ^{15}N to trace nitrogen transformations and transport." He also made a presentation at the VI Congresso Ecologico do Brasil in Fortaleza later that month.

Arctic Research Commission

John Hobbie is serving his second term as a member of the Arctic Research Commission (ARC), and attended commission meetings in Knoxville, Washington, D. C., and Calgary, Canada. In August, the commission toured one of the nation's most productive fisheries ports, Dutch Harbor, on a trip to Alaska's Aleutian Islands. In October, John and other commissioners toured a geothermal power plant in Iceland.

John organized an ARC-sponsored meeting of Arctic researchers interested in the scaling of ecological processes through modeling, held in Seattle in October. The product will be a report to the commission on the state of the art, accomplishments, and future direction of scaling of Arctic terrestrial ecosystems. Ed Rastetter also attended from The Ecosystems Center.

Long-Term Ecological Research (LTER)

The annual meeting of the Harvard Forest LTER was held in Petersham, Massachusetts, in February. Participating from The Ecosystems Center were Liz Burrows, Al Chan, Heidi Lux, Jerry Melillo, Paul Steudler and Sarah Morrisseau.

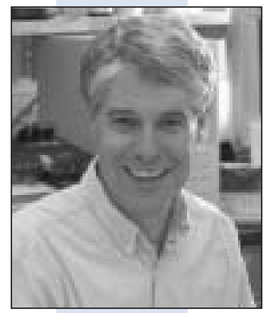
John Hobbie and Debbie Scanlon organized the annual planning meeting for the Arctic LTER, held in March in Woods Hole. Attending were Michele Bahr, Jon Benstead, Zy Biesinger, Mary Booth, Laura Broughton, Chris Crockett, Byron Crump, Linda Deegan, Marcus Gay, Anne Giblin, Adrian Green, Bonnie Kwiatkowski, Jim Laundre, Suzanne Randazzo, Ed Rastetter, Heather Rueth, Diane Sanzone, Gus Shaver, Martin Sommerkorn, Erica Stieve, Joe Vallino, Zhenwen Wan, Ian Washbourne and Yuriko Yano.

The Plum Island Ecosystem LTER project's meeting took place in Woods Hole in April. Chuck Hopkinson organized the gathering, which was attended by Michele Bahr, Hap Garritt, John Logan, Heather Haas, Joe Vallino, Vin Valentine, Corey Lawrence, Bonnie Keeler, John Hobbie, Jane Tucker, Byron Crump, Bruce Peterson, and Linda Deegan.

Gus Shaver, John Hobbie, Liz Burrows, Jim Laundre, Linda Deegan and Anne Giblin attended the LTER All Scientists' Meeting in Seattle in September. Anne gave a plenary talk on long-term studies in estuaries; Liz and MBL summer research intern Margaret Graham presented a poster on the soil warming experiment at the Harvard Forest LTER.


TOM KLEINDINST

Anne Giblin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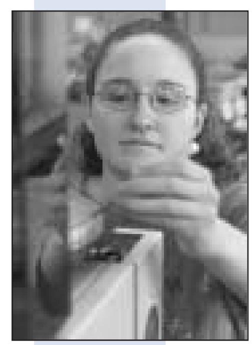
Chris Neill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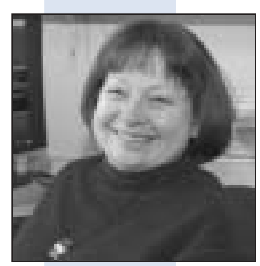
Liz Burrows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Michele Bahr


TOM KLEINDINST

Ann Lezberg


TOM KLEINDINST

Carrie McCalley


MARYKAY FOX

Suzanne Thomas

Estuarine Research Federation (ERF)

At the September meeting in Seattle of the Estuarine Research Federation, Anne Giblin helped organize a session on climate change, attended her final board meeting as past president of ERF, and gave a talk on the effects of freshwater discharge on the nitrogen cycle in low salinity areas of estuaries. Linda Deegan was co-chair of a section on estuarine habitats and presented several posters.

Jane Tucker presented a poster on variations in benthic fluxes in Massachusetts Bay. The subject of Max Holmes' presentation was biogeochemical fluxes to large Arctic estuaries. Max, Bruce Peterson and Jim McClelland presented their research on increasing river discharge to the Arctic Ocean. Bruce, Linda, Joe Vallino, Jeff Hughes and others were co-authors with Max of the poster on hydrological and biological controls of the fate of watershed-derived nitrogen in estuaries.

At the meeting of the Joint Estuarine and Coastal Science Association of ERF, Anne Giblin gave a talk on the ERF initiative in biocomplexity. The meeting was held in April in San Carlos, Sonora, Mexico.

American Geophysical Union

At the American Geophysical Union's annual meeting, held in San Francisco in December, Ben Felzer presented his work on the implications of ozone on carbon sequestration and climate policy in the U.S. using the MIT integrated global systems model. Qianlai Zhuang gave a talk on "Methane emissions from the terrestrial ecosystems at northern high latitudes during the 20th Century: A retrospective analysis with a process-based biogeochemistry model."

Max Holmes, Jim McClelland and Bruce Peterson also attended and Max and Jim made presentations. Max spoke on biogeochemical tracers in Arctic rivers; Jim's talk was on causes of increasing river discharge in the Eurasian Arctic. Paul Steudler presented a poster on work that he, Al Chan and Jerry Melillo have undertaken on long-term trends in soil methane consumption for the Harvard Forest chronic nitrogen addition experiment.

Meetings

At February's meeting of the American Society for Limnology and Oceanography in Salt Lake City, Michele Bahr gave a talk on seasonal patterns of diversity of sulfate-reducing bacteria in a salt marsh. Chuck Hopkinson presented a talk on the stoichiometry of oceanic dissolved organic matter. Joe Vallino chaired a session on the subject of new approaches to modeling food web and ecosystem biogeochemistry and also presented a talk on "Modeling microbial consortiums as distributed metabolic networks."

Bruce Peterson, Jim McClelland and Max Holmes attended the Arctic System Science All Hands Meeting in February in Seattle. They presented three posters on their work in the Eurasian Arctic: a circumpolar perspective on fluvial sediment flux toward the Arctic Ocean; a review of the increasing Arctic river discharge that threatens Atlantic thermohaline circulation, and a poster on long-term variability of the Pan-Arctic hydrological budget and the decline in hydrological monitoring networks.

Jim and Max organized a workshop at MBL in February for the Pan-Arctic River Transport of Nutrients, Organic Matter, and Suspended Sediments (PARTNERS) project, funded by the National Science Foundation, which examines increased discharge from rivers in the Pan-Arctic region. The workshop was attended by more than 20 scientists from Russia, Canada, Germany, and the U.S.

Vin Valentine made a presentation titled "Geomorphological patterns and fractal measures" at the annual meeting of the Atlantic Coast Environmental Indicators Consortium in May at Hollings Marine Laboratory, Charleston, South Carolina. Chuck Hopkinson introduced Vin's presentation with his own presentation regarding research and indicator concepts related to geomorphology at Plum Island and elsewhere. He also presented information about data archiving and metadata development for the Plum Island LTER program.

Michele Bahr attended the general meeting of the American Society for Microbiology in Washington, D.C., in May. She presented a poster on research that she, Byron Crump and John Hobbie had conducted on the molecular diversity of sulfate reducers in salt marsh sediments.

Bruce Peterson, Linda Deegan, Jon Benstead, Adrian Green, Heidi Wilcox and Suzanne Thomas attended the May meeting of the North American Benthological Society (NABS). Jon co-organized a special session on ecological stoichiometry and presented a paper, co-authored with Bruce, Linda, Adrian and others, on the Kuparuk River long-term fertilization experiment from a stoichiometric perspective. Heidi Wilcox presented a poster. Other posters featured research conducted by Diane Sanzone, Bruce, Linda, Chris Crockett, Adrian, and Jon on Arctic springs and streams.

Yuriko Yano made a presentation on the effects of litter quality on dissolved organic matter in a temperate coniferous forest soil at the Fourth North American Forest Ecology Workshop in June in Corvallis, Oregon.

John Hobbie attended the annual meeting of the NSF-sponsored Microbial Observatory program in September in Washington, D. C., reporting on the activities and results of the Plum Island Microbial Observatory.

Jerry Melillo, Gus Shaver, and Qianlai Zhuang attended the annual meeting of the Ecological Society of America, held in Savannah in August. Jerry gave a lecture titled "Science, policy and the grand element cycles." Qianlai spoke on modeling methane consumption and emission between the terrestrial biosphere and the atmosphere.

Al Chan made a poster presentation at the meeting of the American Society of Agronomy/Crop Science Society of America/Soil Science Society of America in Denver in November. The subject was the consequences of nitrogen fertilization on soil methane oxidation in temperate deciduous forests.

Vin Valentine presented a poster, co-authored with Chuck Hopkinson, on the geomorphic indicators of tidal marsh condition at the Third Annual All-Estuarine and Great Lakes Environmental Centers Conference in December, held at the Bodega Marine Laboratory, University of California-Davis.


BONNIE KEELER

Corey Lawrence

Other Workshops and Conferences

Chuck Hopkinson is a member of the Carbon Cycle Science Ocean Interim Implementation Group, which met throughout the year to prepare the report "Ocean Carbon and Climate Change, An Implementation Strategy for U.S. Ocean Carbon Research." The report was prepared under the auspices of the University Corporation for Atmospheric Research with funding from the National Science Foundation.


TOM KLEINDINST

Bonnie Keeler, Linda Deegan, Mike Johnson

Dave Kicklighter and Ben Felzer attended the Massachusetts Institute of Technolgy's Global Change Forum XX in January in San Diego. Dave, Ben and Jerry Melillo attended MIT's Forum XXI in Cambridge in October.

In February, Jane Tucker participated in the Massachusetts Water Resources Authority Annual Science Workshop at Battelle Ocean Sciences in Duxbury.


TOM KLEINDINST

Jim Laundre

Vin Valentine gave a presentation at the Regional Forum on Monitoring and Assessment of Tidal Wetlands, held in April at the National Health and Environmental Effects Research Laboratory, Atlantic Ecology Division of the U. S. Environmental Protection Agency in Narragansett, Rhode Island. Linda Deegan presented information on the Trophic Cascades and Interacting Control Processes in a Detritus-


TOM KLEINDINST

Dave Kicklighter

based Aquatic Ecosystem (TIDES) project. Mike Johnson also attended.

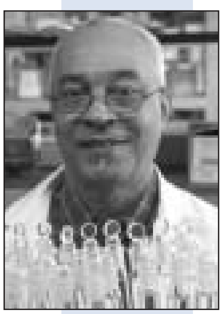
In April, Dave Kicklighter was the discussion leader at the Terrestrial Ecosystem Response to Atmosphere and Climatic Change Workshop on interactions between increasing carbon dioxide and temperature in terrestrial ecosystems, held in Lake Tahoe, California.

Also that month, Ed Rastetter attended the Cary Conference at the Institute for Ecosystem Studies in Millbrook NY. The topic of the meeting was ecosystem function in heterogeneous landscapes. Gus Shaver also attended and was a panelist and speaker.


TOM KLEINDINST

Bonnie Kwiatkowski, Zy Biesinger

Jerry Melillo and Dave Kicklighter organized a meeting in Woods Hole in September of the NSF-funded National Ecological Observatory Network Workshop. Later that month, Dave was a participant in round table discussions at the U. S. Environmental Protection Agency in Washington, D. C., to help develop a new integrated assessment model of climate change called the Climate Change Risk Assessment Framework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Don Burnette

Lectures and Seminars

During the year, members of The Ecosystems Center's senior scientific staff traveled to Providence to lecture to Brown University students as part of the Brown-MBL Graduate Program in Biological and Environmental Sciences. In addition, center scientists went to other academic and research institutions to give lectures and seminars.


TOM KLEINDINST

Dennis Miller

In January, Jerry Melillo gave a talk on climate change in land ecosystems at a Massachusetts Institute of Technology-Scripps Institution of Oceanography Joint Meeting on Climate Change in La Jolla, California.

At the University of Wisconsin-Madison Graduate Student Ecology Symposium in March, Anne Giblin gave talks on the topics of climate change in Arctic ecosystems and controls on denitrification in marine ecosystems.

Gus Shaver gave a seminar on how biodiversity regulates the biogeochemistry of Arctic ecosystems at the Lamont-Doherty Earth Observatory, Columbia University, in April. That month, Chuck Hopkinson lectured at the University of Virginia on the stoichiometry of oceanic dissolved organic matter. In September, Chuck spoke at the University of Massachusetts, Lowell, on Plum Island LTER research.

In March, Max Holmes gave lectures on "Arctic river discharge and climate change" at the Woods Hole Oceanographic Institution and to a symposium of high school science teachers at the MBL. In the fall, Max also presented talks at Cornell University and the University of Washington.

Chris Neill spoke on the results of his research on Martha's Vineyard on the conservation of ecological processes and rare species in coastal plains at a meeting of the Massachusetts chapter of The Nature Conservancy in April, and later at a meeting of the Martha's Vineyard Conservation Partnership.

Committee Memberships

John Hobbie is chair of the advisory committee for the Florida Bay Science Program. In April he presided over the semi-annual meeting of the group in Tampa, Florida. This group of five scientists advises the scientists and project leaders of the Florida Bay and Adjacent Marine Systems Program on the scientific directions of the project. This year the meeting was held jointly with the Greater Everglades Ecosystems Restoration Conference.

John is also a member of the national LTER Executive Committee.

Jerry Melillo is the chair of the International Review Committee of the Millennium Ecosystem Assessment for Western China (MAWEC). The MAWEC studies changes to ecosystems in western China and how these changes affect essential items such as food and clean water. MAWEC is part of the global Millennium Ecosystem Assessment.

Jerry is on the external advisory committee of an international non-governmental organization, Strategic Analysis, Research and Training (START) that helps scientists from developing countries participate in global-change science. He also serves on the external advisory committees of the Directorate for Biological Sciences of the National Science Foundation, the Natural Resources Ecology Laboratory at Colorado State University, and the Center for the Study of Institutions, Population, and Environmental Change at Indiana University.

Ben Felzer is a member of the technical review committee on Global Climate Change and Wildlife for The Wildlife Society.

Gus Shaver represents the Arctic project on the LTER network's coordinating committee. Gus and Chris Crockett are members of the steering committee of the University of Alaska's Toolik Field Station, site of the Arctic LTER project's summer research. Chris attended the yearly meeting in Fairbanks in December.

Chuck Hopkinson is a member of the Hubbard Brook Research Foundation's "Science Links" nitrogen project, a public outreach program that examines sources and effects of nitrogen pollution in northeastern U.S. ecosystems.

Gus Shaver is a member of the Interdisciplinary Advisory Board of the Arctic, Antarctic, and Alpine Research of the University of Colorado and a member of the steering committee of the International Geosphere-Biosphere Programme's Global Change and Terrestrial Ecosystems Network Focus 1: Ecosystem physiology. Gus is also a member of the steering committees of the Study of Environmental Arctic Change and of the Arctic System Science program Land-Atmosphere-Ice Interactions project.

Max Holmes is on the science steering committee of the National Science Foundation's Russian-American Initiative for Shelf-Land Environments in the Arctic Program.

Anne Giblin is chair of the advisory board of the Cooperative Institute for Coastal and Estuarine Environmental Technology.

Chuck Hopkinson is editor-in-chief of *Wetlands Ecology and Management* and Gus Shaver is a member of the editorial board of *Ecosystems.*

Ken Foreman is a member of the Town of Falmouth's Nutrient Management Working Group and a member of the Falmouth Ashumet Plume Nitrogen-Offset Committee. Chris Neill was appointed to the board of directors of the Association to Preserve Cape Cod and to the board of the Falmouth Associations Concerned with Estuaries and Salt Ponds. Jane Tucker continues as a member of the Falmouth Coastal Resources Working Group. Heidi Lux is member of the Mount Grace Conservation Land Trust Stewardship Committee and the Petersham Conservation Commission.

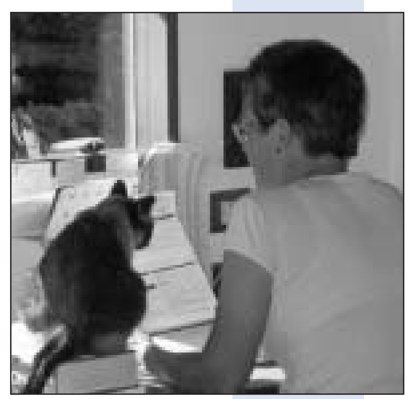
Richard McHorney

MBL Boards and Committees

Jerry Melillo was chair of the search committee for MBL's chief academic and scientific officer and co-chair of the committee to develop a Joint Brown-MBL Graduate Program. Gus Shaver was elected to the MBL Science Council.

Mary Ann Seifert, Debbie Scanlon, John Hobbie

John Hobbie is chair of the MBL Safety committee, of which Don Burnette is a member. Anne Giblin and Jane Tucker are members of the diving control board, and Jane is on the MBL's position evaluation committee. Pat Micks served as the MBL's representative to the Woods Hole Oceanographic Institution-MBL International Committee.



Mardi Bowles and Bastet

Seminars at The Ecosystems Center During 2003

January

7 Mike Neubert, Woods Hole Oceanographic Institution, "Fishery yields and marine reserves: A mathematical analysis."

14 William Sobczak, College of the Holy Cross, "Detritus fuels ecosystem metabolism but not metazoan food webs in San Francisco estuary's freshwater delta."

21 Laura Broughton, Marine Biological Laboratory, "Linking plant communities to soil microbial communities and processes in old-fields."

28 Eric Davidson, Woods Hole Research Center, "Nitrogen limitation in a tropical secondary forest."

February

4 Ranga Myneni, Boston University, "The greening Earth."

11 Martin Sommerkorn, Marine Biological Laboratory, "Gazing into the peat: What controls the fate of belowground carbon allocation in tundra?"

20 Maureen Conte, Woods Hole Oceanographic Institution, "Plant biomarkers in aerosols: A new approach for estimation of terrestrial plant carbon isotopic discrimination on large spatial scales."

25 Rebecca Gast, Woods Hole Oceanographic Institution,"Topics in protistan molecular ecology."

March

4 Serita Frey, University of New Hampshire, "Ecosystem consequences of microbial community structure and diversity."

11 Sandra Shumway, University of Connecticut, "Effects of harmful algal blooms on shellfish and aquaculture."

18 Klaus Nüsslein, University of Massachusetts, Amherst, "Plant roots and microbial communities under heavy metal stress."

25 Anne Giblin, Marine Biological Laboratory, "Global change and the carbon balance of Arctic ecosystems: The importance of carbon-nutrient interactions."

April

1 Thompson Webb, Brown University, "Climatically forced vegetation dynamics in North America during the last 21,000 years."

8 Valerie Eviner, Institute of Ecosystem Studies, "Linking plant community composition and ecosystem dynamics: Interactions of plant traits determine the ecosystem effects of plant species and plant species mixtures."

15 Gus Shaver, Marine Biological Laboratory, "Biodiversity and biogeochemistry in Arctic tundra."

22 Edward Rastetter, Marine Biological Laboratory, "Coexistence without niche separation: Is there an artifact in R-star?"

29 Chris Forest, Massachusetts Institute of Technology, "Uncertainty of climate system properties and implications for 21st century climate change."

May

6 Jeb Barrett, Dartmouth College, "Elementary stoichiometry and ecosystem evolution in the Antarctic Dry Valleys."

13 Peter Groffman, Institute of Ecosystem Studies, "Urban riparian ecology."

September

30 Tom Sinclair, University of Florida, "Resource limitations to increasing plant productivity."

October

7 Heidi Sosik, Woods Hole Oceanographic Institution, "Times series monitoring of coastal phytoplankton communities with submersible flow cytometry."

21 Phil Camill, Carleton College, "Discontinuous permafrost thaw accelerates in boreal peatlands during late 20th century climate warming and implications for regional carbon balance and biophysical feedbacks on climate."

28 Benjamin Felzer, Marine Biological Laboratory, "How will ozone pollution affect future productivity, carbon sequestration, and climate policy?"

December

2 Zoe Cardon, University of Connecticut, "Sweeping water, oozing carbon, and patterns of rhizosphere resource exchange."

9 Stephen Hajduk, Marine Biological Laboratory, "A changing genomic environment: The dynamic relationship of humans to their parasites."

16 (Special seminar) Dmitri Sobolev, University of Texas Marine Science Institute, "Proposed paradigm for nitrogen transformation in medium-salinity marine sediments: Oxidative shortcut from ecosystem to the atmosphere."

16 Ron Prinn, Massachusetts Institute of Technology, "Ensemble climate predictions using a global model coupling economics, chemistry, climate dynamics and ecosystems."

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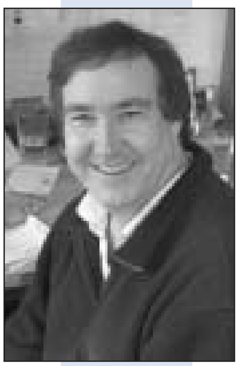
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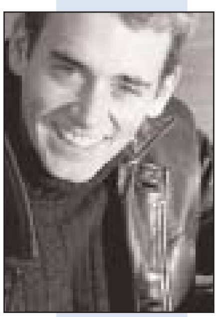
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Pakhomov, E. A., J. W. McClelland, K. Bernard, S. Kaehler, and J. P. Montoya. Spatial and temporal shifts in stable isotope values of the bottom-dwelling shrimp *Nauticaris marionis* at the sub-Antarctic archipelago. ***Marine Biology.***

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Rastetter, E. B., B. L. Kwiatkowski, S. Le Dizès, and J. E. Hobbie. The role of down-slope water and nutrient fluxes in the response of Arctic hill slopes to climate change. ***Biogeochemistry.***

Schmidt, K., J. W. McClelland, E. Mente, J. P. Montoya, A. Atkinson, and M. Voss. Trophic level interpretation based on $\delta^{15}N$ values: The implications of tissue-specific fractionation and amino acid composition. ***Marine Ecology Progress Series.***

Shaver, G. R. Spatial heterogeneity past, present, and future. ***In:*** G. M. Lovett, C. G. Jones, M. G. Turner, and K. C. Weathers (eds.). **Ecosystem Function in Heterogeneous Landscapes.** Springer-Verlag, New York.

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van Wijk, M. T., K. K. Clemmensen, G. R. Shaver, M. Williams, T. V. Callaghan, F. S. Chapin III, J. H. C. Cornelissen, L. Gough, S. E. Hobbie, S. Jonasson, J. A. Lee, A. Michelsen, M. C. Press, S. J. Richardson, and H. Rueth. Long-term ecosystem level experiments in Toolik Lake, Alaska, and Abisko, Northern Sweden: Generalizations and differences in ecosystem and plant type responses to global change. ***Global Change Biology.***

Williams, M. C., S. Filoso, and P. Lefebvre. Effect of land-use change on solute inputs to floodplain lakes of the Central Amazon. ***Biogeochemistry***.

Yano, Y., K. Lajtha, P. Sollins and B. A. Caldwell. Chemistry and dynamics of dissolved organic matter in a temperate coniferous forest on andic soils: Effects of litter quality. ***Ecosystems***.

Yano, Y., K. Lajtha, P. Sollins and B. A. Caldwell. Chemical and seasonal controls on the dynamics of dissolved organic matter in a coniferous old-growth stand in the Pacific Northwest, USA. ***Biogeochemistry.***

Grants for Research and Education During 2003

I. National Science Foundation

NSF-ATM-0120468
"Biocomplexity: Feedbacks Between Ecosystems and the Climate System"
(subcontract from Massachusetts Institute of Technology)
October 2001 – September 2006
Investigator: Melillo
$1,083,333

NSF-ATM-0221835
"Land Water Interactions at the Catchment Scale: Linking Biogeochemistry and Hydrology"
(subcontract from Columbia University)
September 2002 – August 2006
Investigators: Hobbie, Rastetter
$119,956

NSF-DBI-0084048
"FSML: An Analytical Laboratory for Examination of Land Use Change and its Consequences for Aquatic Ecosystems"
September 2000 – August 2003
Investigators: Giblin, Neill
$173,889

NSF-DBI-0301231
"Controlled Environment Facilities for Examination of the Effects of Climate Change and Human Land Use on Terrestrial and Aquatic Ecosystems"
September 2003 – August 2006
Investigators: Shaver, Hobbie, Hopkinson, Vallino
$240,000

NSF-DBI-0352466
"A Regional Network to Improve Understanding of the Carbon Cycle: A Workshop Proposal"
October 2003 – September 2004
Investigator: Melillo
$15,000

NSF-DEB-0080592
"Harvard Forest LTER Program"
(subcontract from Harvard University)
October 2000 – September 2006
Investigators: Melillo, Steudler
$749,400

NSF-DEB-0087046
"LTER CROSS SITE: Interactions between Climate and Nutrient Cycling in Arctic and Subarctic Tundras"
January 2001 – December 2003
Investigator: Shaver
$318,000

NSF-DEB-0089585
"Turnover and Retention of Nitrogen in an Arctic Watershed: Links to Organic Matter Accumulation and Responses to Climate"
September 2001 – August 2004
Investigators: Shaver, Giblin, Rastetter
$1,104,892

NSF-DEB-0089738
"Physiological and Molecular Diversity of Atmospheric CH_4 Oxidizers in Soil"
September 2001 – August 2004
Investigator: Steudler
$1,091,612

NSF-DEB-0108960
"Species-, Community-, and Ecosystem-Level Consequences of the Interactions Among Multiple Resources"
June 2001 – June 2004
Investigators: Rastetter, Shaver
$417,946

NSF-DEB-0111410
"Nitrate Uptake and Retention in Streams: Mechanisms and Effects of Human Disturbances from Stream Reaches to Landscapes"
(subcontract from University of Tennessee)
September 2001 – August 2006
Investigator: Peterson
$486,999

NSF-DEB-0213767
"Trophic Cascades and Interacting Control Processes in a Detritus-Based Aquatic Ecosystem"
October 2002 – September 2006
Investigators: Deegan, Peterson, Vallino, Hopkinson
$2,699,971

NSF-DEB-0315656
"Nitrogen Movement from Uplands to Streams in Forested and Deforested Tropical Watersheds"
September 2003 – August 2006
Investigators: Neill, Steudler
$600,000

NSF-DEB-9810222
“The Arctic LTER Project: The Future Characteristics of Arctic Communities, Ecosystems, and Landscapes”
December 1998 – November 2004
Investigators: Hobbie, Shaver, Peterson
$4,438,753

NSF-DEB-9815990
“Effect of N Deposition on Forest C Balance: Long-term Responses at Stand and Regional Scales”
June 1999 – May 2003
Investigator: Neill
$651,549

NSF-MCB-9977897
“Microbial Observatories: Salt Marsh Microbes and Microbial Processes: Sulfur and Nitrogen”
October 1999 – September 2004
Investigator: Hobbie
$999,246

NSF-OCE-9726921
“LTER: Plum Island Sound Comparative Ecosystem Study (PISCES): Effects of Changing Land Cover, Climate and Sea Level on Estuarine Trophic Dynamics”
July 1998 – June 2004
Investigators: Hopkinson, Hobbie, Peterson, Giblin, Deegan, Vallino
$4,737,167

NSF-OPP-0096523
“Primary Production in Arctic Ecosystems: Interacting Mechanisms of Response to Climate Change”
January 2001 – December 2004
Investigator: Shaver
$533,119

NSF-OPP-0229302
“Biogeochemical Tracers in Arctic Rivers: Linking the Pan-Arctic Watershed to the Arctic Ocean”
October 2002 – September 2007
Investigators: Peterson, Holmes
$1,648,366

NSF-OPP-0408371 (original award NSF-OPP-9911681)
“Developing Process-Level Understanding of Control on Belowground Carbon and Nutrient Dynamics in Tundra Ecosystems”
(subcontract from University of Michigan)
September 2003 – January 2005
Investigator: Rastetter
$2,203,579

NSF-OPP-9732281
“The Response of Carbon Cycling in Arctic Ecosystems to Global Change: Regional and Pan-Arctic Assessments”
March 1998 – March 2004
Investigators: Hobbie, Rastetter
$1,000,000

NSF-OPP-9818199
“Water and Constituent Fluxes Across the Eurasian Arctic: Evolving Land-Ocean Connections Over the Past 20,000 Years”
April 1999 – March 2003
Investigators: Peterson, Holmes
$1,048,619

NSF-OPP-9911278
“Aquatic Ecosystem Responses to Changes in the Environment of an Arctic Drainage Basin”
July 2000 – June 2005
Investigators: Hobbie, Peterson, Giblin, Deegan, Vallino
$4,057,868

NSF-OPP-9911681
“Developing Process-Level Understanding of Controls on Belowground Carbon and Nutrient Dynamics in Tundra Ecosystems”
February 2000 – September 2003
Investigator: Rastetter
$2,080,085

II. U.S. Department of Energy

U.S. DOE-DE-FC02-03ER63613
“Global Warming and Carbon Storage in Mid-Latitude Forest Ecosystems-NIGEC”
September 2003 – August 2004
Investigators: Melillo, Steudler
$147,275

U.S. DOE-DE-FC03-90ER61010
“Human Influences on Forest Nitrogen Budgets and their Implications for Forest Carbon Storage”
(subcontract from Harvard University)
July 1998 – June 2004
Investigators: Melillo, Steudler
$1,077,781

III. U.S. Environmental Protection Agency

EPA-EMPACT
"Near Real Time Monitoring of Inland Suburban Waterways: Application to Three Critical Environmental Issues Facing the Northshore/Metro-Boston Region"
December 2000 – December 2003
Investigator: Hopkinson
$50,843

EPA-R8267701
"Coastal Wetland Indicators"
(subcontract from University of South Carolina)
July 2001 – June 2005
Investigator: Hopkinson
$373,723

IV. National Aeronautics and Space Administration

NASA-NAG5-9515
"Biogeochemical Consequences of Agricultural Intensification in the Amazon Basin"
May 2000 – October 2004
Investigators: Melillo, Neill, Steudler
$1,410,043

NASA-NAG5-10135
"Predicting Changes in Regional and Global Biogeochemical Cycles"
(subcontract from University of New Hampshire)
January 2001 – December 2004
Investigators: Melillo, Peterson, Steudler, Kicklighter
$540,908

NASA-NAG5-11142
"The Role of Land-Cover Change in High Latitude Ecosystems: Implications for Carbon Budgets in Northern North America"
(subcontract from University of Alaska, Fairbanks)
August 2001 – July 2004
Investigators: Melillo, Kicklighter
$149,999

NASA-NCC5-338
"Modeling the Biogeochemical System of the Terrestrial Amazon: Issues for Sustainability"
(subcontract from University of New Hampshire)
July 1998 – December 2003
Investigator: Melillo
$418,364

NASA-NCC5-690
"Key Connections in Amazonian Stream Corridors"
January 2003 – January 2006
Investigators: Deegan, Neill
$667,541

V. National Oceanic and Atmospheric Administration

NOAA-NA16RG2273
"Effects of Varying Freshwater Discharge on Nitrogen Dynamics in the Oligohaline Regions of Estuaries"
(subcontract from Woods Hole Oceanographic Institution)
March 2002 – December 2004
Investigators: Giblin, Hopkinson
$112,626

NOAA-NA16GP2990
"From Site to GCM Grid Box: Building Interactive Hierarchies of Data and Models to Assess Carbon Cycle and Climate Feedbacks Due to Agriculture and Forestry Practices in the Conterminous U.S. and China"
(subcontract from Columbia University)
September 2002 – August 2005
Investigator: Melillo
$110,235

VI. U.S. Department of Agriculture

USDA-01-CA-11242343-051
"Predicting the Influence of N Deposition on Temperate Forest Carbon Uptake and Storage Using ^{15}N Tracers and Modeling"
September 2001 – August 2004
Investigator: Neill
$73,182

VII. U.S. Geological Survey

USGS-00HQGR0092
"A Watershed-Scale Biogeochemical Loading Model for Nitrogen and Phosphorus"
(subcontract from Cornell University)
September 2001 – August 2003
Investigators: Howarth, Marino
$64,809

VIII. Other Research Grants

Andrew W. Mellon Foundation
"The Importance of Sea Salt Aerosol Inputs to the Functioning of Tropical Rainforests"
October 2000 – December 2003
Investigator: Howarth
$265,000

ExxonMobil Corporation
"Investigating the Cycling of Natural and Manmade Nitrogen Compounds"
(subcontract from Bermuda Biological Station for Research)
February 1997 – February 2004
Investigator: Melillo
$55,000

ExxonMobil Corporation
"Global Change Research – Terrestrial Ecosystems Model Collaboration with MIT"
April 1994 – December 2003
Investigator: Melillo
$340,000

Hudson River Foundation
005/98A
"Primary Production, Respiration, and the Processing of Organic C and Nutrients in the Hudson River Estuary"
July 2001 – June 2003
Investigator: Howarth
$109,999

Massachusetts Institute of Technology
5700000403
"Develop an Agro-Ecosystem Model for Assessing Agricultural Sustainability at Regional and Global Scales"
July 1997 – December 2003
Investigator: Melillo
$313,219

Massachusetts Water Resources Authority
S274
"Harbor and Outfall Monitoring III"
(subcontract from Battelle Memorial Institute)
November 1997 – December 2003
Investigators: Giblin, Hopkinson
$808,741

The Nature Conservancy
MAFO-07152003
"Hydrological Science to Support Biodiversity Conservation in Massachusetts"
July 2003 – June 2005
Investigator: Neill
$95,000

Texaco Foundation
"Environmental Fellowship Program"
September 1990 – December 2003
Investigator: Melillo
$535,000

Grants for Support of Semester in Environmental Science

Andrew W. Mellon Foundation
"Semester in Environmental Science"
June 1996 – December 2003
$4,821,249

The Starr Foundation
"Semester in Environmental Science"
December 1997 – December 2003
$750,000

The Harold Whitworth Pierce Charitable Trust
"Semester in Environmental Science"
January 2003 – December 2003
$25,000

Blum Kovler Foundation
"Semester in Environmental Science"
January 2003 – December 2003
$5,000

Environmental Data Research Institute
"Semester in Environmental Science"
January 2003 – December 2003
$12,500

Sources of Support for Research and Education

The annual operating budget of The Ecosystems Center for 2003 was $9,399,402. Approximately 82 percent of the income of the center comes from grants for basic research from government agencies. The other 18 percent comes from gifts and grants from private foundations, including support for the Semester in Environmental Science, as well as from institutional support for administration and income from the center's reserve and endowment funds.

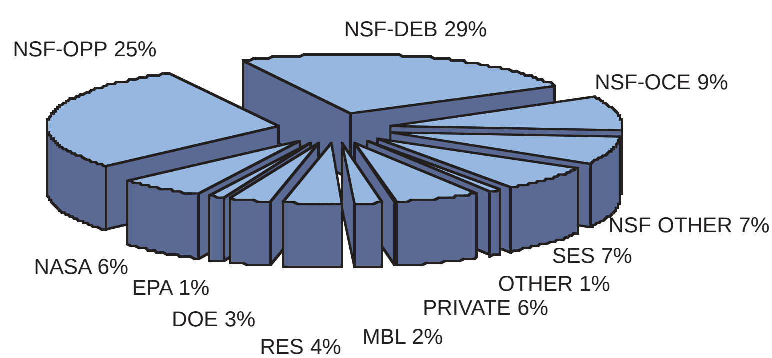
These non-governmental funds provide flexibility for the development of new research projects, public policy activities and educational programs. More information about sources of support appears in the Introduction to The Ecosystems Center and in Research Grants in Effect in 2003.

The combined total value of the center's reserve fund and endowment at the end of 2003 was $5,354,868. Income from the reserve fund and endowment helps defray the costs of operations, writing proposals, consulting for government agencies and the center's seminar program.

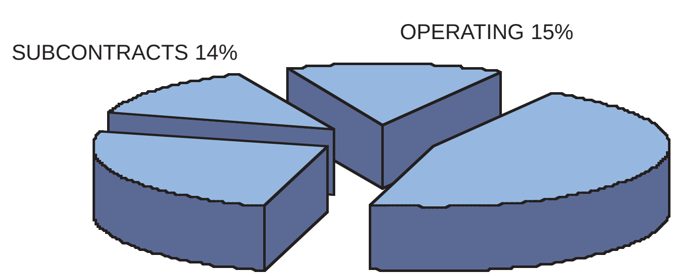
Over the years since it was founded in 1975, the center has received support from these foundations, corporations and industry consortia:

Atlantic Richfield Foundation
The Burroughs Wellcome Fund
Robert Sterling Clark Foundation, Inc.
The Clowes Fund, Inc.
Conservation, Food & Health Foundation, Inc.
The Jessie B. Cox Charitable Trust
Charles E. Culpeper Foundation, Inc.
Arthur Vining Davis Foundations
Davis Educational Foundation
Henry L. and Grace Doherty Charitable Foundation, Inc.
Electric Power Research Institute
Environmental Data Research Institute
Environmental Resources Management Group
ExxonMobil Corporation
Max C. Fleischmann Foundation
The Ford Foundation
General Electric Foundation
Grace Foundation, Inc.
The Grass Foundation
The Harken Foundation
Charles Hayden Foundation
Horizon Foundation
Hudson River Foundation
International Business Machines Foundation
Blum Kovler Foundation
Charles A. Lindbergh Fund
Massachusetts Environmental Trust
Massachusetts Water Resources Authority
The Andrew W. Mellon Foundation
NL Industries Foundation, Inc.
Jessie Smith Noyes Foundation, Inc.
The Harold Whitworth Pierce Charitable Trust
The Proctor and Gamble Company
Rockefeller Brothers Fund
The Rockefeller Foundation
Rowland Foundation, Inc.
Scherman Foundation, Inc.
Ann Osterhout Edison/Theodore Miller Edison and Olga Osterhout Sears/Harold Bright Sears Endowed Scholarship Fund
The Catherine Filene Shouse Foundation
Bill and Phoebe Speck Fund
The Seth Sprague Education and Charitable Foundation
The Starr Foundation
Surdna Foundation, Inc.
Sweet Water Trust
Texaco Foundation
Wingwalker Initiatives
The Worthington Family Foundation, Inc.

2003 Income



2003 Expense



The Ecosystems Center

Marine Biological Laboratory

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