Next-Generation Ecosystem Experiments – NGEE Arctic

Quarterly Report
December 31, 2010

A progress report submitted to

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Synopsis of the NGEE Science and Implementation Plan

The NGEE Science and Implementation Plan will describe how experiments, observations, and process models will quantify the response of physical, ecological, and biogeochemical processes to atmospheric and climatic change across molecular to landscape scales. The plan will focus on interactions that drive climate feedbacks through greenhouse gas fluxes and changes in albedo. Fundamental knowledge will improve representation of processes in Earth System Models and reduce uncertainty and improve prediction of climate impacts and change in high-latitude ecosystems. These goals will be addressed across six integrated science themes, knowing that Arctic systems are complex, highly-coupled, and are characterized by abrupt transitions, steep gradients, and subjected to rapid change.

- **Geophysical Dynamics** – This theme will develop capabilities needed to characterize the subsurface system and develop a predictive understanding of geophysical dynamics in permafrost regions over length scales relevant to microbial through landscape processes.
- **Organismal and Ecosystem Science** – This theme will quantify the impacts of atmospheric and climatic change on plant and bryophyte physiology; community composition through changes in resource availability; and consequential ecological, biogeochemical and energy balance feedbacks.
- **Soil and Subsurface Processes** – This theme will determine chemical and structural changes in soil carbon availability in response to warming; evaluate physical, geochemical and hydrological interactions on changes in microbial degradation of soil carbon; and identify key microbial community interactions with the use of genomic, metabolomic and proteomic tools and assess their role in CO_2 and CH_4 production.
- **Land-Atmosphere Interactions** – This theme will identify mechanisms by which climate change alters the fluxes of greenhouse gases and energy between land and atmosphere; and generate data that link to other modeling and observational programs.
- **Landscape Processes** – This theme will develop the capability to understand the interactions and feedbacks between permafrost warming, landscape dynamics, and the evolution of the carbon and water cycles across scales.
- **Process Modeling and Synthesis** – This theme will facilitate the intentional and diligent integration of the experimental results and observations with Earth System Models.

Details at a Glance

Activities during the October 1 to December 31 quarter include:

- A two-day workshop was held at the International Arctic Research Center (IARC) on the University of Alaska Fairbanks campus.
- Site preparation, ploy layout, and geophysical characterization of soils at the CRREL Permafrost Research Station in Fairbanks are complete. Heater casings and deep-soil heaters are installed and awaiting delivery of control module for final connections.
- LANL initiates HIGRAD and ARCHY simulations in support of NGEE activities. Model simulations include testing of open-top chamber designs and validation. Model development in support of process-level understanding of CO_2 and CH_4 fluxes from Arctic soils.
- AGU session on NGEE held with BER managers and national laboratory partners.

Progress and Accomplishments

Workshop held at University of Alaska:

A two-day workshop, sponsored by the Department of Energy, Office of Science, Biological and Environmental Research, was held October 13-14, 2010 at the International Arctic Research Center on the University of Alaska Fairbanks campus. Through a series of presentations and discussion sessions, speakers emphasized the sensitivity of boreal forests and Arctic tundra to atmospheric and climatic change in the coming decades. All participants were asked to consider how field studies could contribute data and insights to regional and global climate models. In addition, workshop participants identified critical research needs for future global change research in the Arctic. Despite the known challenges of conducting fundamental research in cold regions, participants recommended a concerted effort to address mechanisms underlying greenhouse gas fluxes from warming and thawing permafrost. Tree line migration and shrub advancement into the tundra were also areas where integrated experiments and observations were needed. Given the need to quantify ecosystem-climate interactions in a warming Arctic, a framework was discussed for a new generation of manipulative experiments in tundra and boreal forests driven by the need to address major uncertainties in water, energy and carbon cycle processes, and thus improve modeling and prediction for these biophysical responses and feedbacks in these key regions. A future workshop will focus on the science, technology, and resource requirements of a project of this design and magnitude.

Soil warming prototype installed by U.S. Corp. collaborators:

Staff from the Cold Regions Research and Engineering Laboratory (CRREL) made outstanding progress in site preparation, plot layout, and installation of deep-soil heaters at the Fairbanks permafrost Research Station. Following geophysical characterization of the site, a Geoprobe drill rig was used to position 127 heater casings into the soil. For most of the casings, a solid stem drill pipe was pushed into the soil. This was removed and the heater casing was placed in the resulting hole and positioned to the required depth, leaving 15 cm exposed above the ground surface. Gaps between the native soil and the heater casings were backfilled with silica sand. Soil cores were also taken from a number of locations throughout the plot. In total, over 150 meters of cores were collected. The plastic casing that surrounds each core was split to physically identify the permafrost table. All cores are then covered and

wrapped for storage. Core samples that included both thawed and permafrost soils were sent to Oak Ridge National Laboratory for further analysis and experiments.

Heating elements were placed within each of the 127 heater casings and sealed. The heaters were wired in three zones as designed by ORNL engineers. It was decided to use 90-degree couplings to avoid damage to the wiring by moose. In addition a series of thermcouples and thermisters were installed to monitor the performance of the deep-soil heaters. Soil temperature down to 10 meters will be measured at several locations across the plot and data automatically recorded. An instrumentation shelter was obtained and moved to the site. The building is fully insulated and has lights, electric heat, and storage/work benches. Upon installation of site power by GVEA, the electrical systems will be tested and required modifications to the service panel, building heaters and lights will be made.

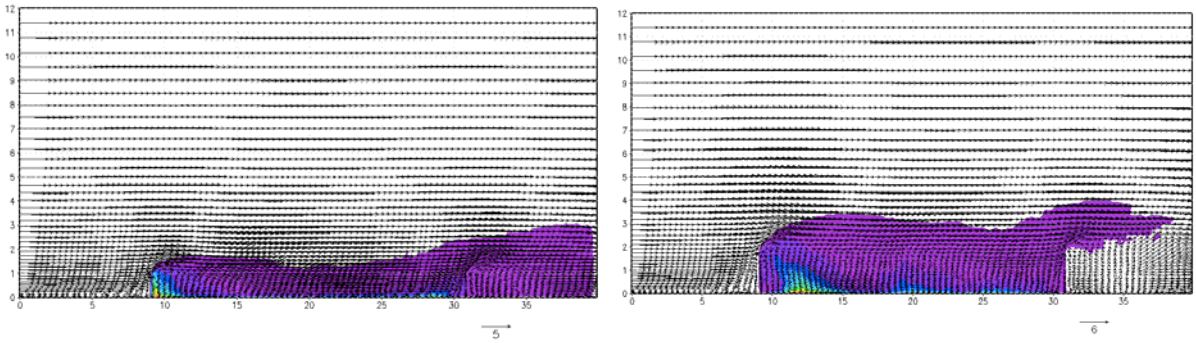
LANL staff conduct open-top chamber validation experiment:

A temporary, adjustable height chamber was constructed for the purposes of providing a validation data set for HIGRAD simulations of NGEE open-top chamber designs. Specifically, the objective of this experiment was to collect data characteristic of the three-dimensional turbulent wind fields within open-top chambers that are suitable for comparison with HIGRAD simulations of similar configurations. The chamber was constructed to approximate an open-top circular cylinder of 12 m diameter via an 18-sided polygon with support poles allowing chamber walls of up to 2 m. Six three-dimensional sonic anemometers (Campbell Scientific, CSAT-3s) were mounted in an array consisting of five sonics internal to the chamber and one sonic external for reference. Sonic heads were set to 80 cm in height and oriented 80 degrees east of north. All heads were triggered simultaneously through the data logger synchronizing device (Campbell Scientific, CR5000), and the three dimensional wind speed arrays were collected at a sampling

rate of 10 Hz. Data were collected in two separate phases over two days in December 2010 for chamber heights of 1 m and 2 m, and are currently being analyzed.

<u>HIGRAD simulations of open-top chambers in support of NGEE</u>:

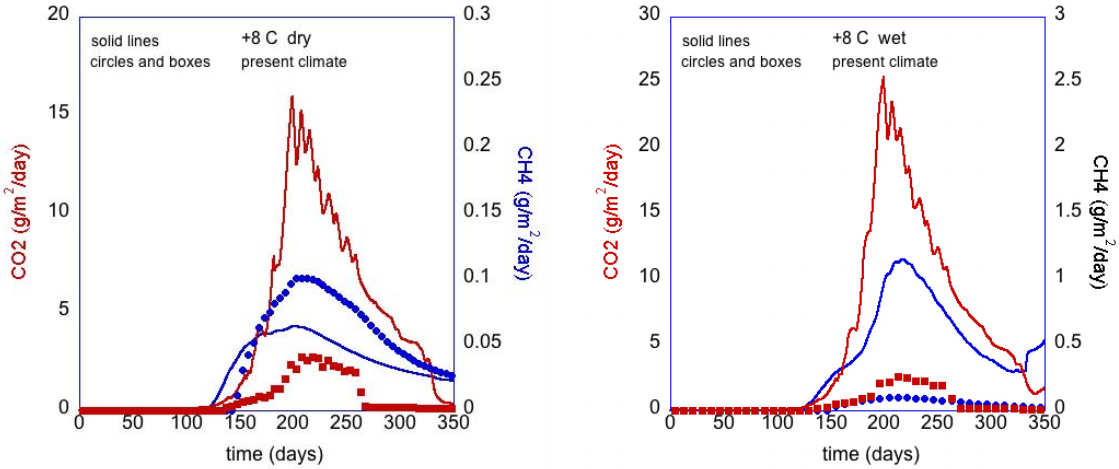
The LANL atmospheric model HIGRAD is being used to simulate the fine-scale (i.e., ~0.1 m) turbulent flows within and around open-top chambers of various configurations relevant to NGEE, and to explore the coupled effects of these turbulent flow fields with various temperature control strategies such as forced air heating and infrared lamps. Recent activity has been focused primarily on validation of the HIGRAD model for conditions relevant to developing suitable chamber-based technology for the Arctic. Effort in this regard has proceeded along two distinct, but closely related, paths: (a) validation of HIGRAD simulations of flow around solid (i.e., closed-top) cylindrical obstacles, for which a significant peer-reviewed literature exists; and (b) application and extrapolation of results obtained in (a) to open-top cylinders, accompanied by a field experiment of an open-top chamber. These efforts will culminate in two publications, the first of which describes the flow and turbulence within and around open-top chambers of different heights. In this regard, the figure below shows HIGRAD simulations of tracer concentration and wind vectors for open-top chambers with sidewall heights of either 1 m or 2 m. The second publication will consider the effects of different heating strategies in open-top chambers under consideration for NGEE.



Passive tracer concentration and wind vectors in a vertical plane through the center of the open-top chamber for chamber heights of 1 m (left panel) and 2 m (right panel).

ARCHY model development and applications:

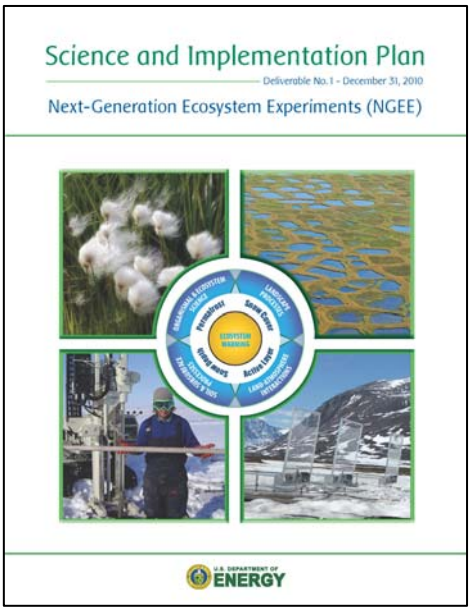
The ARCHY model derives from code developed at LANL for a variety of thermohydrologic and microbial studies, and draws on experience in developing models of complex, non-isothermal reactive flow and transport in porous/fractured media. It has been coupled with the Ecosystem Demography (ED) model of surface vegetation dynamics. This coupled model (AHED) provides a detailed numerical simulator that can operate in 1-D, 2-D or 3-D, is time-dependent, and includes vertical and lateral water and vapor and gas movement in heterogeneous soils and between soils and atmosphere, snow cover, heat transport, spatially variable plant dynamics in response to atmospheric changes, solar irradiation, precipitation, temperature, small scale topography, change of phase between water, ice and vapor, carbon and nitrogen cycles, six spatially distributed species of microbes including aerobes, anaerobes, methanotrophs, nitrogen fixers, nitrifiers and denitrifiers. An inversion capability is part of the new model. In the first quarter of FY11, a paper describing its dynamics and testing it against experimental data, both thermo-hydrologic data, and microbial generation of CO_2 and CH_4, is nearing completion and should be ready for review and submission by late January. A number of comparisons to data, such as a Toolik Lake set of soil temperatures and CO_2 and CH_4 emissions versus time, as well as experiments on unsaturated flow in a domain with a freezing boundary, have been successfully carried out. Coding of the AHED model, that couples ARCHY and ED, has been finished and is being tested against data. Finally, a new set of gas evolution simulations has just been performed, to contrast gas emissions from a drier soil versus a wetter soil column, both with a +8C warmer atmosphere. As expected and as seen in the figure below, there is a lot more CO_2 and CH_4 evolution in the wet column compared to the present day climate, while the drier column shows more CO_2 evolution but less CH_4 than a present climate simulation. The wet column produces more CO_2 and a lot more CH_4 than the dry column. Model simulations such as these will help us generate hypotheses for investigation in the Science and Implementation Plan.



NGEE discussions at AGU meeting with DOE/BER managers and partners:

The AGU meetings held December 13-17, 2010 in San Francisco provided a convenient venue to get national laboratory staff, university partners, and BER managers together for discussion of progress on the NGEE project. Gary Geernaert, Mike Kuperberg, David Lesmes, Dan Stover,

and Joe Graber were able to attend, as were 20-25 scientists from across 5 national laboratories. We covered various aspects of the NGEE project and then focused on the upcoming December 31 Science and Implementation Plan deliverable due to DOE. One of the biggest goals of this meeting was for DOE to hear thoughts from NGEE participants on the role of experiments and observations in supporting the needs of the climate modeling community. We have given this considerable thought and see the opportunity to pursue this connection from two directions. One is a bottom-up approach whereby we conduct hypothesis-drive research that will lead to the development of process-representations for inclusion in Earth System Models. We have a team specifically devoted to helping make this connection possible. In addition, we can also adopt a more top-down approach where we take a landscape perspective and examine processes in a more holistic manner. Both might be appropriate and we will certain pursue research in the Arctic knowing that these are complex systems, and that in order to understand them we may want to merge experiments, observations, and the context of watershed to regional test beds. The agenda for that meeting is included in the Appendix.



Interactions with other Agencies, Universities, and National Laboratories

SDW traveled to Lawrence Berkeley National Laboratory (LBNL) in late November to discuss NGEE activities with Susan Hubbard, Margaret Torn, Bill Riley, Marc Fisher, and others. NGEE activities for the coming year will require expertise in geophysical characterization. LBNL has unique capabilities in this area (as does CRREL) and will be engaged in these areas as the Science and Implementation Plan develops. Additional expertise was explored in the area of land-atmosphere interactions and use of isotopes to better understand and couple field results to models. Toured the Advanced Light Source (ALS) and saw how such a capability could be used to characterize chemistry of soil organic carbon.

SDW also visited Pacific Northwest National Laboratory (PNNL) in early December to inform staff of the NGEE activity. Harvey Bolton served as host and spent much of the day talking to staff and touring facilities. Technical tours of EMSL were excellent and discussions with Nancy Hess suggested that several capabilities could be used in characterization efforts of soil carbon.

A seminar series has been initiated to bring university scientists to ORNL for NGEE-relevant presentations and discussions. In November, Michael Weintraub from the University of Toledo visited and engaged staff in discussions regarding the role of microbes in nitrogen availability and interactions between biogeochemical cycles and responses of vegetation to warming in Arctic landscapes. His abstract is included in the Appendix. A seminar speaker for January has been identified. Howard (Howie) Epstein from the University of Virginia will visit ORNL and give a seminar on vegetation modeling in the Arctic. Howie has developed an ArcVeg model that allows for changing species composition with time (e.g., successional dynamics) and with

changing climate. We will discuss potential collaboration, as use of his model in the context of NGEE would be helpful as a way to identify system senstivities and hypothesis generation. Mac Post will serve as hot for Howie's visit.

SDW had conversations with both Ken Masarie (NOAA) and Charles (Chip) Miller (NASA). Ken is with the NOAA Global Monitoring Division, while Chip is leading a Ventures Mission for NASA aimed at quantifying carbon and methane fluxes from the boreal forest and arctic tundra using aircraft-based measurements. Both are interested in possible connections between their programs and NGEE.

Publications, Presentations, and Posters

Publications:

Hayes, D.J., Hinzman, L.D., McGuire, A.D., Norby, R.J., Thornton, P.E., Walsh, J.E., Wilson, C.J., and Wullschleger, S.D. (2010) Critical uncertainties in high-latitude ecosystems-climate feedbacks: Experimental, observational, and modeling needs. This article is a deliverable from the UAF workshop and is being prepared as a feature article for *EOS*. *EOS* is a weekly science-based newsletter published by the American Geophysical Union (AGU) and is distributed to 50,000 members.

Presentations:

Wullschleger, S.D. (2010) Overview of NGEE-Arctic experiment plans with an emphasis on sensor monitoring, data acquisition, processing, visualization, and analysis needs. Presented in conjunction with a visit to ORNL by Sam Utley, Campbell Scientific. Discussions focused on future measurement and reporting needs of the NGEE project.

Wullschleger (2010) Science and technology in support of climate change research in Alaska. Lawrence Berkeley National Laboratory, Nov. 4, 2010.

Wullschleger, S.D. (2010) Warming up the Arctic: An experimental approach to understanding the response of permafrost and ecosystems to rising temperatures in the Alaska tundra. Seminar presented at Cornell University, November 12, 2010.

Wullschleger (2010) Global change research in the Arctic. Pacific Northwest National Laboratory, Dec. 3, 2010.

Posters:

Wagner, A., Zufelt, J., and Wullschleger, S.D. (2010) Ecosystem warming prototype deployed at the Fairbanks Permafrost Research Station. Submitted to AGU, San Francisco, CA, December 13-17, 2010.

Wullschleger, S.D., Hinzman, L.D., McGuire, A.D., Oberbauer, S.F., Oechel, W.C., Norby, R.J., Schuur, E.A.G., Shugart, H.H., Thornton, P.E., Walsh, J.E., Wilson, C.J. (2010) Climate

change experiments in Arctic ecosystems: Scientific strategy and design criteria. Submitted to AGU, San Francisco, CA, December 13-17, 2010.

Upcoming Meetings:

Symposium on the Application of Geophysics to Environmental and Engineering Problems; April 10-14, 2011, Charleston, SC. This AGU-sponsored workshop provides geophysicists, engineers, geoscientists and end-users from around the world an opportunity to meet and discuss near-surface applications of geophysics and learn about recent developments in near-surface geophysics. This year Beth Astley, one of our CRREL collaborators from Anchorage, will chair a session on "Near-Surface Geophysics in Cold Climates". SDW will attend to learn more about geophysical characterization of permafrost. Web site: http://www.eegs.org/sageep/

Vulnerability of Permafrost Carbon: Research Coordination Network; June 1-3, 2011, Seattle, WA. This activity will host a series of workshops and synthesis meetings over the next two years to quantify the role of permafrost carbon in driving climate change in the 21st century and beyond. This will be achieved by synthesizing current information in a format that can be assimilated by biospheric and climate models, and that can contribute to the next assessment of the Intergovernmental Panel on Climate Change (IPCC). This NSF-sponsored workshop will be hosted Ted Schuur, David McGuire, Valdimir Romanovsky, and others. Several NGEE participants have been invited because of the obvious overlap of goals and objectives of this RCN and NGEE.

Press Releases and News Clips

Stephen Ornes is a freelance science writer who works out of Nashville, TN. He visited ORNL on December 8, 2010 with the specific goal of hearing about the SPRUCE project and touring the prototype site. We also had the opportunity to discuss the NGEE project with Stephen and show him some of our plans that obviously closely parallel some of the plans for the northern Minnesota peatland site. Paul and I await Stephen's first draft of an article.

Appendix

SEMINAR ANNOUNCEMENT

"The Changing Seasonality of Soil Processes in the Arctic Tundra of Alaska"

Michael Weintraub, Ph.D.

Department of Environmental Sciences
University of Toledo
Toledo, Ohio

Thursday, November 18, 2010
1:00 p.m.
Building 1520, Room 202

Host: Christopher Schadt, 576-3982

ABSTRACT: Tundra soils are key regulators of many aspects of the Arctic System. Arctic soils have large stores of carbon (C) and may act as a significant CO_2 source with warming. However, the key to understanding tundra soil processes is nitrogen (N), as both plant growth and decomposition are severely N limited. However, current models of tundra ecosystems and their responses to climate change assume that while N limits plant growth, C limits decomposition. In addition, N availability is strongly seasonal with relatively high availability early in the growing season followed by a pronounced crash. This pattern suggests that low N concentrations in tundra soils at the height of the growing season are likely the result of an increase in soil N uptake associated with the peak in plant growth, either directly by roots or indirectly by microbes fueled by increased root C inputs in mid-July. However, there are multiple questions that still need answers: 1) What causes the seasonal nutrient crash? 2) Does microbial activity switch seasonally between C and N limitation? 3) How will a lengthening of the growing season alter overall ecosystem C and N dynamics, as a result of differential extension of the periods before and after the nutrient crash? 4) What will be the larger impacts of these patterns on the Arctic system? Our current research addresses these questions by: 1) Varying the length and timing of the growing season in the field by advancing snow melt and warming the ecosystem; 2) Establishing the fine scale seasonal time-courses of soil N availability, plant N content, leaf expansion, root growth and rhizodeposition, ecosystem respiration, microbial biomass and enzyme activity; 3) Conducting lab experiments to determine the extent to which microbial activity is limited by temperature, and C and N availability before and after the crash; 4) Determining how the timing of the nutrient crash and plant growth vary across a latitudinal transect; 5) Refining models developed for arctic ecosystems to better handle how plant and microbial systems respond to N limitation; and 6) Testing the large-scale spatial and temporal effects of the seasonality of nutrient availability and how it may change in a warming Arctic with a lengthening growing season.

Next-Generation Ecosystem Experiments (NGEE)

American Geophysical Union Annual Meetings
San Francisco, CA

December 15, 2010

Agenda

Current activities:

- Summary of climate change workshop and submission of *EOS* article
- Science and Implementation Plan
  - Laboratory visits (BNL, LANL, LBNL, and PNNL)
  - Current partners and facilities
  - Identification of science themes
  - Emerging technology; data management; outreach and partnership
  - Conference calls each week; writing assignments
  - Deliverable December 31, 2010
- Prototype design and deployment
  - Computer simulations
  - Fabrication and construction activities
  - Energy costs and resource availability

Mid-term activities:

- NGEE All-hands Science Plan meeting in the spring (ORNL)
- Focus Group – Experimental Design and Infrastructure (LANL and BNL)
- Focus Group – Measurements and Monitoring (ORNL and LANL)
- Focus Group – Data Management and Sharing Policy (TBD)
- Focus Group – Outreach and Partnerships (TBD)
- Science in the Arctic "Genomics to Geophysics" workshop
- Site visits to Alaska in spring (host and dates TBD)

Longer-term activities:

- Meetings
  - Symposium on the Application of Geophysics to Environmental Problems
  - Vulnerability of Permafrost RCN
- Lab-sponsored projects in support of NGEE (LDRD, etc.)
- Manuscripts
- Special session at 2011 AGU conference
- Town Hall meeting at 2011 AGU conference

FY11 deliverables:

- December 31, 2010; annotated outline
- March 31, 2011; initial list of collaborators and areas of responsibility
- June 30, 2011; timeline and milestones for full experiment
- September 30, 2011; final "draft plan" suitable for BER review

AGU Abstract

Ecosystem Warming Prototype Deployed at the Fairbanks Permafrost Research Station

Anna Wagner, Jon Zufelt, and Stan D. Wullschleger
U.S. Army, Cold Regions Research and Engineering laboratory
Oak Ridge National Laboratory

Controlled experiments in terrestrial ecosystems are necessary to understand how changes in climate may affect the interactions among physical, chemical, and biological parameters. Advanced approaches to above and below ground warming will improve our understanding of the biotic and abiotic processes that govern plant and soil response to climatic change in terrestrial ecosystems. A prototype concept for raising soil temperatures in large outdoor plots has been developed at Oak Ridge National Laboratory. The performance of this design has been field-tested in 3-m diameter plots in a temperate deciduous forest and also numerically simulated for experimental plots ranging from 3 to 20 m in diameter. The goal of the present study is to determine if the prototype system can be used to increase the temperature of permafrost soils in arctic and sub-arctic climates. Two sites in Alaska have been selected (Fairbanks and Barrow) for installation and testing of 20-meter diameter plots beginning in the fall of 2010. Fairbanks has a continental climate, with a mean annual air temperature of -3.3^{o}C, mean annual precipitation of 287 mm, and relatively warm (-1 to -2 ^{o}C) permafrost temperatures. Barrow is located within the Alaskan Arctic coastal plain and has a mean annual air temperature of -12.6^{o}C, mean annual precipitation of 124 mm, and colder (-8 to -12 ^{o}C) permafrost temperatures. This presentation focuses on the study site located at the U.S. Army Cold Regions Research and Engineering Laboratory Permafrost Experiment Station, Fairbanks.

The experiment station was established in 1945 and consists of 135 acres of ice-rich permafrost soils generally present to a depth of 60 m with an active layer that varies from 55 to 85 cm in undisturbed areas. The site has a smooth, gentle slope to the west, providing good surface drainage except at the lowest elevations where saturated conditions can exist. Soils consist of tan silt and wind blown loess near the surface and grey silt at depths below 1.4 m. Permafrost moisture contents range from 26 to 41 percent by mass for the frozen silts which makes this relatively low moisture content permafrost. Vegetation is typical of the Alaskan Interior-subarctic taiga forest with white spruce (*Picea glauca* [Moench] Voss), and black spruce (*P. mariana* [Mill] B.S.P) interspersed with lowbush cranberry (*Vaccinium oxycoccos* L.) and Labrador tea (*Ledum groenlandicum* Oeder). Feather moss and sphagnum moss are present in the understory. The experimental plot is a hexagonal shaped area (29 by 25 m) where vegetation had previously been removed but has regrown over the last 40-50 years. Soil warming is accomplished by 127 vertically-installed low-energy heating elements installed at spacing of 2.4 m and to a depth of 4 m. Only the lower 1-m is heated to a setpoint +4 C above ambient. The heated area includes a buffer zone resulting in a test area with a diameter of 20 m. This proof-of-concept study will result in improvements to experimental design and thermal modeling ground-truth data as the scientific community plans for possible next-generation climate change experiments in terrestrial permafrost ecosystems.

AGU Abstract

Climate Change Experiments in Arctic Ecosystems: Scientific Strategy and Design Criteria

Stan D. Wullschleger, Larry D. Hinzman, A. David McGuire, Steve F. Oberbauer, Walter C. Oechel, Richard J. Norby, Edward A.G. Schuur, Herman H. Shugart, Peter E. Thornton, John E. Walsh, and Cathy J. Wilson

Arctic and subarctic ecosystems are sensitive to changes in climate. These are among the largest and coldest of all ecosystems and are perceived by many as especially vulnerable to environmental change. Warming, in particular, is expected to be greatest in northern latitudes with potentially significant consequences for tundra, taiga, and peat lands. Observational evidence suggests that warming is already affecting physical and ecological processes in high-latitude ecosystems. Models predict that permafrost degradation and the northward expansion of shrubs into tundra represent important feedbacks on climate. Manipulative experiments can help understand the vulnerability of ecosystems to climate warming. Previous attempts to manipulate the environment of ecosystems in arctic and subarctic regions have focused on warming plant and soils, but treatments have been limited to small scales and modest increases in temperature. Manipulating the environment at larger scales and exposing ecosystems to higher temperatures for longer periods of time will be required to fully describe the physical, chemical, and biological mechanisms that govern land-atmosphere interactions. A variety of logistical and engineering challenges must be overcome and new approaches developed before we can address the questions being asked of the scientific community especially as we continue to move toward large-scale and long-term experiments.

In light of the many uncertainties that surround the response of high-latitude ecosystems to global climate change, it is important that the scientific community consider how manipulative experiments can address and resolve ecosystem impacts and feedbacks to climate. A workshop sponsored by the Department of Energy, Office of Science was recently held at the University of Alaska, Fairbanks. The goal of the workshop was to highlight conclusions from observational and modeling studies about the response of arctic and subarctic ecosystems to a changing climate. Participants were asked how experiments could best be designed to address issues related to plant and ecosystem dynamics, permafrost degradation, carbon and methane emissions, landscape processes, and the many land-atmosphere feedbacks that are likely to arise as a result of global warming. Recommendations that address the scientific strategy and design criteria of future large-scale, long-term climate change experiments in Arctic ecosystems were contributed. This information will be summarized and evaluated in the context of existing and emerging efforts to better understand high-latitude ecosystems to climate warming.