

II. Science Plan for the Climate Change Response Scientific Focus Area

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ABSTRACT

Experimental work under the Response SFA will focus on the identification of critical response functions for terrestrial organisms, communities, and ecosystems. Both direct and indirect effects of these experimental perturbations will be analyzed to develop and refine models needed for full Earth system analyses. Response SFA research will be organized around a climate change manipulation focusing on the combined response of multiple levels of warming at ambient or elevated CO₂ (eCO₂) levels. The experiment will provide a platform for testing mechanisms controlling vulnerability of organisms and ecosystems to important climate change variables (e.g., thresholds for organism decline or mortality, limitations to regeneration, biogeochemical limitations to productivity). The experiment will evaluate the response of existing biological communities to a range of warming levels from ambient to +8°C. The ambient, +4°C and +8°C warming treatments will also be conducted at eCO₂ (in the range of 800 to 900 ppm). The experiment will be conducted in a *Picea mariana* [black spruce] – *Sphagnum* spp. forest 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 feedbacks on the atmosphere and climate. This science plan for the Response SFA also describes support for core long-term tracking of the hydrologic, biogeochemical and biological response of the Walker Branch Watershed to inter-annual climatic variations.

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EXECUTIVE SUMMARY

The Response SFA provides targeted experiments to assess vulnerability of terrestrial ecological systems to projected changes in climate and atmospheric composition. Quantification of climate change responses allows prediction of the effects of atmospheric and climatic change on ecosystems' capacities to deliver goods and services and on feedbacks from ecosystems to the atmosphere and climate. Fundamental processes controlling vegetation change discovered by these studies will be used to formulate mechanisms for application within terrestrial C cycle and Earth system models.

Vision

ORNL's vision for the Climate Change Response SFA is to provide key components of the science necessary to understand the consequences of climate and atmospheric change for terrestrial ecosystems. 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). The projected magnitudes and rates of future climatic and atmospheric changes, however, exceed conditions associated with current interannual variations or extreme events, and represent conditions that need to be applied to experimental manipulations. Therefore, it seems logical that a suite of ecosystems structures and processes will be impacted in ways that we have insufficient information to predict

To acquire a fundamental understanding of projected changes, ORNL plans to focus future experimental work under the Response SFA on the identification of critical response functions for terrestrial organisms, communities, and ecosystems. This approach includes the development and utilization of experiments that expose critical ecosystems and their components to a broad range of temperature increases (both above- and belowground) combined with atmospheric CO₂ enrichment. Both direct and indirect effects of these experimental perturbations will be analyzed to develop and refine regional and global C cycle models that are needed for full Earth system analyses.

Recent workshops hosted or requested by the US DOE have emphasized that flagship experiments are needed to simultaneously address multiple science questions, engage a broad cross-section of the scientific community, and create a more visible and exciting presence to enhance DOE's important role in climate change research. ORNL experiments executed under the Response SFA will fill this role. New experiments will be implemented in a globally-important, highly-valued and visible terrestrial ecosystem expected to be vulnerable to climatic and atmospheric change and responsive to experimental manipulation. Such an experiment will focus on critical, yet poorly understood processes that we believe will determine rates of mortality and regenerative success of future ecosystems in a changing climate. The work will be characterized by the identification of critical organismal responses (growth, mortality, reproduction and community change) and ecosystem-level functional changes operating through key interactions between organisms and the biogeochemical and hydrologic cycles.

Science Questions

Quantitative information on ecosystem responses associated with climate change is a prerequisite for the development of ecological forecasting tools for policy makers to evaluate

safe levels of greenhouse gases in the atmosphere. These objectives also complement the DOE's mandate to understand both the consequences of atmospheric and climatic change for important ecosystems and the feedbacks between ecosystem response and climate through effects on C cycling (DOE 2009). Providing answers to the following overarching science questions will inform higher-order models of vegetation change for projected future climates.

1. How vulnerable are terrestrial ecosystems and their component organisms to atmospheric and climatic change? Can we quantify the potential for shifts in local species dominance and regeneration success to assist projections of future biome changes over decades to centuries?
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? Do those response functions for ecosystem processes depend on shifts in species interactions and composition?
4. Will full belowground warming release unexpected amounts of CO₂ and CH₄ from high-C-content northern forests.
5. To what degree will changes in plant physiology under elevated CO₂ (eCO₂) 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?

Answering these questions for keystone ecosystems will inform higher-order models of vegetation responses under projected levels of climate variability and atmospheric change.

Response SFA research will be organized around a climate change manipulation focusing on the combined response of multiple levels of warming at ambient or eCO₂ levels. This experiment will provide a platform for testing mechanisms controlling vulnerability of organisms and ecosystems to important climate change variables (e.g., thresholds for organism decline or mortality, limitations to regeneration, biogeochemical limitations to productivity). Such an experiment will evaluate the response of existing biological communities to a range of warming levels from ambient to +8°C. The ambient, +4°C and +8°C warming treatments will also be conducted at eCO₂ (in the range of 800 to 900 ppm).

Studies to understand ecosystem vulnerability to climate change might be deployed in any number of globally important ecosystems valued by society. Here we describe and justify the development of a complex climate and atmospheric change manipulation set in a *Picea mariana* (Mill.) B.S.P. [black spruce] – *Sphagnum* spp. forest 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 feedbacks on the atmosphere and climate. It provides an excellent opportunity to investigate how atmospheric and climatic change alter the interplay between vegetation dynamics and ecosystem vulnerability, while addressing critical uncertainties about feedbacks through the global C cycle.

This science plan for the Response SFA also describes support for core long-term tracking of the hydrologic, biogeochemical and biological response of the Walker Branch Watershed to inter-annual climatic variations. Such support will continue over the next several years until the

activity transitions into the National Science Foundation's National Ecological Observation Network.

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Each individual's role and responsibility is further defined in Section 6.

NARRATIVE

1. BACKGROUND AND JUSTIFICATION

Vulnerability is the degree to which a system is susceptible to, and unable to cope with climate change, including climate variability and extremes. Vulnerability is a function of the direction, magnitude and rate of climate change and the variation to which a system is exposed, and the sensitivity and adaptive capacity of individual ecosystems (Parry et al. 2007; Schneider et al. 2007). Vulnerability includes three elements: exposure to threats (e.g., temperature extremes, reduced available water, nutrient limitations, storms, sea-level rise); sensitivity to those threats; and a coping or adaptive capacity (MEA 2003). A highly vulnerable system is sensitive to anticipated climate change, has threshold responses that are irreversible, and species that have little capacity to adapt. Specific harmful effects might include loss of keystone or locally adapted species, changes in ecosystem services, biogeochemical cycling, energy fluxes and altered interaction or functional linkages to adjacent ecosystems.

Consensus projections of the climatic and atmospheric changes from the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) vary spatially across the globe. Warming is, however, projected to be greatest at high latitudes with temperature increases larger in winter than summer (Christensen et al. 2007). A mean warming of 3.8 and 3.3°C during the winter and summer respectively is expected by the end of this century, based on GCM calculations for the IPCC A1B greenhouse gas emission scenarios. That level of warming exceeds the typically observed variation in mean annual temperatures ($\pm 2^\circ\text{C}$) and therefore represents a range of conditions that necessitates experimental manipulation. In addition, the projected extreme summer heat events may expose ecosystems to acute heat stress that exceed historical and contemporary long-term conditions for which extant vegetation is adapted. Further, forcing estimates greater than the A1B scenario (Christensen et al. 2007) are projected based on current greenhouse gas production (Raupach et al. 2007). Therefore, greater levels of warming should be considered as well. Logical projections from IPCC analyses and the recent evaluation of current emissions (Raupach et al. 2007) suggests that we may need to consider atmospheric CO_2 concentrations at or above 800 ppm based on current fossil fuel use.

Recent science working groups have 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 future projected environmental conditions (DOE/BERAC Workshop 2008). Designing experiments that test model projections to inform those modeling efforts is a fundamental requirement of next-generation experiments. To this end, our group includes a number of process-level and ecosystem modelers to simulate critical stand-level processes. Results from the Response SFA will provide key empirical responses into generalized analyses needed by the Forcing SFA relating changing vegetation composition and function to ecosystem properties relevant to climate feedbacks.

The degree to which species persist, migrate, or perish with climate change is highly speculative (Purves and Pacala 2008). Data on the direction and magnitude of changes in plant

function and growth are mixed in the context of future climate change. Positive growth responses to increased average temperature have been reported in mature trees (Carrer et al. 2007; Nelson et al. 2007; Bronson et al. 2009), while other data suggest limited or negative responses to increasing temperatures for trees that grow in cool environments (Rasmussen et al. 2002; Brooks et al. 1998, Thomson et al. 2009). Because climate change will be associated with an increasing concentration of CO₂ in the atmosphere, the primary effects of eCO₂ on photosynthesis and stomatal conductance can modify the responses of plants to temperature increases and soil drying (Norby and Luo, 2004; Norby et al. 2007). Hanson et al. (2005) simulated the response of a forest ecosystem to simultaneous exposures of forest vegetation to eCO₂, temperature increases, precipitation reductions and ozone and concluded that counterbalancing influences were likely and would demand experimental testing to resolve.

Seedlings represent the life stage most vulnerable to any environmental stress (Purves and Pacala 2008; Lloret et al. 2004). The heightened response of small-stature vegetation results from their small, shallow root systems and limited carbohydrate reserves. Seedling recruitment and early growth are more vulnerable to their environmental conditions, and comprise a topic that has been addressed by few experimental manipulations of realistic global change variables. In bog systems, all woody vegetation is shallow-rooted and therefore not well buffered against changing water regimes. The development of better seedling recruitment algorithms has been identified as a research priority to further understanding the climatic sensitivity of forests and for predicting changes in succession dynamics in an altered climate (Price et al. 2001).

Climate-related species loss can result in ‘novel’ competitive and trophic interactions among the resident species (e.g. release from top-down control may lead to dominance of particular species in a community) that are similar to those resulting from climate-related species invasions. Novel interactions among resident species may facilitate establishment of exotic or migratory species (altered vulnerability to invasion, new niche availability). Climate and atmospheric change will modify environmental conditions for locally extant vegetation resulting in altered species-environment relations.

While this plan focuses on experiments to better resolve Response mechanisms important to the ecological impacts of climatic and atmospheric change, it recognizes that new and expensive experimental investments in manipulative infrastructure may also provide an opportunity to inform Forcing questions. Therefore, where appropriate, the Response SFA experiment will also be used to measure key C cycle processes deemed essential for understanding ecological forcings of the Earth climate system (e.g., altered CO₂ exchange, CH₄ release, etc.).

2. RESEARCH PLAN

This Response SFA experiment will manipulate both temperature (above- and belowground) and CO₂ levels and provide a platform for testing mechanisms controlling vulnerability of organisms and ecosystems to important climate change variables (e.g., thresholds for organism decline or mortality, limitations to regeneration and productivity, environmental controls over C storage and cycling). The experiment will evaluate the response of existing biological communities to warming levels from ambient to +8°C. The ambient, +4°C, and +8°C warming treatments will also include eCO₂ (in the range of 800 to 900 ppm). Details of the experimental design are provided in Section 2.4. All treatments implicitly include the indirect effects of soil drying and altered nutrient cycling associated with the imposed climate change.

New technologies for warming both above- and belowground portions of terrestrial ecosystems are needed to provide a realistic surrogate climate for evaluation at appropriate scales. An ORNL Laboratory Directed Research and Development project to develop new and efficient technologies for warming target ecosystems has reached the stage of prototype testing and will allow rapid progress in the development of the next-generation field work described here. The experimental platform conceived in this plan will host numerous investigators and science objectives, employ new experimental and sensor technologies, and will benefit from the application of enhanced computer modeling for the development of pretreatment hypotheses and post-treatment evaluation of responses. We envision the experiment as a user facility, and we will encourage the development of collaborative studies.

The ecosystem chosen for experimental manipulations must provide an appropriate test bed for the evaluation of hypotheses concerning physiological, organismal, and ecosystem-level sensitivity and vulnerability to individual and multiple interacting effects of climate change. Those effects include warming and increasing atmospheric CO₂, which will affect the form and timing of precipitation (e.g., snowmelt) as well as soil water status. Here we describe and justify the development of a complex climate and atmospheric change manipulation in the context of a northern *Picea-Sphagnum* bog forest.

2.1 Justification for a Focus on the *Picea-Sphagnum* forest

A ‘tipping point’ is a “critical threshold at which a tiny perturbation can qualitatively alter the state or development of a system” (Lenton et al. 2008). 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. Under climate change, increased water stress, increased mortality due to peak summer heat stress, vulnerability to disease, and decreased reproduction rates could lead to large-scale forest dieback and a transition to a more open system. The threshold for boreal forest dieback is suggested to be about 7°C of warming (corresponding to 3-5°C warming at the global scale), but the uncertainty in this estimate is high (Lenton et al. 2008). The boreal forest covers 9 million km² and is equivalent to 6% of total land surface and 27% of the global forest area. Given the global extent of the boreal forests and their uncertain fate with climatic change, we consider it to be a high priority for experimental climate change research.

Because of the large amount of C stored in peatlands and the sensitivity of that C to climatic conditions, peatlands may be one of the most important ecosystems providing feedbacks to global climate change (Hilbert et al. 2000; Bridgman et al. 2008). Carbon loss from peatlands as a result of global warming is estimated at 100 Pg C by 2100 (Davidson and Janssens 2006). Peatlands cover about 3% of the earth land surface and are extremely important ecosystems that contain a disproportionate amount of fixed C, about 19% of the global soil C pool (Batjes 1994; Clymo et al., 1998; Rydin & Jeglum, 2006). Peatlands cover large area of Europe, Asia and North America (Limpens et al. 2008). In the US, more than 60,000 km² of peatlands occur in the Lake States of Minnesota, Michigan, and Wisconsin. Peat deposits largely develop in *Sphagnum* wetlands (Limpens & Berendse, 2003) where long-term storage of C depends on the balance between biomass production and decomposition under the waterlogged and anaerobic conditions of wetlands. *Sphagnum* species are keystone species in bogs as they also regulate acidity, available N, site hydrology, and biogeochemical conditions (e.g. Van Breemen 1995).

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 (National Assessment Synthesis Team 2001) if not for the acidic conditions typical of bogs. Ecosystems located at the margins of major biomes are expected to be sensitive to future warming and associated changes in annual and seasonal precipitation patterns that affect site water balances. Changes in the amount, timing, and form of precipitation will affect peatland water balances which would fundamentally alter peatland biogeochemistry, the release of previously limiting elements, and potentially drive dramatic greenhouse gas feedbacks to the atmosphere in the form of CO₂ and CH₄.

The *Picea-Sphagnum* forests in northern Minnesota are thus a key component of a globally extensive biome that could disproportionately feedback to the atmospheric and climatic systems. The ecosystem and its component organisms are considered sensitive to climate change (Moore 2002; Sage et al. 2008) and may be approaching a critical threshold that would drastically alter the state of the ecosystem – a policy-relevant tipping point. Despite the acknowledged importance of this ecosystem and the uncertainty about its response to climate change, large scale in situ experimental manipulations to simulate climatic warming together with altered atmospheric CO₂ levels have not been done. The relatively short stature of the *Picea* ecosystem makes it amenable to controlled manipulation using new advances in warming technology.

2.2 Field Location Details

The planned experimental site is a bog within the Marcell Experimental Forest (MEF; N 47° 30.171', W 93° 28.970'), which is located approximately 40 km north of Grand Rapids, Minnesota, USA. The MEF is within the Laurentian Mixed Forest Province, which is a transitional zone between boreal and broadleaf deciduous forests (McNab and Avers, 1996). 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. The MEF has an extensive historical database of hydrological, chemical and meteorological measurements that document hydrological, biogeochemical, and ecosystem processes since the 1960s (Nichols and Brown, 1980; Boelter and Verry, 1977; Verry 1981, Grigal 1991; Urban et al. 1989; Verry and Timmons 1982, for a complete list see <http://nrs.fs.fed.us/ef/marcell/data/>).

The climate is subhumid continental, with wide and rapid diurnal and seasonal temperature fluctuations (Verry et al. 1988). 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. According to Kolka et al. (1999), 75% of the precipitation occurs in the snow-free period from mid-April to early November (Verry et al. 1988). Mean annual air temperatures have increased about 0.4°C per decade over the last 40 years (<http://nrs.fs.fed.us/ef/marcell/data/>).

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 msl is designated S1. It is an 8.1-ha *Picea-Sphagnum* bog that was harvested in two successive strip cuts 5 yr apart (1969 and 1974, Verry et al. 1981). The bog surface has a hummock/hollow microtopography with a typical relief of 10 to 30 cm between the tops of the hummocks and the bottoms of the hollows (Nichols 1998). Soils are the Greenwood series (Typic Haplohemist) in the bog and the Warba series (Haplic Glossudalf) in the uplands (Soil Survey Staff, 1987). The peatland has

well-decomposed acidic peat (pH ~4) to varying depths, is overlain by 30–100 cm of less decomposed peat, and has an average depth of 2.5 m (Boelter and Verry 1977; Nichols 1998).

The 25.1-ha upland surrounding the bog is dominated by mature *Populus tremuloides* Michx. and *Betula papyrifera* Marsh. Vegetation within the S1 bog is dominated by the tree species *Picea mariana* (mean height of 3 m in 1999, Kolka et al. 1999). The bryophyte layer on drier hummocks is dominated by various species of *Sphagnum* (*S. angustifolium*, *S. capillifolium*, and *S. magellanicum*; Verry 1984). Other bryophytes include *Aulacomnium palustre* (ribbed bog moss), *Pleurozium schreberi* (big red stem moss), and *Polytrichum juniperinum* (juniper polytrichum moss). The understory also supports a layer of ericaceous shrubs including *Ledum groenlandicum* Oeder [Labrador tea], *Chamaedaphne calyculata* (L.) Moench. [leather leaf], *Andromeda polifolia* L. var. *glaucophylla* (Link) DC [bog rosemary], *Kalmia polifolia* (bog laurel), and *Gaultheria hispidula* [Creeping snowberry]. The bog also has graminoids *Carex trisperma* and *Eriophorum spissum* (cotton grass), as well as forbs *Sarracenia purpurea* (northern pitcher plant) and *Smilacina trifolia* (three-leaved false Solomon's seal).

2.3 Hypotheses To Be Addressed

Overarching hypotheses are presented in seven major research areas. Each of these hypotheses will give rise to a series of more specific, testable hypotheses as we gather preliminary data from the site. These hypotheses are inherently cross-linked. For example, warming-induced changes in the water table (H1) are expected to alter peat decomposition, which could increase nutrient availability (H4) with differential effects on plant functional groups. Changes in plant community composition (H7) can also affect plant productivity (H2), and all of these responses can affect CO₂ and CH₄ production and net C balance (H3).

H1. Air and soil warming will lower the water table and result in drying of the acrotelm.

Increased temperature will increase transpiration in higher plants and evaporation from the upper aerobic layer of peat (acrotelm). Without significant concurrent increases in precipitation, available surface water and the perched water table will decline earlier in the summer and to a greater depth. The *effects* of drying are incorporated into other hypotheses below.

H2. Net primary productivity (NPP) of the ecosystem will not change in response to warming, but relative contributions of different components of NPP will change.

There are many components to this hypothesis with many possible outcomes. The combination of differential effects of warming on physiological responses of component species and indirect responses caused by warming effects on hydrology and nutrient availability make the net effect on NPP difficult to predict. Smaller-scale studies in manipulated bog monoliths showed no response of NPP to experimental warming, but there were differential and sometimes opposing responses of above- and belowground components of production of different plant functional types (Weltzin et al. 2000). Hence, it is especially important that the responses of the different components of ecosystem NPP be determined separately.

Based on the meta-analysis by Rustad et al. (2001), warming at this latitude and mean annual temperature should result in increased plant productivity, and for the boreal forest in general, warming (up to a point) is expected to increase productivity. Our site is near the southern limit of the boreal forest and the range of *Picea mariana*. Provenance tests with *Picea mariana* showed that southern sources (e.g., N46° to N48° Latitude; MEF is at N47°) are currently near their optimum temperatures, suggesting that global warming may cause significant height growth loss

and the potential extirpation of local populations (Thomson et al. 2009). Despite acclimation, photosynthesis of *Picea mariana* grown in high temperature (30°C/24°C day/night) was usually lower than that of seedlings grown in low temperature (22°C/16°C) (Way and Sage 2008). Respiration rates also were lower, but not enough to compensate for reduced photosynthesis, thus reducing net C gain. Growth rates of *Sphagnum* sp. are often positively related to temperature (Dorrepaal et al., 2003); however, such positive effects of warming could be countered by associated drying of surficial peats (i.e., the acrotelm; Robroek et al., 2007). Generally, positive effects of warming on plant productivity in northern ecosystems are expected as the growing season lengthens (Hyvönen et al. 2007).

Drying of the acrotelm (H1) should create a favorable rooting environment for trees and shrubs, increasing their productivity, but a less favorable environment for *Sphagnum* sp. and other bryophytes, especially those species growing on the hummocks (Robroek et al., 2007). Hence, drying of the acrotelm is expected to decrease productivity of *Sphagnum* sp. as a consequence of increased competition from vascular plants (Weltzin et al. 2000, Limpens et al. 2008; Strack et al. 2004). Low water levels can also reduce *Sphagnum* growth by reducing the capillary rise of water to the capitula (Rydin and McDonald 1985). Understory compositional shifts can lead to fundamental change in the functioning of bogs and be critical to the whole-ecosystem NPP response; since *Sphagnum* is mainly responsible for the sequestration of C in bogs (Limpens & Berendse, 2003), an increase in vascular plants may lead to a decrease in C sequestration in bog systems. Also important, but largely unknown, is the response of fine-root production of *Picea* and other vascular plants in this ecosystem. Ruess et al. (2003) concluded that fine-root production in Alaskan black spruce forests exceeded aboveground NPP.

H3. The effects of modest warming on ecosystem C balance will be determined primarily by loss of methane and dissolved organic carbon (DOC).

Temporal and spatial variability of CH₄ emission, which is highly responsive to changes in the water table and vegetation, is much more variable than that of net ecosystem CO₂ exchange (NEE) in peatlands (Moore et al. 1998, Limpens et al. 2008). Daily summer NEE from seven bogs and fens was similar despite large differences in water table, water chemistry, and plant community structure. At a landscape level, internal factors (moisture, temperature, plant community, nutrient status) were less important influences on NEE than photosynthetically active radiation (PAR), probably because internal factors have many offsetting effects on different components of the C cycle (Limpens et al. 2008). Bridgham et al. (2008) showed that different kinds of peatlands can rapidly gain or lose C following hydrological changes, but homeostatic responses return them to a characteristic water table.

Sustained warming, however, is expected to lead to accelerated peat decomposition, releasing C that had been accumulating over many decades and providing a critical positive feedback to the climate system. Production and emission of CH₄ may increase substantially with warming as microbial respiration is stimulated (Updegraff et al. 2001). However, drying that accompanies warming may increase CH₄ oxidation and/or alter the relative importance of CO₂ and CH₄ as decomposition end-products. Availability of nutrients, particularly N, has also been shown to affect CH₄ emissions from wetlands (Schimel 2000, Keller et al. 2006), and warming-enhanced decomposition rates may increase nutrient availability (see also H4 below). DOC production and export may also increase as peat decomposition is enhanced by warming. Further, it has been suggested that CO₂ stimulation of plant NPP can account for the observed increase in DOC export in rivers draining high latitude peatlands (Freeman et al. 2004). Thus, it is likely that

warming and CO₂ treatments will have significant effects on peat decomposition, although the relative effects on the different decomposition end-products are highly uncertain.

H4. Accelerated peat decomposition will provide increased availability of N, P, and other nutrients, which will increase *Picea* and shrub production but decrease bryophyte production.

Precipitation is the only input for N and P to the highly acidic and nutrient limited *Picea-Sphagnum* bog at Marcell. Therefore this ecosystem has a closed nutrient biogeochemistry that constrains changes to ecosystem structure. Experimental warming of mineral soils (absent drought) generally increases rates of soil microbial activity and net soil nitrogen (N) mineralization (Rustad et al. 2001; Melillo et al. 2002). However, the precise effect of warming and eCO₂ on nutrient biogeochemistry is unknown because nutrients released upon decomposition of organic matter are potentially immobilized in a high C environment by stimulation of peat microorganisms. Warming, drying and eCO₂ are all predicted to drive the nutrient cycle to a more open biogeochemical system via several possible mechanisms, including: (1) increasing soil organic matter decomposition and net release of reactive N and phosphorus (P), (2) stimulation of fine-root growth that increases reactive N and P uptake by plants, and (3) creating potential habitat for colonization by N fixing *Alnus incanna* spp. rugosa (L.) Moench. ssp. If correct, altered biogeochemical cycles will lift existing nutrient constraints on growth of the vegetation and accelerate growth of surviving species under eCO₂.

Increased mineralization of peat, as would likely occur with warming and lowering of the water table, has been shown to increase growth of vascular plants in peatland ecosystems, leading to increased shading and reduced growth of intolerant *Sphagnum* (Malmer et al. 1994). Increased N and P mineralization should improve growth of *Picea mariana* as well (Wall 1967, Watt and Heinselman 1965) if high temperature is not physiologically limiting, which may result in increased shading in the understory and growth limitation of herbs, bryophytes, and shrubs.

H5. Warming and CO₂ enrichment will alter microbial community structure and activity through alteration of the oxygenation of the acrotelm, rhizosphere C availability and changes in the timing, duration and depth of snowpack.

Previous work in peatland systems has described multiple microbially driven responses in respiration and trace gas fluxes due to potential treatment influences, including CO₂, warming and water table changes (Ding et al. 2004; Updegraff et al. 2001; Wagner et al. 2003). Additionally, while largely unstudied in saturated systems, soil respiration and trace gas fluxes in other cold dominated environments have shown sensitivity to seasonal snowpack characteristics that could vary due to warming treatments (Brooks et al. 1997; Monson et al. 2006). Microbial communities and corresponding activity in these systems are likely to be strongly influenced by the increased warming and changes in water depth, resulting in shifts in overall activity levels and changes in the balance between the balance of aerobic (e.g. methane oxidation and ammonium oxidation) and anaerobic metabolisms (e.g. methanogenesis and denitrification) that will occur with depth in the warming treatments (Dedysh et al. 2001; Dedysh et al. 2006; Hornibrook et al. 1997; Sundh et al. 2004). Changes in methane oxidation rates may also occur through the proliferation of plant roots in response to eCO₂ and warming, as the increased C and oxygen in the rhizosphere has been shown to have large effects on methanogens (Calhoun and King 1997; Ding et al. 2004; Van Bodegum et al. 2001; Vann and McGonigal 2003). The timing, duration and amount of snow cover can affect growing season microbial processes associated

with the active plant rhizosphere through turnover and nutrient releases that occur at snowmelt as well as through changes in winter decomposition processes that occur in subsoils at slow but steady rates due to the insulating effects of the snowpack (Brooks et al. 1997; Lipson et al. 2002; Lipson et al. 2004; Schadt et al. 2003; Schmidt et al. 2007).

H6. CO₂ responses will be small in ambient temperature but increase with warming.

Responses to eCO₂ are expected to be small in this ecosystem under current conditions. At the scale of the leaf physiology, eCO₂ increases the optimum temperature for photosynthesis, and relative responses to CO₂ enhancement are smaller at low temperatures (Long 1991). This response is reflected in global models of NPP; the LPJ models predicts a 10-15% increase in NPP in northern Minnesota at 550 ppm CO₂, compared with a global average increase of 24.5% (Hickler et al. 2004). As temperature increases, the photosynthetic and growth responses to eCO₂ are expected to become more positive. Modeled NPP responses of the boreal forest at Flakaliden, Sweden, showed a greater response to eCO₂ when combined with warming (Luo et al. 2008).

The LPJ model did not include nutrient feedbacks, and the low nutrient status of the ombrotrophic bog is expected to reduce growth responses to eCO₂ (Oren et al. 2001) to much less than the 10-15% cited above. Nutrient limitation at the Flakaliden site resulted in small to negligible responses in aboveground growth to eCO₂ (Pepper et al. 2007). However, if accelerated decomposition increases N availability, foliar N can increase (but see Way and Sage 2008) and larger CO₂ response again would be expected.

Reduced conductance in eCO₂, if it does occur (Ellsworth 1999), could counteract effects of warming on *Picea mariana*, but could also exacerbate effects of occasional high summer temperature on needle stress and cause increased foliar loss, as was observed in *Liquidambar styraciflua* L. (Warren et al. 2008).

H7. Changes in biogeochemistry and hydrology with extreme warming will lead to a reorganization of plant community.

Changes in the biogeochemistry and hydrology will change the large-scale reorganization of the plant community, which will have feedbacks on albedo, C balance, methane production and other critical atmosphere and climate interactions, consistent with the “tipping point” concept of Lenton et al. (2008). The southern range limits for arctic/alpine species are determined by maximum summer temperatures, and climatic factors seem to be the most important variables influencing the species richness and floristic composition of raised bogs (Glaser 1992). There are three factors associated with extreme warming that could affect plant community composition: (1) temperature stress, (2) dryer conditions, and (3) increased nutrient mineralization.

High temperature stress in *Picea mariana* could result in mortality at the highest levels of warming, although moderate warming may actually increase growth and survival (Nelson et al. 2007). In the case of increased *Picea mariana* mortality, tree species from the surrounding uplands may not colonize the bog because of the low pH, in which case it is more likely that shrubs will compete well. However, *Acer rubrum* (red maple), a locally abundant species, is tolerant of high moisture conditions and may colonize depending on the available nutrients, pH, and hydrology (Moizuk and Livingston 1966).

Dryer conditions potentially associated with extreme warming may favor ericaceous shrubs or *Picea mariana* over sedges and *Sphagnum* spp. (Weltzin et al. 2000). Further, locally adapted species such as *Drosera rotundifolia* (sundew), a unique component of northern *Picea-Sphagnum* forest that is listed as vulnerable to extirpation in some regions (NatureServe 2004),

require continually moist conditions for optimal survival and performance (Reed 1988). Drier conditions may also affect competition within *Sphagnum* species. For example, it has been shown that under sustained periods of drought, the competitive balance between species seems to shift towards *Sphagnum* species that naturally occur higher on the hummock–hollow gradient (Breeuwer et al., 2008). Eventually, this could lead to species loss and the evening out of the typical hollow–hummock pattern of raised bogs (Robroek et al., 2007).

Lastly, potential increases in N and P mineralization from greater peat decomposition rates may increase the abundance of nutrient-limited *Picea mariana* (Wall 1967, Watt and Heinselman 1965) or ericaceous shrubs (Chapin et al. 2004), increasing shading in the understory and limiting herbs, bryophytes, and graminoids. Greater nutrient availability may directly threaten locally adapted species such as *Sarracenia purpurea* and *Sphagnum* species. Increased N deposition was predicted to result in a substantial risk of extinction to the northern pitcher plant (Gotelli and Ellison, 2002), while N fertilization substantially decreases *Sphagnum* cover (Chapin et al. 2004), which could affect peat production and decomposition.

2.4 Experimental Design

The objectives of the experimental design are to provide statistically robust data on ecosystem responses to increasing temperature, with the expectation that the responses will be non-linear, and to evaluate interactions with eCO₂. We are planning for an ANOVA design with temperature and CO₂ treatments replicated in 3 treatment blocks (Figure R1). We plan to use five levels of warming (0, +2, +4, +6 and +8 °C) to allow temperature response to be partitioned into linear and quadratic effects. We will limit the investments in the CO₂ × warming treatment combinations to the low (+0°C), mid-range (+4°C) and high (+8°C) temperature treatments and will analyze CO₂ by temperature interactions on that subset of the overall design. The eCO₂ treatment will target a value between 800 and 900 ppm.

While funding and measurement logistics have caused us to limit the number of planned replicate blocks in this design, adding a fourth experimental block was considered. A fourth block would only marginally increase statistical power for most response variables, but for some variables, such as *Picea mariana* growth or inherently variable understory community composition, even one additional replication could significantly enhance the power of the statistical design. Moreover, there are other non-statistical reasons for adding the additional block including allowing for unanticipated natural disturbances (e.g., wind damage, fire, insect and disease outbreaks). Adding an additional block thus provides some insurance that at least three blocks will be maintained over the length of the experiment.

The experiment will employ a combination of large (12-m diameter) open-top aboveground enclosures and a new method for warming soils from the surface down to approximately 2 meters using circumferential vertical heaters to achieve the target levels of ecosystem warming (Hanson et al. ORNL Laboratory Directed Research and Development Project; Figure R2). Forced–air heating (e.g., Norby et al. 1997) will be used to warm an aboveground encircled treatment space. Key technologies to make this a functional approach at larger scales include the partial recirculation of heated air and the capping of the enclosed space during non-precipitation nights to limit the energy requirements for heating. The final design will represent a compromise between a totally open system (too costly) and a constrained space that still allows substantial exposure of the treatment area to natural radiation, precipitation, and atmospheric deposition. The eCO₂ will be added during daytime hours of the active growing season (May through September) by injection into the heated air streams (Wan et al. 2004). Because the warming

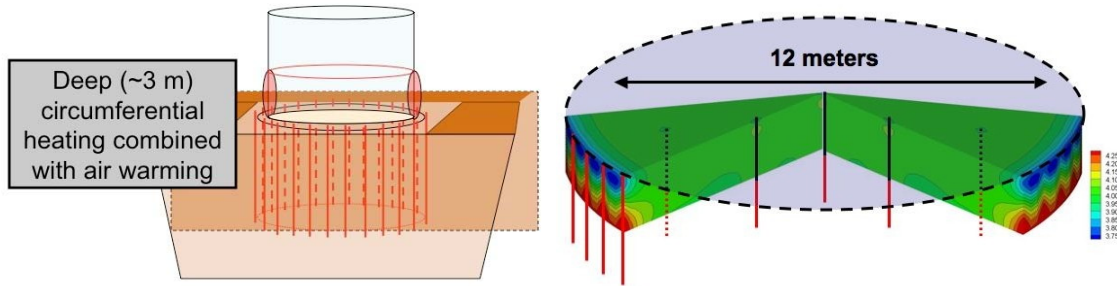


Figure R2. Diagram of the circumferential belowground warming system (left) showing only the outer ring of 3 m heaters. In the temperature contour simulation (right) embedded belowground heaters are also shown. Those heaters only heat from -2 to -3 m.

The deep-circumferential heating concept will use a ring of 48 vertically oriented guard heaters (0 to -3 m) just within the perimeter of the target plot area together with embedded deep-only heaters (from -2 to -3 m) located in two internal concentric rings of 12 and 6 heaters. Simulation, prototyping and testing of a 3 m design at a target temperature differential of 4°C are underway and producing satisfactory results (Figure R3). Simulation of a 12 m version of the plot has also been completed and will be prototyped and tested in the coming months (Figure R2-right). The belowground warming system is designed for gradual warming to the target temperature differentials. When combined with a suitable air heating methods this mild (low wattage) belowground heating approach will achieve temperature targets gradually over multiple weeks.

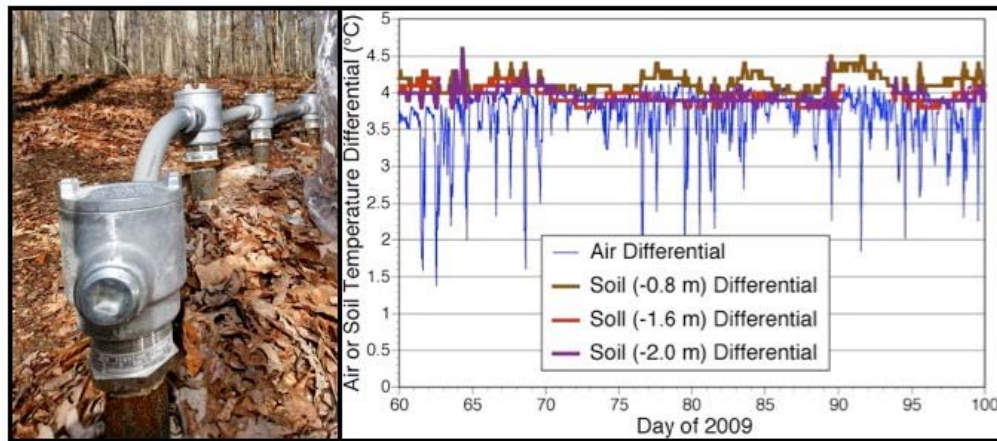


Figure R3. Performance of the 3-m above and belowground warming prototype including pictures of several belowground heating elements.

Because of the routinely high water tables in the *Picea-Sphagnum* bog under the current climate, we are contemplating a subsurface flow barrier approximately 1 to 3 m depth outside of the enclosures. We will design subsurface lateral water flow barriers to 1) maintain hydrological losses via evapotranspiration under extreme warming and to slow vertical flow through the underlying clay aquitard, and 2) prevent the lateral inflow of water into the treated areas. This barrier is considered desirable since the warming treatments are hypothesized to lower the local water table to deeper depths than typically occur under the current regime. The water barrier will encircle each enclosure and extend to the depth of the silty-clay mineral soil subsurface layer.

This aquitard limits vertical flow of water from these perched bog peatlands into the deeper regional groundwater system (Boelter and Verry 1977). Although subject to current discussions and dependent upon assessment of the prototype to be developed in FY 2010, the water barrier might extend to the peatland surface to prevent lateral inflow and outflow of surface water during brief times of high water that occur during spring snowmelt. Alternatively, the barrier walls may allow flow through the top 0.3 m of peat surface (i.e. via the hydrologically and biologically active acrotelm that corresponds to the depth over which the water table fluctuates during a typical year) while excluding lateral inflow below 0.3 m depth during dry summer periods via the catotelm (i.e. the biologically and hydrologically “dead” zone that is permanently saturated).

Current plans and objectives have identified a 12-m diameter experimental plot as a logical size to provide adequate space to evaluate biological responses over multiple years at feasible costs. An assessment of the performance, logistics, and cost of operation for the large scale plots and new above- and belowground manipulation technologies is ongoing. A main objective of the FY 2010 funding cycle will be to complete and demonstrate the viability of the experimental technologies prior to expending funds for the construction of the fully replicated study.

3. MEASUREMENTS

Measurements during the first years of experimental treatments will be focused on (1) the physiological and growth responses of individual species (2) changes in understory community composition (at the level of individual species and life forms) including recruitment and survival, and (3) changes in biogeochemical (e.g., nutrient availability and organic matter decomposition) and hydrologic processes. The FY 2010–2012 timeframe for the current science plan emphasizes the pre-treatment observations needed to provide a solid basis for evaluating response variables once manipulations are initiated in FY 2012.

3.1 Plant Growth Responses

Vascular plant production – We will use multiple measurements to determine the net primary production of the main vascular functional groups in each plot including tree species, ericaceous shrubs, perennial sedges and annual forbs.

The aboveground and coarse root biomass (oven dry mass at 70°C) of trees and ericaceous shrubs will be determined based on site-specific allometric relationships (as in Dyck and Shay 1999, Bond-Lamberty et al. 2002) developed from harvests in adjacent plots destined to be damaged during the construction process. Allometric equations for stem, branch, coarse roots, and needle mass of *Picea mariana* will be determined based on stem diameter at a defined height (and tree height if height provides substantial improvement). Allometric equations for the ericaceous shrubs will be determined based on stem diameter at 15-cm, canopy circumference, and total stem height (Dyck and Shay 1999).

Annual aboveground wood + coarse root production of trees and shrubs will be determined from non-destructive measurements at the end of each growing season. Allometric equations will be used to estimate annual growth as a difference in dry mass between years. All trees greater than 1 m tall will be measured within delineated subplots. Foliage production can be calculated from annual change in foliage mass (from allometry) and litter production (described below), but will be supplemented for *Picea* with branch production from annual assessments of terminal

branch elongation (Bronson et al. 2009). In each treatment plot, *Picea mariana* trees will be marked at the defined measurement height to facilitate accurate annual diameter measurements.

The annual aboveground production of perennial sedges and annual forbs will be determined via annual destructive harvests of multiple subplots (0.5 × 0.5 m) that will not be re-sampled in the subsequent years (i.e. Thormann and Bayley 1997). Subplot locations will be stratified to include microtopographical differences within each plot. Sedges and forbs will be separated from standing litter, sorted by species, oven-dried at 70 °C, and weighed. We will assume that the accumulation of graminoid and forb biomass over the current growing season is equal to their aboveground net primary production (cf. Thormann and Bayley 1997). If the subplots encompass ericaceous shrubs, they will be clipped and sorted by species into current-year and older growth and the oven-dried biomass of stems, branches, and leaves will be determined (Bond-Lamberty et al. 2004). This will help validate allometric equations, and also provide tissue for nutrient analyses (Section 3.7b).

Bryophyte production - Annual growth of *Sphagnum* and other bryophytes will be evaluated using the cranked wire approach of Clymo (1970) and Vitt (2007) as described by Weishampel et al. (2009). We will set up 0.5 m² arrays of 50 cranked wires each in peatland subplots, taking care to stratify sampling to include microtopography, which can determine the dominance of different *Sphagnum* species. Where possible, the arrays will be set up in monocultures of *Sphagnum* to estimate species-specific growth. The arrays will be placed out in the spring of each year after snowmelt (late April), and the vertical growth of *Sphagnum* along the wires will be measured at the end of the growing season (mid-October). We will cut 10 cm × 10 cm × 10 cm sections of peat associated with each array to determine *Sphagnum* stem density (number of stems per unit area) and the mean mass per unit length of stem. *Sphagnum* production will be determined as the product of mean vertical growth, mass per unit length of stem, and density of the bryophyte layer. The production of individual *Sphagnum* species will be scaled based on cover estimates discussed below (Section 3.3).

Leaf and litter production - We will collect litterfall from *Picea mariana* in five 38-cm diameter plastic baskets with mesh liners per plot (Weishampel et al. 2009). Litter will be removed periodically during the growing season and once after senescence, oven-dried at 70°C, weighed, and analyzed for C and nutrient content as discussed in Section 3.7b. Although *Picea mariana* foliage production can be calculated from allometry, we will separately measure needle and litter production on branch samples to calculate the contribution of foliage production to NPP since the treatments could cause departures from the assumptions about leaf thickness, the foliage: stem ratio, and new foliage:litter ratios.

Belowground production – Although minirhizotron measurements have been used successfully in boreal ecosystems (Ruess et al. 2003, Kalyn and Van Rees, 2006), we will conduct preliminary observations in FY 2011 and 2012 to ensure that we can differentiate fine roots against a matrix of fibric peat. If the approach is viable, we will install five minirhizotron tubes per plot at a 45 degree angle. A BTC-2 minirhizotron camera with a Smucker handle and the Bartz I-CAP system will be used to capture the appearance, elongation and disappearance of roots throughout the course of the growing season. Images will be digitized to obtain root diameter and length using RooTracker software. Fine-root length production, mortality, standing crop, and annual turnover rate (per unit viewing area) will be calculated (Iversen et al. 2008).

At peak fine-root standing crop in each year, 5-cm diameter × 30-cm deep soil cores will be taken to sample fine roots within each of the destructive clip plots, where the soil surface will be set as the bottom of the green *Sphagnum* layer (as in Bridgman et al. 1998). Roots will be picked

by hand from the peat, oven-dried at 70 °C, and weighed to assess standing crop. Fine-root mass production per unit area will be calculated from peak standing crop and turnover rate derived from the minirhizotron measurements.

Root in-growth cores (5-cm diameter × 30-cm deep) will be used to supplement minirhizotron measurements, and also to obtain newly produced fine-root tissue for nutrient analyses (described below in section 3.7b). Peat will be obtained from outside of the experimental plots, and processed through a fine mesh to remove existing roots and homogenize the peat. The peat will be packed to the original bulk density in a cylinder of plastic mesh with 4-mm diameter pore size. The in-growth cores will be installed in three locations within each treatment ring at the start of the growing season (early May) by snugly placing the in-growth core in a similar sized core made in the peat. In-growth cores will be harvested in late August, at the end of the growing season. In-grown roots will be separated from the milled peat by hand, oven-dried at 70 °C and weighed to determine net fine-root production. Where possible, roots will be identified to species to facilitate estimates of species-specific belowground production.

3.2 Plant Community Composition Responses

Shifts in plant community structure are vital for understanding whole-ecosystem responses to climate change. Our plant community analyses will comprise two focal areas: 1) tree demography (regeneration), and 2) understory community composition.

Pre-treatment measurements – In FY 2010, an extensive vegetation survey will be conducted at the field site, to obtain a list of extant plant species and to determine the spatial heterogeneity of the vegetation. In FY 2011, a pre-treatment spatial analysis of plant community composition for both overstory and understory vegetation will be conducted to 1) determine the appropriate spatial and temporal scale of plant community analyses, and 2) to obtain ‘baseline’ data enabling future ‘before-after-control-impact’ analyses of plant community composition (BACI; Stewart-Oaten and Bunce 2001).

Plant species percent cover will be evaluated across the entire plot for trees, and evaluated within designated subplots for ericaceous shrubs, sedges, forbs, and bryophytes. Assessments will be conducted during the dormant season for trees and evergreen ericaceous shrubs, and both early and late in the growing season for other plant species. For *Picea* trees (adults, saplings, and seedlings) as well as for the dominant ericaceous shrubs stems will be individually tagged and pre-treatment density will be measured. The origin of *Picea* regeneration (sexual or vegetative layering) will also be assessed.

Tree demography (regeneration) – For *Picea* and ericaceous shrub species, seed germination, emergence, and early seedling establishment are key regeneration processes that are likely to be influenced by warming and/or eCO₂. Regeneration processes also play a central role in determining shifts in tree and shrubs species composition. Despite this central role, few studies have investigated regeneration processes under climatic change.

Seedling recruitment can be sub-divided into several stages (e.g., Price et al., 2001). In our experiment, we will concentrate on effects of warming and eCO₂ that impact dynamics of *Picea mariana*, dominant shrubs, and newly establishing trees by acting on the germination, establishment, survival and growth. Newly established seedlings and *Picea* layer sprouts will be identified and tagged and height and diameter will be measured annually post-growing season. Mortality of regenerating trees and shrubs will also be recorded as noted.

Understory community composition – We will extensively monitor the spatiotemporal dynamics of the understory community. Direct and indirect responses of the understory

community to warming and/or eCO₂ will be examined by measuring changes in abundance and density of all species of epiphytes, chamaephytes (mosses, fruticose lichens, perennial grasses), hemicryptophytes (crustose lichens, bryophytes), and cryptophytes. At a later stage, species might be aggregated into functional types and analyzed based on their functional traits. Understory dynamics will be analyzed for taxonomic trait-based community composition and diversity (e.g. Sorenson's evenness index).

During the snow-free period, cover of all individual species will be monitored in four permanent subplots in each main plot. Plant cover, stratified by topographic position, will be estimated to the nearest 10%, with cover categories of 5, 1, and 0.5% used for small and (or) less abundant species. The size of the subplots will be determined based on the pre-treatments analyses of spatial vegetation and topographic heterogeneity. Subplot size may be adjusted for species with low densities or larger individuals.

Within bog understory communities, *Sphagnum* sp. forms the major component, both for cover and diversity (Glaser et al., 1990). *Sphagnum* species differ in their biomass production and decomposability (Clymo & Hayward, 1982; Rochefort et al., 1990; Bragazza et al., 2006). As a result, the species composition of the *Sphagnum* vegetation is an important determinant of C uptake in ombrotrophic bogs (Gunnarsson 2005; Gorham, 1991). Complementary to the *Sphagnum* growth measurements (Section 3.1), species-specific *Sphagnum* cover will be measured with the point-quadrat method (Jonasson, 1988). *Sphagnum* species strongly differ in their niche requirements (e.g. hummock species vs. hollow species); hence, key functional changes in the *Sphagnum* vegetation may occur in response to changing environmental conditions (Rydin 1993).

We anticipate that natural colonization from outside species pools will be slow relative to the duration of our experiment. Therefore, in addition to measuring demography parameters of individuals initially present and those arriving by mean of natural colonization, after a number of treatments years (perhaps 3 to 5) have passed we will sow seeds of several woody species into the treatment plots in areas previously designated for prior destructive NPP observations. We will select species that are likely to colonize northern bogs based on their climatic and ecological amplitude, and on their presence in adjoining tracts (e.g., *Alnus*, *Betula*, *Picea alba*, *Acer rubrum*, etc.). Two 2 × 4 meter subplots will be assigned to seeding treatments. Within each plot, seeds will be sown in a regular grid at 20 cm spacing; locations of individual seeds will be marked with small plastic markers to facilitate monitoring. We will monitor rates of emergence, growth, and survival for at least five growing seasons.

3.3 Soil Community Responses

Warming may stimulate rates of biogeochemical cycling through increased microbial activity. Moreover, warming effects on water table elevation may indirectly affect soil microbial communities. Concomitant aeration of the deeper peat layers may affect microbial activity and community composition of microbes and higher trophic level soil organisms. Measurements of soil and *Sphagnum* microbial community dynamics (fungi, bacteria & archaea) will include both phylogenetic characterization and quantification based on rRNA genes, as well as profiling of molecular markers for important microbial functions, such as nitrification (ammonium monooxygenase - *amoA*), denitrification (nitrite reductase - *nirS* & *nirK*), methane consumption (methane monooxygenase - *pmoA*) and methanogenesis (methyl coenzyme M reductase - *mcrA*). Changes in communities due to temperature and CO₂ interactions and the associated effects on water level and snowpack will control the biological processing of N, C and other constituents

(e.g., S). Specific analyses will use a combination of 1) rRNA gene sequence based analysis, 2) quantitative PCR for select genes and broad phylogenetic groups (fungi, bacteria, archaea), and 3) functional gene microarray based methods. We have developed and deployed each of these methods in various soil systems previously (Schadt et al. 2003; He et al. 2007; Nemergut et al. 2008; Zhou et al. 2008; Castro and Schadt, unpubl.). Depth-specific sampling for these studies and measurements corresponding with major redox boundaries within saturated and unsaturated zones will be conducted bimonthly throughout the year together with trace gas fluxes described in Section 3.7. Rhizosphere specific sampling will be conducted monthly during the growing season by separation of peat adhering to roots. Whenever possible these sampling efforts will be timed coincident with other task measures to link microbial population information to ecological functions and processes of interest and to minimize repeated soil sampling impacts. Sampling is anticipated to be focused during time-zero assessments conducted in the year preceding treatment initiation in FY 2012 to account for plot-to-plot initial variation, with the majority of the planned effort to be conducted in later years.

Soil organisms of higher trophic levels can also play a critical role in regulating decomposition and mineralization in bog systems. In bogs systems, the effect of warming on C and nutrient dynamics may be related to the activity of microbial-grazing soil organism, such as nematodes and enchytraeids (Cole et al., 2002). In bogs, the majority of nutrients are fixed in microbial biomass and plant (*Sphagnum* sp.) tissue. Therefore, even small changes in microbial biomass/activity by climate-induced changes in microbial grazing by soil fauna may have large consequences for plant-available nutrients and C dynamics. In F2011, pre-treatments analyses of abundance and functional composition of nematodes (sugar floatation extraction and enchytraeid communities (Baermann funnel extraction) will be conducted to evaluate their potential role in decomposition responses to the climate treatments.

3.4 Phenology

Vegetation phenological patterns will be quantified throughout the growing season based on weekly observations of vegetative and reproductive activity supported by the archiving of daily digital photographs of each plot canopy and designated understory subplots. Vegetation phenology would include bud expansion and leaf development in *Picea mariana* and shrub species, the occurrence of recognizable foliar growth for sedges and forbs, and the timing of autumnal senescence in non-evergreen species. Reproductive phenology, including flowering, fruit or cone formation and seed dispersal of dominant species will also be tracked through direct observation. Ripened fruits, cones and seeds will be collected and stored for experimental use.

3.5 Microtopography

Warming and eCO₂ may affect the topography of the *Sphagnum*-peat surface, for example by influencing the production and decomposition of plants or by shrink-swell due to subsurface hydrology or other physically mediated controls on topography. Therefore, at the beginning, middle and end of the study the spatial configuration of the topographic extent of hummock peak and hollow depth will be measured. Within-plot spatial configuration of the topographic extent of hummock peaks and hollow depths will be measured with respect to fixed reference heights established in each plot using a rod surface elevation table device (Cahoon et al. 2002). Topographic measurements will coincide with the designated subplots targeted for understory species evaluations. These plots will be carefully designated as 'no traffic' zones in both winter and summer and will be key to the evaluation of long-term change. Ground based LIDAR

(Laudermilk et al. 2007) would be useful for this measurement and could be calibrated to the fixed reference heights.

3.6 Plant Physiological Responses

Photosynthesis and respiration – Prior to treatment initiation, preliminary measurements will be conducted to evaluate variability of foliar physiology for the dominant vegetation types (*Picea*, ericaceous shrubs, and *Sphagnum* spp.). Foliar gas exchange will be assessed using a Li-Cor 6400 gas exchange system. Measurements of vascular plants will be taken initially at the prevailing chamber temperature and [CO₂], using a fixed level of irradiance based on preliminary work. As the experiment continues, photosynthesis and respiration will be evaluated for acclimation to temperature and CO₂ (Sage et al. 2008; Way and Sage 2008). Early physiological observations will be used to determine the needed frequency of physiological measurements and the detail necessary to fully characterize responses. Foliar samples will be frozen for anatomical and biochemical analyses described below. As distinct treatment responses are identified, additional physiological investigation may be conducted to evaluate mechanistic limitations to leaf C balance (e.g., A/Ci, temperature and light responses) and other changes associated with extreme temperature and moisture stress (e.g., loss of hydraulic conductivity, cellular damage, or shifts in C allocation).

For *Sphagnum* sp., samples of the dominant species will be collected from hummocks and hollows, and analyzed for physiological properties. Measurement of light-saturated assimilation of upper capitula and lower stem/branch tissue will be taken at constant temperatures on fully hydrated tissue, then repeated on the same samples as their water content declines to identify the water content for maximal assimilation (Williams and Flanagan 1996, Granath et al. 2009). To assess impacts of diurnal environmental patterns on *Sphagnum* C balance, assimilation and dark respiration will be quantified on an optimally hydrated subset of samples exposed to increasing temperature and PAR regimes in the lab. Seasonal *Sphagnum* physiological patterns will be evaluated during the growing season.

Sampled plant materials will be retained for analysis of nutrient (especially N and P) and chlorophyll contents. Materials will be retained for additional biochemical analyses (e.g., non-structural carbohydrates and phenolics). Physiological data will contribute to the modeling of foliar and *Sphagnum* photosynthesis based on field measurements of soil water content, PAR and temperatures.

Water relations – Plant water relations including plant hydraulic conductivity, rhizosphere water flux, plant-soil water stress and dynamics of the soil-plant-atmosphere continuum will be assessed when treatments are established. Soil water content, water potential, and temperature gradients will be measured within the hummock/hollow complex and into the acrotelm (Section 3.8). Diurnal patterns of mature spruce root water transport will be monitored *in situ* by measurement of the relative magnitude and direction of root sap flow. Seasonal root conductivity and vulnerability to embolism will be measured on a limited number of destructively sampled roots (2-5 mm) from outside-plots (initially) and from inside-plots (mid-study). Water stress will be quantified on important vascular species based on foliar osmometry or quantification of xylem pressure of stem and leaf tissue samples. Hydraulic flux of selected woody species will be measured *in situ* and in the lab using hydraulic flow meters, isotopes and/or dye tracers. For the *Picea*, leaf hydraulic conductivity and threshold of hydraulic failure under drying conditions may be examined by direct measurements, or by estimating water flow through leaves as they dry by use of a timed-rehydration technique (Brodribb & Holbrook 2003; Woodruff et al. 2007) that

along with pressure-volume curves can be used to estimate leaf conductance. Results will generate a leaf xylem vulnerability curve that relates conductance with leaf water potential. In addition, foliar or woody xylem tissue will be retained and preserved so that vessel anatomy can be characterized using microscopy to determine treatment induced impacts on morphology and potential for hydraulic failure.

Seasonal patterns of *Picea* sap flow will be quantified in ambient plots during the year prior to treatment, and assessed in all treatment plots for initial years, mid-point and end-of-experiment periods. Sap flow will be quantified using thermal dissipation sensors (Granier 1987) installed across the active sapwood. Sensor choice and deployment will be determined prior to the pre-treatment measurements. *Picea mariana* contributions to ecosystem transpiration will be estimated by basal area-based scaling to the plot level. Transpiration from the understory shrubs will be estimated based on spot measurements of leaf water potential and porometry (gas exchange) in relation to concurrent environmental conditions, such that relationships between transpiration and vapor pressure deficit or PAR can be used to model shrub water flux during non-measurement periods. *Sphagnum* water flux will be assessed from modeled relationships to soil moisture. Generation of soil water release curves and soil water transport parameters based on peat and *Sphagnum* physical characteristics will allow for linkages of simple measurements of soil, peat and *Sphagnum* water content to models of water flux thereby enabling seamless integration into large-scale model representation of ecosystem function.

3.7 Biogeochemical Cycling Responses

Biogeochemical cycling response measurements will be organized around three themes: hydrology, element cycling, and C pools and processes.

3.7a Hydrologic Cycle

***Sphagnum* water content** – The water film surrounding *Sphagnum* stem and leaf tissue indirectly regulates C uptake through diffusive resistance of CO₂ into and within the chlorophyllose cells, by maintaining hydration of those cells, and by providing an external pathway for nutrients or growth regulator transport within the system. The external water film and related hydration of water-filled hyaline cells is dependent on atmospheric conditions that impact evaporation and latent heat loss, *Sphagnum* density and canopy architecture, and depth to water table. The water content of *Sphagnum* is thus central to its physiology and vigor, with direct impacts on photosynthetic rate, tissue temperature, and ecosystem water exchange.

Sphagnum water content through the vertical canopy will be modeled based on measured soil water status using relationships to be developed. We will destructively sample *Sphagnum* and underlying peat for gravimetric water content through the unsaturated upper peat zone (e.g., 2, 5, 10, 20, 30 cm) concurrent with observations of (1) peat matric water potential (pore-water pressure), (2) bulk volumetric water content and (3) depth to water table (Thompson and Waddington 2008). Water potential and water content will be monitored using appropriate sensors (i.e., tensiometry, psychrometry, frequency domain capacitance), and will require preliminary pre-treatment field tests to determine reliability, accuracy and precision of equipment, and necessity of depth-dependent calibrations. Pretreatment destructive sampling of *Sphagnum* canopies across the microtopography of the site (lawns, hollows and hummocks) will be used to calibrate the relationships between measured soil water status, ambient environmental conditions and *Sphagnum* water content across the range of saturation. These relationships will then be used as indices of *Sphagnum* physiological status and C uptake through results from the

intensive gas exchange campaigns in the lab. Results of this modeling effort will dictate the most appropriate deployment of moisture sensors across each of the plots in relation to *Sphagnum* physiological status and upper soil hydrology (cf. Section 3.7a).

Soil water and groundwater – The bog water table is usually at or within 30 cm of the bog surface. The highest water tables occur during snowmelt and the lowest levels can occur in summer, autumn, or winter, depending on the timing and amount of precipitation in any given year. Water table elevations within enclosures are predicted to decline with warming treatments, which could have significant impacts on primary productivity of trees, shrubs, and bryophytes, nutrient cycling, and peat decomposition. Changes in water table levels will be monitored in two ways: (1) water table elevation will be recorded hourly to determine the depth to the saturated zone in a water table well at a central location in each experimental chamber, and (2) nested sets of piezometers at different depths (e.g., 10, 30, 60, 100, and 200 cm) within each experimental chamber to determine hydraulic gradients. The piezometers will also be used to measure conductivities and collect subsurface water samples for dissolved nutrients and peat decomposition products (as described in subsections 3.7b and 3.7c).

Water balance – Total water balance will be calculated for each enclosure to determine effects of warming on total evapotranspiration and vertical subsurface loss rates. If justified by pre-treatment lab testing, a conservative anion tracer (e.g., Cl, Br) will be added to the peat early in spring each year when the water table is at the surface. Periodic measurements of the tracer in subsurface waters combined with water table elevations throughout the year will allow calculations of tracer mass balance. Stable isotopes of water can also be used to determine dynamics of the water transport within the system and may be used to complement our tracer studies. Water samples collected from rain gauges, depth-stratified piezometers, and living *Sphagnum* within the unsaturated zone will be analyzed for $\delta^{18}\text{O}$ and δD using a Picarro G1102-i isotopic H_2O analyzer. This approach will also be validated using the physically-based water table recession approach described by Nichols and Verry (2001). Results will be used to determine seasonal patterns of evaporation, transpiration, deep seepage, and precipitation inputs on water availability in the enclosures.

Stomatal conductance – Spatial and temporal variability in environmental parameters that affect stomatal conductance (temperature, humidity, available water, and CO_2) contribute to differences in foliar ^{13}C abundance in C_3 terrestrial vegetation. Changes over time in foliar ^{13}C abundance, as well as inter-specific differences, can be indicative of changes in the ratio of C assimilation to transpiration, and these changes are sensitive to soil water availability and changing hydrologic cycles. Foliar ^{13}C abundance can yield a seasonally-integrated estimate of stomatal conductance and A/E ratios when accompanied by measurements of ambient CO_2 concentrations, temperature, and relative humidity (Farquhar et al. 1982; Sternberg et al. 1989, Garten and Taylor 1992). Once annually, late in the growing season, we will sample foliage from trees and understory plants occupying hummocks and hollows in the warming treatments under ambient atmospheric CO_2 concentrations. Samples will be analyzed for C isotope ratios.

3.7b Element Cycle Measurements

Plant nutrient status – Before the initiation of treatments, plant tissues (including leaves, wood, and fine roots) of the dominant species that are destructively harvested during the installation of boardwalks and monitoring equipment will be analyzed for a suite of nutrients, including: C, N, P, K, Ca, Mg, Zn, Fe, Mn, Cu, B, S, and Cl. After initiation of the treatments, subsamples of the above and belowground tissue of harvested plants, in addition to roots

harvested from in-growth cores (Section 3.1), will be analyzed for nutrient content to determine N and P uptake, and to examine whether eCO₂ has led to a decline in tissue nutrient concentrations (Cotrufo et al. 1998). If the pre-treatment samples indicate that nutrients other than N and P may also be of interest in quantifying plant responses to warming and eCO₂ (for example, K or Ca), subsequent analyses will also include these nutrients.

Peat characteristics – Total peat C, N and P content, in addition to K, Ca, Mg, Zn, Fe, Mn, Cu, B, S, and Cl, peat bulk density, and pH will be measured at depth increments corresponding to the living *Sphagnum* layer (0-5 cm), the acrotelm (5-15 and 15-30 cm), and the catotelm (30-60 cm) at the start of the experiment. Thereafter, total peat C, N and P content, peat bulk density and pH will be measured annually at the start and end of the growing season. Total C and nutrient content will be determined based on element concentrations and peat density. Carbon and nutrient content will also be corrected for ash content as measured by combustion in a muffle furnace at 500 °C for 4 hours.

Nutrient availability in the peat – Nutrient availability within the bog is potentially highly variable, both spatially and temporally, and we will employ multiple approaches for measuring the effects of warming and eCO₂ on nutrient availability: (1) WECSA resins (2) laboratory incubations to determine potential gross N and P mineralization rates in surface peat, (3) aerobic and anaerobic laboratory incubations to determine net potential N and P mineralization rates in the acrotelm, and (4) pore water sampled from multiple levels in the saturated peat profile.

Ion exchange resin capsules (WECSA, Inc, Montana, USA) will be placed at varying depths that include the living *Sphagnum* layer (5 cm), the aerobic peat layer (acrotelm, 15 cm and 30 cm) and the anaerobic peat layer (catotelm, 60 cm) to monitor *in situ* changes in cations and anions (i.e., NH₄-N, NO₃-N, K, P, S, Ca, Mg, B, Zn, Mn, Cu, Fe) during the growing season. Care will be taken to stratify locations of access tubes so that at least one hummock and one hollow are sampled in each plot.

In situ nutrient measurements are often difficult to interpret in peatland ecosystems (Bridgman et al. 2001), so an isotope dilution technique using P-33 as a tracer will be used to measure the relative effects of climatic change on the rate of gross phosphate immobilization and mineralization in laboratory incubations (i.e., Kellogg et al. 2006). A similar isotope dilution experiment will be conducted to determine gross rates of ammonification and NH₄⁺ immobilization (Hart et al. 1994); nitrification is expected to be negligible in this ecosystem due to its high acidity.

Potential net N and P mineralization under both aerobic and anaerobic conditions will be determined as in Bridgman et al. (1998). Mineralization rates will be corrected for differences in bulk density determined from an additional set of cores (see Peat Characteristics). The laboratory incubations will be repeated *in situ*, and at different peat depths, if it is determined that warming or CO₂-enrichment has affected the potential rates measured in the laboratory.

Water samples from lysimeters in the unsaturated zone will be analyzed for the same suite of elements as the ion exchange resins to determine what differences exist between time integrated and instantaneous measurements of nutrient availability. In addition, samples will be collected seasonally from the nests of piezometers in each experimental unit and analyzed for major ions, dissolved N and P species (NH₄⁺, NO₃⁻, dissolved organic N, PO₄⁻, dissolved organic P). These measurements will be used to infer changes in net mineralization rates of N and P within the peat (and therefore increased availability of these nutrients for plant uptake or subsurface water loss). Various measurements of nutrient availability will be statistically analyzed for both treatment effects and changes over time.

In situ whole system indicators of changing N biogeochemistry – Despite the complexity of the N cycle, N rich ecosystems (those with relatively open N cycles) have been repeatedly differentiated from N poor ecosystems (those with relatively closed N cycles) by an examination of foliar N-15 abundance (Garten 1993; Garten et al. 2007). Each year, during the growing season, we will sample and measure N-15 abundance in foliage from trees and understory plants occupying hummocks and hollows in the warming and CO₂ treatments along with N-15 in *Sphagnum* and underlying peat (acrotelm and catotelm). Changes in foliar N-15 are also useful for discerning the relative importance of N immobilization to net nitrification (Garten and Van Miegroet 1994) and, therefore, can be used to indicate or corroborate treatment effects on changes in microbial activity. Following the first three years of research, we will evaluate the utility of natural abundance measurements and the need for N-15 tracer studies to evaluate treatment effects on ecosystem N cycling. In addition, we will explore the use of the dual isotopes of nitrate ($\delta^{18}\text{O}$ and $\delta^{15}\text{N}$) to determine the fate of atmospherically deposited nitrate after rainfall and snowmelt events to specifically quantify the residence time in peat pore waters using an $\delta^{18}\text{O}$ -nitrate mixing model approach described in Sebestyen et al. (2008) to assess sources of soil water nitrate in upland soils.

3.7c Carbon Stocks and Decomposition

Fine litter decomposition – Tissue from *Sphagnum magellanicum* (a common hummock species), *Eriophorum* spp. (a common sedge), *Chamaedaphne calyculata* (a common evergreen shrub), and *Picea mariana* will be used to quantify C and nutrient loss from the decomposition of fine litter (see e.g., Limpens and Berendse 2003; Bragazza et al. 2007). We will sample *Sphagnum* tissue, senesced leaves and fine roots (less than 0.5 mm diameter) of the vascular species to examine the effects of warming and eCO₂ on decomposition rates using a traditional litterbag experiment (Breeuwer et al. 2008). *Sphagnum* and vascular plant tissue will be destructively sampled from outside of the treatment plots, using litter baskets to collect senesced leaves from the trees and shrubs, and subsamples will be characterized for morphology (area, diameter distribution) and chemistry (lignin, N, P and K content). Homogenized, air-dried *Sphagnum*, leaf, and root tissue will be placed in litterbags and placed in several locations within each treatment plot to encompass micro-topographical differences, and will be anchored just below the living *Sphagnum* layer. One set of litterbags from each plot will be harvested eight times over a period of 5 years (at 3, 6, and 9 months and 1, 2, 3, 4, and 5 years) to assess percent litter mass remaining as well as N, P, and K loss. We will use plant tissues sampled from outside of plots as standard material in all warming × [CO₂] combinations given that a reciprocal transplant experiment is not logistically feasible with multiple treatment combinations and tissue types. Differences in chemistry among litter types will allow us to evaluate interactions between tissue nutrient content and microclimate on decomposition rates. We will consider using uniform wood sections collected from adjacent plots (analogous to O'Lear et al. 1996) to assess decomposition rates in the peat profile to 30 cm depth (i.e., the bottom of the aerobic acrotelm).

Peat decomposition – Due to the highly anaerobic and acidic conditions that prevail in the catotelm, decomposition of organic matter is strongly inhibited, limiting both nutrient availability via element cycling and giving rise to peat being the largest stock of ecosystem C (Weishampel et al. 2009). Decomposition of organic matter, particularly the large stocks of accumulated peat, is predicted to increase with warming and lowering of the water table. Moreover, increases in organic matter decomposition may have important effects on the flux and chemical form of C losses, potentially converting the bog ecosystem from a net C sink to a net C

source of atmospheric CO₂ and CH₄, and increased losses of DOC in lateral and subsurface drainage water.

Fluxes of CO₂, CH₄, and N₂O from the surface of the bog to the atmosphere will be measured in each treatment plot using closed chambers (Sundh et al. 1994; Alm et al. 1999). Monthly measurements will be made throughout the snow-free season supplemented by under or through-the-snow flux measurements when necessary (Hubbard et al. 2005). The gas emission chambers will be temporarily placed over permanently installed collars in a stratified design that includes the top and bottom of hummocks. Concentrations of CO₂, CH₄, and N₂O in the chamber will be measured (by gas chromatography on syringe samples) over incubation periods of 15 minutes to 1 hour to determine rates of gas efflux from the peat. Chamber measurements of CO₂ emissions will be cross-checked using a Li-Cor LI-8100 automated soil CO₂ flux system.

We will seek to use a source of CO₂ in the eCO₂ treatments that has a C isotope composition different from ambient CO₂ (similar to the DOE FACE experiments) to allow changes in peat C dynamics to be tracked over time in response to warming and drying. We will measure the isotopic composition of surface CO₂ emissions using a Picarro G1101-i isotopic CO₂ analyzer. In addition, the C-13 abundance in *Sphagnum*, plant roots, and peat pools will be used to determine changing peat C stocks and the source of CO₂ efflux from the surface of the bog under eCO₂.

Measurements of dissolved organic matter (DOM) concentration and composition (e.g. DOC, DON, DOP, ultra-violet absorbance, excitation emission spectra, lignin-phenols, phenol oxidase, analytical absorption chromatography) as well as dissolved CO₂, CH₄, and N₂O concentrations will be made on subsurface water samples collected monthly from piezometers. These measurements will be used as indicators of changes in peat decomposition rates at various depths in the saturated zone. The relative change in DOC, CO₂, and CH₄ concentration will provide information on the mechanism and end products of peat decomposition (DOC production, fermentation, CO₂ reduction) in response to the experimental treatments. Increased rates of DOC production will be estimated from measurements of DOC in subsurface waters and calculated vertical subsurface water loss from water balance measurements within each treatment plot.

3.8 Environmental Monitoring

Measurement of the environments of all experimental plots will be conducted at 30 minute intervals for the characterization of treatment conditions and as a driver for future modeling activities. Air temperature, atmospheric CO₂, and both relative and absolute humidity will be measured at 0.5 and 2 meters above the bog surface (ericaceous shrub and tree mid-canopy height, respectively). Incident PAR will be measured above the *Picea mariana* canopies in each plot. PAR at 0.5 m (i.e., just above the ericaceous shrub layer) will be evaluated at south, middle and northern positions along the plot diameter. Surface and soil temperatures will be evaluated for hummocks and hollows and at the following depths below the mean hollow elevation -0.1, -0.2, -0.5, -1, -1.5, and -2 m. Both hummock and hollow 'soil' moisture in the unsaturated zone will also be measured along with additional hydrologic observations described earlier (Section 3.7a). Regional data for N deposition (NADP/NTN 2009 Site MN16), mercury deposition (NADP/MDN 2009 Site MN16) and ozone exposure (a new ozone system will be deployed with the NADP instruments at MEF in 2009) will be obtained.

Tipping bucket rain gages will be used to measure the timing and magnitude of rainfall and snowfall (heated in winter). Especially during the initial years, the effect of enclosures on the spatial distribution of snow depth and water equivalent will be measured at multiple locations within each enclosure with Mt. Rose snow tubes.

3.9 Measurement Opportunities for Future Collaborators

The experimental infrastructure will become a user facility for studies beyond those explicitly delineated in this document. To that end, we anticipate and will encourage the participation of USFS, National Laboratory, and university researchers to develop proposals for funding to added new research and supplement the capacity and expertise of the initial research group. Although not inclusive, the list below indicates a number of areas for research that we will actively encourage outside research groups to consider for development.

Table R1. Additional research topic areas for which a measurement task might be developed within the planned temperature x CO₂ study

Canopy albedo changes
Remote sensing of the canopy/surface function (NDVI, etc.)
Microscale LIDAR surface analysis using ground-based systems
Whole-chamber CO ₂ and H ₂ O flux (if possible)
Bole respiration
Biogeochemical cycling of trace elements, particularly mercury
Trace gas emissions other than those listed previously
Mycorrhizal studies
Nitrogen fixation
Herbivory studies (foliar losses, seed consumption)
Insect populations (esp. mosquitoes and flies)
Amphibian and reptile populations
Food web linkages of insects to amphibians
Lichen productivity and decomposition
Pest and pathogen interactions (host defense vs. pathogen virulence)
1. eastern dwarf mistletoe (<i>Arceuthobium pusillum</i>)
2. spruce budworm (<i>Choristoneura fumiferana</i>)
3. spruce sawfly (e.g., <i>Pikonema alaskensis</i>)
4. fungal rust and blight pathogens.

3.10 Modeling

In their recent review of the relationship of peatlands to the C cycle, Limpens et al. (2008) concluded that new modeling approaches are needed to incorporate the complex relationships between warming, drying, mineralization processes and vegetation responses associated with climate and atmospheric change. Modeling appropriate to this complex study will include: hydrologic models that simulate water table depth and soil water content from weather data and edaphic conditions; terrestrial biogeochemical models that assess how plant productivity and C storage respond to environmental conditions and interact with available plant nutrients and landscape models that assess how site-level changes influence plant production, ecosystem C balance, and community composition at regional to global scales.

A number of terrestrial biogeochemical models might be employed in the interpretation of these experimental results and we anticipate a large number of modelers will use results from this experiment. In particular, ORNL researchers will use data to evaluate the land component of the CCSM model (CLM-CN; Thornton et al. 2007, 2009). The USFS investigators are interested in evaluating a version of the PnET family of models (Aber et al. 1996, 1997) currently being parameterized for *Picea mariana* forests of the northern Lake States, and Biome-BGC (Thornton et al. 2002), which has recently been adapted to include the impacts of poorly drained forest soils (Bond-Lamberty et al. 2007). Experimental data generated in this study can lead to key improvements in how biogeochemistry models represent the temperature dependence of C losses

as CO₂ and CH₄ and the extent to which they might be counter-balanced by enhanced NPP driven by elongation of the growing season, nutrient enrichment and eCO₂ atmospheres.

Landscape models appropriate for application within digital vegetation models will also be considered for development or improvement using data from this study (e.g., ED2, LPJ, ORCHIDEE). Such models can integrate site-level process models into a raster-based, spatially explicit geographic information system and simulate the response of *Picea mariana* peatlands to climate change over entire regions. Demographic, vegetation dynamics, and individual-based gap models have a history of being used to simulate individual plant interactions that impact species diversity and patterns of forest succession (Moorcroft et al. 2001; Smith et al. 2001; Bugmann et al. 2001), but empirical data are necessary to inform the mechanisms necessary to study the response of forest structure and competition under a changing climate.

Current forest models capable of addressing changing species composition in the context of climate change (e.g., Wullschleger et al. 2003; Moorcroft 2001) have no adequate mechanistic basis for capturing the processes of seedling establishment and early growth from periodic canopy seed supplies. Age-dependence of allocation patterns is also a critical factor during the transition from seedling to sapling, ignored in most process-based ecosystem models (Law et al. 2001). A quantitative framework for capturing these processes and their uncertainty is needed and will be built for use in the context of this experiment. Figure R4 diagrams regeneration processes (Price et al. 2001) in an integrated form that could be developed into a functional and quantitative model of forest plant regeneration and growth. This work will complement new efforts to introduce age-class distribution into CLM (see Forcing SFA, Task F1c).

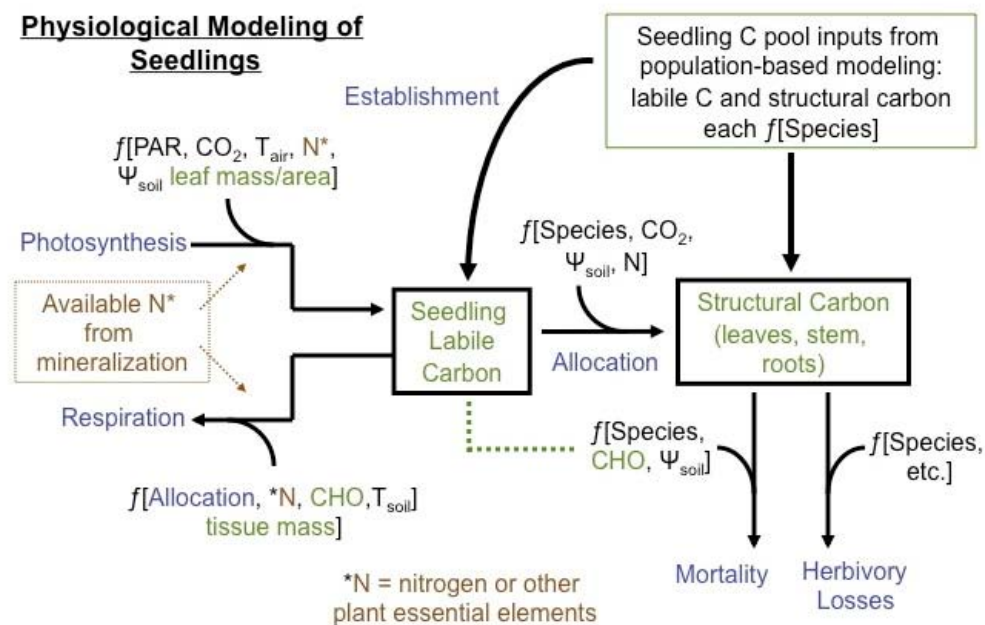


Figure R4. Conceptual model of key processes responsible for plant regeneration success that might be considered for an improved vegetation model to inform future succession under future climate and atmospheric change.

3.11 Data and informatics

Goals for Response SFA data management are to ensure the fidelity and accessibility of the SFA data, minimize the amount of time research personnel need to spend on data management activities while achieving high quality data and metadata, and ensure that the data and metadata

can be located and used by project personnel (initially) and the broader scientific community. The suite of activities that collectively comprise this component of the SFA will naturally evolve over the life of the SFA, and they will be done in collaboration with data management components of other Climate SFAs. Initial data management work will focus on defining the data collection and distribution requirements, identifying key leverage points across SFAs and other projects, ensuring that site characterization data is maintained, and resolving any critical informatics knowledge gaps identified in the requirements definition. As the experiments begin to collect high resolution data, the data management activities will shift to ensuring that the experimental data are properly archived and distributed according to the SFA's data access policy. Data from the Response SFA will be a combination of observational data recorded by researchers and data collected by automated equipment. Further details can be found in Annex C.

The data management component will leverage the expertise and tools in the Environmental Data Science and Systems (EDSS) group, particularly the Carbon Dioxide Information and Analysis Center (CDIAC) and the Atmospheric Radiation Measurement (ARM) program archive, to ensure that both observational and automated data are robustly archived in relational data models with necessary timestamp, spatial, temporal, and provenance metadata.

4. WALKER BRANCH WATERSHED LONG-TERM MONITORING— TRANSITION PLAN TO NEON

Walker Branch Watershed (WBW) is a long-term forested watershed research site on the Oak Ridge Reservation and represents one of only a handful of long-term watershed studies in the deciduous forest ecosystem of the eastern U.S. Hydrological, biogeochemical, and ecological studies in WBW have made and continue to make important contributions to our understanding of effects of changes in atmospheric deposition and climate variability and change in this region. Current research in WBW involves long-term measurements of climate and catchment-scale hydrology, atmospheric chemical deposition and stream chemical outputs, soil chemistry, and forest composition and biomass. Objectives of the long-term observations are to:

1. quantify responses of an eastern upland oak forest ecosystem to inter-annual and long-term variations in climate and atmospheric deposition of sulfur and N, and
2. provide integrated, long-term data on climate, forest vegetation, soil chemistry, and hydrologic and chemical fluxes at the catchment scale to support other focused research projects on the Oak Ridge Reservation and elsewhere in the region.

We now have a 40-year record of forest inventory data that we are analyzing to determine rates of forest succession and evaluate effects of climatologic variations on forest succession. We also now have a 40-year record of hydrology and a 20-year record of weekly stream chemistry data that we are analyzing to determine inter-annual variations in catchment hydrology and biogeochemistry in response to inter-annual weather/climate variability and long-term trends in biogeochemistry in response to observed warming (particularly in winter) over the past two decades. Results of these analyses will be submitted for publication in FY 2009 or early FY 2010. A paper to be published in *Global Change Biology* in FY 2009 used the long-term stream chemistry record to identify effects of an unusual weather event in spring 2007 (freeze event) and implications for future climate change involving winter warming and advances in forest leaf phenology in spring (Mulholland et al. in press).

We are in a transition period for the long-term WBW measurements. WBW has been chosen as a core wild-land site in the planned National Ecological Observatory Network (NEON), to be funded by the National Science Foundation. NEON will install three new eddy covariance towers for canopy-atmosphere CO₂ and energy exchange, instrumentation for monitoring climate, soil, vegetation, and stream ecological variables and process rates related to climate change, biodiversity and invasive species, biogeochemistry, and ecohydrology. NEON also will conduct annual sampling of soils, vegetation, and biweekly (for water chemistry) or semi-annual (for most biological and benthic chemistry characteristics) sampling of the stream to acquire critical ecological and biogeochemical data for which in situ instrumentation is not yet available. Implementation of the NEON site in WBW is likely to be during the period FY 2012–2013. When implemented, NEON will provide a substantial expansion of the variables and process rates being routinely measured in WBW enhancing its value as a reference site for experimental and other observational climate change research on the Oak Ridge Reservation and in the Southeastern Appalachian region. The ongoing and past measurements in WBW will extend NEON data records backward in time thus increasing the value of the WBW data record in historical reconstructions of responses to climate variability and change. We will continue the long-term hydrological and catchment-scale biogeochemical measurements in WBW until the NEON site is implemented to avoid a break in the record.

5. RESEARCH TIMELINE, MILESTONES, AND DELIVERABLES

5a. Warming by CO₂ Experiment Deliverables

FY 2010 (with some scoping activities in FY 2009)

Summer 2009 – Inventory *Picea mariana* basal area across S1, conduct a peat depth survey, initiate water-level observations to characterize local water table geometry, heterogeneity and seasonal variation to enable the determination of optimum locations for treatment blocks within the S1 bog.

Oct 2009 – Finalize the ORNL/USFS Interagency Agreement.

Nov 2009 – Initiate National Environmental Policy Act (NEPA) process.

Nov 2009 to Apr 2010 – Snow cover and depth surveys.

Dec 2009 to May 2010 – Establish and test operational aboveground 12-m prototype at ORNL.

Winter 2009 to 2010 – Evaluate pre-treatment *Picea mariana* characteristics.

Apr 2010 – Complete NEPA Process.

May 2010 – Complete access roads, truck turnarounds and cleared areas for staging the experiment (key USFS involvement).

Jun 2010 – Install main access boardwalks for each treatment block.

Jun 2010 – Bring electrical power to the S1 site.

Jun 2010 – Lease and locate movable office/storage space.

Jul 2010 – Initiate the collection of baseline understory plant data.

Jul 2010 – Initiate continuous environmental monitoring on ambient plots.

May to Jul 2010 – Establish and test a belowground corral prototype in a non-critical area of the S1 bog following NEPA approvals.

FY 2011

Oct 2010 – Complete experimental engineering plans and diagrams.

Oct 2010 to Jan 2011 – Conduct allometric evaluations on Picea and shrubs.

Dec 2010 to Mar 2011 – Experimental construction.

Jul 2011 – Add concrete pad for the CO₂ storage tank.

All year – Continue environmental data collection.

Apr to Oct 2011 – Collect pretreatment biological observations.

FY 2012

Dec 2011 to Mar 2012 – Experimental construction.

May 2012 – Complete construction of all above- and belowground infrastructure.

Jun 2012 – Bring in CO₂ tank and test systems.

Apr to Oct 2011 – Collect pretreatment biological observations.

Sep 2012 – Initiate temperature and CO₂ treatment.

5b. Walker Branch Long-Term Studies Deliverables

FY 2010

Oct 2009 – Submit journal publication on long-term successional forest dynamics and responses to climatic variability.

Feb 2010 – Submit publication on long-term trends in stream chemistry and input-output budgets and responses to climatic variability.

Apr 2010 – Complete analysis and update annual hydrology, atmospheric deposition, stream chemistry and input-output budgets for calendar year 2009.

FY 2011

Oct 2010 – Submit publication on response of stream metabolism to climate variability and projected change based on 6-year continuous record.

Apr 2011 – Complete analysis and update annual hydrology, atmospheric deposition, stream chemistry and input-output budgets for calendar year 2010.

FY 2012

Apr 2012 – Complete analysis and update annual hydrology, atmospheric deposition, stream chemistry and input-output budgets for calendar year 2011.

Mid-2012 – Transition long-term monitoring of Walker Branch to NEON.

6. RESPONSE SFA ORGANIZATION AND PERSONNEL ROLES AND RESPONSIBILITIES

Paul Hanson will be the research manager for the Response SFA reporting to the ORNL CCP Director. He will have overall responsibility for the Response SFA and for communicating directly with each technical task leader for a variety of functional and measurement tasks associated with the SFA. The Response SFA will include scientific staff with the most relevant expertise as needed to support the SFA tasks.

The USDA Forest Service (USFS) is providing the land base for this large and complex experiment and has offered to provide on site support to the study through ‘in kind’ support of their staff. ORNL encourages the USFS staff to become fully engaged in the experimental science to the extent that their other commitments allow. To that end various USFS staff are included in Figure R5 where initial discussions have indicated particular interests for collaboration. A key ORNL-USFS activity to be initiated upon approval of this SFA by the US DOE will be the development of a comprehensive Interagency Agreement (IAG) laying out the

responsibilities and expectations of both parties as we begin this exciting collaboration. At the outset, ORNL is expected to provide full funding for all experimental materials, construction costs, utilities, and the support of their staff in conjunction with the operation, maintenance and measurements for this study.

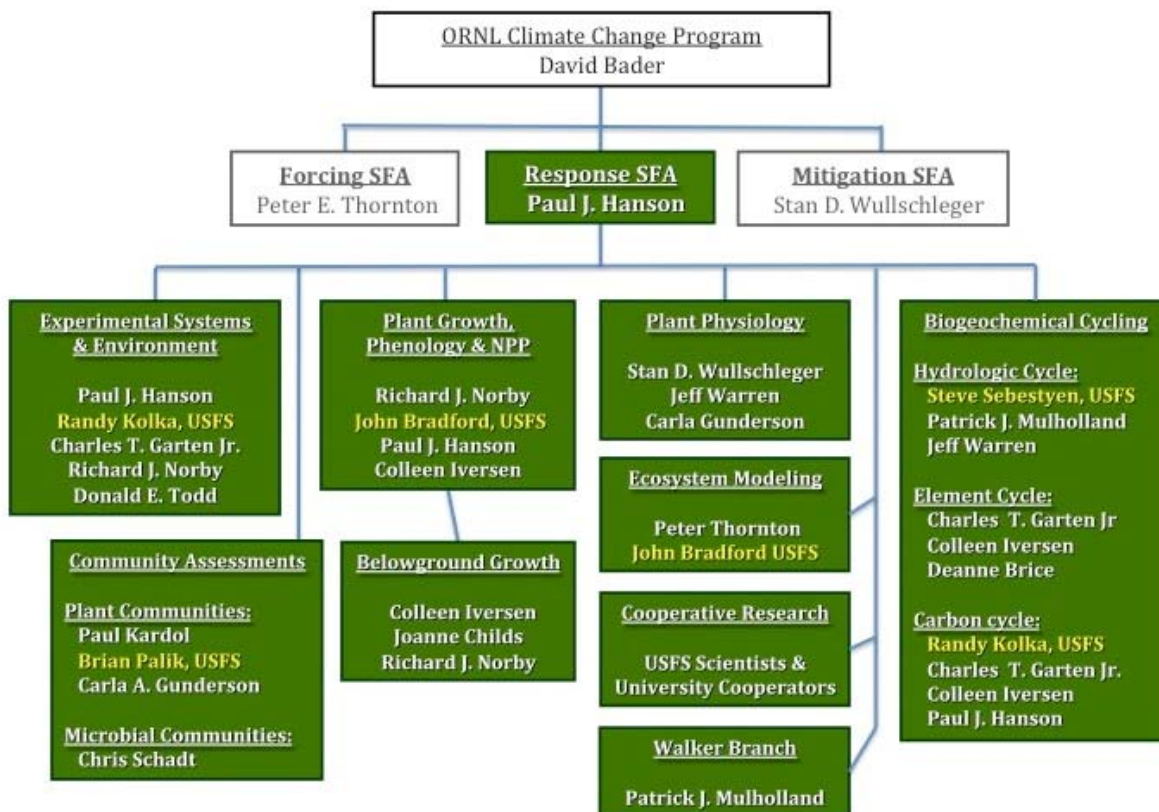


Figure R5. Response SFA organization and key personnel.

Task R1. Experimental design, maintenance and environmental documentation

Paul Hanson will lead this effort in conjunction with the Randall Kolka of the USDA Forest Service. Charles Garten, Richard Norby and Donald Todd will also be actively engaged in the experimental design and optimization phases taking place in FY 2010 and FY 2011. Starting late in FY 2012 in conjunction with the beginning of experimental treatments, ORNL will hire or transfer a full time staff person to off-site status to live in northern Minnesota to provide day-to-day operation and oversight for the experiment.

Task R2. Plant growth phenology and net primary production (NPP)

Richard Norby will organize plant growth, phenology and NPP observations efforts in coordination with John Bradford, Paul Hanson, and Colleen Iversen. Effort will include major annual measurement campaigns focused on the experimental response of trees, ericaceous shrubs, sedges/forbs and *Sphagnum* sp. Belowground response measurements will be lead by Colleen Iversen with notable technical assistance from Joanne Childs.

Task R3. Community composition

Efforts to characterize community compositional changes in response to the experimental treatments will be co-lead by Paul Kardol (understory & Sphagnum) and Brian Palik of the USFS (tree demography) with key contributions from Carla Gunderson. Chris Schadt will develop and lead a related effort on microbial community changes.

Task R4. Plant Physiology

Characterization of pre- and treatment plant physiological responses to both seasonal dynamics and induced treatment regimes will be coordinated among Jeff Warren, Stan D. Wullschlegel and Carla Gunderson.

Task R5. Biogeochemical cycling responses

Charles Garten will take the overall lead for biogeochemical cycling responses. Work on hydrologic cycling will be lead by Steve Sebestyen and Pat Mulholland with input from Jeff Warren. Charles Garten and Colleen Iversen will lead the element cycling subtask. Carbon cycle observations focused on peat changes and C emissions will be led by Randall Kolka with support from Charles Garten, Colleen Iversen, and Paul Hanson.

Task R6. Modeling of terrestrial ecosystem responses to temperature and CO₂

Peter Thornton will lead efforts to utilize and incorporate experimental results into improved modeling frameworks for understanding the terrestrial C cycle and its feedbacks to climate. John Bradford of the USFS will work to enhance two biogeochemical cycling models using various outputs from the experiment. Both will work together to organize an *a priori* model projection exercise before treatments are initiated.

Task R7. Walker Branch long-term measurements of potential climate impacts

Patrick Mulholland will provide expertise on hydrologic and biochemical processes and feedbacks at the ecosystem and landscape scales in support of the Walker Branch measurement objectives. He will be supported by Paul Kardol and Donald Todd.

Support of data management archiving and distribution in the early years of the project (i.e., FYs 2010 and 2011) will be obtained by fractional funding of staff available through the CDIAC and ARM data centers at ORNL and the purchase of requisite hardware (see budget justifications). In FY 2012 a half-time individual will be hired to manage and track automated data streams and other key site data for the Response SFA

Independent funding for the participation of many other researchers from the USFS and other laboratories and Universities is expected to develop with time as the experimental site transitions to a user facility for ecological observations.

A coordinating panel made up of the Response SFA research manager (Hanson), the local USFS contact (Kolka), the Technical Task leaders listed earlier, and several external experts (yet to be finalized) will make up the experimental advisory panel. This panel will serve as the decision-making body for major operational considerations throughout the duration of the experimental activity and it will be the panel for vetting requests for new research initiatives to be conducted within the experimental system (see also Section 6).

Detailed person month contributions by Response SFA Task for all researchers and some unnamed postdoctoral associates are provided in Table R2 for the FY 2010–2012 funding cycle.

Table R2. ORNL person hours by investigator and major research task for FYs 2010, 2011, and 2012 (1 Person month = 160 hours)

Investigator (Affiliation)	Response SFA							3-Year Total Hours
	Task R1 Exp & Envir.	Task R2 Growth	Task R3 Community	Task R4 Physiology	Task R5 Biogeochem.	Task R6 Modeling	Task R7 Walker Br.	
	FY10,11,12	FY10,11,12	FY10,11,12	FY10,11,12	FY10,11,12	FY10,11,12	FY10,11,12	
Scientific Staff								
Garten	320, 160, 160	---	---	---	229, 740, 740	---	---	2349
Gunderson	---	---	1000,1000,1000	320, 320, 320	---	---	---	3960
Hanson	900, 900, 900	320, 320, 320	---	---	220, 220, 220	---	---	4320
Kardol	--	1060,1060,1060	---	---	---	---	---	3180
Mulholland	---	---	---	---	100, 100, 100	---	500, 500, 500	1800
Norby	320, 320, 320	400, 360,1100	---	---	---	---	---	2820
Schadt	---	---	0, 160, 320	---	---	---	---	480
Thornton	---	---	---	---	---	200, 200, 200	---	600
Wullschleger	---	---	---	900, 900, 900	---	---	---	2700
Data staff	160, 160, 400	---	---	---	---	160, 160, 300	---	1340
Postdoctoral Staff								
Iversen	---	90, 450, 450	---	---	90, 450, 450	---	---	1980
Warren	---	---	---	378, 246,1000	160, 200, 440	---	---	2424
Unnamed	---	80, 80, 80	260, 260, 260	160, 160, 160	---	400, 400, 400	---	2700
Technical staff								
Brice	---	---	---	---	0, 500, 500	---	640, 640, 640	2920
Childs	0, 160, 160	300, 1320, 1320	100, 320, 320	---	---	---	---	4000
McCracken	---	---	---	---	---	---	400,400,400	1200
Todd	320, 800, 800	---	---	---	280, 280, 280	---	---	2760
Hours By Task	7260	10170	5000	5764	6299	2420	4620	41533

Table R3. Summary of planned person hours of ‘in kind’ support anticipated by USDA Forest Service investigators from FY 2010 through FY 2012

Investigator (Affiliation)	Response SFA							3-Year Total Hours
	Task R1 Exp & Envir.	Task R2 Growth	Task R3 Community	Task R4 Physiology	Task R5 Biogeochem.	Task R6 Modeling	Task R7 Walker Br.	
	<u>FY10,11,12</u>	<u>FY10,11,12</u>	<u>FY10,11,12</u>	<u>FY10,11,12</u>	<u>FY10,11,12</u>	<u>FY10,11,12</u>	<u>FY10,11,12</u>	
Scientific Staff								
Bradford**	---	80, 80, 80	---	---	---	160, 160, 160	---	720
Kolka**	160, 160, 160	---	---	---	320, 320, 320	---	---	1440
Palik**	---	160, 160, 160	160, 160, 160	---	---	---	---	960
Sebestyen**	160, 40, 40	---	---	---	320, 320, 320	---	---	1200
Hours By Task	720	720	480	0	1920	480	0	4320

**USFS researcher time commitments are estimated ‘in kind’ contributions without direct US DOE support during the FY 2010–2012 time period.

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