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SPRUCE-PEATLAND RESPONSES UNDER CLIMATIC AND ENVIRONMENTAL CHANGE AN IN SITU WARMING BY CO_2 MANIPULATION OF A CHARACTERISTIC HIGH-CARBON ECOSYSTEM

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SUMMARY

We are constructing an experimental platform to address climate change response mechanisms in a *Picea*/*Larix*/*Sphagnum* ombrotrophic bog ecosystem located in northern Minnesota. This ecosystem located at the southern extent of the spatially expansive boreal peatland forests is hypothesized to be especially vulnerable to climate change and to have important feedbacks on the atmosphere and climate. The regression-based experiment will allow us to test mechanisms controlling vulnerability of organisms and ecosystem process changes for multiple levels of warming (up to +9 °C) combined with elevated CO_2 exposures (900 ppm). New methods for whole-ecosystem warming at plot scales of 12- to 14-m diameter have been developed for this study.

KEY WORDS: Experiment, Warming, Elevated CO_2, Carbon cycle, Vulnerability, Methane

INTRODUCTION

Measurements through time and across space have shown that the responses of terrestrial ecosystems to both chronic and acute perturbations of climatic and atmospheric drivers can lead to changes in ecosystem structure (e.g., species composition, leaf area, root distribution) and ecosystem function (e.g., plant physiology, soil microbial activity, and biogeochemical cycling). Furthermore, because the projected magnitudes and rates of future climatic and atmospheric changes exceed conditions associated with current interannual variations or extreme events, they represent conditions that need to be applied to experimental manipulations. Recent science working groups have also focused on next generation ecosystem experiments (Hanson *et al.* 2008) and concluded that there is “a clear need to resolve uncertainties in the quantitative understanding of climate change impacts” and that “a mechanistic understanding of physical, biogeochemical, and community mechanisms is critical for improving model projections of ecological and hydrological impacts of climate change.” Experimental work has also been identified as the only viable means of addressing long-term climatic and atmospheric change impacts on ecosystems that have never experienced projected environmental conditions (DOE/BERAC Workshop 2008).

To address this need, we are executing the Spruce and Peatland Responses Under Climatic and Environmental Change Experiment (SPRUCE) to assess vulnerability of a globally important, highly valued and visible terrestrial ecosystem expected to be vulnerable to climatic and atmospheric change. SPRUCE is a climate change manipulation that focuses on the combined response of multiple levels of warming at both ambient and elevated CO_2 (eCO_2). The experiment is being set up as a platform for testing mechanisms that control vulnerability of organisms and ecosystems to important climate change variables (e.g., thresholds for species decline or mortality, limitations to regeneration, biogeochemical regulations of productivity). This project addresses key science questions essential for informing higher-order models of vegetation change under projected climates:

1. How vulnerable are terrestrial ecosystems and their component organisms to atmospheric and climatic change?
2. Will novel species assemblages or loss of species that result from species-specific responses to climatic and atmospheric change have unanticipated impacts on ecosystem processes? Do changes in ecosystem services precipitate a change in state (e.g., loss of a dominant plant functional type)?
3. What are the critical air and soil temperature response functions for ecosystem processes and their constituent organisms?
4. Will full belowground warming release unexpected amounts of CO_2 and CH_4 from high-C-content northern forests?
5. To what degree will changes in plant physiology under elevated CO_2 (eCO_2) impact a species' sensitivity to climate or competitive capacity within the community?
6. Will ecosystem services (e.g., biogeochemical, hydrological or societal) be compromised or enhanced by atmospheric and climatic change?

MATERIALS AND METHODS

Justifying a *Picea mariana* – *Sphagnum* Ecosystem

SPRUCE is being established in a *Picea mariana* [black spruce] – *Sphagnum* spp. forested peatland in northern Minnesota. This ecosystem, located at the southern extent of the spatially expansive boreal peatland forests, is considered to be especially vulnerable to climate change and to have important future feedbacks on the atmosphere and climate. The boreal forest was one of three terrestrial biomes that met the criteria of Lenton *et al.* (2008) for policy-relevant tipping points in the climate system. The threshold for boreal forest dieback was suggested to be about 7 °C of warming (corresponding to 3-5 °C warming at the global scale). Given the global extent of the boreal forests and their uncertain fate with climatic change, we considered them to be a high priority for experimental climate change research. Furthermore, because of the large amount of C stored in peatlands, and the sensitivity of that C to climatic conditions, peatlands have also been highlighted as one of the most important ecosystems providing feedbacks to global climate change. *Picea mariana* is common and widely distributed in boreal forests, often as the dominant component of the forest or as a nearly exclusive tree species in much of the boreal biome. The *Picea mariana* forests of Minnesota are located at the southern boundary of the boreal forest where future replacement by northern deciduous hardwoods might be projected under climate change if not for the acidic conditions typical of bogs. Despite the acknowledged importance of this ecosystem and the uncertainty about its responses to climate change, large scale *in situ* experimental manipulations that simulate climatic warming together with altered atmospheric CO_2 levels have not been done. The relatively short stature of the *Picea* ecosystem makes it amenable to controlled manipulation that uses new advances in warming technology.

Field Location Details

The planned experimental site is a bog within the Marcell Experimental Forest (MEF) approximately 40 km north of Grand Rapids, Minnesota, USA. The MEF is within the Laurentian Mixed Forest Province, a transitional zone between boreal and broadleaf deciduous forests. The landscape is a typical moraine landscape of the Upper Great Lakes Region, and includes uplands, peatlands, and lakes. Peatlands at the MEF range in size from several hectares to several tens of hectares and may have forest, shrub, or sedge cover. Over the period from 1961 through 2005 the average annual air temperature was 3.3 °C, with daily mean extremes of -38 °C and 30 °C, and the average annual precipitation was 768 mm. Within the 1141–ha MEF research area, the manipulation will be located in an ombrotrophic bog (a raised dome peat bog in which water and nutrient inputs originate from atmospheric sources).

The study site at N 47° 30.476'; W 93° 27.162' and 418 m above mean sea level is designated S1. It is an 8.1-ha *Picea-Sphagnum* bog that was harvested in two successive strip cuts in 1969 and 1974. We will be using the regrowth forest in the 1974 strip cut area. The bog surface has a hummock/hollow microtopography with a typical relief of 30 cm between the tops of the hummocks and the bottoms of the hollows. The peatland has well-decomposed acidic peat (pH ~4) with an average depth in the area of the experiment of 2 to 3 m. Vegetation within the S1 bog is dominated by the tree species *Picea mariana* (mean height of 3 m in 1999) with irregular contributions from *Larix laricina*. The bryophyte layer is dominated by various species of *Sphagnum* including *S. angustifolium, S. magellanicum*). The understory also supports a layer of ericaceous shrubs with *Ledum groenlandicum* Oeder and *Chamaedaphne calyculata* (L.) Moench being the most widely distributed. The S1 Bog also has some graminoids *Carex trisperma* and *Eriophorum spissum* (cotton grass), and is poplulated with the forb *Smilacina trifolia*.

Experimental Methods for Whole-Ecosystem Warming and Elevated CO_2 Manipulation

We succeeded in bringing our vision of a whole-ecosystem warming and CO_2 exposure enclosure to reality. In October 2009 we had a conceptual idea for an enclosure that would provide both above- and belowground warming treatments to a complex ecosystem including trees, shrubs and a high-C soil. Hanson *et al.* (2011) demonstrated the capacity of our new approach to produce logical temperature differentials both above- and belowground to depths of at least 2 meters, and further indicated that the new method may produce disproportionately high CO_2 emissions from deep soil storage pools or enhanced root activity that have not been previously observed in warming studies.

We constructed and tested a full 12-m diameter version of the above- and belowground warming concept (Fig. 1) at Oak Ridge National Laboratory (ORNL). The enclosure was populated with a variety of sensors including temperature sensors (air and soil), relative humidity sensors, an array of radiation sensors to evaluate its actual energy use, and CO_2 sampling ports in order to evaluate the homogeneity of temperature and atmospheric conditions within the enclosure, and the energy demands needed to attain target warming temperatures. While planning and constructing the warming enclosure, we engaged ORNL expertise in complex fluid dynamics modeling in various exercises to estimate the turbulence dynamics and energy use needs of the enclosure. Experimental temperature treatments imposed with this infrastructure will range from ambient to a +9 °C differential from ambient for both air and deep soil. Those treatments will be repeated in combination with ambient or elevated CO_2 atmospheres approaching 800 to 900 ppm.

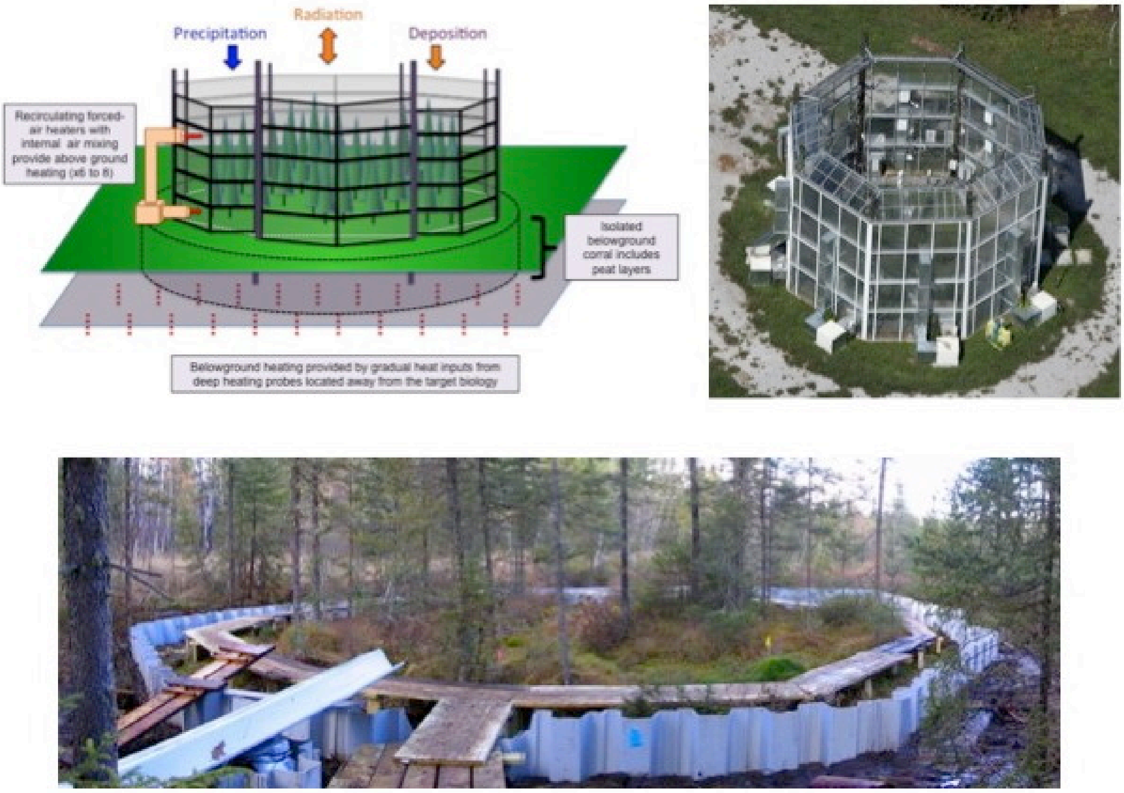

Fig. 1. SPRUCE ecosystem warming enclosure concept (left photograph) and the final fully instrumented prototype (right photograph). The warming enclosure has instrumentation for measuring turbulence, air temperature, and relative humidity at multiple heights, and soil temperatures to depths as much as – 2m. Sampling tubes for [CO_2] measurements are also installed. The lower photograph shows a full-scale prototype corral installed in the S1 Bog in Minnesota. Interlinked sheet piles between 3 and 4 meters long were driven through the peat to the underlying ancient lake bottom to seal a hydrologic basin for testing.

In addition to constructing the warming prototype in Oak Ridge, Tennessee we recently completed a full-scale prototype of our belowground corral on the S1 Bog of the Marcell Experimental Forest (Fig. 1 lower photograph). This flow barrier will serve two purposes: (1) prevention of flow into the plots if snowmelt desynchronizes between the chamber and the surrounding peatland, or if water table gradients develop between inside and outside of the experimental plots due to changes in water use inside the chamber, and (2) a means to collect and measure the volume and chemical composition of surface runoff from each plot. Design documents were prepared and a prototype constructed under subcontract with Minnesota vendors to allow upcoming testing of the system. If proven to be an effective barrier, the corral will allow us to better characterize the hydrologic budget of the manipulated peatlands and more appropriately capture the full influence of warming on integrated ecosystem processes and functions.

Experimental Design

The treatment levels and their allocation to the available experimental units on the S1 Bog are being configured to provide optimal data for characterizing a range of temperature response curves for plant- or ecosystem-level phenomenon. The original 2009 plan proposed an incomplete factorial using 28 experimental units that included four replicates. Although this approach was an option, project participants realized that the incomplete factorial design was statistically weak, open for criticism, and not the best approach for addressing our priority science questions surrounding responses to warming. Through quantitative analysis of different possible experimental designs, we concluded that a more flexible regression-based experimental design including a broad range of temperature levels would yield more statistical power and better long-term data to characterize response curves for application within ecosystem and earth system models. Such a modification of the experimental design will provide the flexibility to choose the number of treatment levels from 28 surveyed experimental plots and allow us to accommodate the costs of constructing, operating, and adding instruments to the warming enclosures. We are pursuing a regression-based experimental design appropriate for detecting the shape of the temperature or other environmental response curves. Such an approach has greater flexibility for characterizing response shapes than traditional analysis of variance (ANOVA). A minimum of six experimental units for each level of CO_2 (ambient and ~900 ppm) deployed over the range of temperatures from 0 to +9 C is needed to provide redundancy for protection against infrastructure failure while still allowing the flexibility to evaluate a range of forms for response curves.

RESULTS AND DISCUSSION

We completed testing of the field performance of an all-electric prototype for air warming, deep belowground warming and the production of elevated CO_2 atmospheres between January and November 2011. Results from testing the electrically heated prototype show that temperature differentials of as much as +7 °C can be achieved for variable energy inputs. Propane-based heating will be needed in Minnesota to achieve target warming levels of +9 °C because local electrical supplies are not available at those demand levels. During testing, ORNL engineers simulated and designed the addition of a frustum to the initial aboveground enclosure, which had straight sides for simplicity to further deflect external winds and limit energy losses. Following installation of the frustum the turnover time of warmed air within the enclosure was increased and energy use went down. At target temperatures of +3 and +6 °C the enclosure yielded a mean differential per energy input value of approximately 0.17 and 0.09 °C per kW of energy input.

Since October 2009, progress has been made on all planned SPRUCE activities including the design and development of experimental infrastructure, the installation of environmental monitoring on the S1 Bog of the Marcell Experimental Forest, testing and evaluation of measurement methods, and the planning for and execution of *a priori* model simulations to guide plans for pre- and post-treatment observations. The presentation will provide details on the experimental approach and measurement goals for this study anticipated to last a decade. Additional SPRUCE details can be found at http://mnspruce.ornl.gov.

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