**Results from Most Recent NSF Funding:** 

<u>Measurement and modeling the effects of fire on the structure and function of boreal forests.</u> Integrated Research Challenges in Environmental Biology. NSF DEB-0077881. S.T. Gower (PI) Overall Project Objectives of the IRCEB proposal are:

1. Quantify the effects of wildfires on the microclimate, structure, and function of successional boreal black spruce forests in northern Manitoba, Canada, and compare these results to other boreal forest age-sequence studies.

2. Quantify active and past aerial extent of wildfires for North American boreal forests using current (AVHRR, Landsat-7) and future (MODIS) satellite-borne sensors.

3. Examine the effects of fire on the exchange of energy, water, and CO<sub>2</sub> between boreal forests and the atmosphere using terrestrial ecosystem models.

4. Use ecosystem models to explore the potential sensitivity of regional-scale ecosystem processes to increases in fire frequency and extent.

Funding began October 2001 with the following 17 manuscripts published, in press or submitted to date (all can be found in the literature cited section):

Bond-Lamberty et al. submitted, Bond-Lamberty et al. 2005, Bond-Lamberty et al. 2004abc, Bond-Lamberty 2003, Bond-Lamberty 2002abc, Ewers et al. 2005, Gower 2003, Lefsky et al. 2002, Litvak et al. 2003, Manies et al. submitted, Wang et al. 2003, Wang et al. 2002ab,.

<u>Collaborative Research: Restricted Plasticity of Canopy Stomatal Conductance: A Conceptual</u> <u>Basis for Simpler Spatial Models of Forest Transpiration.</u> NSF Hydrologic Science. EAR-040531. B.E. Ewers (PI) Collaborating PIs D.S. Mackay (SUNY Buffalo) and E.L. Kruger (U. of Wisc.).

The hypotheses being tested by this proposal are:

1. Reference canopy  $g_s$  ( $G_{Sref}$ ) varies in response to spatial gradients within forest stands and the response varies among species, and yet the relationship between  $G_{Sref}$  and its sensitivity to VPD is unaltered.

2a. Variation in leaf  $g_{\text{Smax}}$  within and across species and environments is positively related with leaf nitrogen content and leaf-specific hydraulic conductance.

2b The relative response of  $g_s$  to light intensity (Q) is governed in large part by leaf water potential and this dependence underlies stomatal sensitivity to VPD.

Corollary  $2b_i$ :  $g_s$  will increase with increasing Q until it reaches a limit imposed by critical water potential, which for a given leaf is mediated primarily by VPD.

Corollary  $2b_{ii}$ : The limit imposed on relative stomatal conductance  $(g_S/g_{max})$  by critical water potential is consistent within and across species.

**3.** The model complexity needed to accurately predict transpiration is greater in areas of steep spatial gradient in species and environmental factors.

Funding began in 2004, one round of field measurements has been completed and three manuscripts are currently in preparation.

#### **INTRODUCTION**

The boreal forest is the second largest forest biome on Earth (Gower et al. 2001), is expected to experience the greatest warming of any forest biome (IPCC 2001), and stores more carbon (C) than other forest types (Gower et al. 1997; Goetz et al. 1999). In central Canada, the boreal black spruce ecosystem is comprised of a complex mosaic of different-aged stands and varying soil drainage. The water cycle, while less studied than the carbon cycle, is a key part of the climate, ecology and biogeochemical cycles of the boreal forest (Vörösmarty et al. 2001). The hydrology of the boreal forest is unusual because of a greater contrast between summer and winter hydrologic states, and how water table depth influences ground cover species composition, nutrient availability, overstory leaf area index, and net ecosystem C production and exchange (Betts et al. 1999; Bisbee et al. 2001; Swanson and Flannagan 2001). The water cycle, with its sensible and latent heat exchanges, is also central to understanding the link between the carbon cycle and climate.

Wildfire is an important disturbance in boreal forests, but its effect on the magnitude and duration of changes in the soil hydrology and microclimate are largely unknown (Kasischke et al. 1995), but likely to vary with edaphic conditions (Hodkinson et al. 1999; O'Neill et al. 2002). A better understanding of the effects of wildfire on the soil microenvironment is needed because soil microcli-

mate affects the onset of vegetation growth (Bergh and Linder 1999), rooting depth and root phenology (Tryon and Chapin 1983; Steele et al. 1997), and decomposition and mineralization rates (Van Cleve et al. 1983; Flanagan and Van 1983). Cleve Canopy architecture and leaf area index change dramatically during succession following fire (Bond-Lamberty et al. 2002a; Figure 1). The effect of increasing tree height and leaf area on CO<sub>2</sub> uptake and water loss has been investigated (Ryan and Yoder 1997; Hubbard et al. 1999;



Schafer et al. 2000; Ryan et al. 2000; Ewers et al. 2005) but the interpretation of these results is disputed (Becker et al. 2000; Mencuccini and Magnani 2000; Bond and Ryan 2000; McDowell et al. 2002; Niklas and Spatz 2004).

The impact of bryophytes on water budgets is critically important in the black spruce forests of central boreal Canada (O'Neill 2000, Turetsky 2003). Typically, a relatively closed-canopy black spruce overstory with a continuous feathermoss (dominated by *Pleurozium schreberi* and *Hyloco-mium splendens*) ground cover (BSFM) occurs on moderately well-drained soil, while an open-canopy black spruce overstory with a *Sphagnum* spp. ground cover (BSSP) occurs on poorly-drained soil (Harden et al. 1997, Bisbee et al. 2001). Species composition, ecosystem structure and C budgets change with environmental conditions; BSSP systems exhibit greater peat accumulation, higher water tables, and lower decomposition rates than BSFM (Sveinbjornsson and Oechel 1992, Camill et al 2001; Bisbee et al. 2001). Recent modeling work suggests that different bryophyte species can acclimate differently to environmental conditions and ultimately change the hydrologic and carbon budgets of peatland ecosystems (Yabe and Uemera 2001; Nungesser 2003; Bond-Lamberty et al. submitted). Topographic and disturbance effects may change bryophyte species distribution, degree

of ombrotrophy and rate of paludification, depth of the water table, size and distribution of *Sphagnum* spp. hummocks (Bauer et al. 2003) and ultimately affect the C and water dynamics.

An improved mechanistic understanding of the effects of global change on the hydrologic budget of boreal forests has important <u>societal</u> ramifications. The study area is the primary watershed for provincial hydroelectric facilities that generate 5000 megawatts of electricity which is traded and sold to many U.S. power companies. Since 1990, Manitoba's increasing use of hydroelectric power has decreased greenhouse gas emissions by more than 850,000 tons C. The need for a mechanistic understanding of ecohydrologic processes in boreal and all other forest types will only increase with the human population and disturbance frequency and extent (Vitousek et al. 1997). These changes to the water cycle have the potential to change global and regional climates (Marland et al. 2003).

#### **OVERALL STRATEGY**

We will use measurements and ecosystem models to quantify the interactive effects of climate, disturbance, and species composition on the water budgets of boreal black spruce ecosystems. We propose to: 1) quantify and explain the interaction between tree species composition and recovery from disturbance on ecosystem water balance; 2) incorporate bryophyte water use into ecosystem water balance modeling; 4) incorporate a plant hydraulic model into an existing ecosystem flux model; and 4) explicitly scale tree and bryophyte water use to the ecosystem level using a state-of-the-art ecosystem model and geostatistics. All four are novel approaches to ecosystem science; they can be applied to a variety of forested ecosystems; and the results will have very broad applications through 1) elucidation of fundamental controls on whole-plant ecophsyiology, 2) education of graduate and undergraduate students and aboriginal populations of central Manitoba, and 3) more informed global climate change policy that better reflects the centrality of ecosystem hydrology.

#### **PROJECT OBJECTIVES**

Objective 1. Quantify the effects of species composition and stand structure on the major components of the water cycle (canopy tree transpiration  $(E_C)$ , bryophyte water flux  $(E_B)$ , and soil drainage and lateral flow) for four stands comprising critical stages of a wildfire chronosequence. (Parenthesized initials refer to the responsible PIs.)

a. Measure the response of the major bryophyte species  $E_{\rm B}$  to environmental conditions. (STG & BEE)

b. Quantify soil and peat drainage and lateral flow, and measure properties that control both. (STG & BEE)

c. Quantify the effect of species and tree structural changes on  $E_C$  (BEE)

d. Determine the link between shifts in carbon allocation and water relations in response to tree structural and hydraulic changes. (BEE)

# Objective 2. Compare the major components of the water cycle for well- and poorly-drained boreal forest chronosequences.

a. Quantify the effect of edaphic conditions on water vapor exchange between boreal forests and the atmosphere. (BA & BEE)

b. Determine the impact of edaphic conditions on the relative flux of water among the major components of the water cycle. (BEE)

# **Objective 3. Test a model of ecosystem water fluxes across the well- and poorly-drained chronosequences, and use the model to explore important global change scenarios.**

a. Test model estimates of  $E_B$ , deep soil drainage, lateral flow and  $E_C$  against measurements of chamber fluxes, pan lysimeters, piezometers, trenches, soil/peat water potential, and sap flux measurements. (STG & BEE)

b. Use geostatistics to quantify spatial variability of the following on scaling water fluxes from plots to landscape: i vegetation (overstory, understory, bryophyte cover and LAI), ii parameters of key vascular and non-vascular plant water relations, and iii soil/peat hydrologic properties. (BEE & STG)

c. Examine the potential effects of wildfire dynamics and climate change on the water budget of the boreal forest. (BEE, STG, & BA)

#### **STUDY SITES**

The study will be conducted near Thompson, Manitoba, Canada (55°53'N, 98°20'W), where Gower has done C cycling research for the past 10 years. Gower has formed valuable collaborations with local scientists and resource managers from TOLKO (a private timber company), Manitoba Department of Natural Resources, Manitoba Hydro, and the Nisichawa-yasihk (Nelson House) First Nation, that greatly facilitate project logistics. Moreover, Gower has focused all his research efforts on understanding the effects of global change on the ecology of boreal forests, and is the PI of four relevant projects (two of which are near completion):

1. MODIS validation of vegetation cover, LAI, and NPP for a 5 x 5km footprint centered on the



NOBS flux tower (see http://www.orst.edu/spacers/BigFoot). This project is relevant because we have developed and tested quantitative approaches to scale point measurements to landscapes, and these tools will be useful to address Objective 3.

2. An NSF-funded Integrated Research Challenges in Environmental Biology project to examine the effects of wildfire on boreal forest C budgets. This project, which is nearing completion, has contributed to the conceptual foundation for this proposal, and provided valuable insight into key stages of boreal forest development following wildfire.

3. A DOE-funded whole ecosystem warming experiment to examine the effects of ecosystem (both soil and vegetation) warming on ecosystem structure and carbon and water cycles of a boreal black spruce stand. This project will provide the needed data on the effects of climate warming on the water cycle, and these data will be used to model water budgets for boreal forest in a warmer climate.

4. A NASA-funded MODIS project to examine effects of wildfire on vegetation reflectance and reexamine Myneni et al.'s (1997) conclusions that climate warming is the cause for the earlier green-up signal reported in the historic analysis of AVHRR data. We hypothesize that long-term changes in vegetation reflectance can be explained by increased wildfire. Project 4 will provide spatial data sets for wildfire and climate. We will use these tools to address Objective 3.

We propose to focus the measurements of this project on a chronosequence of four stands that originated in 1989, 1964, 1930, and 1850 wildfires. These four stands represent key phases of succession and stand development: tree establishment (1989), high tree and understory diversity (1964), maximum leaf area (1930), and leaf area decline (1850) (Figure 1). Although unreplicated, our single chronosequence compares well with a variety of secondary sites measured throughout the region (Figure 2; Bond-Lamberty et al. 2004a). Components of the water budget to be measured are shown in Figure 3.

#### **RESPONSE TO PREVIOUS REVIEWS**

The previous version of this proposal, submitted in January 2004, was recommended for funding by both the Hydrologic and Ecosystem Science panels but ultimately not funded due to insufficient funds. We have improved the proposal, based on the reviewer and panel comments, preserving and in some cases expanding upon its already-identified strengths: 1) the use of a sophisticated model that incorporates an evolutionary logic between bryophyte, gymnosperm, and angiosperm plant functional types; 2) the explicit incorporation of non-vascular plants; 3) rigorous component flux and model validation against independent ecosystem water flux measurements; 4) a wealth of information being gathered at these sites; 5) the potential to examine alternative explanations for the earlier greening of this region that has been observed by satellites; 6) a geostatistical approach to scaling that is novel and particularly powerful when linked to whole ecosystem water flux measurements. We have addressed specific concerns raised by the reviewers and panels. A major concern was overlap with other Fluxnet-Canada sites, especially the BERMS project



Figure 3 illustrates key ecosystem water fluxes from well- and poorly-drained boreal black spruce ecosystems. All of the arrows are the same size because their magnitude would change due to hypothesized changes along the chronosequence. This figure depicts the oldest stand in the chronosequence composed of only black spruce. The measurements will take place at four stands comprising critical stages in stand development following stand-killing wildfire (Bond-Lamberty et al. 2002a; Figures 1 and 2). There is no general agreement on how hydrologic budgets and component water fluxes will change in response to global change (Vörösmarty et al. 2001) and there is a paucity of information on bryophyte contribution, emphasizing the gap filled by the proposed research. Total evapotranspiration ( $E_T$ )from well- and poorly-drain sites (1 and 4 respectively) is measured by energy balance, tree transpiration (2 and 5) will be measured with sap flux sensors, and bryophyte transpiration (3 and 6) will be measured with closed system chambers and an IRGA. Lateral flow (7) will be quantified with piezometers, soil water potential, tracers and trenches. Soil drainage (8) will be measured with equilibrium tension open pan lysimeters. Total  $E_T$  composed of spatially explicit measurements of 2, 3, 5 and 6 will be compared to energy balance  $E_T$ . Soil water content and permafrost will be monitored using automated micrometeorological stations. Precipitation in both liquid and frozen forms will also be measured.

(http://berms.ccrp.ec.gc.ca/) and the fire chronosequence of Goulden and Litvak (Litvak et al. 2003). The Goulden and Litvak project did not address poorly-drained sites at all, focused on carbon fluxes, and will be shut down as of May 2005. The chronosequence work at BERMS is much more limited than our project, and only addresses old vs. young sites, but is nevertheless linked to our proposal through the inclusion of Brian Amiro, the principal investigator for the work at BERMS and Fluxnet-Canada. This will provide direct, coordinated comparisons between southern and northern boreal ecosystems. Further, we have focused the revised proposal to stress the water and energy balance only, which will allow both well- and poorly drained sites to be measured simultaneously from sepa-

rate flux towers without expensive fast response IRGA measurements. We have addressed the concerns of lateral flow in these systems by adding trench-based estimates of total lateral flow.

# **OBJECTIVE 1:** Quantify the effects of species composition and stand structure on the major components of the water cycle

# Issues to be resolved:

Little is known about the interactive effect of physiological and species compositional changes resulting from disturbance on ecosystem water fluxes. Most model investigations of the water balance of ecosystems recovering from disturbance have used leaf area index and the Penman-Monteith equation in single species or single vegetation types, underestimating evapotranspiration  $(E_{\rm T})$  during succession (Thornton et al. 2002). An accurate representation of canopy transpiration ( $E_{\rm C}$ ) will de-

pend upon correctly describing the species' effects on transpiration (Figure 4) because  $E_{\rm C}$  and stomatal conductance are intimately linked (Monteith 1995). A growing body of evidence emphasizes the need to study whole-plant gas exchange in the context of the underlying hydraulic architecture (Tyree and Ewers 1991; Sperry et al. 1998; Hacke et al. 2000; Ewers et al. 2000; Sperry 2000; Meinzer et al. 2001; Sperry 2002). The exact mechanisms of stomatal response to external factors remain unclear (Meinzer 2002; Franks 2004), but recent evidence suggests that most vascular plant species' stomatal conductance responds to leaf water potential to prevent runaway cavitation  $(K_{\rm L})$ Sperry et al. 1998; Oren et al. 1999; Ewers et al. 2000; Schafer et al. 2000). This nearuniversal response can be described with the following (Whitehead and Jarvis, 1981, Whitehead et al. 1984; Oren et al. 1999):

$$g_s = K_L \cdot (1/D) \cdot (\Psi_s - \Psi_L) \quad (1)$$
  
$$g_S = g_{\text{Sref}} \cdot \delta \cdot \ln D \qquad (2)$$

$$g_{\rm S} = g_{\rm Sref} \cdot \delta \cdot \ln D$$



where  $g_S$  is stomatal conductance, D vapor pressure deficit,  $\Psi_L$  leaf water potential,  $\Psi_S$  soil water potential,  $K_{\rm L}$  hydraulic conductance per unit leaf area,  $g_{\rm sref}$  reference  $g_{\rm S}$  at D = 1 kPa, and  $\delta$  the sensitivity of  $g_s$  to D (-dg<sub>S</sub>/dlnD).

A test of Equations 1 and 2, using data from the upland areas only of the proposed study site (Ewers et al. 2005), is shown in Figure 5D-F. The dotted lines indicate a perfect regulation (of 0.6) of  $\Psi_{\rm L}$  to prevent runaway cavitation (Oren et al. 1999; Ewers et al. 2000; Gunderson et al. 2002; Equation 2). All of the species regulated leaf water potential to prevent runaway cavitation except for the two oldest black spruce stands (Figure 5D) which had a significantly lower slope than that predicted by equation 2. In addition, black spruce showed the surprising trend (as first reported by McDowell et al. 2002) of decreasing sapwood-to-leaf area ratios in the oldest stands (Figure 5A, compare with aspen Figure 5C) as compared to plant hydraulic expectations (Schafer et al. 2000), while  $\Psi_L$  declines with height. The deviant behavior exhibited by black spruce in which it responds less than expected to climate drivers (Goulden et al. 1997) can be accommodated by allowing the minimum  $\Psi_L$  to decline, reproducing the lower relationships found in Figure 5D (Ewers et al. 2005).

Our experimental design will test whether these relationship work in poorly-drained conditions potentially increasing their broad applicability.

Bryophytes also have a large impact on the carbon budgets of boreal black spruce forests (Turetsky 2003, O'Neill 2000, Oechel and Van Cleve 1986, Camill et al. 2001, Gower et al. 1997, Harden et al. 1997, Bisbee et al. 2001, O'Connell et al. 2003ab; Table 2), but less is known about their contribution to water budgets. Most work on water relations of bryophytes has focused on the impact of hydration on productivity (Bisbee et al. 2001, Delucia et al. 2003). Betts et al. (1999) estimated the impact of surface wetness including the bryophyte layer on our 1850 site (NOBS from BOREAS) and found that evaporation increased by 50% when the bryophytes were wet. Bryophyte evaporation plus canopy interception was found to be 35% of the total  $E_{\rm T}$  from a boreal black spruce site (Price et al. 1997: Kim and Verna 1996).

The poorly-drained areas of our proposed study sites have *Sphagnum fuscum* and *S. capillifolium* while the upland sites are dominated by *Pleurozium shreberi*, *Hylocomium splendens* and *Ptililum cristacastrensis* (feathermoss). These two functional groups (*Sphagnum* and feathermoss) use



sensitivity of stomatal conductance to D ( $\delta$  Eq. 2) for D) black spruce E) trembling aspen and F) jack pine. The dotted lines in D, E, and F indicate the hypothesized relationship for stomatal regulation of leaf waterpotential from equation 2. (Ewers et al. 2005)

different sources of water, with *Sphagnum* tapping soil or ground water directly and feathermosses utilizing precipitation (Busby et al. 1978; Longton and Greene 1979; Skre et al. 1983; Vitt 1990, Titus et al. 1983; Malmer 1993 Bisbee et al. 2001, Carleton and Dunham 2003). While hydration is an important component of bryophyte physiology (DeLucia et al. 2003), little is known of their water transport mechanisms in general and even less about species effects (Raven 2003, Proctor 2000). Both feathermosses and *Sphagnum* do not actively transpire and appear to lose water primarily through the capitula, or growing points at the top of the bryophytes (Price et al. 1997). However, water loss may be enhanced by distillation of water from saturated peat layers below by live bryophytes, suggesting a physiological role (Carleton and Dunham 2003). Most studies have modeled bryophyte saturation as a function of days since precipitation and radiation (Betts et al. 1999, DeLucia et al. 2003, Bond-Lamberty et al. submitted), and assume that knowledge of bryophyte species is not important (Nungesser 2003).

Our preliminary data show that *Pleurozium shreberi* water flux varies greatly with bryophyte hydration (Figure 6), and even at a moderate hydration could constitute up to 40% of the total water flux to the atmosphere in the highest transpiration stand (Figure 2). We do not know if the other feathermoss species would show the same response. Both *Sphagnum* species in our chronosequence are known to occur in hollow, intermediate, and hummock habitats (Bauer et al. 2003), indicating a high degree of acclimation to different moisture conditions. The size and shape of such hummocks can be an important indicator of both species effects and climate (Nungesser 2003; Yabe and Uemura 2001) and the contribution of hummocks and hollows to evaportranspiration of the poorly-drained areas may be fundamentally different. We will make measurements on both intact and microcosm

feathermosses and *Sphagnum* mosses, allowing us to determine the amount of species information necessary to robustly scale bryophyte water fluxes.

In previous studies that have focused on water budgets of forested stands, the watershed mass balance approach (Helvey et al. 1965) is modified into a local water balance (LWB) by replacing the outflow component with direct measurements of soil moisture (Oren et al. 1998a, Ewers et al. 1999). The LWB approach relies on site specific parameterization of the *b* exponent and saturated hydraulic conductivity of the Clapp and Hornberger (1978) relationship for soil hydraulics, and assumes no lateral flow based on nearly zero slope (Oren et al. 1998a). While the LWB approach is particularly well-suited for this study, recent ecohydrology studies have highlighted the need for quantifying lateral flow in systems like our proposed well- and poorly-drained chronosequence. In flat, upland conditions, zero-tension pan lysimeters can quantify total drainage including preferential flow (Brye et al. 1999ab, 2000). Conditions that lead to lateral flow through preferential flow include saturated soil overlying unsaturated soil or bedrock (Wilcox et al. 1997, Newman et al. 1998), anisotropy (Campbell et al. 2002), permafrost (Leenders et al. 2002), infiltration through wetlands (Parsons et al. 2004) and leaf litter (Campbell et al. 2004). While the use of single or multiple tracers such as dyes, stable istopes, or ions provides mechanistic detail behind lateral flow processes (Morris and Mooney 2004; Gazis and Feng 2004; Öhrström et al. 2004; Flury and Flüher 1995) they only give instantaneous estimates and can only be done once at the same site. A tractable solution for this study, which is focused on the mechanism governing  $E_{\rm T}$  across a chronosequence, is the use of slope edge bulk flow collectors in trenches to quantify lateral flow combined with simple measures necessary for flow routing (Brown et al. 2003). Thus, we propose measurements of bulk lateral flow, hydraulic head, water table depth, and soil moisture to quantify and parameterize simple lateral flow algorithms (Brown et al. 2003; Grant 2004; Bond-Lamberty In Review).

#### **Hypotheses for Objective 1:**

1. Vulnerability to cavitation will compensate for species-specific changes in root-to-leaf and sapwood-leaf area ratios across the well- and poorly-drained chronosequences.

2. Black spruce will be less vulnerable to cavitation than the other species.

3. There is a trade-off between vulnerability to cavitation and maximum tree hydraulic conductance across species.

4. There is a significant difference between the evaporation from the feathermoss and Sphagnum groups, but within each group microtopography and radiation input will override species effects.
5. Deep drainage and lateral flow will be a significant portion of annual water fluxes but will only occur during snowmelt periods.

#### **Objective 1 Methodology**

Two types of plots, intensive and extensive, will be used. Intensive plots measure all variables (detailed below) necessary to quantify and explain the components of  $E_{\rm T}$  across the four stands of the chronosequence. There will be eight intensive plots representing the well- and poorlydrained conditions of all four ages. These plots will be 16 m in diameter and already contain canopy access scaffolding from ongoing projects at the sites. Extensive plots, 4 m in diameter, will measure fewer parameters but quantify the spatial



variation of these parameters, and span the drainage gradient of each stand (see Objective 3 below).

**Objective 1a (response of bryophyte species) Methodology** We will modify the soil carbon flux method of Wang et al. (2002a) to estimate water flux under ambient conditions directly from both feathermosses and *Sphagnum* mosses. We will take measurements at eight collars in each of the intensive plots along the well- and poorly-drained soil age sequences at monthly intervals throughout each growing season. In addition, we will use microcosms (10 cm diameter and depth), placed within environmentally controlled chambers attached to a Li-Cor 6400, to determine bryophyte gas exchange (DeLucia et al. 2003). For each of the five major bryophyte species and for each stand along the chronosequence, five microcosms will be constructed for a total of 100 microcosms. Such microcosms will test for species effects and allow us to experimentally manipulate radiation, temperature, relative humidity and hydration to determine its effect on bryophyte evaporation.

**Objective 1b (drainage and lateral flow) Methodology** Soil water deep drainage (below the rooting zone at 1 m) will be measured using an equilibrium tension pan lysimeter developed at the University of Wisconsin, and successfully used continuously for five years in northern agroecosystems and prairies exposed to high summer heat and frozen soils for much of the winter (Brye et al. 1999a-b, 2000). We will install two lysimeters in each of the four different-aged stands in the well-drained sites. The dimension of the pan is  $25.4 \times 76.2 \times 15.2$  cm. The lysimeter tension is controlled continuously to match that of the surrounding soil, using a Campbell data logger and pre-calibrated heat dissipation sensor (Model 229-L, Campbell Scientific, Logan UT). During dry periods, upward fluxes of water from soil will be estimated from  $E_{\rm T}$  component fluxes. Permafrost depth will be measured with thermocouples.

We will measure hydraulic head piezometers at three replicated transects, with five measurements each, which cross the boundary from the well-drained to the poorly-drained locations of our stands. We will install three low slope (all of our slopes meet the criteria of < 10%) edge flow collectors in the transition between all four well- and poorly-drained stands using the methodology of Brown et al. (2003). A plastic sheet will be buried in a triangular pit 2.5 m wide at the collection point to collect surface and vadose zone lateral flow. The uphill side is perpendicular to the slope and is left open and the downhill side of the triangle will pass water to a funnel. A pipe, with wire mesh to prevent blockage, will provide drainage to a buried bucket that ensures sufficient head. The pit will be backed filled with stones and covied with plastic to prevent any precip from entering the bucket. The water content of the bucket will be quantified every other week except during snowmelt when it will be emptied as often as necessary.

**Objective 1c (changes in tree species and structure) Methodology** We will measure sap flux in twelve trees of each intensive plot; this number ensures a coefficient of variation for each species less than 20% for half-hourly measurements (Ewers unpublished data). We will use Kucera-type sap flux sensors for trees less than 4 cm dbh (Ewers and Oren 2000; Ewers et al. 2002) and Granier-type (Granier 1987) sensors in larger trees. Spatial and temporal scaling of point measurements of Granier-type sap flux to canopy transpiration and canopy stomatal conductance of whole trees will be performed using standard circumferential and radial trend techniques (Phillips et al. 1996; Cermák and Nadezhdina 1998; Clearwater et al. 1999; Ewers and Oren 2000; Lu et al. 2000; James et al. 2002), tree capacitance estimates (Schulze et al. 1985; Köstner et al. 1992; Granier et al. 1996; Martin et al. 1997; Phillips et al. 1997; Ewers and Oren 2000; Rayment et al. 2000; Maherali and Delucia 2001) and canopy coupling estimates (Choudhury and Monteith 1988; McNaughton and Jarvis 1991; Magnani et al. 1998; Ewers and Oren 2000). Our data from the well-drained areas indicate that only black spruce trees in the two oldest stands need circumferential and radial trend measurements (Ewers et al. 2005) but we will test whether this is true of the poorly-drained areas with additional

circumferential (north vs. southwest and southeast) and radial (0-20, 20-40, and 40-60 mm from the cambium) measurements of all trees over 4 cm.

Leaf water potential ( $\Psi_L$ ) measurements will be made with a pressure chamber (Model 610; PMS Instruments, Corvallis Oregon) six times a growing season on three trees of each species at all stands of the chronosequence at pre-dawn and mid-day. At each of the three trees,  $\Psi_{\rm L}$  will be measured in the top, middle, and bottom thirds of the canopy to determine the impact of vertical trends in leaf area. In addition, once a growing season all  $\Psi_{\rm I}$  measurements will be made every three hours for a 24 hour period. These measurements will be facilitated by existing scaffolding towers at all of the stands of the chronosequences. Full micrometerological measurements will be made at all eight intensive plots (See objective 3b), including net and photosynthetically active radiation, soil temperature, moisture (CS616-L, Campbell Scientific), and water potential (229-L, Campbell Scientific) at 3 depths to 1 m, wind speed and direction, air relative humidity and temperature, stem temperature, and tipping bucket and standard manual rain gauges to estimate throughfall precipitation (Oren et al. 1998). Continuous snow depth measurements will be made at all sites using an ultrasonic device (SR50-L; Campbell Scientific, Logan, UT). Snow water content will be measured continuously at the 1989 site using a pair of field capable gamma radiation detectors (Canberra Co., Canberra, Aust.). Additional snow water content measurement will be made monthly during winter using snow cores and at the same frequency as lateral flow measurements during snowmelt.

We will quantify xylem vulnerability to cavitation (Alder et al. 1997; Hacke et al. 2000; Ewers et al. 2000), focusing most of our measurements on roots because recent evidence (Sperry and Ikeda 1997; Ewers et al. 2000) agrees with the segmentation hypothesis of Zimmerman (1980) that they are the most vulnerable portion of the hydraulic pathway. Thus, we will sample five roots between 1.5 and 4.0 mm in diameter and three branches for each species at each intensive plot. The relationship between water content water potential of both mineral and organic soil as well as peat will be quantified using a water potential meter at 5 depths to 1 m and 2 depths above the mineral soil (WP4; Decagon Devices). The WP4 measures water potential by determining the relative humidity of the air above the sample in a closed chamber at temperature equilibrium. Such an instrument is particularly well suited to the vagaries of peat and organic soil water potential (Lauren and Mannerkoski 2001) and will provide the accuracy necessary to test the Sperry Model (see below).

**Objective 1d (links tree C and water fluxes) Methodology** Carbon allocation to leaf and sapwood area will be estimated using site- and species-specific allometric equations (Gower et al. 1997; Bond-Lamberty et al. 2002ab). Coarse root biomass will be estimated using general allometric equations (Haynes and Gower 1995; Steele et al. 1997; Bond-Lamberty et al. 2002b). We will use the BTC-100X minirhizotron camera system and image capturing hardware (Bartz Technology Co., Santa Barbara, CA) to quantify fine root area dynamics monthly from April to November). The length of fine root growth or disappearance will be converted from length to mass using specific fine root mass (Steele et al. 1997; Bisbee et al. 2001) and correlated to peak fine root mass obtained from monthly growing season soil cores. Gower has extensive experience in determining species-specific fine root biomass and species of origin in boreal forests. All of these measurements will be used to determine how changes in carbon allocation to sapwood-to-leaf area ratio and root-to-leaf area ratio affects whole plant hydraulics and subsequent canopy stomatal conductance behavior (Equations 1 and 2).

# **OBJECTIVE 2:** Compare the major components of the water cycle for well- and poorlydrained stands

#### Issues to be Resolved:

In boreal forests, edaphic controls on water flux across the landscape can be at least as important as climatic controls. Mackay et al. (2002) showed that the traditional Penman-Monteith approach to  $E_{\rm T}$ 

failed to match eddy covariance measurements in Northern Wisconsin when species-level differences in transpiration per unit leaf area and the contribution of forested wetland were not included. The major edaphic controls at our site are due to subtle variation in topography. The dry areas occur on upland, moderately drained montmorillonite clay soils classified as GrayLuvisols (Boralfs), characterized by the formation of a clay-enriched B horizon and no permafrost development (Veldhuis 1995). The wet areas occur on poorly-drained clay soils, underlain by permafrost at 100-150 cm depth, and generally classified as Luvic Gleysols (Aqualfs), Terric Fibrisols (shallow Fibrists). These poorly-drained areas of our sites are minerotrophic fens with a low degree of ombrotrophy due to groundwater input and/or lateral flow from uplands; see description of a nearby large fen by Lafleur et al. (1997). The hydraulic head, water table depth, and lateral flow measurements will verify the accuracy of this for each stand along the chronosequence. In addition, it appears as though paludification, the direct establishment of peat in areas formerly occupied by upland vegetation, is not occurring. While wildfire disturbance can contribute to paludification (Bauer et al. 2003) we see no evidence of Sphagnum expansion after a wildfire in any of our chronosequence stands. Given the importance of edaphic controls across the chronosequence, our dataset will allow us to test the degree of detail necessary to scale from our intensive and extensive plot types (see Objective 3b) to the  $E_{\rm T}$ estimated from energy balance measurements (see Objective 2).

## **Hypotheses for Objective 2:**

1. The proportion of  $E_{\rm T}$  from poorly-drained areas relative to well-drained areas will decline with increasing stand age.

2. Tree transpiration and bryophyte transpiration are inversely correlated due to attenuation of light by tree leaf area.

Objective 2ab (quantify effect of edaphic conditions) Methodology We will measure ecosystem energy balance components to calculate  $E_{\rm T}$ . The technique involves measuring net radiation (net radiometer NR-Lite; Kipp and Zonen), ground heat flux (soil heat flux plates model HFT3; REBS, and soil thermocouples) and sensible heat flux, and solving for  $E_{\rm T}$  by the energy balance residual. Sensible heat flux will be measured using the eddy covariance technique with a 3-axis sonic anemometer/thermometer (CSAT-3; Campbell Scientific). This technique has been used successfully in hydrology studies (Amiro and Wuschke 1987) and simplifies the measurements by not requiring a fast-response water-vapor sensor. It does not increase the uncertainty because direct water-vapor flux measurements have uncertainty associated with closure of the energy balance (e.g., Twine et al. 2000), and energy balance closure makes the direct measurement largely redundant. A sonic anemometer is needed to capture the high frequency turbulence components near the canopy (the original Amiro and Wuschke technique used a propeller anemometer). This technique is cheaper and more reliable than the direct water vapor flux measurement, and night-time issues with eddy covariance underestimates during low turbulence are not a factor because  $E_{\rm T}$  is negligible at night. Incoming and reflected photosynthetically active radiation (SZ-190, Li-Cor), and air temperature and relative humidity (HMP 45C; Vaisala) will also be measured.

The measurements will be made on towers at about 1.5 times the canopy height at the four chronosequence sites (1989, 1964, 1937, 1850) over both well- and poorly drained locations. The 1850 site (NOBS) is currently being measured by Dr. Steve Wofsy (Harvard University) until March 31, 2005; Amiro has a proposal to continue this site from April 1, 2005 to March 31, 2007. With our measurements starting in spring 2006, there will be two years of complementary measurements among the studies, offering a period of strong collaboration and cost savings if both studies are funded.

The specific locations of the eight towers will correspond to the eight intensive plots (see Objective 3b) to facilitate traditional, paint-by-numbers approaches to scaling up (Mackay et al. 2002). By incorporating the geostatistics from our extensive plots and knowledge of wind direction, we can determine if subtle changes in microtopography, bryophytes species, tree cover, tree species do or do not affect  $E_{\rm T}$  fluxes from both the well- and poorly-drained areas separately.

# **Objective 3: Test a model of ecosystem water fluxes**

# Issues to be resolved:

Our understanding of how biophysical and biogeochemical processes change during succession is incomplete (Thornton et al. 2002; Bond-Lamberty et al. 2005). Most hydrologic models include only the most rudimentary aspects of tree hydraulic function (Entakhabi et al. 1999; Sperry 2000) and bryophyte functioning (Bond-Lamberty et al. submitted). In order to capture the effects of varying water relations on the canopy trees (Figure 5), models must include not only a stomatal conductance model based on carbon relations (Ball et al. 1987) but also a tree hydraulic model to account for stomatal behaviour when water fluxes are high and most hydrologically relevant (Mackay et al. 2003). Only by incorporating tree hydraulic mechanisms (e.g. Tyree and Sperry 1988; Mencuccini and Grace 1995; Sperry et al. 1998; Wullschleger et al. 1998; Oren et al. 1999; Ewers et al. 2000; Sperry 2000; Meinzer 2002; Ewers et al. 2005) can models of ecosystem water flux respond realistically to global change scenarios.

Sperry et al. (1998) presented a model, hereafter referred to as the "Sperry Model," that predicts the limits of hydraulic failure based on the vulnerability of xylem to cavitation, root-to-leaf area ratio, and soil properties. The model predicts that plants adjust their hydraulic pathways to soil and atmospheric water limitation as a result of evolutionary adaptation to biological and edaphic controls (McCulloh et al. 2003). Importantly, the supply function has built-in limitations because  $K_L$  declines with  $\Psi_L$ ; (Equation 1) owing to drying soil, xylem cavitation, and other factors. The opposition between an increase in driving force required to sustain an increase in transpiration per unit leaf area ( $E_L$ ) and the decrease in  $K_L$  creates a minimum  $\Psi_L$  ( $\Psi_{Lcrit}$ ) and associated maximum transpiration rate ( $E_{Lcrit}$ ). When  $E_{Lcrit}$  is exceeded, hydraulic failure occurs by driving  $K_L$  to zero (Tyree and Sperry 1988). The  $E_{Lcrit}$  as a function of  $\Psi_S$  defines the maximum water extraction capability of the plant.  $E_{Lcrit}$  is dependent on soil texture, root-to-leaf area ratio and cavitation resistance (Sperry et al. 1998, Hacke et al. 2000, Ewers et al. 2000). The model output is the relationship between  $E_L$  and  $\Psi_L$  and  $E_{Lcrit}$  at any set of input environmental conditions.

We will use BIOME-BGC (see below), a dynamic ecosystem model that normally runs in a onedimensional mode (Running and Hunt 1993) but can be used at the landscape and biome level as well. BIOME-BGC links land surface processes (surface energy, water, and carbon balance), vegetation phenology (changes in leaf area and physiological activity over the season), biogeochemical processes (productivity, litterfall, litter turnover, and soil carbon and nitrogen dynamics), and vegetation dynamics (changes in vegetation structure and composition over time). The model has been applied to regional and global ecosystem process studies (Churkina and Running 1998, Keyser et al. 2000), compared to flux tower measurements in various biomes (Kimball et al. 1997b, Amthor et al. 2001, Law et al. 2001, Thornton et al. 2002), and checked against biometric field data (Kimball et al. 1997a, Bond-Lamberty et al. 2005b). The model itself is well-established, with known parameter sensitivities (White et al. 2000, Bond-Lamberty et al. 2005a).

Most ecosystem level studies rely on traditional plot-level measurements of pools and fluxes to determine ecosystem fluxes (Oren et al. 1998; Mackay et al. 2002). Recent advances in geostatistical sampling (Burrows et al. 2002) enable more sophisticated approaches. Our data and sampling approach address the physical and physiological variables that control water flux from ecosystems and have wide ranging implications for water flux from many forested ecosystems. The results of the

spatial data sets will enable us to 1) incorporate semivariograms into Mixed Model ANOVAS (Little et al. 1996) testing species and age effects on component water fluxes, 2) determine which variables control the spatial variability in water flux, and 3) quantify and explain the edge effects between the well- and poorly-drained sites.

**Objective 3a (model**  $E_B$ , deep soil drainage, lateral flow and  $E_C$ ) Methodology Our modified version of Biome-BGC combines Ball-Berry (Ball et al. 1987; Leuning et al. 1995), Jarvis (1976), and the Sperry model within a single framework to address acknowledged limitations in the stomatal conductance formulation of the Biome-BGC family of models (White et al. 2000; Ewers et al. 2001; Bond-Lamberty et al. 2005). The Ball-Berry model is used under low light conditions when photosynthesis limits conductance. When light levels are sufficiently high, photosynthesis is not limiting and stomatal conductance levels off. At high vapor pressure deficit (D), stomata close to reduce the rate of water loss (Ball et al. 1987; Monteith 1995; Saliendra et al. 1995; Yong et al. 1997; Oren et al. 1999) and minimize the risk of hydraulic failure in the plant (Sperry et al. 1998; Oren et al. 1999; Ewers et al. 2000). These mechanisms are encapsulated in the following equation:

$$G_{S} = \begin{cases} G_{Sref}(\mathbf{f}_{1}(A) \times \mathbf{f}_{2}(\theta)) &, \quad Q < Q_{crit} \\ \\ G_{Sref}(\mathbf{f}_{2}(\theta)) - \delta \cdot \ln D &, \quad Q \ge Q_{crit} \end{cases}$$
(3)

where  $G_S$  is canopy average stomatal conductance,  $G_{Sref}$  is reference conductance at D = 1.0 kPa,  $f_1(A)$  determines  $G_{Sref}$  as a function of CO<sub>2</sub> assimilation,  $f_1(\theta)$  as a function of soil moisture and  $Q_{crit}$ 

is the light level at which stomatal no longer respond to light. The Sperry model will be used to determine the  $E_{\rm L}$  and thus  $G_{\rm S}$  under high Dconditions (D > 1 kPa; Ewers et al. 2001).  $Q_{crit}$ will be determined for each species based on measured responses of stomatal conductance to variation in Q and D. At three canopy positions within three trees of each species (canopy access towers will be used for taller trees), stomatal conductance will be monitored on individual leaves exposed to an ascending Qsequence (0 – 2000 µmol m<sup>-2</sup> s<sup>-1</sup>) using a Li-Cor 6400 portable gas exchange system. For a given leaf, stomatal Q response will be measured at each of three Ds (e.g., ~1, 2 and 3 kPa). These



data will be used to calculate  $\delta$  (Equation 2) at each Q, and correspondingly to determine speciesspecific (and if necessary age/height-specific) relationships between  $\delta$  and Q. To capture phenology, we will conduct these measurements four times during each growing season.

BIOME-BGC has recently been upgraded and extended by Gower's research group, allowing it to explicitly handle lateral flow, multiple vegetation types (Figure 7), nonvascular plants, and more effectively model forested wetlands (Bond-Lamberty et al. 2005a, Bond-Lamberty et al. submitted). We will incorporate the Sperry model describing tree hydraulic function into BIOME-BGC's existing hydrology routines, combining the stomatal conductance model with carbon metabolism, environmental constraints and tree hydraulics. In addition, a more detailed lateral flow and drainage submodel suitable for boreal ecosystems (Grant 2004) has been added to the hydrological modifications proposed by Bond-Lamberty et al (2005a). The reduction in modeling uncertainty gained by adding these three components will be directly tested by comparison with energy balance water flux measurements that are independent from the measured component water fluxes. Sensitivity analyses will test the relative importance of each major factor on water flux aboveground, deep drainage, lateral flow and water table depth in wetlands. The ability to model bryophytes (Bond-Lamberty et al. 2005a) is unusual for process-based forest models, and critical, given the dominant role such plants frequently play in the carbon (Vitt et al. 2001, O'Connell et al. 2003), nitrogen (Turetsky 2003), and water (Dilks and Proctor 1979, Kim and Verma 1996) fluxes of poorly-drained boreal systems.

**Objective 3b** (quantify spatial variability of vegetation and hydrology) Methodology We will use the spatially explicit cyclic sampling procedure of Burrows et al. (2002) which improves on earlier spatial measurement schemes by efficiently sampling pairs of points at all distances throughout the spatial sampling grid. We will draw upon results from the NASA-funded BigFoot project, of which the mature black spruce stand was one of four sites (Burrows et al. 2003; Cohen et al. 2002, 2003ab, Turner et al. 2002 & 2003ab) and Earth Observing System projects (Burrows et al. 2002, Burrows et al. 2003, Ahl et al. 2004), to develop a cyclic sampling design for the extensive plots that will adequately characterize the composition and structure of the vegetation in the footprints of all eight towers. Burrows et al. (2002) provide a complete treatment of the *a priori* analysis and selection of a suitable cyclic sampling design. We will establish 200 plots, running from the upland well-to the poorly drained tower in all four stands. The plots will be surveyed for diameter, tree and bryophyte species, slope and aspect.

In the extensive plots, continuous sap flux measurements will be made on the largest tree of each species, resulting in 200 to 400 trees sampled at each stand age (in addition to the trees sampled for sap flux in the traditional plots described in objective 1). Additional spatial measurement campaigns will be conducted four times each growing season to quantify leaf water potential, soil and peat moisture, and bryophyte hydration. In addition, detailed measurements of peat depth with metal probes, and microtopography with surveying equipment, will be made at each of the cyclically sampled extensive plots. This scale of spatial measurement will adequately sample both the well- and poorly-drained areas of the chronosequence based on estimates of spatial leaf area variability at NOBS (Burrows et al. In Review); larger spatial scales will be quantified using the remote sensing and replicated sites (Figure 2) information from the ongoing NSF IRCEB and NASA MODIS projects. In the extremely unlikely event that the geostatistical sampling does not produce useful results, we will average the plots together in the well- and poorly-drained locations and produce extremely robust estimate of the error in stand transpiration as originally suggested by Oren et al. (1998b) but never before attempted. Such error estimates (either spatial or well-sampled traditional) will explicitly test whether the traditional plot or spatially explicit sampling method produces better scaling in comparison to the ongoing whole ecosystem water flux measurements across the chronosequence.

**Objective 3c (examine potential effects of wildfire and climate change) Methodology** We will test measured component fluxes of water from both the well- and poorly-drained sites across the chronosequence using Biome-BGC. To understand the processes involved in the measured ecosystem fluxes, the model (already parameterized for this site from the ongoing NSF project) will be compared to the sap flux, bryophyte water flux and soil drainage measurements. Such a test will be an improvement over previous models of boreal black spruce water fluxes that lumped  $E_{\rm T}$  into one term and could not decipher the contribution and mechanistic effects of trees and bryophytes (Betts et al. 1999). To understand the effect of growing season on water fluxes, the model will be tested against 2-3 years of well- and poorly-drained sap-flux, bryophyte water flux, and soil drainage data. By combining the multiple years of data collection, especially at the well-drained sites, the effects of the water cycle changes across the chronosequence on surface energy budgets will be explored and tested against the energy balance data and process level measurements.

The earlier spring green up of boreal forests has been attributed to earlier biological activity as a result of climate warming (Myneni et al. 1997); the initiation of biological activity is strongly controlled by tree water balance (Bergh and Linder 1999). We will examine the environmental controls by changing the spring soil thaw date and growing season length using historic (33 years) climate data (Bond-Lamberty et al. 2005). A second interpretation is that increased disturbance is causing the soil to thaw earlier because of removal of the canopy and surface detritus. Albedo effects could also be important due to increasing albedo of bryophytes with increasing dessication (Nungesser 2003). We will use our bryophyte hydration measurements in concert with our radiation measurements to quantify the impact of albedo on energy budgets. We will simulate a variety of fire cycles including the effects of predicted climate change scenarios (Flannigan et al. 2004).

## PROJECT AND DATA MANAGEMENT

Ewers will oversee the entire project. Responsibilities of the three PIs are detailed above in the PRO-JECT OBJECTIVES section. Ewers will supervise a post-doc (Kwon), one graduate and undergraduate student. Amiro will supervise one technician and graduate student. Gower will supervise a postdoc (Bond-Lamberty) and data acquisition specialist (Tanner). Collaboration will be facilitated by joint field operations and annual meetings rotating to each home institution.

## INTEGRATION OF RESEARCH, EDUCATION, AND OUTREACH

This project complements prescribed burning effects on ecosystem fluxes of sagebrush steppe (USDA-NRI) and tree species effects on water cycling (NSF)to Ewers. Amiro is a key member of Fluxnet-Canada and has extensive micrometeorology experience in boreal forests. Gower now has all his major research projects located in Thompson, Manitoba, and they all complement his effort to understand the effects of global change on the ecology of boreal forests. Gower has supervised NSF REU funded undergraduates in the past and he continues to do so on the recently funded NSF IRCEDB proposal. Ewers, Gower, and Amiro will make a special effort to work with and train both Caucasian and aboriginal high school students. Ewers, Gower, and Amiro will also oversee a unique boreal ecosystems experience for outstanding students from around the United States and Canada. This project will involve bringing students to several locations in Manitoba to examine the impacts of hydro-power generation (Winnipeg), fishing (Thompson and Nelson House), forest management (Thompson and Nelson House), and mining (Thompson) on boreal ecosystems and regions. The course will be funded by tuition to offset the cost of offering the course, which will be for two credits through the Universities of Wisconsin, Wyoming, and Manitoba.

# DISSEMINATION OF RESULTS AND OUTREACH TO THE GLOBAL COMMUNITY

Besides traditional research outlets in high-quality peer-reviewed journals, Amiro will directly facilitate the linkage of this project to the water and energy balance components of Fluxnet-Canada (http://www.fluxnet-canada.ca/). Strong ties have been developed with Manitoba Hydro through Gower's DOE soil warming project, and our results will be rapidly made available to Manitoba Hydro to assess the impact of changing fire regimes on water fluxes throughout their hydro generating region. Gower also has direct connections to TOLKO (a private timber company), Manitoba Department of Natural Resources, and the Nisichawa-yasihk (Nelson House) First Nation. These ties represent a unique connection between state-of-the-art ecosystem science and relevant land managers.

#### PROPOSED MEAUREMENT TIME TABLE

We request a start date of September 2005. In the winter of 2006, Ewers and Amiro will recruit graduate students and Ewers and Gower will order/fabricate equipment. Amiro will oversee the setup and calibration of energy balance instruments by traveling to Wyoming in winter 2006. The first field season will begin in May 2006 and measurements will operate continuously through October 2008.