The Dynamics of Change in Alaska's Boreal Forests: Resilience and Vulnerability in Response to Climate Warming

Project Summary

The cornerstone of the Bonanza Creek (BNZ) LTER research has been the **state factor** approach, which allows prediction of ecosystem properties based on "independent" controls such as climate, parent material, topography, potential biota, and time and **interactive controls**, i.e., processes internal to ecosystems that both affect and respond to ecosystem processes. The **intellectual merit** of the proposed research involves expansion of this theoretical framework to address processes underlying ecosystem resilience and vulnerability. Our objective is to identify factors that buffer systems from radical changes in structure and functioning (resilience) vs. factors that might precipitate changes to alternative states (vulnerability). This requires an extension beyond the assumptions of steady state dynamics to ask under what conditions changes in drivers might trigger a fundamental change in the nature of boreal ecosystems. The central question of our research is: **How are boreal ecosystems responding, both gradually and abruptly, to climate warming, and what new landscape patterns are emerging?**

We study the **dynamics of change** in several steps. (1) **Climate sensitivity** of physical and biological processes to temporal variation in the environment, which defines the limits of resilience to climate change; (2) changes in the **successional dynamics** caused by changes in climate and disturbance regime, which define the points in the adaptive cycle of disturbance and recovery at which ecosystems are most vulnerable to change; (3) **threshold changes** that are likely to cause the boreal forest to function in a qualitatively new way and (4) **integration and synthesis** in which we integrate these modes of climate response across multiple temporal and spatial scales and explore their societal consequences.

The research design combines long-term observations, long-term experiments, and process studies to identify ecological changes and to document controls over ecosystem processes and successional dynamics in three landscape units: floodplains, uplands, and wetlands. We test hypotheses about controls over ecosystem dynamics by manipulating selected interactive controls. These plot-level studies are extended to larger spatial scales (watersheds, regions, and the state of Alaska) in a hierarchical research design, using extensive measurements, remote sensing, and modeling. Temporal scales of the research span hours (weather), years (growth, populations), successional cycles (stand-age reconstructions), and millennia (vegetation and climate reconstructions).

We explore **societal consequences** by identifying past and potential future changes in ecosystem services that boreal forests provide both locally (e.g., subsistence resources) and globally (e.g., carbon sequestration). Involvement in LTER cross-site comparisons enables us to understand boreal processes in a broader context. To make this information available and useful to a broader community, we work closely with schools, community outreach programs, the broader scientific community, and resource managers through collaborations, outreach, and web-based data management. Information management emphasizes secure archival of the information we have collected, promotion of its use in synthesis, and development of web-based databases to facilitate its use by the scientific community.

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Section 1 Results of Prior Support

Bonanza Creek (BNZ) LTER research has emphasized successional dynamics in the Alaskan boreal forest. Initially we focused on state factors (independent controls) and interactive controls (factors that affect and respond to ecosystem processes) (Jenny 1980, Van Cleve et al. 1991, Chapin et al. 1996, Van Cleve et al. 1996, Yarie et al. 1998). Due to rapid recent changes in climate, fire, and insects (Kasischke and Stocks 2000, Hinzman et al. 2005), we expanded our goals in the previous funding cycle to ask "**How have changes in climate and disturbance regime altered the functioning of Alaska's boreal forest?**" This section summarizes the highlights of our second book synthesizing Alaskan boreal research (Van Cleve et al. 1986, Chapin et al. 2006) published in January 2006, with an emphasis on recent accomplishments. We placed the BNZ LTER research in a circumboreal context through two special issues that emerged from the 2004 International Boreal Forest Association conference that we hosted in 2004 (Apps and McGuire 2005, McGuire and Apps In press).

1.1 Climate Sensitivity

Alaska warmed rapidly at the end of the last glacial period. After the thermal maximum in the early Holocene (ca 11,000-9000 years ago), climate became wetter and gradually cooler (Lloyd et al. 2006). Deciduous woodland and shrubland dominated in the early Holocene (Edwards et al. 2005), followed subsequently by white spruce, then rather suddenly by black spruce. The expansion of black spruce coincided with a threshold *increase* in fire frequency 6,000 years ago, despite cooler, moister climate, suggesting that vegetation rather than climate drove long-term trends in fire regime (Lynch et al. 2002, Lloyd et al. 2006) (Fig. 1). Thus the boreal forest has shown both gradual and abrupt climate responses through the Holocene.

Warming during the 20th century has *decreased* the growth of white spruce (Fig. 2), due to warming-induced drought stress (Jacoby et al. 1999, Barber et al. 2000), with projections of zero net annual growth and perhaps the loss of white spruce and birch from uplands before the end of the 21st century (Lloyd and Fastie 2002, Wilmking 2003, Juday et al. In press). At the southern limit of Alaska's boreal forest, spruce bark beetle outbreaks eliminated extensive areas of forest, because warmer temperatures reduced tree resistance to bark beetles and shortened the life cycle of the beetle from two years to one, shifting the tree-beetle interaction in favor of the insect (Werner and Holsten 1985, Werner and Illman 1994, Wallin and Raffa 2004, Werner et al. 2006, Werner et al. In press). At its altitudinal and latitudinal limits, the boreal forest is expanding into tundra because of high rates of tree recruitment beyond treeline during recent warm decades (Silapaswan et al. 2001, Lloyd and Fastie 2002). At arctic treeline, spruce establishment in tundra depends at least partially on thawing permafrost (Lloyd et al. 2003b). In contrast to the expansion of predominantly white spruce forests at treeline, which occurs independent of disturbance by fire, northward expansion of black spruce may depend on fire (Lloyd et al. 2006). In summary, current trends show gradual expansion of forest into tundra in the north, abrupt decline in the south, and impending major compositional changes in central portions of Alaska's boreal forest, suggesting that the boreal forest is on the cusp of major structural and functional changes.

Many boreal animals exhibit large population fluctuations. Densities of small mammals (*Microtus* and *Clethrionomys*) correlate most strongly with climate (Rexstad and Kielland 2006), whereas larger mammals (moose and hares) appear to be more sensitive to food availability and predation (Flora 2002). Two native insects have changed from decadal outbreaks to consistently low populations (large aspen tortrix since 1985; spear-marked blackmoth since 1975), whereas other species that had negligible populations before 1990 have shown large outbreaks (eastern spruce budworm, spruce coneworm, larch sawfly, and aspen leaf miner) (Werner 1994, 1996)(Table 1). Thus, several factors, including climate, influence animal population densities.

Ecosystem processes in Interior Alaska are sensitive both to topographic variation in environment and to successional age. Aboveground production, for example, varies by more than an order of magnitude among forest types (Van Cleve et al. 1983, Yarie and Van Cleve 2006) (Fig. 3). It is greatest in midsuccessional stands on floodplains, where soil temperature and moisture are relatively high, and is constrained on south-facing slopes by drought and on north-facing slopes by soil temperature. On temperature-limited sites, mosses account for 45% of aboveground production (Fig. 4). Temperature constraints on tree production appear mediated largely by nitrogen supply (Yarie 1997, Yarie and Van Cleve 2006).

Low temperature and nitrogen supply promote belowground allocation. Thus, carbon and nutrient cycling rates in fine roots are several orders of magnitude faster than in aboveground tissues (Ruess et al. 1998, Ruess et al. 2003, Vogel et al. 2005). Fine root production is concentrated close to the soil surface (Fig. 5), and there is a progressive increase in fine root production into deeper soil layers as the soil warms through the season. Fine root life span and the associated physiological and morphological traits of roots vary across sites in parallel with patterns observed for aboveground tissues (Ruess et al. 2006). Cross-site studies demonstrate that boreal trees are similar to most woody plants in the morphological, phenological, and physiological traits of first-order roots and differ primarily in root allocation, size distribution, and lifespan (Burton et al. 2002, Pregitzer et al. 2002).

Ratios of aboveground litterfall to soil respiration in interior Alaskan forests are among the lowest recorded in North America (Raich and Nadelhoffer 1989, Ruess et al. 1996), suggesting that a large proportion of boreal soil respiration originates from root-derived C. Fine-root respiration constitutes approximately 60% of soil respiration in black spruce forests (Ruess et al. 2003, Vogel et al. 2005). Trenching to eliminate root production caused a 12% loss of total soil C within 2 years (Fig. 6), suggesting that much of the root-derived soil carbon is labile and can decline rapidly in the absence of root inputs. In summary, biogeochemical processes are quite sensitive to temperature, but many of these effects are mediated by variations in species composition, allocation, and nitrogen supply.

1.2 Succession

The major physical disturbances in Interior Alaska are flooding in floodplains, fire in uplands, and water-table changes in wetlands. River discharge and flooding are climatically sensitive, but glacial rivers have maximum discharge in midsummer glacier melt is maximal, whereas clearwater rivers have maximum discharge with spring snowmelt (Fig. 7). Fire return time varies regionally from <50 years to > 100 years (Yarie 1981, Fastie et al. 2002). Area burned correlates positively with temperature (r = 0.63) and vegetation cover (r = 0.65) and negatively with precipitation (r = -0.61) (Kasischke et al. 2002, Duffy et al. 2005). In association with recent warming, Interior Alaska has experienced a sharp increase in wildfire. Seven of the 11 largest fire years since 1950 occurred since 1988, accounting for half of the cumulative area burned (Fig. 8). In the last two years alone, 4.6 million ha (10% of Interior Alaskan forests) have burned. During large fire years, 36% of the area burns after 1 August, when soils are deeply thawed and well drained, leading to unusually severe fires. Lightning, which accounts for 90% of the area burned (Kasischke et al. 2006), is controlled by both synoptic processes related to El Niño and by local factors such as topography and presence of forest vegetation (Dissing and

Verbyla 2003). Human ignitions, which account for 60% of the fires in Alaska, generally produce small fires that occur at times and places where fire does not readily spread (Kasischke et al. 2002, Chapin et al. 2003). Human activities reduce area burned because suppression has greater impact than human ignitions (DeWilde 2003) (Fig. 9).

The trajectory of succession is sensitive to environment, propagule availability, legacies associated with prefire vegetation, and disturbance severity. Primary succession predominates in the active floodplain. After initial establishment, competition, facilitation, and herbivory interact to drive successional change (Walker et al. 1986, Walker and Chapin 1987, Adams 1999). Ecosystem controls change at key *turning points* (thresholds), where a shift in dominance of plant functional types radically alters the physical and chemical environment that govern ecosystem processes and disturbance probability (Van Cleve et al. 1991). In the floodplain, intense herbivory by moose initially constrains canopy development, creating an ecosystem dominated by physical controls over soil water movement, surface evaporation and gypsum accumulation at the soil surface (Dyrness and Van Cleve 1993, Marion et al. 1993, Van Cleve et al. 1993, Kielland and Bryant 1998). Colonization by alder shifts the system from physical to biological control (Van Cleve et al. 1991, Viereck et al. 1993), adds 60-70% of the nitrogen that accumulates during succession (Van Cleve et al. 1971, Van Cleve et al. 1983, Van Cleve et al. 1993, Uliassi et al. 2000, Uliassi and Ruess 2002), and causes herbivory to change from a deterrent to an accelerator of succession by eliminating palatable early successional species (Bryant and Chapin 1986, Bryant et al. 1991, Kielland et al. 1997, Kielland and Bryant 1998) (Fig. 10). Other key turning points include (1) a shift to balsam poplar dominance, where changes in productive potential and litter chemistry enhance NPP and nitrogen cycling rates (Van Cleve et al. 1983, Schimel et al. 1996) and (2) the shift to white spruce dominance, where mosses grow rapidly in the absence of smothering broadleaved litter (Oechel and Van Cleve 1986), reduce nutrient cycling rates by sequestering nutrients in low-quality litter (Yarie 1997), and increase fire probability by producing resinous fuels that dry quickly (Chapin et al. 2003). In late-successional black spruce stands, root turnover governs nutrient supply.

Secondary succession is the rule in the uplands. Self-replacement, in which the prefire tree species returns to dominance shortly after fire, generally occurs in extreme environments, whereas succession with multiple stages is more common in intermediate sites (Mann and Plug 1999, Fastie et al. 2002, Chapin et al. 2004a). Late-successional conifers establish during the initial 1-2 decades after fire, but their establishment success is sensitive to the depth of the organic mat remaining after fire (Johnstone and Chapin In Press-a), understory species composition (Cater and Chapin 2000), and seed availability from on-site serotinous cones (black spruce) or off-site seed sources (white spruce) (Zasada et al. 1992, Mann and Plug 1999, Cater and Chapin 2000, Johnstone and Chapin 2003). Variations in fire frequency (Johnstone and Chapin In press-b) or severity (Mann and Plug 1999, Johnstone and Chapin In Press-a, Harden et al. Submitted) can alter plant regeneration feedbacks that stabilize community composition and cause rapid shifts in forest cover types (Johnstone and Kasischke 2005). Changes in any of these processes could alter vegetation composition and successional trajectory.

Species diversity is low in the boreal forest (Waide et al. 1999) and varies through succession with peaks in early succession (e.g., fire-specialist plants, herbivorous insects, neotropical migrant birds, and mammals) (Rees and Juday 2002, Werner 2002, Rexstad and Kielland 2006) and late succession (non-vascular plants and saprophagous insects) (Chapin and Danell 2001). Logging reduces plant diversity by 30% by eliminating fire specialists (Rees and Juday 2002). We are beginning to document patterns of microbial diversity using genomics.

N_2-fixation inputs by *Alnus crispa* (uplands) and *A. tenuifolia* (floodplain) account for the largest percentage of total N accumulated during succession and appear to be strongly limited by soil P availability (Uliassi and Ruess 2002, Anderson et al. 2004) or periodic insect or pathogen attacks (Ruess et al. Submitted). Fixation inputs appear to exceed plant N demand, and significant amounts of fixed N may be lost via leaching or denitrification, particularly in mid-successional stages (Uliassi and Ruess 2002), where nitrification potential is high and soil microbial biomass is more C- than N-limited (Brenner et al. Submitted).

Mammalian herbivores play a key role in the biogeochemistry of the boreal forest. In the floodplain willow communities, they consume 40% of aboveground NPP (Kielland and Bryant 1998). When they are excluded, biogeochemistry changes more quickly from a system dominated by inorganic C cycling and solubility equilibria, to a biologically controlled pattern of cycling dominated by NPP and decomposition (Kielland and Bryant 1998, Ruess et al. 1998).

Despite the large concentrations and rapid cycling of organic N and high proteolytic activity in boreal soils (Fig. 11) (Kielland et al. Submitted-a), the vegetation is strongly N-limited (Yarie and Van Cleve 1996, 2006). However, this organic N is quite dynamic. Amino acids turn over more rapidly than inorganic N (Kielland 2001, Jones and Kielland 2002) and are a major source of N absorbed by both plants and microbes (McFarland et al. 2002) (Fig. 12, 13).

Long-term forest harvest studies permit an assessment of potential future human impacts on Alaska's boreal forest. Low intensity forest harvest (no scarification) reduces initial seedling establishment but maximizes long-term growth of tree seedlings (Wurtz et al. 2006) (Fig. 14). Overstory retention treatments had no long-term effect on tree recruitment and growth (Wurtz and Zasada 2001). These studies suggest that low-intensity management after clear-cutting, an approach that mimics *certain* aspects of natural fire cycles, may maximize ecological recovery.

1.3 Thresholds and State Changes

Presence or absence of permafrost is probably the most important threshold regulating the structure and functioning of Alaska's boreal forest. Permafrost is generally present on north-facing slopes and valley bottoms, where it leads to cold water-logged soils, and absent on south-facing slopes, where soils drain freely. In flat upland areas, the presence or absence of permafrost in black spruce forests correlates strongly with the depth of organic layer lying on top of mineral soil (Kasischke and Johnstone 2005). Permafrost temperatures are now typically warmer than -2˚C, and have warmed about 0.7˚C per decade since 1970 (Osterkamp and Romanovsky 1999) in response to regional warming and changes in insulation by snow and vegetation. Currently 38% of our research watershed (CPCRW) has unstable or thawing permafrost (Yoshikawa et al. 2002, Hinzman et al. 2006) (Fig. 15), and continued warming would likely lead to extensive permafrost degradation within 10-25 years (Romanovsky et al. 2001).

Permafrost response to climate warming depends on changes in insulation by snow, moss, and the surface organic mat (Osterkamp and Romanovsky 1999, Sazonova and Romanosky 2003, Kasischke and Johnstone 2005). Insulation declines dramatically after fire, increasing the layer of thawed soil from about 50 cm to 2-4 m. As permafrost recovers during post-fire succession, an unfrozen layer (talik) forms between a seasonally frozen layer and original permafrost. In sloping terrain, water drains laterally through the talik, drying surface soils. Thawing of ice-rich permafrost may cause subsidence of the ground surface (thermokarst), leading to impoundment or drainage depending on topography (Myers-Smith 2005). Thus the impact of climate warming on soil moisture in permafrost terrain depends strongly on factors controlling talik formation and drainage conditions (Yoshikawa et al. 2003).

Low-permafrost watersheds or watersheds with well-developed taliks have greater base flow (80% of discharge) and are less flashy (i.e., less likely to cause floods) than high-permafrost watersheds, in which base flow increases from 50-60% of discharge in early summer to values similar to those of low-permafrost watersheds in late summer when mineral soils have thawed (Ishikawa et al. 2001, Hinzman et al. 2002). Thick aufeis in areas with abundant winter groundwater flow kill most woody vegetation. Groundwater flow also generates higher concentrations of base cations, inorganic nitrogen, and dissolved CO_2 and less dissolved organic carbon and nitrogen than in permafrost-dominated watersheds, where most water flows through the organic mat (MacLean et al. 1999, Petrone et al. 2000). Thus permafrost and talik distribution strongly influence soil moisture, land-water interactions, and stream discharge and chemistry. In contrast to temperate ecosystems, nitrate losses in streams are 4 to 5-fold greater than deposition inputs (Fig. 16, 17), a result that we cannot currently explain in light of the strong nitrogen limitation of watershed vegetation.

Fires are a second major cause of threshold changes in the boreal forest. Extensive large fires in the 1860's set the stage for the current age distribution and C dynamics in Alaska and Canada (McGuire et al. 2004). Differences in fire severity strongly influence patterns of vegetation C storage across the circumboreal north; western and central Siberia are dominated by ground fires that tend not to kill trees, whereas far eastern Siberia and boreal North America are dominated by crown fires that do tend to kill trees (McGuire et al. 2002).

The interaction between fire and permafrost thaw is a particularly important determinant of climate feedbacks (Myers-Smith 2005). The lower albedo and greater sensible heat flux of spruce compared to deciduous forests or non-forested wetlands (Chapin et al. 2000, Chambers and Chapin 2002) (Fig. 18) suggest that northward forest expansion could be a positive feedback to regional warming, but that loss of forests to the south or net conversion from conifer to deciduous forests resulting from fire could have a net cooling effect, one of the few negative feedbacks to high-latitude warming that has been identified (Chapin et al. 2000, McGuire and Chapin 2006). Boreal forests contain approximately 27% of the world's vegetation carbon inventory and 28% of the world's soil carbon inventory (equivalent to 75% of the total atmospheric carbon) (McGuire et al. 1997), so warming effects on net ecosystem production (NPP – decomposition) or on fire regime could substantially alter the global climate system (Potter et al. 2001, Clein et al. 2002). Warming appears to enhance carbon release in dry areas, enhance uptake in wet areas, and enhance methane release in wet areas (Thompson et al. In press, Zhuang et al. In press). The net effect of fire depends on fire severity and on changes in fire frequency (Kasischke et al. 1995, Zhuang et al. 2002). All of these effects on trace-gas feedbacks hinge on permafrost and hydrologic changes, which are poorly known (Chapin et al. 2000, Harden et al. 2003, McGuire and Chapin 2006) (Fig. 19). The recent shrinkage of lakes and wetlands in interior Alaska suggests, however, that the CO_2 efflux is increasing and methane efflux is decreasing (McGuire et al. 2004).

Boreal forest dynamics thus reflect a complex interplay between disturbance regime, climate, and species interactions. Our prior research leads to the prediction that resilience to external perturbation (e.g., climate warming) will depend on the traits of the dominant species (e.g., those species' ability to affect ecosystem properties) and the degree of coupling between climate and disturbance. It is this question of resilience and response to perturbation that we address in this proposal.

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BNZ LTER Datasets and submission dates (2002-2005)

Year	**Dataset Title**
2005	Aboveground biomass and ANPP along the Delta Fire Chronosequence
2005	Active Layer Depth Data for the BBC collapse scar for 2003 and 2004.
2005	Active layer depths: Bonanza Creek Fireline
2005	Active layer depths: Wickersham Fireline sites
2005	Air Temperature and Relative Humidity at LTER weather stations: Hourly Data
2005	Air Temperature at LTER weather stations: Daily
2005	Alder canker survey 2005
2005	Annual thaw depths at BCEF LTER floodplain sites
2005	Barometric Pressure at LTER1 weather station: Daily
2005	Biomass and %N and %C data for biomass for the BBC collapse scar for 2003 and 2004
2005	Black spruce allometric measurements
2005	Black Spruce Seedling Survay Results at the Tanana River Exclosures: 2003 - 2005
2005	Caribou Poker Creeks Research Watershed: Caribou Peak Climate Data
2005	Caribou Poker Creeks Research Watershed: CT1600 Climate Data
2005	Caribou Poker Creeks Research Watershed: CT2100 Climate Data
2005	Caribou Poker Creeks Research Watershed: Helmer's Ridge Climate Data
2005	Caribou Poker Creeks Research Watershed:C4 Climate Data
2005	Chena River Discharge Values (1947 - 2004)
2005	CO2, CH4, and H2O flux data and associated environmental variables for the BBC collapse scar for 2004
2005	Cold Regions Research Laboratory: CRREL Station Climate Data
2005	Controls over pathways of carbon efflux from soils along climate and black spruce productivity gradients in interior Alaska
2005	Conversion factor between acetylene reduction and 15N2 uptake rates for Alnus tenuifolia and Alnus crispa in six different successional habitats
2005	CPCRW Litterfall 1998-2004
2005	CPCRW Soil Moisture 1998-2004
2005	CPCRW Soil Respiration 1998-2004
2005	CPCRW Soil Temperatures 1998-2004
2005	CPCRW Tongue Depressor Decomposition
2005	CPCRW Tree Frequency, DBH, and Basal Area
2005	D and 18O data for a core from the center and moat of the BBC collapse scar
2005	Diatom assemblages for 3 cores from the center, moat and surrounding burn (0, 12, and 30 m) of the BBC collapse scar
2005	Fire Line Surface and Thaw Depths: Wickersham Sites
2005	Hajdukovich Creek Burn: Mineral soil temperature and moisture measurements
2005	Hajdukovich Creek Burn: Organic layer depth measurements
2005	Hajdukovich Creek Burn: Point Quarter data for tree diameter/density estimates
2005	Hydrology of CPCRW: Discharge, hourly data from Parshall flumes with 9" throat
2005	Isotope water data from BNZ

2005	Litter Trap Results at the Tanana River Exclosures
2005	Litterfall and Hare Pellet Summary at Bonanza Creek Experimental Forest Control Plots
2005	LTER Study Sites and Locations of Interest: Spatial Data
2005	Maximum active layer depths for ten random points in 150 extensive mature black spruce sites in interior Alaska
2005	Measurements of Lodgepole Pine Plantations in Alaska
2005	Morel Productivity
2005	N-fixation rate and leaf N content in two species of Alnus and their relationship to diversity of symbiotic Frankia
2005	Nitrogen cycling at treeline: latitudinal and elevational patterns across a boreal landscape
2005	Organic Layer Thickness: Wickersham Sites
2005	Paleoenvironmental changes at treeline in central Alaska: a 6500-year long pollen and stable isotope record
2005	Population dynamics of black spruce at its northern limit in the Brooks Range, AK
2005	Precipitation at LTER weather stations: Daily
2005	Relative Humidity at LTER weather stations: Daily
2005	Reserve West Tree Establishment and Growth after Fire: Reserve West Hectare Reference Stand
2005	Riparian Denitrification Rates, CPCRW, 2003-2004
2005	Riparian Groundwater Chemistry, CPCRW, 2003
2005	Site summaries and environmental variables for 150 extensive mature black spruce sites in interior Alaska
2005	Snow Depth at LTER weather stations: Daily
2005	Soil and air temperature at black spruce sites along three elevation gradients and latitudinal gradients in interior Alaska, USA
2005	Soil data for cores from a transect from the center of the BBC collapse scar into the surrounding burn
2005	Soil Moisture at floodplain sites, 1985-Present: Hourly
2005	Soil Moisture at LTER1, LTER2, and upland weather stations: Daily and hourly
2005	Soil Temperature at floodplain sites 1985-Present: Hourly
2005	Soil Temperature at LTER weather stations: Daily and hourly data
2005	Soil temperature controls of N2 fixation by A. viridis spp. fruticosa across a successional chronosequence in Interior Alaska through the growing seasons of 1997 and 1998
2005	Solar radiation at BCEF (LTER1 and LTER2) climate stations
2005	Spatial Data for Caribou Poker Creeks Research Watershed (CPCRW) and Frostfire
2005	Stand and tree characteristics for 150 extensive mature black spruce sites in interior Alaska
2005	Stream water chemistry of CPCRW, 2002
2005	Survey Line Fire Soil Moisture 2003-2005
2005	Survey Line Fire Soil Respiration 2003-2005
2005	Survey Line Fire Soil Temperatures 2003-2005

2005	Survey Line Fire Tree Frequency, DBH, Basal Area, and Age
2005	Tanana River Discharge Values (1973 - 2004)
2005	Tree Band Growth Data Taken at BCEF Sites (1989 - 2004)
2005	Tree ring width data for trees adjacent to the BBC collapse scar
2005	Vegetation and plant community composition for 150 extensive mature black spruce sites in interior Alaska
2005	Vegetation Plots of the Bonanza Creek Experimental Forest (1975 - 2004)
2005	Wind Direction and Velocity: Hourly 1991-2005, Daily 1991-2005, LTER1, LTER2 (3m and 10m)
2005	Yearly Seedfall Summary at Bonanza Creek Experimental Forest Control Plots (1958 - 2005)
2004	Air Temperature, Soil Temperature, Precipitation, Snow Depth at LTTG Sites;1968-Present : Weekly
2004	Alaska Tree Ring Data
2004	Average Tree Growth (DBH, Circumference, and Basal Area) at LTTG Sites, 1969-Present: Yearly
2004	Ground Water and River Level readings at floodplain sites, 1985 - Present: Hourly
2004	Ground Water Readings at LTER Floodplain Sites, 1991 - Present: Weekly
2004	Impact of wildfire on forest floor organic matter bioavailability in a black spruce forest
2004	Litterfall collected from LTTG Sites (1 meter litter trays); 1967 - Present: Yearly
2004	Litterfall Weights from LTER Study Site Treatment Plots; 1990 - Present
2004	Soil carbon stabilization along productivity gradients in interior Alaska
2004	Soil Moisture at various LTER weather stations: Daily
2004	Species list for Bonanza Creek Experimental Forest
2004	Throughfall Precipitation at LTER Drought Study Sites: 1991-Present: Weekly
2004	Throughfall Precipitation at LTTG Sites: 2001-Present; Logging Rain Gauge
2004	Tree Growth data taken at LTTG sites: 1969-Present; Yearly
2003	2002 MODIS Leaf Area Index estimates
2003	Analysis of vegetation distribution in interior Alaska and sensitivity to climate change using a logistic regression approach
2003	Carbon cycling in extratropical terrestrial ecosystems of the Northern Hemisphere during the 20th Century: A modeling analysis of the influences of soil thermal dynamics
2003	Characteristics and variation in lakes along a north-south gradient in Alaska
2003	Classified images at 1km and 25km grain size centered on BNZ
2003	Densities of snowshoe hares in Interior Alaska (1999-2002)
2003	Environmental variation, vegetation distribution, carbon dynamics, and water/energy exchange in high latitudes
2003	Evaluation of temporal and spatial scaling issues in simulating soil thermal dynamics
2003	Fine root respiration
2003	Frostfire storm event chemistry and discharge for CPCRW
2003	Historical and projected carbon balance of mature black spruce ecosystems across North America

2003	Influence of the phenolic compound bearing species Ledum palustre on soil nitrogen cycling in a boreal hardwood forest
2003	Land Cover Classification at 1km and 25-m grain size
2003	Modeling soil thermal and carbon dynamics of a fire chronosequence in interior Alaska
2003	Modeling stand-level canopy maintenance respiration of black spruce ecosystems in Alaska: Implications for spatial and temporal scaling
2003	Net Nitrogen Mineralization Rates for Mature Balsam Poplar and White Spruce
2003	Paleoecological data from Deuce and Dune Lakes, Interior Alaska, USA
2003	Snowshoe hare pellet counts in Interior Alaska
2003	Soil Moisture (TDR) at floodplain sites, 1994-Present: Weekly
2003	Soil moisture (TDR) at upland sites, 1994-Present: Weekly
2003	Soil Respiration: Floodplain Black Spruce
2003	Soil Water (Lysimeter) Chemistry for Mature Balsam Poplar and White Spruce
2003	SPOT HRV 1990, LANDSAT TM 1991 Satellite images BNZ LTER
2003	Tanana River Floodplain Dissolved Organic Nitrogen (DON) Budget
2003	The Treeline Ecotone in Interior Alaska - From theoretical concept to planning application and the science in between
2003	Tree regeneration after fire: Aspen removal experiment
2003	Tree regeneration after fire: Delta 1994 burn surveys
2003	Tree regeneration after fire: Effects of burn severity
2003	Tree regeneration after fire: Wickersham Dome long-term vegetation study
2003	Tree regeneration after fire: Yukon Lodgepole Pine Surveys
2003	Vegetation Study of the Tanana Flats Wetlands Complex in Interior Alaska
2002	Artificial communities experiment
2002	del 15N Values for Tanana River Floodplain Soils and Xylem Sap Samples
2002	Lightning Sensor data from BLM, Alaska Fire Service
2002	Soil Moisture at LTER Drought Study Sites: 1991-2002: Weekly
2002	The Nel-Rep plots: Spruce and alder heights and diameters 1990-2002

Section 2: Proposed research

Introduction and Conceptual Framework

A major challenge facing society is to understand and predict the patterns and rates of change in regional systems in response to directional changes in physical, biological, and social drivers (Vitousek et al. 1997, Berkes and Folke 1998). We will address this challenge explicitly for Alaska's boreal forest in the next phase of the Bonanza Creek (BNZ) LTER research. Our guiding research question is: **How are boreal ecosystems responding, both gradually and abruptly, to climate warming, and what new landscape patterns are emerging?** The boreal forest is an ideal region in which to explore the dynamics of change for several reasons. (1) Its cultures and natural ecosystems are relatively intact, making it easier to understand the natural coupling of physical, biological, and social components of regional systems. (2) The biophysical and social drivers of regional processes are changing rapidly (Krupnik and Jolly 2002, Hinzman et al. 2005). In particular, climate warming has accelerated in the last 30 years (Fig. 20) (Chapin et al. 2005). (3) Climatically sensitive processes include permafrost dynamics, movement of the forest-tundra boundary, and outbreak behavior of key forest mammals and insects. The boreal forest is the northernmost forested biome, so we expect it to be sensitive to recent warming. (4) The boreal region is the second largest biome on Earth and plays a major role in the global climate system (Pielke and Vidale 1995, Chapin et al. 2000, McGuire and Chapin 2006). (5) Long-term research by the BNZ LTER program has documented natural patterns of interannual and successional variability against which we can detect changes in system behavior.

The warming in Alaska results from both natural climate variability and climate forcing caused by increases in greenhouse gas concentrations produced by human activities concentrated in temperate and tropical latitudes. Thus the major human impacts on boreal ecosystems are mediated by activities occurring *outside* the boreal zone. This simplifies our task of addressing the overarching question of the U.S. LTER network (How do changes in human populations and their behavior, climate variation, altered biogeochemical cycles, and biotic structure interact to affect ecosystem structure and function and their services to society?). In the boreal zone this question becomes: How does boreal climate change alter the biophysical, biogeochemical, demographic, and socio-ecological interactions that govern the structure and functioning of Alaska's boreal forest, and what are the societal consequences—essentially identical to our over-arching research question. Thus our research is explicitly focused on the central science issues identified by the LTER network.

The **state factor** approach (Jenny 1941, 1980, Amundson and Jenny 1997) developed in ecosystem ecology is the conceptual framework that guided much of the past research of the BNZ LTER and is the starting point for our proposed research. This approach views ecosystem properties as being a function of "independent" controls such as climate, parent material, topography, potential biota, and time, which (with the exception of time) are assumed to change so slowly that they can be considered constant. Clearly climate and potential biota (exotic species) are now changing on ecologically important time scales.

We have extended the state-factor framework through study of **interactive controls**, i.e., the processes internal to ecosystems that both affect and respond to ecosystem processes (Fig. 21). These include functional groups of organisms, soil resources, microclimate, disturbance regime, and human activities (Van Cleve et al. 1991, Chapin et al. 1996). Interactive controls are "slow variables" (Carpenter and Turner 2000) that are sensitive to both state factors (external forces) and changes in the internal dynamics of ecosystems. Changes in any interactive control,

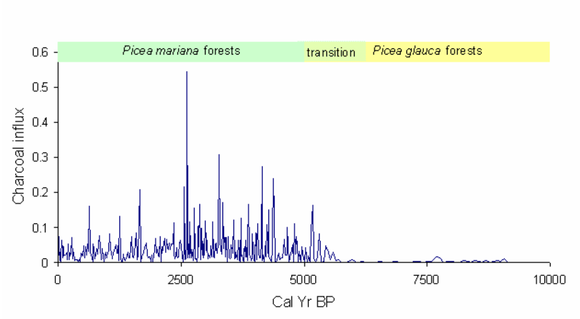


Fig. 1. Charcoal influx at Dune Lake Alaska over the last 10,000 years. Fire became much more frequent about 6000 yr BP, coinciding with arrival of black spruce on the landscape (Lynch et al. 2002).

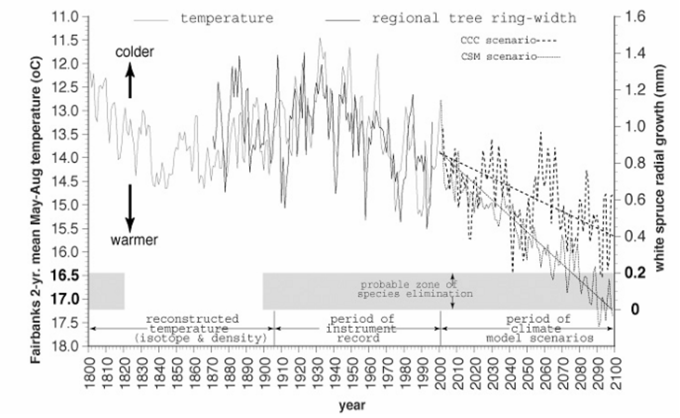


Fig. 2. Past and projected future summer temperature and radial growth of white spruce in interior Alaska (Juday et al. In press). Temperatures before 1917 were reconstructed from tree rings. Future temperatures and ring-width are projected from GCM simulations of climate and the observed climate-ringwidth relationship. Projections suggest that white spruce will approach zero annual growth by the end of the 21st century.

Table 1. Insect abundances

Species	1955-64	165-74	1975-79	1980-84	1985-89	1990-94	1995-99
Spruce beetle	20235	210039	286505	744989	595725	1114587	1265364
Spruce budworm	0	0	121	4452	907	219125	259855
Larch sawfly	0	0	0	0	0	45540	651099
Larch bud moth	202350	4047	238773	0	36018	4087	651099
Spear-marked black moth	2347260	526110	1092690	159452	32552	4832	0
Large aspen tortrix	0	2590080	19426	54877	261367	60379	24036

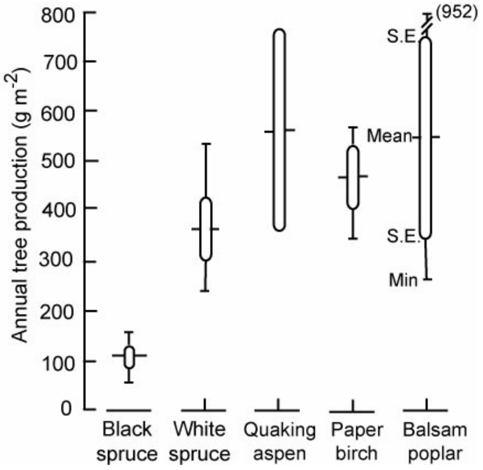


Fig. 3. Annual aboveground tree production of major forest types in interior Alaska (Viereck et al. 1983).

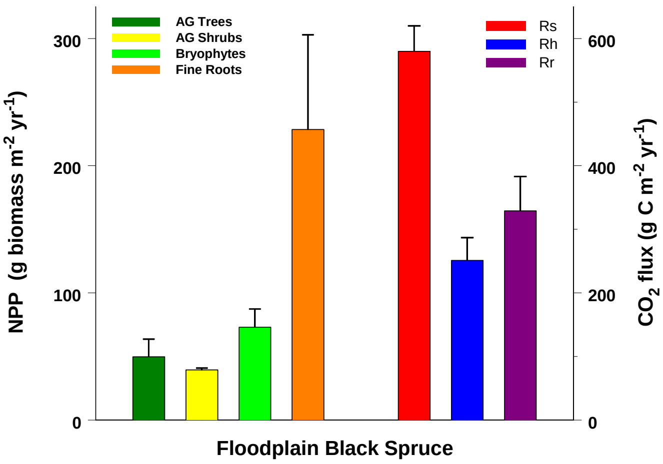


Fig. 4. Contributions of trees (aboveground; 13%), shrubs (11%), bryophytes (20%), and fine roots (56%) to total stand production in floodplain black spruce stands. Also shown are contributions of roots (Rr) and heterotrophs (Rh) to total soil respiration (Ruess et al. 2003)

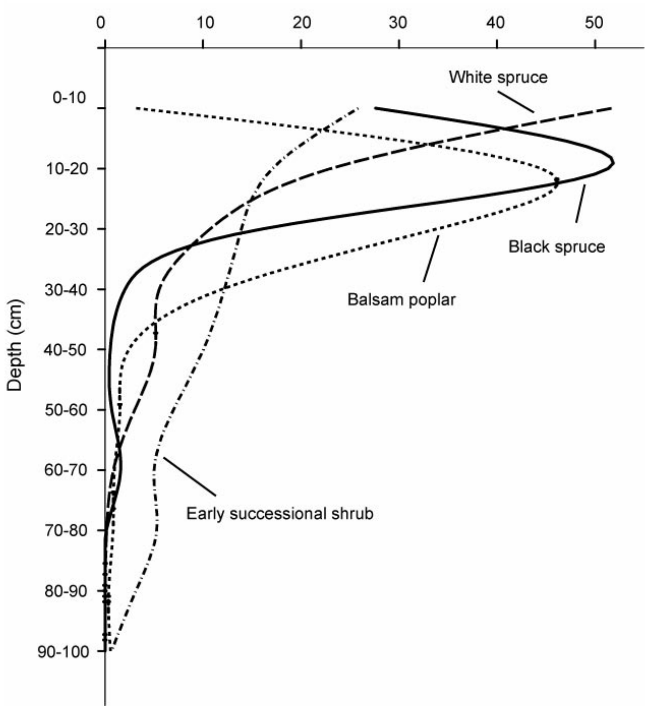


Fig. 5. Percentage of total annual fine root production distributed by 10 cm soil horizon increments for 4 Tanana floodplain ecosystem types (Ruess et al. 2006).

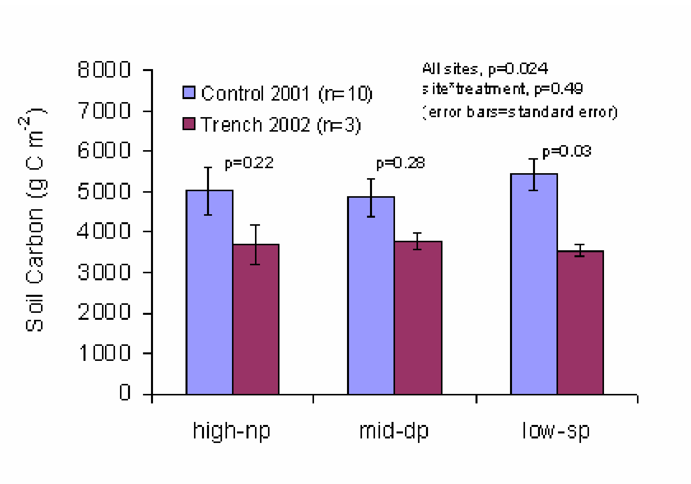


Fig. 6. Root exclusion (trenching) at 3 black spruce reduces stands total soil carbon after only 2 years, demonstrating that forest floor C depends on substantial annual root inputs to maintain or accumulate carbon (Vogel et al. 2005).

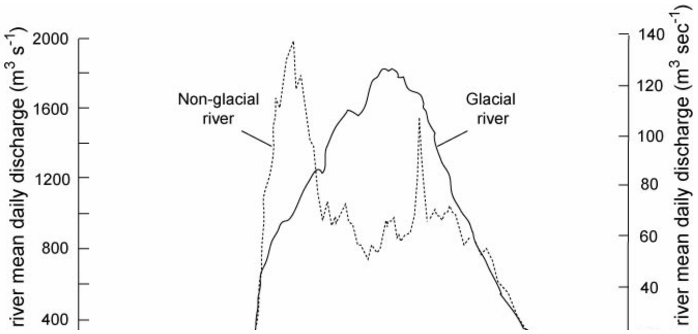


Fig. 7. Mean daily discharge of rivers whose headwaters are glacial (Tanana River) or non-glacial (Chena River) (Adams 1999).

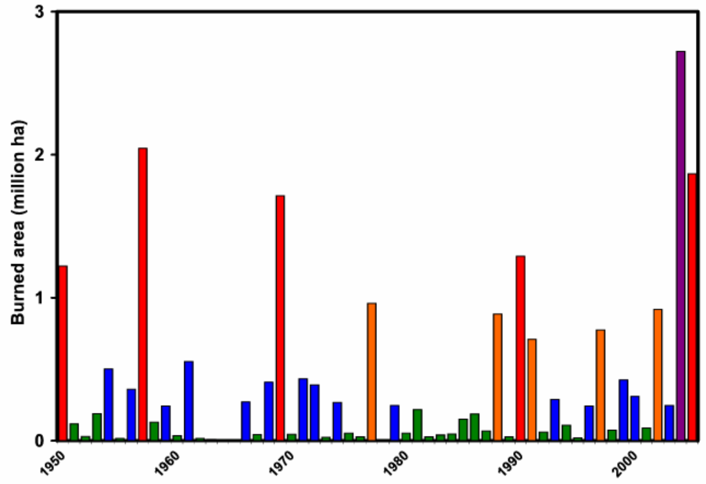


Fig. 8. Time course of area burned in Alaska. Between 1950 and 2005, 22.2 million ha were affected by fire in Alaska (Key: purple: those years which had > 10% of total burned area from 1950-2005; red: 5-10%; orange: 3-5%; blue: 1-3%; green: < 1%).

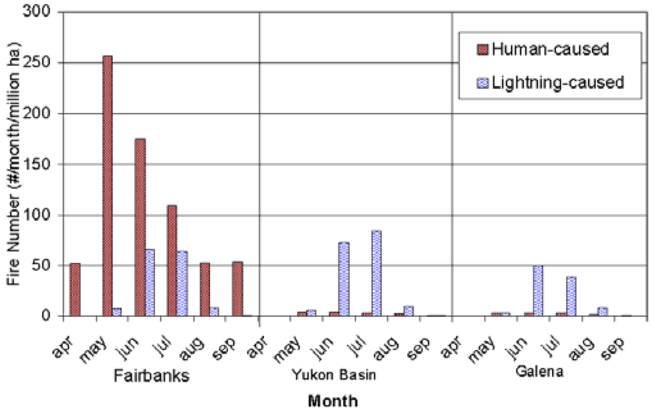


Fig. 9. Total number of fires per unit area from 1950-2000 for a heavily populated region (Fairbanks) and two sparsely populated regions (Yukon Basin and Galena) in interior Alaska (DeWilde 2003). Most fires are produced by lightning in sparsely populated regions, but human activities account for most fires and double the length of the fire season in populated areas.

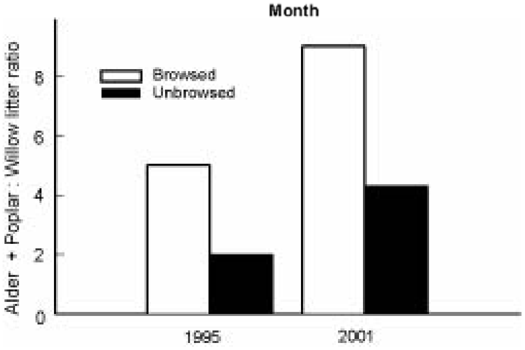


Fig. 10. Ratio of alder and poplar to willow biomass in browsed (control) and unbrowsed (exclosure) plots in the Tanana Floodplain. Browsing speeds succession by removing early successional willows (Kielland and Bryant 1998).

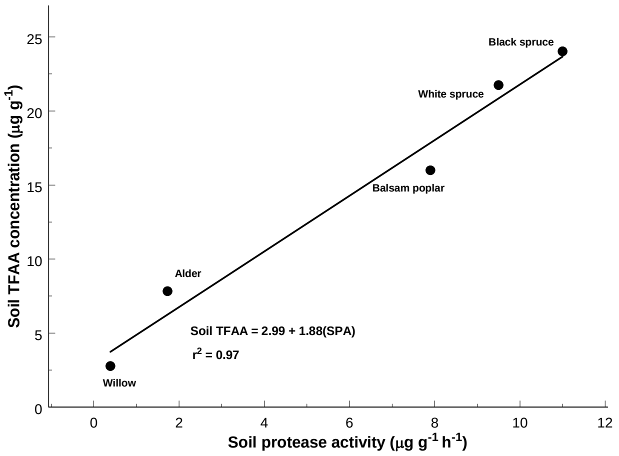


Fig.11. Relationship between total free amino acid concentrations and soil proteolytic activity across a successional sequence of Tanana floodplain forests (Kielland et al submitted)

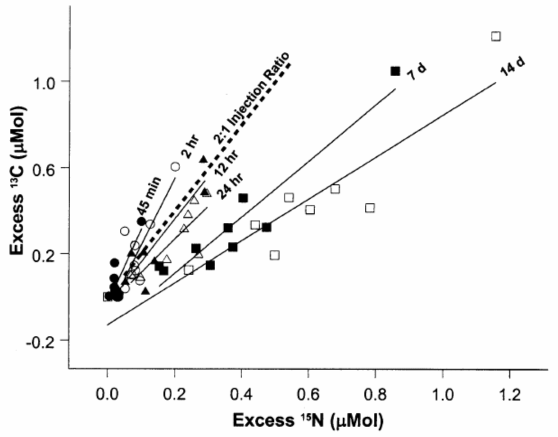


Fig. 12. Relationship between excess (above ambient) ^{13}C and ^{15}N in fine roots derived from ^{13}C^{15}N-glycine injected in situ and followed over a 14-day period. The rapid attenuation in slope over time demonstrates substantial root uptake of naturally occurring organic N, The dotted line shows the 2:1 ratio of injected glycine (McFarland et al. 2002).

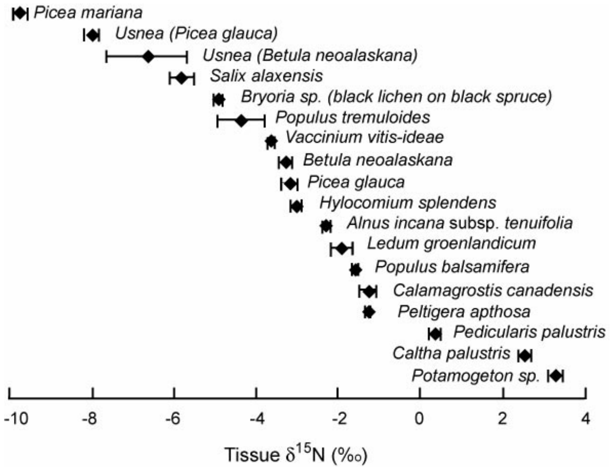


Fig. 13. Species variation in foliar δ^{15}N values among boreal plant species. Data are means $\pm$ SE. Data from Kielland et al. (1998) and Kielland (2001).

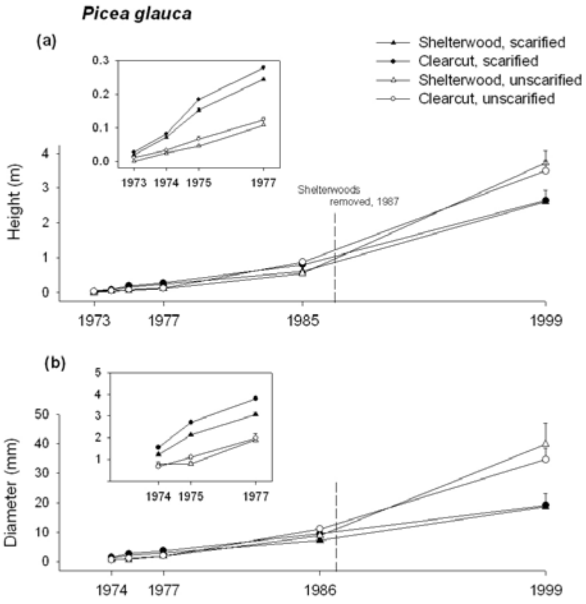


Fig. 14. Effects of forest harvest on growth of white spruce trees.

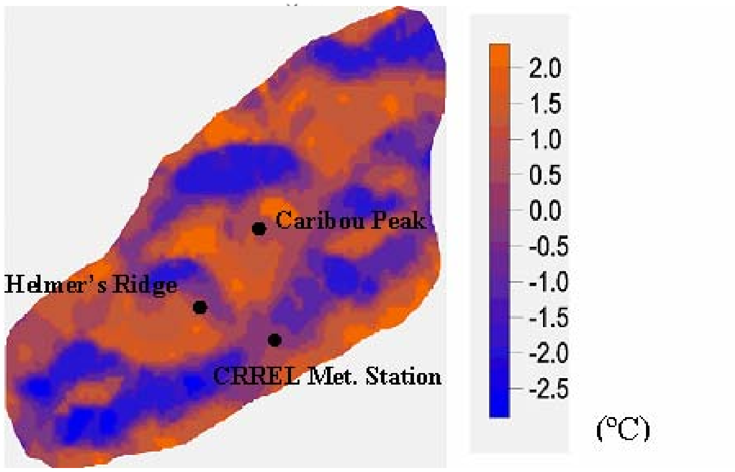


Fig. 15. Modeled mean annual surface temperature of CPCRW for 1997-98. Currently 38% of the watershed has unstable or thawing permafrost (Hinzman et al. In press).

to

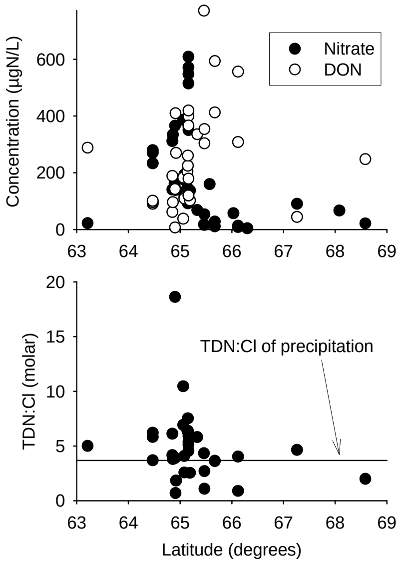


Fig. 16. Nitrate and DON concentrations in streamwater along a latitudinal gradient. Concentrations are highest in zones of discontinuous permafrost in interior Alaska. Using total dissolved N (TDN):Cl as an index of N retention, watersheds in discontinuous permafrost appear be losing N; whereas more northern latitudes are closer to steady state. Toolik data (Peterson et al. 1992) and BNZ data collected along a transect (Jones and Finlay unpubl.) were used to construct this relationship.

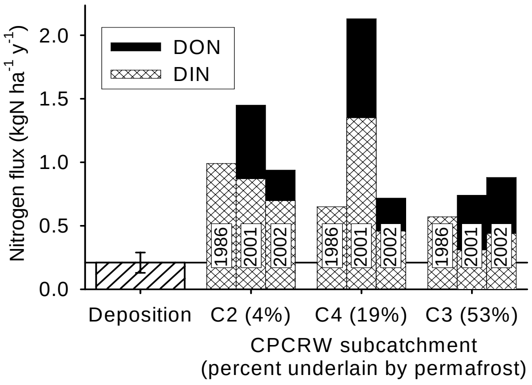


Fig. 17. N fluxes in CPCRW subcatchments. Inputs calculated from 10 years of data are from an NADP site at CPCRW. Output in stream flow for 3 years of intensive sampling (1986, 2001, and 2002).

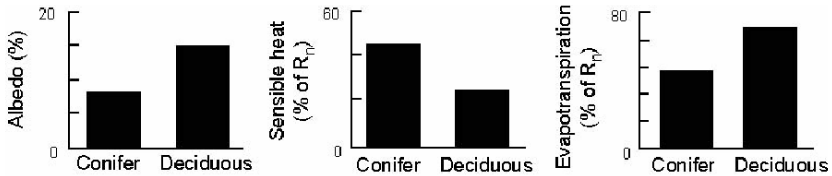


Fig. 18. Conifer forests tend to warm the atmosphere, whereas deciduous forests tend to cool the atmosphere. Expansion of boreal forests northward could lead to a positive feedback to warming, whereas expansion of deciduous forests in the event of more frequent fires could lead to a negative feedback to warming (Baldocchi et al. 2000, Chapin et al. 2000, McGuire and Chapin 2006).

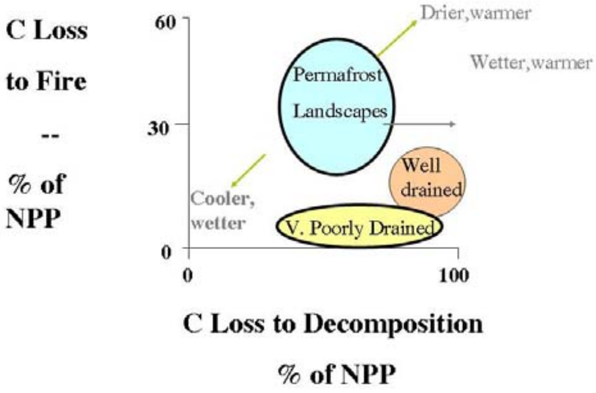


Fig. 19. The response of carbon storage in interior Alaska to climatic change depends on fire severity and frequency, which are influenced by changes in the hydrologic state of the system (Harden et al. 2000).

whether triggered exogenously or endogenously, will modify the structure and functioning of ecosystems. Through study of interactive controls, we have learned that important negative feedbacks (e.g., successional changes in nutrient availability or flammability) tend to maintain the system within certain bounds until it exceeds critical thresholds (**turning points**). If thresholds are exceeded, positive feedbacks push the system toward a new state (Van Cleve et al. 1991, Wilson and Agnew 1992, Carpenter 2003, Folke et al. 2004) (Fig. 22, 23). Legacies such as organic matter accumulation, past fire history, post-fire recruitment, or persistence of species by vegetative reproduction constrain ecosystem response to the current environment and disturbance regime (Foster et al. 1998, Foster et al. 2003).

In the next phase of the BNZ LTER research, we will broaden this conceptual framework to incorporate **resilience theory** (Folke et al. 2002, Gunderson and Holling 2002, Berkes et al. 2003), a theoretical framework that addresses the dynamics of change. Resilience is the capacity of a system to absorb disturbances so as to maintain its structure, functioning, and feedbacks (Holling 1986, Folke et al. 2004, Walker et al. 2004). Ecosystems are often quite resilient to stochastic variation or even directional changes in driving variables, until some threshold is exceeded, causing them to shift to a fundamentally new state (Gunderson and Pritchard 2002, Folke et al. 2004, Walker et al. 2004). The resilience framework requires that we reach beyond the assumptions of steady-state dynamics to ask what changes in drivers might trigger a change in ecosystem state (Holling 1986, Gunderson and Holling 2002, Scheffer and Carpenter 2003). Resilience theory is increasingly recognized within the LTER network as a useful framework for studying abrupt changes (regime shifts) in ecosystems as diverse as fresh water lakes (Carpenter 2003, Carpenter and Brock 2004), cities (Musacchio and Wu 2002), deserts (Geist and Lambin 2004, Peters et al. 2004), tropical forests (Lugo et al. 2002), arctic tundra (Zimov et al. 1995), and boreal forests (Chapin et al. 2004b) and was the science theme of the most recent LTER coordinating committee meeting.

Resilience theory provides a framework for restating our guiding question (**How are boreal ecosystems responding, both gradually and abruptly, to climate warming, and what new landscape patterns are emerging?**): Under what circumstances will the boreal forest be resilient to climate warming, and under what circumstances will it change abruptly to a new state with substantially different structure and functioning? Our null hypothesis is that the boreal forest will respond in a continuous fashion to variation in climate, without fundamentally altering its current structure and dynamics. Our alternative hypothesis is that key controls over ecosystem processes will exhibit rapid threshold changes, just as we observe at turning points between successional stages (Fig. 23). Threshold behavior of ecosystems is challenging to study because thresholds are difficult to anticipate: they are generally detected only after the ecosystem crosses a threshold and shifts to a new state. Regime shifts are typically surprises that can only be recognized in retrospect (Carpenter 2003, Scheffer and Carpenter 2003). In the boreal forest, however, we already know many of the factors that are likely to cause state changes, providing a unique opportunity to study the threshold behavior of ecosystems. Changes in ecosystem properties and processes that we expect to cause threshold changes include:

1.Loss of permafrost when the soil warms above 0˚C, causing major changes in soil moisture and nutrient dynamics.

2. Climate-induced increases in fire and flood severity and frequency and lowered water table, causing changes in successional trajectory and fundamental biogeochemical processes.

3. Changes in abundance of keystone and dominant species, including white spruce, alder, *Sphagnum* mosses, moose, snowshoe hares, and defoliating insects, which could initiate cascades of ecosystem change.

Finally, we recognize that Alaska's boreal forest is a social-ecological system in which society receives ecosystem services (benefits provided by ecosystems to society) but also affects ecosystems through a variety of mechanisms (Millennium Ecosystem Assessment 2005) (Fig. 24, 25). Most of our LTER research focuses on the non-human component, where we study the interactions between the structure and functioning of ecosystems. However, climate warming, which is our major driver of change, is substantially affected by the global human population. A developing focus of our proposed research is on two classes of ecosystem services, subsistence resources used by rural Alaskan communities and climate feedbacks, through which changes in carbon and energy balance of the boreal forest influence both regional and global climate and therefore the well-being of society globally.

Our previous proposal was poorly reviewed and the BNZ site placed on probation primarily because "the level of cross-theme coordination has been considerably less than optimal, …there was minimal integration among individual studies proposed, and…. the many hypotheses and sub-projects in the second half of the proposal were very disparate, often poorly described, disjointed, and confused." In response to these criticisms we have completely restructured our framework for project integration from "population dynamics, biogeochemistry, and landscape processes" (previous proposal) to integrate these levels of organization within each phase of the research, as described below. We have also elevated synthesis to a central role in the design and interpretation of the research.

Research design

Resilience theory provides a logical basis for organizing our research on the **dynamics of change** into four sections.

1. **Climate sensitivity**. Over a wide range of conditions, ecosystems may show relatively modest responses to changes in response to drivers such as climate change. We study climate sensitivity to identify the range of conditions, responses, and feedbacks that characterize boreal resilience to climate change. Long-term monitoring of climate and ecosystem processes using permanent plots and satellite imagery for change detection enables us to document seasonal and interannual variation. Paleoecological approaches allow us to document longer-term (decadal and greater) variability. Experimental manipulations of the environment provide further tests of environmental sensitivity and allow study of underlying mechanisms and feedbacks.

2. **Successional dynamics**. Resilience theory recognizes that most systems are not static but go through repeating "adaptive cycles" of collapse in response to disturbance, followed by reorganization and development to the same or a different system (Holling 1986). Thus systems are expected to be least resilient during the collapse phase of the cycle when relatively weak biotic interactions provide opportunities for new species or new sets of interactions to assume prominence. Variation in landscape heterogeneity and in the synchrony of adaptive cycles in the landscape often influence whether the cycle repeats itself or shifts to a new state (Peterson et al. 1998, Chapin et al. Submitted). Stand-replacing disturbances are ubiquitous in the boreal forest. All of our major disturbances (flooding, fire, insect outbreaks, and permafrost loss) are sensitive to climate, and post-disturbance successional stages differ in their climate sensitivity (e.g., permafrost responds most sensitively to climate in early succession, but trees are more

vulnerable to insect outbreaks in late succession). We must therefore understand the successional time course of climate sensitivity to predict boreal response to climatic change.

3. **Threshold changes**. When the limits of ecosystem resilience are exceeded, systems can suddenly change to a new state—a regime shift. We approach our study of thresholds in two ways. First, we conduct targeted studies of ecosystem responses to those factors that we hypothesize can trigger threshold changes (changes in permafrost, disturbance severity, and key functional types). Secondly, we use paleoecological records to identify past threshold responses. In practice, our study of thresholds is tightly integrated with study of climate sensitivity and succession, because unexpected or non-linear changes in these dynamics are likely to indicate threshold responses.

4. **Integration and synthesis**. To assess the overall importance of resilience and state changes, we must integrate our understanding of climate sensitivity, successional dynamics, and threshold changes at larger temporal and spatial scales and explore interactions among processes occurring at different scales (Peters et al. 2004). Watershed studies are a key element in this integration, because they integrate processes occurring in topographically distinct temperature and moisture regimes over time scales of days to decades and enable us to detect the integrated consequences of changes in permafrost, disturbance, and vegetation. In addition, we assess the spatial relationship of ecosystem structure and functioning to microclimate and disturbance through hierarchical mapping efforts. Landscape and regional models are key synthesis tools that allow us to simulate past, present, and projected changes in landscape and regional patterns of ecosystem structure (e.g., community composition, carbon stocks, and fuel loads). This enables us to test our mechanistic understanding, to explore alternative hypotheses about change dynamics (e.g., linear vs. threshold dynamics) of ecosystems), and to explore their societal consequences for interior Alaska. We explore societal consequences by identifying past and potential future changes in ecosystem services that boreal forests provide both locally (e.g., subsistence resources) and globally (e.g., climate feedbacks). Synthesis is a central feature of all phases of our program and will serve to integrate ongoing research, design new research, and identify emergent patterns.

We focus on three **integrative measures of ecosystem state** to assess patterns and rates of state change. These are (1) integrity of permafrost, (2) carbon and nitrogen stocks in plants and soils, and (3) species composition and diversity of plant, animal, and microbial communities. Each of these properties can be measured relatively unambiguously and could exhibit a variety of direct and indirect (and continuous and threshold) responses to climatic changes. They are slow variables (Carpenter and Turner 2000) that regulate boreal community and ecosystem dynamics. In addition, diversity of functional types and climate responses are thought to be key features that determine ecosystem resilience (Elmqvist et al. 2003, Folke et al. 2004). Where we detect changes in these integrative variables, we will explore the processes responsible for their change. This provides an objective basis for selecting a small number of processes for focused study. Our challenge is to understand the mechanistic links between climate change, measures of ecosystem state, and interactive ecosystem processes through observations, experiments, and modeling. We will also explore the use of integrative process variables that might serve as early warnings of state changes. Early warning indicators that we will test include ^{14}C, ^{13}C, ^{15}N, and N:P ratios. Each of these metrics provides independent, integrated information about ecosystem carbon and nutrient cycling fluxes that can be combined with the ecosystem stocks to better understand the processes that shape ecosystem state over time. We expect, for example, that mobilization of

Pleistocene-aged organic matter due to permafrost thaw will reduce ^{14}C concentrations in soil respiration and reduce the N:P ratio of deep-rooted species.

Our study design recognizes three **landscape units** that differ in their environmental controls and likely response to climatic change. These are uplands and floodplains, which have been the focus of previous BNZ LTER research, and wetlands, which are widespread in the boreal region but have not been intensively studied in Alaska (Fig. 26). Alaska contains more than half of the wetlands in the United States. Our research is concentrated at two intensive study areas that contain representative sites of each landscape unit: (1) At Bonanza Creek Experimental Forest (BCEF), we maintain permanent plots in primary floodplain succession and secondary post-fire succession (3-5 successional stages x 3 replicate sites/stage; Fig. 27; Table 2). We will establish additional permanent plots in wetlands as part of the proposed research. (2) At the Caribou-Poker Creek Research Watersheds (CPCRW), we maintain four intensive watersheds, two of which are unmanipulated (low vs. high % permafrost) and two of which have burned recently (a low-severity experimental burn in 1999 (Hinzman et al. 2003) and a high-severity natural wildfire in 2004). For selected variables, we extend observations from intensive studies at BCEF and CPCRW to the Tanana Valley, the watershed in which our intensive sites are situated and which drains the northern flanks of the Alaska Range. The Tanana Valley contains both pristine glacial and non-glacial watersheds and the major areas of agricultural and forestry development in interior Alaska, providing opportunities to examine social-ecological interactions. Where available, we maintain databases of climatic and ecological variables for all of interior Alaska as a basis for modeling and synthesis. Our research design thus gives us a hierarchical study design from plots/watersheds to all of interior Alaska (Fig. 27).

Our BNZ **research strategy** has been to assemble a team of highly motivated boreal scientists who collaborate effectively; to provide them with a research infrastructure consisting of long-term measurements on permanent plots and experiments and data management services; to provide enough funding for each investigator to study the long-term ecological dynamics of their focal interest; and to encourage them to seek external funding for process studies that explore the underlying mechanisms. The research described here is the long-term research funded by the NSF and USDA Forest Service funding of the LTER. We mention (but do not describe) the mechanistic research that is funded elsewhere. Detailed methods and relationship to other funded research are presented at www.lter.uaf.edu/proposal_methods.cfm.

Climate Sensitivity

Hypothesis: The effects of climate change on boreal ecosystem processes are primarily indirect, acting through temperature and precipitation effects on other environmental parameters. The most important of these indirect effects differ among landscape units, with south-facing uplands being most responsive to summer drought (conifers) and season length (deciduous), north-facing uplands to early-winter soil temperature, wetlands to water table height, and active floodplains to river height, which correlates positively with summer temperature and glacial melt.

Study of climate sensitivity enables us to document the range of climatic variation over which the boreal forest is resilient to climatic change. Non-linear climate responses suggest the presence of thresholds and state changes. Although one might expect the cold-dominated boreal forest to be extremely sensitive to the direct impacts of climate warming, many of the most important effects are indirect (see prior research) and involve interactions and feedbacks among a variety of slow variables. For example, in association with recent climate warming in Alaska: (1) growing seasons have lengthened by 2.5 days decade^{-1} (Keyser et al. 2000), with most change occurring in spring (Euskirchen et al. In press); (2) summer water deficits have increased by 6.5 cm decade^{-1}, due to a summer temperature increase of 0.5˚C decade^{-1} (Oechel et al. 2000) and no trend in precipitation (Hinzman et al. 2006); (3) winters have warmed by nearly 2˚C decade^{-1}, delaying the date at which soils freeze (Euskirchen et al. In press); and satellite indices of vegetation greenness have switched from a positive (1970-90) to a negative trend (Angert et al. 2005, Goetz et al. 2005). Our research on climate sensitivity will therefore address not only the direct temperature effects on ecosystem processes, but also some of the indirect effects, particularly those associated with (1) earlier spring and midsummer drought; and (2) the delayed soil freezing associated with warmer winters.

Summer warming: Earlier spring and midsummer drought

Model simulations suggest that earlier growing seasons have increased rates of carbon cycling over the last 40 years, with NPP increasing by 9 g C m^{-2} yr^{-1} per day earlier thaw in the spring (Euskirchen et al. In press). Our field results suggest, however, that boreal ecosystems differ in their climate responses in complex ways. Eddy covariance studies show, for example, that evergreen conifers begin carbon fixation earlier in the growing seasons than deciduous species, but fix less carbon in mid-summer (Röser et al. 2002, Liu et al. 2005). However, we do not yet know whether these differences in physiological strategy translate into different sensitivities of NPP to spring conditions or whether trends differ among landscape units or successional stages. Tree growth is sensitive to increasing summer water deficits (Barber et al. 2000, Juday et al. In press), although this response may be sensitive to landscape position and prevailing climate (Lloyd and Fastie 2002, Wilmking et al. 2004). Our goal in this section is to improve our understanding of the climate sensitivity of ecosystem processes in interior Alaska.

1. How has climate change altered the physical environment of the BNZ LTER site and how have different stand types (conifer vs. deciduous; upland vs. floodplain vs. wetland) differed in their responses to the direct and indirect effects of summer warming?

Task C1 (i.e., task 1 of the climate sensitivity section). *Conduct a retrospective analysis of the relationship of litterfall, diameter increment, and seed production to thaw date, summer air temperature, growing degree days, daily temperature maxima and minima, summer soil temperature and moisture, early-winter soil temperature, and precipitation.* We will continue to maintain long-term measurements of macroclimate (main LTER weather stations), microclimate (including permafrost), and vegetation characteristics in each major vegetation type and successional stage (Table 3). Comparisons of these microclimate measurements with those at the main LTER weather stations document the vegetation effects on microclimate and the environment experienced by organisms. Annual measurements of litterfall, diameter increment, and seed production in these stands provide three measures of plant performance at an annual resolution. We now have 20 years of data at 24 sites in uplands and lowlands for this analysis and shorter time series at a dozen additional sites. We will use multiple regression analysis to relate biological response to climate variables, other variables that may be important at specific sites (e.g., river height in the floodplain), and biotic variables that appear important (e.g., densities of outbreak insects specific to spruce and aspen). We will also make qualitative assessments of the role of extreme events (e.g., snow-breakage or insect outbreak) in affecting plant and ecosystem processes as a basis for developing rule-based models. We will statistically remove successional and age-related trends before analyzing climate sensitivity.

Task C2. *Use tree-ring analysis to assess the sensitivity of tree-ring width to climatic variation*. We will conduct separate analyses for each major tree species (white spruce, black spruce, birch, aspen, poplar) in mature stands in uplands and floodplains and use existing tree-ring chronologies (developed by Juday, Lloyd and others) and new chronologies for sites/species that have not been adequately sampled in the past. Climatic sensitivity will be estimated as the proportion of variation in growth that can be explained by observed climate. Within a landscape unit (floodplain or uplands), we will compare sensitivity among species. We will also evaluate the sensitivity of individual species across environmental gradients (landscape units). Finally, because some boreal species are known to exhibit threshold responses to warming (D'Arrigo et al. 2004, Wilmking et al. 2004), we will compare the climate responses of sensitive species over time to identify changes in climate response (e.g., those that may be associated with indirect effects of warming such as drought stress) and to identify potential climate thresholds for species in which climate response varies. We hypothesize, based on the current distribution and known Holocene history (Lloyd et al. 2006), that threshold responses to temperature will prevail in the conifers but not in the hardwoods (which formed the dominant forest type during the warmer and drier millennia in the early Holocene). This analysis can consider only those climate variables that can be estimated from the 100-year Fairbanks climate record.

Task C3. *Document the effects of climate variability, vegetation type, and predation on herbivore abundance*. Our past studies suggest that small, short-lived herbivores (microtines and insects) are more sensitive to climate variation than are large herbivores and that food availability and predation become increasingly important regulators of population dynamics as body size increases (Fig. 28). We will continue to monitor population parameters (density and turnover) of snowshoe hares, which are a keystone species in the boreal forest (Krebs et al. 2001), in early and late succession and will use this information and agency data on lynx abundance to assess the effects of climate, vegetation, and predation on hare population densities and cycles. Agency data on moose density, birth rates, and mortality in areas that differ in climate, vegetation, hunting pressure and wolf densities allow an initial assessment of the relative importance of predation, climate, and nutritional status (a function of vegetation) on the population dynamics of moose. We have a 27-year record of population densities of major insect herbivores (both outbreak and non-outbreak species) in interior Alaska and shorter records for abundances of microtines, hares, and moose.

Task C4. *Manipulate soil moisture to assess its effects on NPP and other ecosystem processes*. We use ecosystem experiments to test the factors that we hypothesize to explain the climate sensitivity of Alaska's boreal forest (Table 4). Surprisingly, complete elimination of summer rainfall for 12 years using rainout shelters reduced tree growth on the floodplain (where we expected groundwater from the river to provide moisture) but not in the uplands (where all moisture comes from on-site precipitation). The seasonal pattern of soil water potential suggests that soil recharge during spring snowmelt supplies most of the water transpired by trees during the early-summer growth period, perhaps explaining the insensitivity of tree growth to summer rainfall. We will therefore initiate a new snow-removal experiment that removes snow just prior to snowmelt before meltwater can enter the soil. We will measure soil moisture with TDR and tree growth annually in snow-removal, rainfall exclusion and control plots to determine which moisture source has greatest influence on tree growth in uplands and floodplains. We have initiated studies on soil carbon stocks, decomposition rate, and nitrogen mineralization rate to assess indirect effects of soil moisture on forest production and will determine whether these treatments affect abundance of plant pathogens. In wetlands we will manipulate water table depth (raised and lowered by 5 cm), summer temperature (increased 1-3˚C using ITEX passive warming chambers), and winter temperature (by adding foam insulation) and examine the response of community composition, NPP, and summer CO_2 and CH_4 fluxes to these manipulations. Based on these observations, we will develop a simple rule-based model to describe wetland vegetation responses to these environmental changes.

2. How does winter warming influence ecosystem processes in Alaska's boreal forest?

Task C5. *Document the relative importance of winter and summer processes through observations and field experiments*. Recent measurements in arctic and alpine ecosystems and in our LTER site show that microbes remain active down to about –5˚C and that a substantial proportion of annual soil respiration and nitrogen mineralization occur during winter (Kielland et al. Submitted-b) (Fig. 29). However, we know very little about the temporal dynamics or thermal dependence of these processes. Since high-latitude warming is most pronounced in winter, it is critical that we initiate studies of the "winter biology" of boreal ecosystems. Our goal in this task is to assess whether processes occurring during winter have a significant effect on the net annual behavior of boreal ecosystems. Documentation of the winter thermal environment is described in Task S3. We are currently testing the use of insulative foam to increase winter soil temperature in wetlands and early successional communities. If these manipulations are successful, we will extend them to late successional forest stands on the floodplain and uplands, where we will measure selected ecosystem processes in early winter (in control and winter-warmed treatments) for comparisons with other seasons to determine which processes exhibit a significant proportion of their annual activity during winter. These measurements will include plant transpiration, net nitrogen mineralization, and soil respiration.

Relationship to past and future research

The research on climate sensitivity builds on our ongoing monitoring of climate (Table 3), vegetation-influenced microclimate in 13 stand types (Table 2, 3), plant and animal population dynamics (density, recruitment, and mortality), productivity, and selected ecosystem processes (Table 3). Our focus during this research phase is to synthesize this information to assess the climate sensitivity of ecosystem structure and function. We continue to follow long-term manipulation of factors that may mediate climate sensitivity, including summer precipitation, nutrients, and herbivory, and we add new manipulations of snow-melt inputs and winter temperature. Our observations and water-table manipulations in wetlands are also new. Measurements of ecosystem processes in winter were initiated in 2004. Our long-term strategy is to identify the processes that are most sensitive to climatic change and determine the mechanistic links between specific climate parameters and ecosystem response. This will lead to LTER-related proposals to study these processes in greater detail.

Successional Processes

Hypothesis: Climate influences the rate and trajectory of succession by altering disturbance regime and the abundance of key species.

Our study of successional dynamics focuses on the adaptive cycle of disturbance and recovery that is central to understanding system resilience. One of the most important *indirect* effects of climatic change on ecosystems is the modification of disturbance regimes. This creates disturbance legacies that influence the sensitivity of ecosystems to changes in climate (Chapin et al. 2004a, Harden et al. Submitted). In the boreal forest, there are at least four distinct sources of disturbance that we expect to respond sensitively to climatic change. These include flooding due to increased glacier melt, fire, thermokarst (thawing and subsidence of ice-rich permafrost), and insect/pathogen-induced plant mortality, often triggered by drought (Juday et al. In press). We discuss the first two disturbances in this section and the second two (which are more likely to induce rapid state change) in the thresholds section. We currently have only a qualitative understanding of the linkages between climate and disturbance regimes, making it difficult to predict future patterns of ecosystem processes in the boreal forest. Our goal in this section is to document the major linkages between climate, disturbance regime, and successional changes in ecosystem processes in interior Alaska.

1. How has recent climate warming altered disturbance regimes and successional development in interior Alaska?

Task S1 (i.e., task 1 of the succession section). *Develop predictive relationships among climate, glacier melt, and discharge within and among years to assess their effects on water availability and nutrient supply in the Tanana River floodplain.* Although we know that spring ice jams and mid-summer flooding are the principal disturbances that initiate succession in the Tanana River floodplain, we lack a good understanding of their climatic basis. We will use historical river discharge data for the Tanana River to construct hydrologic budgets for the river basin to determine the relative contributions of summer precipitation and glacier melt to river discharge. Seasonal sampling of oxygen isotopes in precipitation and river water will provide a test of this relationship. We will explore *inter*annual variation in climate and discharge using multiple regression to test the relationship between longer-term variations in climate and peak annual discharge. Based on the river-height/groundwater-height relationship, we will estimate the seasonal pattern of groundwater height and compare this with the vertical distribution of roots. We will use seasonal time series of oxygen and hydrogen isotopes in vegetation, precipitation, and river water to determine the relative importance of current precipitation and river water in supporting plant growth (see also Task C4).

Task S2. *Develop predictive relationships between climate and fire regime, specifically the number, size, and severity of fires.* We have reasonably good predictive relationships between climate and area burned, based on the fire record of the last 56 years (prior research; Fig. 30), but we do not know whether this relationship has changed through time, nor the factors that determine fire severity (soil organic matter loss by combustion). Previous LTER research has shown that the amount of surface organic-layer material remaining after fire affects seedbed condition, vegetative reproduction, and soil moisture and temperature and therefore subsequent tree recruitment and postfire succession (Johnstone and Kasischke 2005, Kasischke and Johnstone 2005). We will examine the depth of burning into the organic layers of black spruce forests and factors that control the moisture levels of these layers, including: (a) inter and intra-annual variations in climate; (b) physiography (slope, aspect, elevation, and mineral soil texture); and (c) prefire organic-layer depth. Under this task, we will carry out three activities: (a) measure depth of burning as a function of factors that impact soil moisture (to supplement our current database of 150 sites in 26 fires); (b) analyze and model factors influencing seasonal permafrost thaw and the moisture of the deeper organic layers before fire (Task S3) and after fire; and (c) evaluate the utility of satellite-derived indices to assess the spatial patterns of burn severity. We will test several satellite indices of burn severity (Duffy et al. Submitted) for fires that occurred in early and late summer and in wet and dry years/sites to develop relationships between climate, site moisture, and satellite indices of burn severity. We will use field observations to correlate these satellite indices with components of burn severity that have different ecological consequences. These include canopy consumption (which influences seed input from semi-serotinous cones), depth of duff consumption (which influences carbon loss in fire and resprout potential), and areal extent of mineral soil exposure (which influences seed bed characteristics).

To assess whether the relationship of climate to area burned has changed through time, we will develop a map of stand ages and vegetation types for portions of the Tanana Valley. We will use existing maps of vegetation (Calef et al. 2005) and fires that have occurred since 1950 (Kasischke et al. 2002) to assess the relationship of climate and vegetation to area burned for 1950-2000. We will document the ages of stands that did not burn in this time interval to develop more complete maps of stand ages, building on the results of previous field studies of portions of the area (Mann and Plug 1999, Fastie et al. 2002, Hollingsworth et al. Submitted) (Rupp and Mann unpubl.). We will develop these maps first for the two intensive LTER study areas, BCEF and CPCRW (see also Task I/S3). By comparing landscape units (floodplain, wetland, and upland), we can look for potential differences among landscape units in the sensitivity of their fire regimes to climate change. We will extend this analysis to road-accessible portions of the Tanana Valley as feasible, working with other funded research projects to avoid duplication.

2. How do legacies and disturbances interact to determine changes in abundances of key plant, animal and microbial taxa through succession and what are the consequences for ecosystem processes?

Legacies of disturbance history influence ecosystem characteristics through effects on soil properties and seed sources (Foster et al. 1998, Foster et al. 2003). In this way legacies determine the likelihood that the system will follow a successional sequence similar to that which occurred previously, with a predictable sequence of species abundances (Franklin and MacMahon 2000). The functional traits associated with these plant, microbial, and animal species then interact with climate to determine ecosystem structure and functioning (Fig. 21). We know the general patterns of disturbance and successional change in our study area. Our goal in this section is to develop explicit rules that define the relationship between disturbance regime and the successional changes in plant, animal, and microbial functional types and to assess the implications of these successional dynamics for ecosystem processes in Alaska’s boreal forest.

Task S3. *Analyze the relationships among climate, disturbance regime, ecosystem structure (vegetation composition and organic layer depth) and permafrost distribution.* In order to place climate sensitivity and successional processes in a common conceptual framework, we must determine the effects of seasonal and interannual climate variation, disturbance legacies, and subsequent vegetation development on soil temperature, moisture, and permafrost regime. We will use our existing soil thermal models (Romanovsky et al. 1997, Zhuang et al. 2002) to address the effects of summer and winter air temperature, snow properties, disturbance regime (e.g., silt deposition thickness or burn severity) and subsequent vegetation development on soil environment. These model results will be validated in LTER plots where we have measured soil temperature for 5-22 years after fire/flooding. These disturbance and succession effects on soil environment will be incorporated into regional models of ecosystem processes (Task I/S3).

Task S4. *Analyze the relationship between disturbance properties and plant successional pattern as a basis for rule-based models of succession*. Flooding, fire, and water table change have multiple influences on successional development: Floods carry propagules (alder seeds; uprooted willow and alder shrubs), provide new substrate for seed germination, and bury white spruce seedlings that establish early in succession (Krasny et al. 1988, Yarie et al. 1998, Adams 1999). Similarly, fire severity and pattern influence seed availability, resprout potential, and seedbed characteristics (Johnstone and Kasischke 2005). Finally, changes in water table, whether caused by climate variation, fire, or thermokarst, cause changes in soil aeration and in bryophyte communities of wetlands and peatlands, which in turn control carbon storage and energy exchange (Bubier et al. 1998). We will compare vegetation data from LTER plots with documented disturbance histories to develop simple rules that serve as hypostheses for studies of upland post-fire successional trajectories and lowland post-fire and post-watertable manipulations. This will enable us to incorporate the legacy effects of disturbance history into successional models. Because we have data on stand biomass and productivity for the LTER plots, we will be able to incorporate successional changes in these ecosystem properties into models (Task I/S3). Teasing apart legacy effects of water table histories from recent and future effects of changing water tables will be increasingly possible as we monitor water table and vegetation along the gradient (Dunne et al. 2004). Based on these observations, we will develop a simple rule-based model to describe wetland succession in response to water table depth.

Task S5. *Document the effects of key plant functional types on ecosystem processes*. Successional research on turning points has suggested two major transitions in ecosystem processes that are driven by changes in plant functional types—the arrival of alder and the arrival of mosses. We will continue efforts to improve predictive models of the effects of (1) flood events and herbivory on establishment of *A. tenuifolia* and (2) microclimate and soil resource availability on N fixation inputs. We will also synthesize information from existing long-term experimental plantations of alders in floodplains and uplands to document their effects on ecosystem processes. Similarly we will maintain long-term moss-removal experiments to assess moss effects on ecosystem processes. Lodgepole pine is actively migrating through western Canada toward Alaska and may ultimately become interior Alaska's first fire-prone coniferous pioneer species. We will compare carbon stocks and controls over carbon and nitrogen cycling beneath existing plantations of lodgepole pine and naturally occurring birch, aspen, and spruce forests.

The introduction of exotic, invasive species is particularly problematic in ecosystems, like the boreal forest, in which single species (e.g., *Alnus tenufolia*) are capable of having profound effects on ecosystem function. In this funding cycle, we therefore propose to expand our analysis of key plant species and functional types to include invasive species. Invasive species appear to have increased their rate of range expansion in Alaska in the last decade, and we expect this trend to become more pronounced, if climate warming and increased access to remote areas (via road construction, off-road vehicle use, and recreation along rivers) continues. As part of our long-term monitoring of our permanent LTER plots and in our more extensive field studies, we will document arrival or changes in abundance of species that are likely to have large ecosystem effects, paying particular attention to invasive and non-native plants (especially N fixers), plant diseases, insect outbreak species, and mammals that have recently increased in abundance (e.g., beavers). Our analysis of the effects of key plant functional type on ecosystem processes will be expanded to include the effects of exotic invasive plant species. For example, *Melilotus alba* is a non-native nitrogen fixer that, until 1999, was sown by the State of Alaska Transportation Department to stabilize road shoulders. *Melilotus* has recently moved from roads to river floodplains at bridges and has heavily colonized the floodplains of at least three rivers, including several tributaries of the Tanana River upstream of our BCEF study site. This provides us with a unique opportunity to study the consequences of invasive species early in their invasion, and to put those consequences in the context of our existing understanding of the overwhelming importance of particular species in the boreal forest.

Task S6. *Determine the long-term effects of snowshoe hares and moose on ecosystem processes in floodplain succession*. We will continue to conduct mark-recapture studies of snowshoe hares four times per year to estimate population parameters. We will also continue monitoring two sets of hare/moose exclosures (2 and 17 years old; Table 4) to document herbivore effects on integrative variables (vegetation composition, C and N stocks, and permafrost) at different successional stages. We will initiate browse surveys in our LTER permanent plots to document herbivore effects on vegetation. We will use analysis of covariance to determine whether climate effects on herbivores (Task C3) operate independently or interactively with the direct climate effects on vegetation (Task C1). We will also model landscape-level ecological effects of interactions between herbivory, erosion from flood disturbance, and primary succession in floodplains of the Tanana River (See also Task I/S4).

Task S7. *Establish baseline characterization of soil fungal community composition among successional stages, soil horizons, and seasons in floodplain and upland ecosystems*. Understanding how climatic-induced changes in disturbance regimes modify biogeochemical cycling requires a comprehensive characterization of soil microbial diversity – something that has never been done at our LTER site or for any other terrestrial ecosystem. We have begun this characterization for soil fungi, by extracting DNA directly from soil, followed by PCR fingerprinting, clone library construction and sequencing. In selected sites, we are repeating these measurements seasonally and are simultaneously analyzing 1) DNA to characterize total fungal community composition, and 2) RNA to pinpoint that subset of the fungal community that is most active in different seasons. We will measure fungal production and mycorrhizal-to-saprophyte ratios across upland and floodplain successional stages using in-growth bags, followed by PLFA, ergosterol and molecular analysis. Ergosterol gives us a measure of fungal biomass, PFLA reveals microbial biomass and the bacterial:fungal ratio, and the molecular work provides information on the relative abundance of various guilds of fungi. Our preliminary data suggest unexpectedly high fungal production, and fungal:bacterial and mycorrhizal:saprophyte ratios. The proposed research will determine whether these patterns change temporally and through succession. These studies of microbial community structure will be coupled to functional studies of soil enzyme activities using fluorescent substrates (Marx et al. 2001).

Relationship to past and future research

Successional research has been the central focus of the BNZ LTER site from the beginning, so our permanent plots for long-term monitoring of microclimate, plant diversity, ecosystem structure, and biogeochemical processes capture the successional variation in ecosystem structure and function in three successional sequences (floodplain, north-, and south-facing uplands), with three replicate stands per successional stage (Table 2). Long-term herbivore exclosures provide experimental tests of herbivore effects on successional changes in ecosystem structure and functioning. The major new thrusts in the research proposed here are (1) a quantitative assessment of the relationship between climate and disturbance regime (flooding and fire), (2) synthesis of currently available information to develop predictive rules that describe successional changes in vegetation and ecosystem processes, (3) initiation of new baseline research on the seasonal and successional patterns of microbial diversity using molecular approaches, and (4) initiation of successional research in wetlands. We also initiate preliminary studies of the functional consequences of these patterns of microbial diversity (N fixation rates, plant growth, and soil enzyme activities). We anticipate that future phases of the LTER will develop more targeted studies of the microbial diversity-function relationships, once we have documented the general patterns of microbial diversity and tested plausible links to function.

Thresholds and State Changes

Hypothesis: Novel boreal landscape patterns emerge, when climate change leads to disturbance regimes that alter permafrost integrity and the abundances of key functional types.

The boreal forest provides a unique opportunity to study threshold responses of ecosystems that lead to a change in state because we know the precise conditions under which certain key thresholds occur (thawing of permafrost at 0˚C mean annual soil temperature) and some of the factors that cause non-linear changes in system functioning (e.g., turning points associated with successional changes in plant functional types). If our hypothesis for thresholds is correct, it suggests that we can use our understanding of contrasting climate sensitivity of different landscape units and of successional dynamics to predict causes and consequences of threshold responses to climate change. Although unanticipated surprises will certainly occur, we have developed a study design that improves our likelihood of detecting, understanding, and predicting state changes. Our goal in this section is to determine the frequency and location of changes in ecosystem state and their causes and consequences.

1. How often and under what circumstances does wetland drying or thawing of permafrost cause a change in ecosystem state?

Task T1 (i.e., task 1 of the thresholds section). *Document hydrologic changes in permafrost-dominated wetlands (extent of open water) inside and outside burns.* We will analyze Landsat images of burned wetlands (pre- and post-fire) and unburned wetlands to estimate changes in area of open water. This will provide a measure of the relative frequency of thermokarst (enlarging lakes) and drying/draining as causes of wetland change and determine the role of fire in triggering these changes. Once areas of thermokarst and drying have been detected and mapped, we will use multivariate analysis of spatial and ecosystem variables such as elevation/topography, soils, vegetation, permafrost distribution, and disturbance to develop a set of rules for predicting the circumstances where threshold changes are most likely to occur. Maps produced from this type of effort could guide future field-based studies on threshold change, and the rules can be incorporated into models of landscape change (Task I/S3).

2. What disturbance-induced changes in functional types might trigger a change in ecosystem state, and what are the ecosystem consequences?

Task T2. *Determine the effects of altered disturbance regime on successional trajectory and ecosystem processes*. We will follow tree establishment and community composition in 90 permanent study sites that burned in 2004 and span a broad range of soil moisture and burn severity. We will determine the frequency and conditions under which the new successional trajectory will differ from that of the pre-fire vegetation. This will enable us to develop, within a landscape context, simple rules to predict successional trajectory based on fire severity, pre-fire vegetation, and nearby seed sources (Task S4; Fig. 31, 32). For example, how does site moisture mediate both the probability of a severe fire and the type of successional response? Do successional trajectories differ between sites dominated before the fire by feathermoss vs. *Sphagnum*? We are also testing experimentally the processes that are most critical in causing shifts in successional trajectory We have sown seeds and planted seedlings of the major boreal tree species (including lodgepole pine, which is actively migrating westward in the Yukon) in 38 sites that burned in 2004 and exhibit a range of soil moisture and fire severity. The LTER will follow the long-term growth and survival of these seedlings to determine the circumstances under which each species might establish. We have also planted out each of these seedlings in 100 m^2 plots in a recent burn at BCEF to examine the long-term ecosystem consequences of different successional trajectories. In half of these plots we have established exclosures to protect seedlings from herbivory by moose and hares.

In selected sites, where sudden changes in state have occurred, we will document change in integrative variables (permafrost integrity, C and N stocks, and species composition) and carbon and nutrient cycling processes and measure our early warning indicators of state change. In parts of CPCRW that burned in 2004, we identified a matrix of replicated sites that vary in fire severity and soil drainage. Although all sites were previously dominated by black spruce, the drier and more severely burned sites have the highest abundance of hardwood tree seedlings, suggesting that high fire severity may send well-drained sites on a hardwood-dominated successional trajectory. Over the next five years, we will follow plant biomass accumulation, net primary productivity, and species composition, soil C stocks and N and P transformations, and active layer depth across this matrix of sites in order to determine the ecosystem consequences of altered successional trajectory. We are taking a similar approach of measuring integrative variables and early warning indicators in another site where climate-induced thermokarst (soil subsidence after thawing of permafrost) has initiated a state change within the last several decades. At this site, we have largely focused on the processes that control ecosystem C balance, including the response of vegetation and soils. In particular, ^{14}C measurements of the age of respired CO_2 documents the contribution of ancient C to the current ecosystem C cycle, and thus can be used as a metric of the degree of threshold change in the C cycle of this ecosystem. Studies that focus on sites where thresholds changes are occurring are especially important for developing methodologies to detect future threshold changes elsewhere on the landscape.

To extend our temporal perspective on state changes, we will seek external funding to conduct a synthesis workshop to explore the Holocene vegetation history of boreal North America to identify (and explain) past abrupt transitions in the boreal forest. This workshop will bring together paleoecologists working in Alaska and Canada; the outcome will help place the results of LTER research in a broader spatial and temporal context. We hope that the synthesis workshop will result in testable hypotheses that can be explored in the context of the LTER.

Task T3. *Document impacts of disease and insect outbreaks on ecosystem processes*. Warming has been accompanied by changes in the abundance of specific pathogens and several instances of insect and disease outbreaks, with potentially large ecosystem effects. We take two approaches to studying insect and pathogen dynamics: (1) We document interannual variation in the abundance of a suite of insect (Task C3) and pathogen species in different thermal environments, for example the leaf pathogen communities on selected shrub species along an elevational gradient, and (2) we document the community and ecosystem consequences of a few key insect and pathogen outbreaks. We currently focus on alder canker and aspen leaf miner, which have exploded in the last 2-5 years. We are documenting their impacts on microclimate, stand dynamics (mortality and recruitment), and aboveground NPP in permanent LTER plots. We also measure the effects of major insect defoliators such as the aspen leaf miner on other defoliating insects in terms of competition for food resources and the effects of pathogens on insect herbivory. We will also expand our recently-initiated study of the effects of stem canker on NPP and N fixation in *A. tenuifolia* to asses the impacts of the disease throughout the Tanana basin. We currently collaborate with forest health agencies that conduct extensive surveys to document the rate of spread and spatial extent of outbreaks.

Relationship to past and future research

Most of the research in this thresholds section is new and exploratory, because we have not addressed resilience and thresholds in our previous LTER research. The extent to which it will be incorporated into the long-term LTER research design will depend on results obtained during this 4-year period of research. Our long-term goal is to develop rules for predicting climate- and disturbance-induced changes in ecosystem state.

Integration and Synthesis

The research described in previous sections (climate sensitivity, succession, and threshold changes) addresses mechanisms that operate at a variety of temporal and spatial scales. However, to truly evaluate our overall question (How are boreal ecosystems responding, both gradually and abruptly, to climate warming, and what new landscape patterns are emerging?) requires that we synthesize our findings in a way that clearly specifies the temporal and spatial scales at which ecosystems respond to climate, the nature of interactions between climate and succession, and the abrupt thresholds that are likely to be manifested. In this section we describe a set of field and modeling activities that integrate processes across scales and explore their societal consequences.

1. How are boreal ecosystems responding, both gradually and abruptly, to climate warming, and what new landscape patterns are emerging?

Task I/S1 (i.e., task 1 of the integration and synthesis section). *Monitor patterns of retention and loss of water, carbon, and nitrogen from watersheds of differing permafrost extent and stability*. We will use watershed hydrologic and solute transport studies as a tool to investigate catchment-scale responses to changes in climate and disturbance and their threshold responses. Using end-member mixing models, we can distinguish at least three major flowpaths: a shallow flowpath through the surface organic mat that predominates in high-permafrost watersheds, a flowpath through mineral soil that predominates in low-permafrost watersheds, and a deeper groundwater flowpath that predominates during low- and winter-flow conditions (Fig. 33). Seasonal changes in the relative contribution of the three flow paths and discharge dynamics reflect responses to hydrologic inputs (including snowmelt) and the depth of seasonally frozen soils (Fig. 34). Long-term monitoring of discharge and stream chemistry should show responses to changes in permafrost extent and integrity. For example, as permafrost is lost from the high permafrost watershed, we anticipate that watershed flowpaths, storm hydrographs, and nitrogen exports will transition towards patterns similar to lower permafrost catchments. The lower permafrost watersheds, in turn, will likely change, and the smaller stream channels may become ephemeral.

In addition to the three watersheds that have been our primary focus, an additional medium-permafrost watershed burned extensively in 2004. We have several years of pre-fire stream discharge and chemistry data providing the rare background information to study fire disturbance effects on stream hydrology and nutrient fluxes. We are also following three new streams caused by catastrophic loss of permafrost, enabling us to identify a thermokarst signature and the role of thermokarst on the formation of new streams and exports of water and nutrients from the landscape.

We will continue to measure soil moisture and temperature profiles in permanent plots, inputs of precipitation and nitrogen (NADP collector), and stream discharge and solutes in four study catchments (three previously studied watersheds + new burn watershed) and thermokarst streams. We will estimate changes in permafrost stability in these watersheds by modeling permafrost extent today and 50 years ago (when mean annual temperature was 0.8˚C lower and the snow-free season 12.5 days shorter). In addition, work will continue to further resolve the end-member mixing model through end-member mixing analysis (Christopherson and Hooper 1992). Lastly, we will begin to develop a spatially explicit integrative model of watershed hydrologic and solute fluxes by coupling the hydrologic model TopoFlow with the solute chemistry of different vegetation types and major flowpaths through watersheds (Zhang et al. 2000. Using this approach, we will be able to discern the regions within watersheds contributing water to stream flow, especially during storms. Having spatial information will allow us to advance our end-member approach with an understanding of how contributing area to stream flow relates to the distribution of permafrost and vegetation (vegetation map layer (Jorgenson et al. 1986)). Lastly, the watershed model will provide a means to couple the impacts of climate change via thawing of permafrost with disturbance (fire and thermokarst) and may provide an early signal of threshold changes in ecosystem behavior due to interactions between climate and disturbance.

We will also relate the regional variation in stream chemistry to climatically and disturbance-driven changes in permafrost stability. We hypothesize that the watersheds with the largest area of unstable permafrost will show the highest nitrogen concentrations. We will survey stream chemistry within the Tanana River basin and along a north-south transect (stratified into recently burned and unburned) to assess regional variability in stream chemistry. We will compare these interior Alaskan streams with streams in arctic Alaska, where permafrost is stable (the Arctic LTER site) and in southern Alaska, where permafrost has been absent for centuries.

Task I/S2. *Document the temporal and spatial patterns of vegetation distribution and their interaction with climate*. Within our intensive study sites (BCEF and CPCRW) we will map vegetation and relate these patterns to microclimate (function of slope, aspect, elevation) and stand age (Task S2) to assess the extent to which vegetation can be predicted from microclimate and stand age. We will also compare our results to earlier vegetation maps as a way to assess vegetation change over time related to succession and changes in climate. Outliers in this relationship could reflect important environmental controls that we have not considered or legacies and thresholds of which we are unaware. Documentation of these fine-scale (5 m resolution) patterns enables us to assess the relative importance of climate sensitivity, succession, and unexplained factors such as thresholds, legacies, and non-climatic controls in determining vegetation distribution. We will focus future process-based studies in areas where the relationship between microclimate, stand age, and vegetation type is the most difficult to predict.

Task I/S3. *Integrate research on gradual and abrupt responses of boreal ecosystems to climate warming to assess recent and projected changes*. We will use information on climate sensitivity, successional dynamics, and thresholds to improve parameterization of two models: (a) the Terrestrial Ecosystem Model (TEM), a model of ecosystem processes with a biogeochemical emphasis and (b) the Alaska Frame-based Ecosystem Code (ALFRESCO), a landscape model with an emphasis on disturbance and succession. In our previous research we parameterized these models for our LTER sites and incorporated boreal characteristics such as permafrost effects on hydrology and soil temperature (Zhuang et al. 2001) and effects of stand-replacing fires and mammalian herbivory on vegetation distribution across landscapes (Rupp et al. 2002, Butler et al. Submitted, Kurkowski et al. Submitted). Our goal is to simulate the response of our integrative variables (vegetation composition, permafrost distribution and C and N storage) to recent and projected changes in climate and disturbance regime, using information from BCEF and CPCRW. Simulations will be validated with information from the Tanana Valley and the BOREAS site in Canada. Results will be simulated at 1 km resolution for the Yukon drainage basin (Alaska and adjacent Canada). We will test model sensitivity to shapes (e.g., linear/nonlinear) of climate response functions and assumptions about disturbance (e.g., remaining carbon stocks and thermal conductivity of the surface soil layer after disturbance). We will also examine the sensitivity of output to model rules about disturbance frequency and vegetation transitions after disturbance under differing conditions of climate and propagule availability. Where the model proves sensitive to climate response functions for which we have insufficient data, we will focus field research on studies of those relationships. Simulations of the Holocene history will provide tests of model ability to simulate large temporal scales that include past threshold changes in ecosystem structure and functioning (Lloyd et al. 2003a). Projections of future trends will use a range of climate change scenarios that have been projected for the region; specifically, we will used a subset of climate change scenarios from the IPCC Special Report on Emission Scenarios (Nakicenovic et al. 2000).

After we have confidence that both TEM and ALFRESCO adequately capture the sensitivity to climate and disturbance that we observe in our field observations and experiments, we will couple the two models off-line to integrate the important interactions of ecosystem (TEM) and landscape (ALFRESCO) processes. In TEM, for example, we will incorporate information about vegetation transitions that influence rates of change in soil environment (moisture and temperature) and in carbon stocks of soil and vegetation. We will also incorporate rules that are developed in ALFRESCO to simulate disturbance severity and extent. In ALFRESCO, we will incorporate information on the climate sensitivity of biomass and soil carbon accumulation through succession and their influence on disturbance probability (bank stability and fire). An important long-term goal of the modeling effort is to simulate changes in ecosystem state based on an understanding of climate- and disturbance-sensitivities of key ecological processes.

Task I/S4. *Use ecosystem and landscape models to assess the regional consequences of state changes and threshold responses to climate change*. We will use TEM and ALFRESCO to integrate our observations of threshold responses of ecosystem processes to insect outbreaks, disease, and altered fire regime to assess their regional consequences. We will focus on specific cases where we expect the effects to be profound, for example the increased erosion from enhanced glacier-melt may interact with moose herbivory and alder diseases to affect nitrogen fixation by alder, which has long-term implications for ecosystem productivity. We already know that nitrogen fixation by alder is the major source of nitrogen in the successional sequence of floodplains. We also know that moose herbivory interacts with erosion (and deposition) in creating early successional habitat and shifting it from willow to alder dominance (Butler et al. Submitted), while alder canker kills alder and reduces nitrogen-fixation (Ruess et al. Submitted). The ALFRESCO modeling approach is ideally suited for quantifying the interactive effects of process-level studies at the landscape scale and in a spatially explicit manner (see Fig. 35 for example). We can then incorporate the landscape patterns simulated by ALFRESCO into TEM to address the effects of climate change on long-term ecosystem productivity and carbon sequestration and emissions.

2. What are the societal consequences of recent and projected changes in Alaska's boreal forest?

In the future, the BNZ LTER plans to integrate fully a human dimensions component into its long-term research program through an investigation of ecosystem provisioning services (ecosystem goods) to rural subsistence-based communities of interior Alaska and climate-regulation services of concern to the global population. In this research phase we begin to establish the framework that will be necessary for these future studies

Task I/S5. *Summarize recent and projected changes in boreal ecosystem services and assess their consequences for Alaskan communities*. Our LTER research quantifies and assesses past and potential future changes in most of the ecosystem services identified by the Millennium Ecosystem Assessment. In the research proposed in this section, we emphasize two major categories of ecosystem services: provisioning services and climate-regulating services. Provisioning services determine the availability of subsistence resources to Alaskan communities, and climate-regulating services assess the feedbacks to the climate system of past and potential future changes in boreal ecosystems. With respect to subsistence resources, we plan our work in two phases. The first phase (years 1-2) includes scoping of issues, including working with villages to document local perceptions of ecological changes. What are the key climate-change issues of concern by local harvesters? What are the patterns of change observed through their on-the-land activities? What do they view as the most important research questions to be considered by the Bonanza LTER program? The first phase also identifies existing agency and community datasets and synthesizes key patterns of change as revealed in those data. We undertake this first phase of the project through interactions with regional advisory councils, key local organizations of select partner communities, and government resource management agencies. Our selection of local communities will be determined by relevance of their ecological context to current LTER research as well as communities' interest in and capacity to be involved. We strive to build partnerships with a few communities that represent the diversity of rural conditions in Alaska (e.g., off-road/on road, Native, non-Native.). The second phase of the research (years 3-4) builds on the findings of phase one to construct scenarios of possible futures in rural Alaskan villages in cooperation with partner communities. We have already begun developing algorithms using the ALFRESCO-TEM modeling framework to simulate regional patterns of ecosystem services (e.g., abundance of moose, furbearers, firewood availability, and berry production as a function of vegetation types and stand age; timber production and carbon credits as a function of time since disturbance). Scenarios and model projections serve as the basis of a vulnerability analysis, which considers inherent social-ecological resilience and constraints and policy alternatives for coping with change (Fig. 36).

We will use the ALFRESCO-TEM modeling framework to estimate the major climate feedbacks (albedo changes and net CO_2 and CH_4 emissions) for interior Alaska (Fig. 37). We have developed methods to quantify changes in albedo and integrated net exchange of CO_2 and CH_4 over a particular time period in a common currency of W m^{-2} (Chapin et al. 2005; Euskirchen et al., in preparation). This allows us to integrate the feedbacks to the climate system and determine whether projected responses of ecosystem structure and function in Alaska have the potential to exacerbate or mitigate the effects of greenhouse gases on the climate system.

3. How can we contribute most effectively to within-site and cross-site synthesis?

Task I/S6. *Use monthly and annual meetings to synthesize systematically our major research themes and to place this in a global context*. In our next phase of LTER research, we expect synthesis activities to play a central role in all phases of the program. We will promote integration and synthesis through monthly meetings focused on tasks within themes and annual meetings to synthesize findings among themes. Over the four years of proposed research our synthesis will focus sequentially on climate sensitivity (year 1), successional dynamics (year 2), thresholds and state changes (year 3), and overall synthesis and societal consequences (year 4). One focus of our annual synthesis meetings will be to incorporate important findings (along with other existing data and emerging findings) to further the development of our regional modeling framework (Tasks I/S3). We will then use this framework to evaluate the potential resilience/vulnerability of boreal forests in interior Alaska to a range of climate change scenarios that have been projected for the region. These annual synthesis workshops will include some presentation of new results, but the primary goal will be to provide a forum for discussion and writing; we envision that each annual meeting will produce at least one synthesis paper and/or proposal, as well as spawning more informal interactions and collaborations.

We also plan to place our results within a global context through synthesis of data from other boreal regions and involvement in cross-site activities within the LTER network (Table 5). In particular, we plan to participate actively in current LTER network synthesis activities. We view the BNZ and ARC LTERs as being at one end of a spectrum of current human impacts on social-ecological systems. Comparisons of social-ecological systems across a spectrum of human population densities and impacts could provide valuable insights about how human activities influence the resilience of social-ecological systems.

Relationship to past and future research

Our synthesis activities build on long-term field programs of watershed monitoring, a new program that documents changes in the spatial relationship of properties to microclimate, and modification of TEM and ALFRESCO to simulate resilience and state changes of ecosystem and landscape processes, respectively. The past model development now provides us with an excellent synthesis tool for integrating the multiple pathways by which climate change affects Alaska's boreal forest. The use of these models to explore concepts of resilience and to assess changes in boreal ecosystem services is a new direction that we hope to expand on in future years through the LTER and associated research projects. We are particularly interested in using this as a launch pad for more thorough study of social-ecological interactions, so we can more effectively study the boreal forest as an integrated social-ecological system. We anticipate that future phases of this research will incorporate societal responses to changes in ecosystem services, and scenarios by which these responses feed back to human impacts on ecosystems.

Summary

The research described in this proposal and summarized in Table 6 represents a substantial reorientation of our approach to scientific integration and synthesis. Rather than organizing our research along levels of organization (populations, ecosystems, landscapes), as in our previous proposal, we integrate these levels of organization and approach our research at three levels of complexity: climate sensitivity, successional dynamics (which incorporates climate sensitivity and its interaction with disturbance at larger temporal and spatial scales), and threshold dynamics (which addresses climate sensitivity and successional dynamics in the context of directional changes in environmental drivers and the potential state changes that are likely to occur). In addition to this intellectual shift in our conceptual framework and research design, we are placing primary emphasis on synthesis as a tool both to identify key relationships and to adjust our research design in response to improved understanding.

Although our research design is ambitious, we know from past experience that this breadth of activity is feasible. As described earlier, our BNZ strategy is to establish an integrative framework for boreal research, involve a cadre of highly qualified researchers who work well together, and encourage them to link other funded research projects to the LTER framework. This externally funded research of individual investigators focuses primarily on detailed process studies that are beyond the scope of LTER funding capabilities (See Table 8 in budget justification for listing of projects).

The reorganization of our research, as described in this proposal, reflects both our need to understand the non-steady-state dynamics of the boreal forest and in our interest in contributing to and helping define the recent shift in LTER network goals toward synthesis and toward an integration of human dimensions research into the LTER research design. We have adapted the Millennium Ecosystem Assessment focus on ecosystem services as our starting point for studying social-ecological systems. We expect to continue participating actively in LTER cross-site synthesis activities, especially those dealing with changes in climate and disturbance regimes, non-steady-state dynamics, and social-ecological systems.

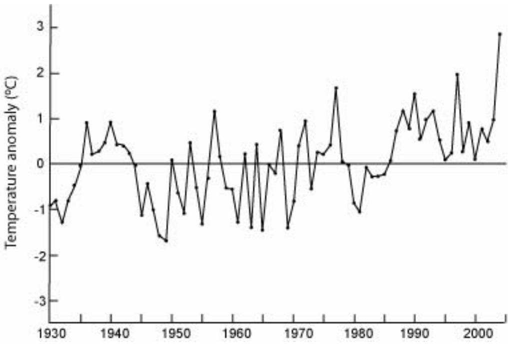


Fig. 20. Temperature trends in Alaska (Chapin et al. 2005).

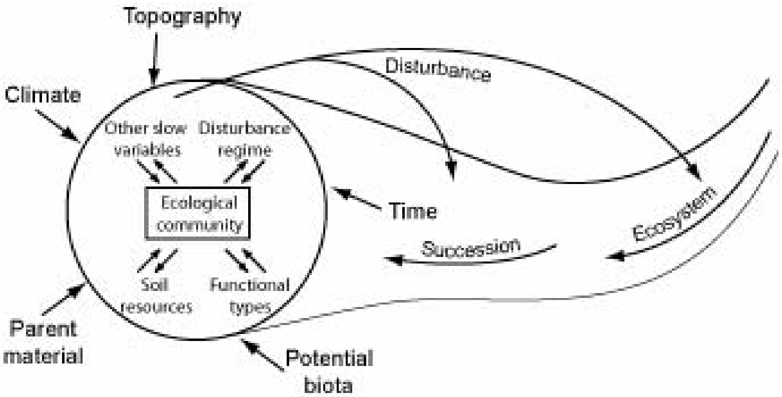


Fig. 21. The relationship between state factors (outside the circle), interactive controls (inside the circle), and ecosystem processes (inside the box). The circle represents the boundary of the current ecosystem, whose structure and functioning respond to and affect interactive controls, which are ultimately governed by state factors. Ecosystem properties are also determined by legacies related to long-term ecosystem development (e.g., past migrations) and short-term succession change. Disturbance and other factors can push the system toward some new state or initiate a new cycle of succession (Chapin et al. 2006).

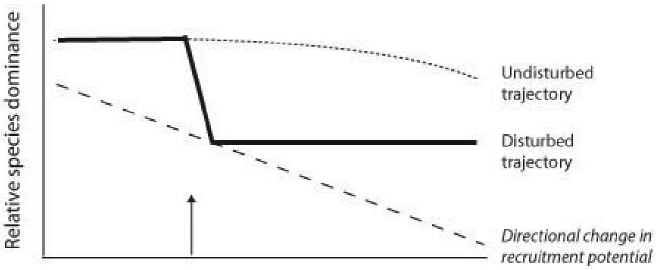


Fig. 22. Temporal changes in ecosystem structure in a directionally changing world. In response to a gradual environmental change, ecosystem structure may change slowly (dotted line), despite substantial changes in factors governing recruitment potential (dashed line). Once a threshold is exceeded, however, the community may change rapidly to a new state (solid line), the nature of which depends on the nature of the environmental change and the legacies of the initial ecosystem structure.

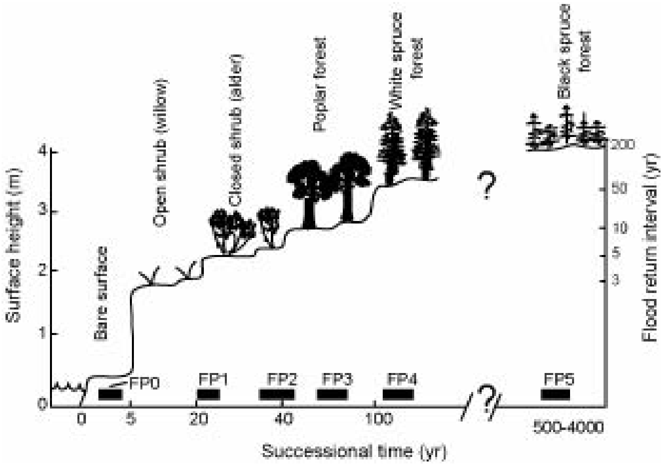


Fig. 23. Diagram of floodplain succession (Viereck et al. 1993), showing representative surface heights above the river (Yarie et al. 1998, Adams 1999), flood return intervals (Yarie et al. 1998), surface ages (Walker et al. 1986), and turning points.

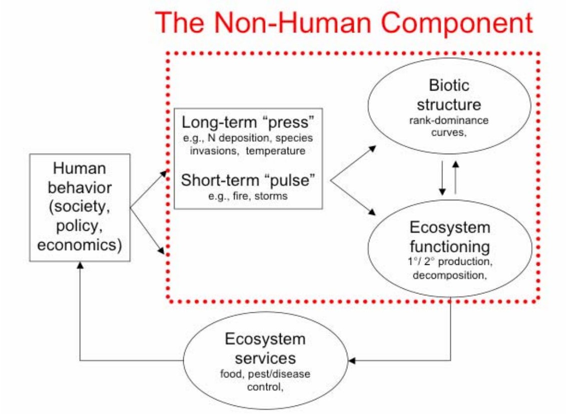


Fig. 24. LTER Network framework for integrating natural and social sciences.

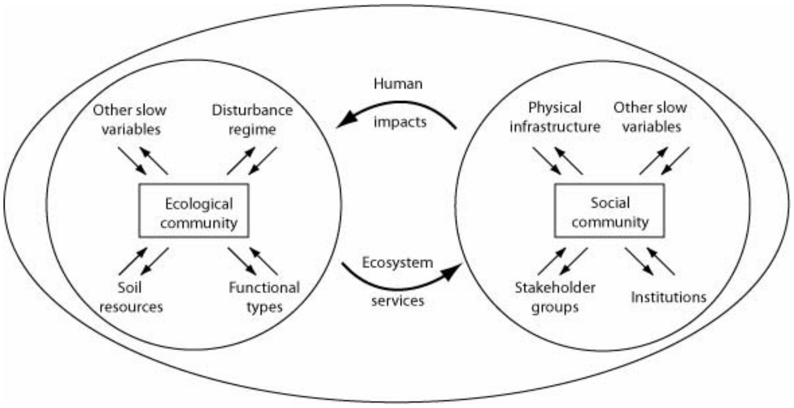


Fig. 25. BNZ LTER framework for studying social ecological systems.

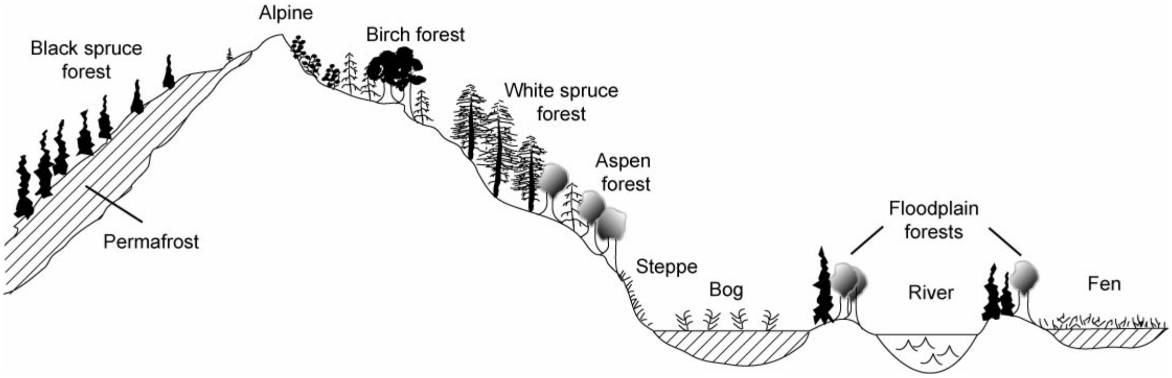


Fig. 26. Generalized topographic cross-section in the Fairbanks area showing uplands, floodplains, and wetlands (bogs and fens).

Table 2. Successional stages in which vegetation and climate plots are located.

Type	Disturbance	Year of disturbance	Dominant Vegetation	Initial measurement	Remeasurement frequency
South facing uplands					
Early	Fire	1983	Herbs and saplings	1989	1983-84, Every 3 years
Mid	Fire	1940	Birch or Aspen	1989	Every 6 years
Late	Fire	1783	White spruce	1989	Every 6 years
North facing uplands					
Early	Fire	1999	Herbs	1999	Annually
Mid	Fire	1971	Willow	1971	1971-75, 2002; Every 6 years
Late	Fire	1915	Black spruce	**No site selected yet**	Every 6 years
Floodplain					
Early	Fire	2000	Charred ground	2000	Annually
Sandbar	Flooding	1990	Bare soil	1989	Annually
Open shrub	Flooding	1980	Willow	1989	Every 3 years
Closed shrub	Flooding	1960	Alder	1989	Every 3 years
Poplar	Flooding	1900	Poplar	1989	Every 6 years
White spruce	Flooding	1800	White spruce	1989	Every 6 years
Black spruce	Flooding	Pre 1500	Black spruce	1989	Every 6 years

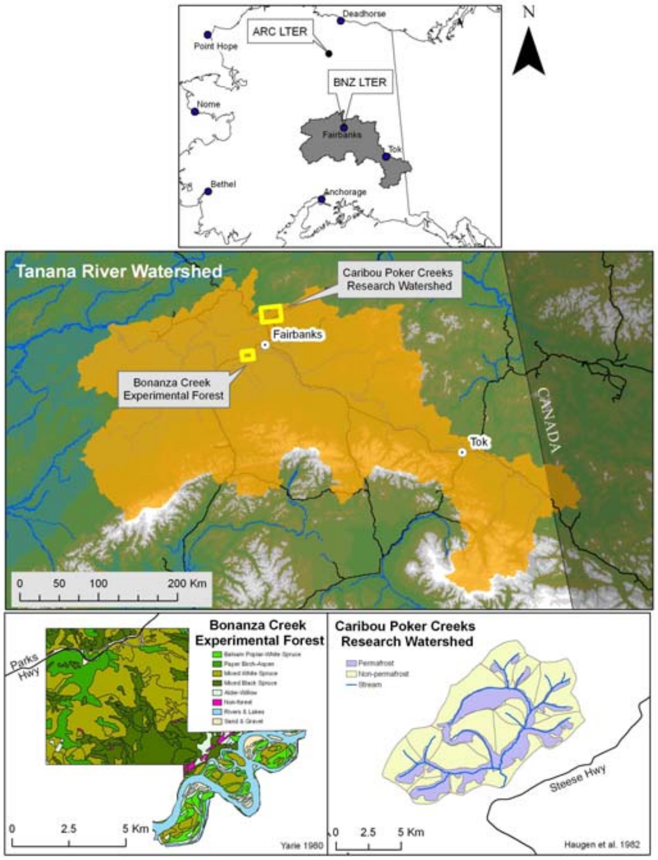


Fig. 27. Hierarchical experimental design of the BNZ LTER, with intensive study sites and watersheds nested within experimental areas (BCEF and CPCRW), which is nested within the Fairbanks Region and the state of Alaska.

Table 3. Parameters measured at LTER intensive sites.

Parameter	**Location**	**Dates**	**Responsible PI**
Climate*			
Air temperature	BCEF, CPCRW	1984-	Hinzman*
Soil temp at 6 depths	BCEF, CPCRW	1984-	Hinzman
Relative humidity	BCEF, CPCRW	1984-	Hinzman
Precipitation	BCEF, CPCRW	1984-	Hinzman
Evaporation	BCEF,	1984-	Hinzman
Wind speed, direction	BCEF, CPCRW	1984-	Hinzman
Solar radiation (global)	BCEF, CPCRW	1984-	Hinzman
UV	BCEF,	1984-	Hinzman
PAR	BCEF, CPCRW	1984-	Hinzman
Shortwave in/out	CPCRW	1988-	Hinzman
Longwave in/out	CPCRW	1988-	Hinzman
Sun photometer	BCEF,	1994-	J.Hollingsworth
Snow depth	BCEF, CPCRW	1968-	Hinzman
Thaw depth	BCEF, CPCRW	1992-	Hinzman
Snow moisture	BCEF, CPCRW	1983-	Hinzman
River height	BCEF,	1985-	Hinzman
Vegetation			
Tree density, biomass	BCEF	1989-	T. Hollingsworth, Juday
Tree seedling density	BCEF	1989-	T. Hollingsworth, Juday

Understory cover, biomasss	BCEF	1989-	T. Hollingsworth, Juday
Root biomass	BCEF	1989-	Ruess
Seed rain	BCEF	1955-(c)	T. Hollingsworth
Insect defoliators (index)	BCEF	1976-	Werner
Microtine density	BCEF	1999-	Kielland
Snowshoe hare density	BCEF	1999-	Kielland
Biogeochemistry			
Carbon and nutrient stocks			
Trees	BCEF	1989-	Yarie, Ruess
Understory	BCEF	1989-	Yarie, Ruess
Soils	BCEF	1989-	Valentine
Litterfall	BCEF	1975-	Yarie, Ruess
Diameter increment	BCEF	1989-	Yarie, Ruess
Fine root production	BCEF	1992-	Ruess
Browse consumption	BCEF	1990-(c)	Kielland
Soil respiration	BCEF, CPCRW	1998-	Ruess, Valentine
N mineralization	BCEF, CPCRW	1999-	Kielland
Nitrogen deposition (NADP)	CPCRW	1993-	Hinzman
Watershed research			
Discharge	CPCRW	1969-	Hinzman
Stream chemistry	CPCRW	1978-	Jones

*Hollingsworth (site manager) is responsible for climate measurements at BCEF

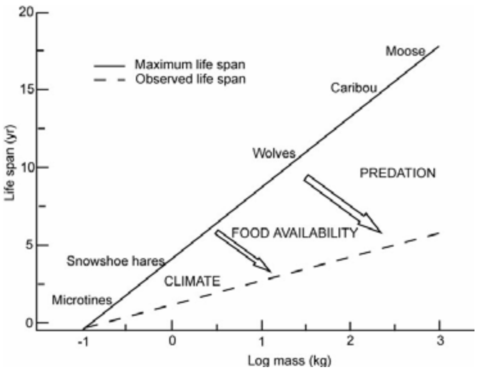


Fig. 28. Estimated maximum and observed life spans of wildlife species of different mass in interior Alaska. The observed life span is estimated from field measurements of population turnover (density divided by annual recruitment). The major factors that limit lifespan are shown for animals of different sizes.

Table 4. Long-term experiments in the BNZ LTER site

BNZ long-term experiments	Responsible PI	Date initiated
Resource manipulations		
Annual N addition	Yarie	1989
Annual N and P addition	Ruess	1997, 2003
One-time sawdust or sugar addition	Yarie	1989
Summer precipitation exclusion	Yarie	1989
Snow removal	Yarie	2004
Added insulation	Taylor	2004
Root-trenching experiment	Valentine	1999
$^{15}NH_4$ post fire retention	Mack	1999
Monitoring floodplain biogeochemistry	Kielland, Jones	2002

Community manpulations		
Mammalian herbivore exclosures	Kielland	1990
Alder-spruce competitions	Wertz	1990
Artificial alder communities	Chapin	1990
Insect population monitoring	Werner	1976
Small mammal population monitoring	Kielland	1999
Herbivore effects on white spruce	Kielland, Wurtz	2002
Fire effects on soil thaw depth	Viereck	1983
Ecosystem manipulations		
Forest harvest experiments	Wurtz	1972
Experimental burn (FROSTFIRE)	Chapin	1999
Monitoring watershed hydrology	Hinzman	1970

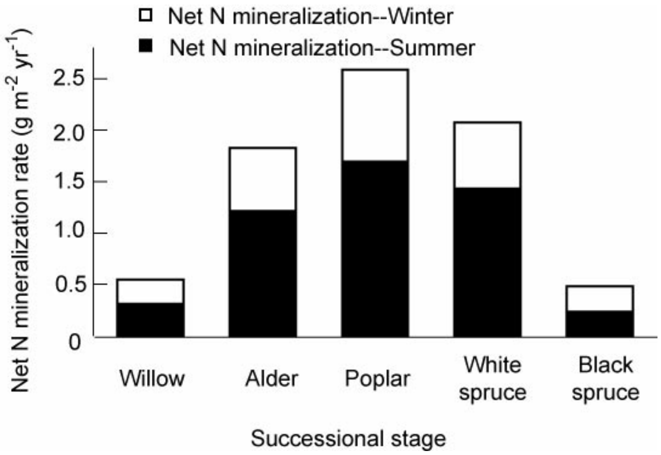


Fig. 29. Successional changes in summer, winter, and annual net N mineralization in the Tanana River floodplain.

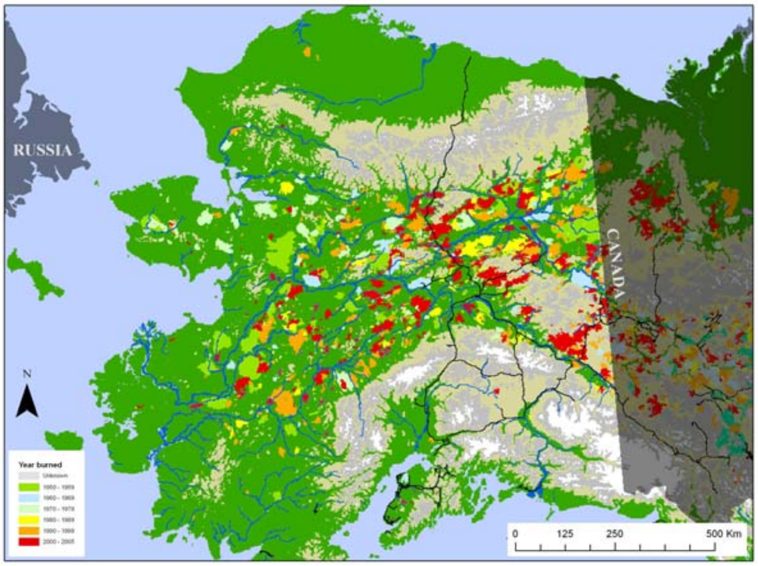


Fig. 30. Map of large fires that have occurred in interior Alaska since 1950.

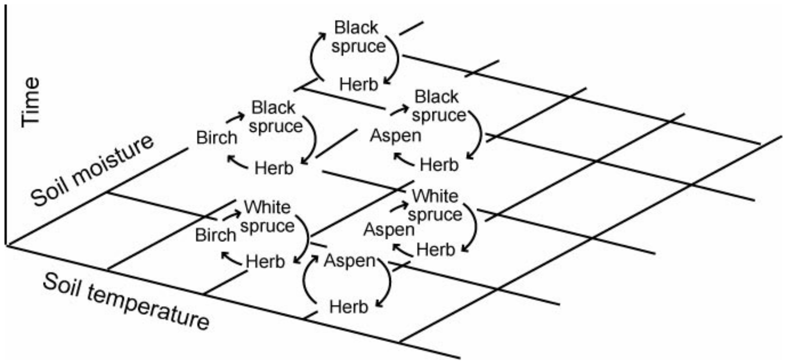


Fig. 31. Representative successional trajectories on upland sites in interior Alaska along gradients of soil temperature and soil moisture. Upward arrows indicate successional changes in community composition; downward arrows indicate vegetation change caused by fire (Chapin et al. 2004).

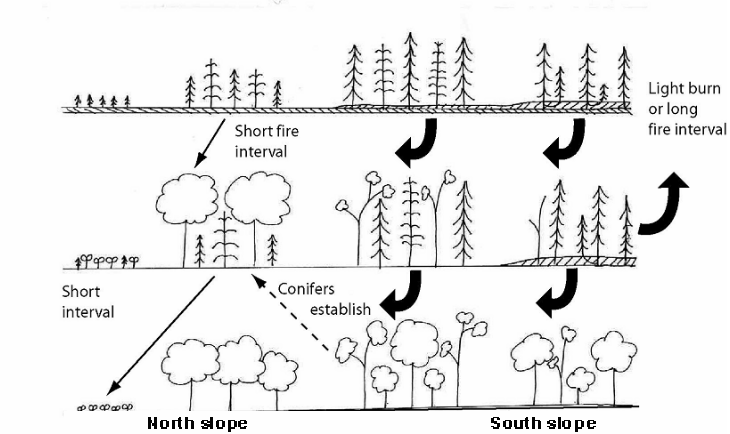


Fig. 32. Triggers for change in successional trajectory (Johnstone 2003). Each successional trajectory tends to repeat itself but unusual events can trigger a shift in successional trajectory.

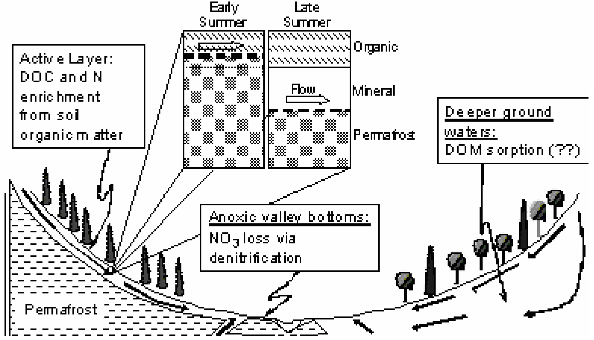
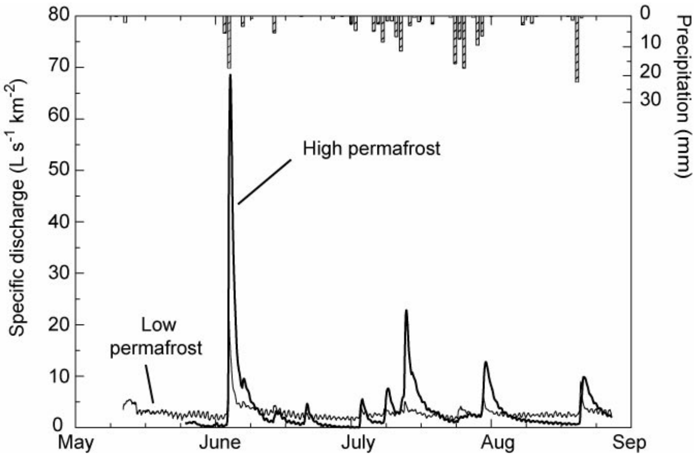


Fig. 33. Conceptual model of the influence of permafrost on watershed hydrology and biogeochemistry. Permafrost forms an impermeable barrier and restricts subsurface flow to the shallow active layer of soils. The hypothesized consequences for N cycling are shown.

Fig. 34. Specific discharge (stream flow normalized by basin area) in a high-permafrost and a low-permafrost watershed. Data from Bolton et al. (2000).



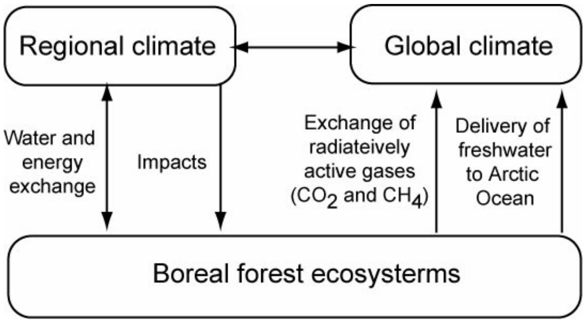


Fig. 35. State and transition model of successional dynamics driven by interactions of herbivory with geomporphic processes (accretion and erosion) and vegetation processes (colonization and succession) (Buttler 2003).

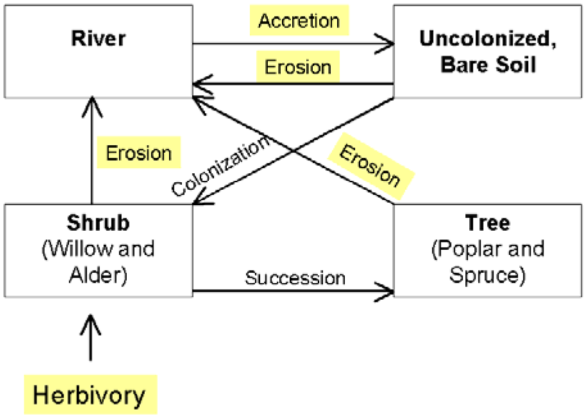


Fig. 36. Key vulnerabilities in the Alaskan boreal forest. Changes in climate, human activities, and exotic species drive nonlinear changes in ecosystem dynamics, particularly those related to disturbance (fire, thermokarst) which initiate changes in forest dynamics (animal dynamics and successional trajectory, biogeochemistry, and landscape dynamics (e.g., wetland drainage). These changes in ecosystem dynamics alter the ecosystem services that are important to society.

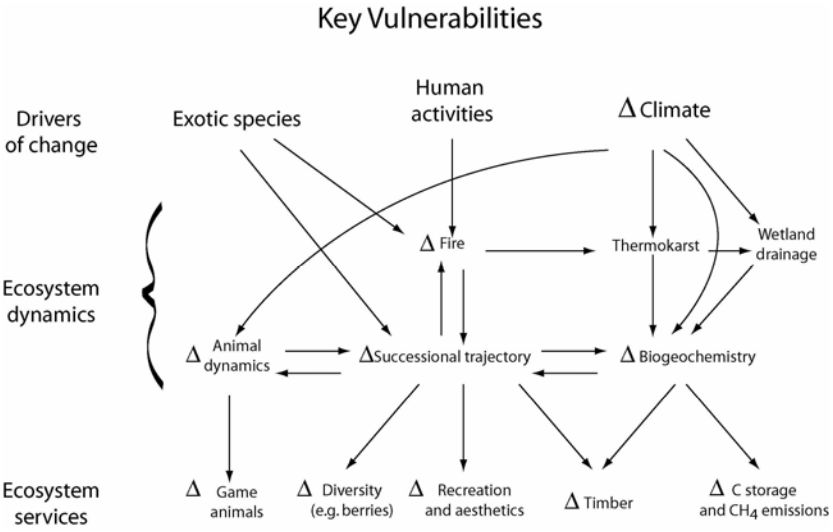


Figure 37. The major pathways through which the structure and functioning of boreal forests may influence the climate system.

Table 5. BNZ involvement in cross-site comparisons (LTER and others) over the history of the LTER.

Project	**Lead PI**	**BNZ PI**
Climate network	Greenland	Hinzman
High-latitude transects	McGuire	McGuire
LIDET (litter decomposition)	Harmon	Yarie, Valentine
Log decomposition	Harmon	Yarie
Productivity-diversity relationships	Waide	Juday
Fine root dynamics	Pregitzer	Ruess
ILTER: BG processes/respiration partitioning	Schuur, Clark	Schuur, Ruess
USFS-LTER fire fuel accumulation	Gould, Gonzalez	Nettleton-Hollingsworth
Disturbance dynamics	Turner	Chapin, Yarie
Hydrologic processes	Post	Hinzman
Watershed biogeochem (grad student cross site)		Betts
NASA-LTER-MODIS		Verbyla
USFS-LTER-NADP		Hinzman
Climate variability and ecosystem response	Greenland	Juday
Climate/extreme events (XE)	Goodin	Juday
Moss production and decomposition	Sveinbjornsson	Sveinbjornsson, Mack
^{15}N Plant-soil tracer experiment	Nadelhoffer	Mack
Paleolimnology of northern lakes	Brubaker	Rupp
Resilience Alliance	Carpenter	Chapin

Table 6. Major activities of the BNZ research program, showing ongoing research (black) and **new research initiatives (bold red)**. Task numbers are in parenthesis.

	Climate sensitivity	**Succession**	**Thresholds**
Drivers	Met stations (C1)	Exptl. Burn (S2)	**Thermokarst (S3)**
	Rain exclusion (C4)	Fire record analysis (S2)	**Fire severity (S2, T2)**
	Snowmelt exclusion (C4)	**2004 fire monitoring (S2)**	**Hydrolog. change (T1)**
	Winter warming (C4)	**Hydrologic synthesis (S1)**	
	Watertable manipula. (C4)		
Biotic response	Biomass & NPP (C1)	**Stand-age maps (S2)**	**Disease & insect impacts (T3)**
	Tree rings (C2)	Species effects (S5)	
	Insect monitoring (C3)	**Invasive species (S5)**	
	Hare & moose monitor (C3)	Herbivore exclosures (S6)	
	Biogeochem. monitor (C1)	Plant & animal diversity (C1)	
	Seasonal biogeochem. (C5)	**Fungal diversity (S7)**	
Landscape response	**Community mapping (I/S2)**	Succession models (S4)	Watershed proc. (I/S1)
	Wetland transects (C1)	Biogeochem models (I/S3)	**Thresh. model (I/S4)**
Societal impacts	**Ecosyst. service synth. (I/S5)**	**Ecosyst. service model (I/S3)**	
	Synthesis focus (I/S6)	**Climate feedbacks (I/S3)**	

Section 3 Site Management

Leadership structure

NSF and the USDA Forest Service, through the Pacific Northwest Research Station, jointly fund the BNZ LTER project. The NSF and FS components of the LTER program are thoroughly integrated into a single program, so we describe the management as it actually functions, rather than distinguishing between the NSF and USFS components. Our leadership team consists of the PI and co-PIs: Chapin, Lloyd, McGuire, Ruess, Hanley. Scientific decisions in the BNZ LTER are made at several levels:

1. Chapin serves as the PI of the LTER research program and is ultimately responsible to NSF for the overall design and implementation of the research program.

2. In practice, the five-person leadership team makes decisions jointly about the design and implementation of the research program. Each of us has responsibility for overseeing specific aspects of the program: Chapin, overall integration (within-site and with network); Lloyd, paleoecological perspectives, Ruess, site management; McGuire, data management and modeling; Hanley, Forest Service communication.

3. The LTER executive committee (leadership team plus Hollingsworth, Verbyla, Jones, Yarie, Kielland, site manager, data manager, and student representative) provides feedback about major issues associated with program direction (e.g., conceptual framework and general design of this proposal). In practice, these meetings are open to all LTER personnel, and there is broad participation by the LTER community.

4. Two or three individuals are responsible for coordination and integration within each research theme: climate sensitivity (McGuire and Yarie), successional dynamics (Ruess and Kielland), thresholds (Chapin, Jones, and Schuur), integration and synthesis (McGuire and Lloyd).

5. There are 1-2 leaders plus a planning team responsible for designing and implementing each research task (Table 6) and for making sure that this research addresses the hypotheses and questions of the research themes and the overall project goals.

6. Each investigator is allocated a budget and is responsible for designing and implementing her/his portion of the research program (see Budget Justification).

Program integration and communication

We will meet monthly to address practical issues and to plan and coordinate our within-site synthesis activities and annually at our research symposium to conduct synthesis of our major themes (climate sensitivity, successional dynamics, thresholds, and integration/synthesis. A final level of communication and integration is often facilitated by the need to coordinate transportation for travel to field sites.

Budgeting and accountability

Each PI is responsible for her/his own budget and implementation of research. Every two years each investigator must submit a progress report that includes major findings, publications, datasets that are on line or being prepared, and a mini-proposal that describes research plans for the next two years. These reports and mini-proposals serve as a basis for evaluation and budget reallocation by the leadership team. If necessary, more frequent budget reallocations will occur at the time of the annual progress report to NSF, as we have done in the past. Project PIs also obtain separate project funding to complement their NSF work ($7.8/NSF LTER $; see budget justification, Table 8).

In addition to budgets for each research project, we maintain separate budgets for core research, data management, and general project costs. Core research includes monitoring of climate, hydrology, vegetation, and other essential long-term site measurements. General project costs include national travel, and some infrastructure costs.

Site security and site management

The BNZ research program has two intensive research sites: The Bonanza Creek Experimental Forest (BCEF) is within the Tanana Valley State Forest and is managed by the Boreal Ecology Research Unit (i.e., the FS component of the LTER) through a renewable 50-year lease to the FS (renewable in 2018). The Caribou-Poker Creek Research Watersheds (CPCRW) includes lands under the jurisdiction of the University of Alaska and the Alaska Department of Natural Resources. The LTER manages BCEF and CPCRW, with the Interagency Hydrology Committee, which represents agency interests in Alaskan hydrology, acting as an external advisory committee. We have close working relationships with both the Tanana State Forest and the Alaska Division of Natural Resources. The Alaska Legislature recently passed legislation to transfer the BCEF and CPCRW from the State of Alaska to the University of Alaska to be managed by the BNZ LTER, enhancing the long-term site security.

The BNZ site manager (Jamie Hollingsworth) is responsible for managing LTER research in the two research sites, including permitting, transportation, and the planning and implementation of the core research program. Significant improvements in site management in the last funding cycle include automation and wireless radio communication with climate and microclimate stations, improved coordination of field work, improved boat communication and safety, and assessment of statistical power and required sample sizes for long-term vegetation measurements. These efforts have substantially improved the quality, continuity, efficiency, and safety of data collection, releasing time to undertake new activities.

Engagement of new investigators and non-LTER scientists

We added 6 new investigators to our research team in the last two years and 6 more in the current proposal. We have been modestly successful in increasing diversity at our site, going from one woman and no minorities 6 years ago to 9 women (32%) and two minority among the PIs in our current proposal. Our 41 graduate students in the last two years include two Native Americans and two Asians (10%) and 23 women (56%). Our major effort to enhance diversity is through recruitment of minority graduate students, particularly Alaska Natives. Minority recruitment has been a strong emphasis of the IGERT program in Resilience and Adaptation (see Outreach), and many of these students become involved in BNZ LTER research.

A key way in which we engage non-LTER investigators in our LTER research is through our affiliate LTER investigator program (Table 7). The BNZ LTER affiliates are encouraged to participate in our annual symposium, have the same access to LTER data, field sites, and facilities as do LTER PIs, and are encouraged to archive their data in the LTER database. We attempt to provide transportation costs to the LTER symposium and assist with field logistics whenever possible. Many affiliates have written proposals with LTER investigators as a result of this collaboration.

Table 6. Planning team responsibilities for research tasks. C = Climate sensitivity; S = Succession; T = Thresholds; I/S = Integration and synthesis

	Primary Responsibility	Secondary Responsibility
Chapin	I/S5, I/S6	T2
McGuire	C1, I/S3, I/S4	C4, C5, S3, I/S5, I/S6
Ruess	T3	S1, S5, S7, I/S2, I/S4, I/S6
Hanley		C3, I/S4
Harden	C4	C5, I/S5
Hinzman	I/S1	S1
J. Hollingsworth	C1	
T. Hollingsworth	S4, I/S2	T2
Johnstone	S4, T2	I/S4
Jones	S1, I/S1	
Juday	C2	
Kasischke	S2	S3, S4, T2
Kielland	C3, C5, S6	S1, S7, I/S4
Kofinas	I/S5	
Lloyd	S2, T2	C2, I/S6
Mack	S5, T2	
Mulder	T3	S5
Romanovsky	S3	
Rupp	I/S3, I/S4	S2, S4
Schuur	T2	
Sparrow	SYLTER	
Sveinbjornsson		S5
Taylor	S7	
Turetsky	C4, S4	C5, S5
Valentine	S5	C4
Verbyla	S2, T1	
Werner	C3	T3
Wurtz	S5	
Yarie	C4	S1

Table 7. BNZ LTER affiliate scientists and their principal research areas and primary contacts with LTER PIs. BNZ affiliate scientists are encouraged to participate fully in LTER activities (attend symposium, participate in monthly meetings, use and contribute to LTER database) and to receive logistic support to the extent possible, but they do not receive LTER funds to support their research.

Research Area	**Affiliate scientist**	**LTER collaboration**
Forest Dynamics		
Plant pathogens	Bitty Roy	Mulder
Forest growth and yield	Ed Packee	Valentine
Tree ring studies	Chris Fastie, Val Barber	Lloyd, Juday
Stand-age reconstructions	Dan Mann	Rupp
Plant species effects	Donie Bret-Harte	Mack, Chapin
Biogeochemistry		
Soil carbon turnover	Jason Neff	Schuur, McGuire
Eddy flux studies	Jim Randerson	Chapin
Stream biogeochemistry	Jacques Finlay	Jones
Soils	Chien-Lu Ping	Valentine
Microbial ecology	Josh Schimel, Rich Boone	Chapin, Valentine, Jones
Landscape Dynamics		
Permafrost dynamics	Masami Fukuda	Hinzman, Chapin
Fire behavior	Sam Sandberg	Chapin, Rupp
Climate transect	Ed Berg	McGuire, Chapin

Section 4 Information Management

Goals and objectives:

Information management plays an integral role in the support of site operations and contributes to broader LTER network activities. The primary goals of data and information management at the BNZ LTER are to ensure the long-term archival of the program's datasets. We employ current technologies and data management techniques in order to provide a system that engenders trust, collaboration and efficient information exchange. Of primary concern are metadata, quality control, accessibility, current data, and security of datasets. Additionally, the data manager explores the possible use of new technologies in data management.

Background:

We hired our current data manager, Mr. Brian Riordan, less than two years ago. Brian has worked with the leadership team and BNZ support staff to formulate a long-term plan for database management. This new plan will use open source products when possible, allow for growth over the next 10 years, and attempt to standardize the BNZ database structure. While the implementation of this plan is time-consuming, we believe the rewards will pay off in the long run. We have taken several steps to ensure continuity of BNZ data management structure and implementation, regardless of potential future personnel changes. These steps include greater consistency with LTER network database structure, involvement of the University of Alaska Bioinformatics Program and the Arctic Region Supercomputing Center (ARSC) in the design and implementation of database management, and improved documentation of our new program with controlled vocabularies and data dictionaries.

The current data management system:

We have transitioned from a data storage/retrieval system that focuses on text files as the primary means of data dissemination to a more robust client-server relational database system. This conversion should be finalized by the middle of 2006. This new system is characterized by regular back-ups and web applications that allow users to generate secondary datasets and analyze data online. We believe that this system will provide the user with a more interactive and productive web capability when looking for specific datasets or exploring the breadth of our data holdings. In addition, over the past year BNZ LTER has generated and is harvesting valid EML documents for 139 of the **140** datasets at (a high) level 2-3.

At BNZ the primary role of the data manager is to provide the tools and system architecture to accommodate secure long-term archival of LTER datasets. In addition, the data manager provides advice to investigators in the areas of data management, software selection and use, and keeps abreast of new opportunities from innovative software and hardware developments or new trends in data management technology. The data manager also offers advice and expertise in data collection, storage, and archival issues where needed, particularly as new studies are designed. The BNZ data manager is also the IM representative at all LTER network activities. These activities range from annual IM meetings to participation in network efforts to design future network tools.

Datasets in the BNZ LTER database are available to other scientists in as timely a manner as possible at www.lter.uaf.edu/data.cfm, where there are detailed data, eml metadata, and publication lists. Full pdfs of publications have recently been added to the publication database to promote distribution of BNZ-LTER published results. Climate data are uploaded to the website monthly. Several of our major weather stations provide web-accessible data in real time http://www.uaf.edu/water/projects/cpcrw/metdata/c4/current.html. All other datasets are updated or added as soon as annual fieldwork ends and the data are entered. In general, datasets are made publicly available as soon as they are archived.

The worldwide web provides an efficient means of serving information about our program. Server logs indicate that our site receives approximately 1500 unique visitors a month with about 30,000 hits a month. We employ one of the most liberal monitoring systems on dataset access in the LTER network. While we can monitor page hits we do not monitor the number of times a dataset is opened or downloaded. Users do not need to submit any information to view or use our data. We feel this policy maximizes open science and a truly diverse research community.

Our intranet website has been used more extensively over the last two years. Approximately 60 people now log into our intranet to update the LTER database, provide news, and information to the group as well as archive datasets.

Participation of scientists in data archival and data manger activities:

The data manager interacts with investigators at several levels. First the data manager attends all executive committee meetings and general group meetings. Graduate students are encouraged to consult with the data manager prior to their first field season. The data manger is encouraged to suggest changes to procedures for data collection, data archival, and research products as well as generating new ideas. There is constant interaction and changing of webpage layouts and functions in response to needs or concerns of investigators. The new changes to the database allow investigators to have a more hands-on experience with their data.

Our data archival policy is that investigators must submit project data within two years of collection. To date, no graduate student or PI has requested to withhold data from the web. Compliance with our data archival policy is mandatory and supported by our leadership team and executive committee. Data archival has become an important aspect of our internal review and budget reallocation process. Investigators who refuse to submit their data for online archival and use will not receive continued LTER funding. Compliance is assessed annually by the data manager and one of the members of the leadership team (McGuire), who communicates the need for compliance with non-compliant investigators. Each investigator must explicitly address their compliance with the data archival policy in the progress report they submit every two years (see budgeting and accountability). Our recent emphasis on the necessity for dataset submittal has substantially increased the rate of dataset submittal. Greater involvement in data archival is also evolving as scientists see data archival as beneficial to them. For example, the data management staff has been able to enhance archival of data by providing useful tools that help organize and enhance the quality of data for the scientists. We are also linking publications with data sets on the web site so data that give rise to a publication can easily be identified, accessed, and properly acknowledged.

Dataset quality control is the responsibility of the submitting principal investigator. Scientists rely on various quality control methods including plotting, visual inspection, and programmatic range checking. The data manager assists in quality control efforts where advanced technical solutions are needed.

System security is of utmost importance for a program dedicated to long term archival of information. Our strategy includes routine backup of essential data and informed use of software and hardware defenses to prevent unauthorized intrusion in case the system is compromised.

Data resides on each investigator's computer until it is archived on the main server. It is the responsibility of the investigator to ensure that their data is safe and backed-up while it is in their possession. Data on the server is backed up every two days to 8mm tape. Additionally, a copy of the entire website, database and data files is burned to compact disk and stored off-site. The server is located in a secure area in a locked room. The servers are protected from unauthorized intrusion by hardware and software firewalls, limited remote accessibility, a minimum number of user accounts, and stringent complex password requirements.

Local and Network-level activities:

The BNZ LTER shares a computer network with the broader University of Alaska Fairbanks and receives much of its computing support through participation and agreements with the ARSC. We provide services to the community as well with file hosting, large format map scanning, and data consultations. BNZ LTER staff involvement in the larger computing community issues provides opportunities to leverage BNZ LTER investments with additional computing resources and staff.

The BNZ LTER data manager, Brian Riordan, is active in LTER NIS programs. These include ClimDB, SiteDB, Bibliography, and the emerging LTER Trends module. We intend to submit data for two sites into HydroDB this coming year. Brian is active in IM work groups, and he has volunteered to be an editor for the next DataBits issue. We have recently started to harvest EML documents for 99% of our datasets. We will increase the richness of our EML documents over the next year.

Anticipated system enhancements:

We pride ourselves on our data management system at Bonanza Creek LTER and are continually looking for ways to improve the system. This section outlines four future services. *Web design upgrades:* By taking into account the best practices that the IM community has outlined for LTER websites, we will bring our website into a more standardized look to achieve greater uniformity among the LTER sites. *Database/Server upgrade:* With the majority of our LTER data now stored in MySQL tables, we have seen a noticeable decline in server performance. In order to compensate for this decline in performance we are purchasing a robust mid-level server. *Ecological Metadata Language and Data Synthesis:* We intend to enrich all of our current 139 EML documents to level 5 (access/integration) over the next two years. Some of this work will require investigating legacy data to locate missing information. The data manager is also standardizing our most frequently requested data so they can be readily used in synthesis activities, for example by standardizing our climate records and tree growth data. *Expansion of internet map services and GIS capability:* In spring of 2003 we launched an internet map server that displays spatial information about our datasets, projects, study sites, administrative boundaries, and ecological characteristics of interior Alaska. At present our map service is an 'out of the box' software solution that provides basic functionality. We intend to invest more time and energy into developing customized applications that will deliver more useful mapping benefits to researchers who may have limited familiarity with GIS and who may not be able to use the current software because of its complexity.

Section 5 Outreach

BNZ Education and Outreach goals and activities are consistent with those outlined by the LTER Network Education, Outreach and Training (EOT) Committee.

K-12 Education

The Schoolyard LTER program has been one of the most successful components of BNZ outreach. We have teamed up with two similar science education programs, GLOBE (NASA and NSF) and Global Change Education Using Western Science and Native Observations (NSF), to train science teachers in 38 Alaskan towns and villages in engaging their students in long-term environmental research. LTER funding enabled 6 Fairbanks elementary and high school teachers to be added to the program. These schools have initiated their own long-term ecological research projects and developed their own web sites. Sparrow, the SYLTER PI, and Verbyla, another BNZ PI, developed a phenology unit that involves K-12 students in ground validation measurements of remotely sensed data, a first such opportunity for many children in rural Alaskan communities. This module has been incorporated into the GLOBE Teacher's Guide and is used internationally. In the coming phase of LTER research we will expand efforts to integrate traditional ecological knowledge into the science curriculum in rural schools as part of our involvement in the joint SYLTER-GLOBE program. BNZ SLTER will continue to participate in cross-site education outreach activities: the BNZ SLTER PI is in the LTER Executive Education and EOT Committee activities and has been active in the Alaska Science Content Standards and the Alaska Science Performance Standards (Grade Level Expectations) Committees.

LTER PIs regularly work with local K-12 teachers, serve as judges in science fairs, and mentor high school students on science-fair projects, leading to several top honors in statewide, national, and in the case of one student, an international competition. Two SLTER teachers received the British Petroleum Award for Excellence in Teaching and one SLTER teacher the Presidential Award for Excellence in Math and Science Teaching for secondary teachers.

University Education

University of Alaska faculty regularly use the BNZ research sites for field trips and laboratory exercises because of its proximity to campus. Undergraduates also participate in summer research as REU students or research assistants. An REU symposium at the end of each summer provides opportunities for students to present their results formally and to get feedback from faculty and other students.

At the graduate level, the BNZ LTER has been an important venue for training graduate students in ecology. There are currently 41 graduate students conducting research through the BNZ LTER program from biological, geophysical and social sciences. A recent addition to the graduate community are interdisciplinary students in Resilience and Adaptation, an NSF-sponsored IGERT graduate program that links ecological, economic, and cultural aspects of sustainability and resilience. Graduate students participate in the LTER program by conducting their own research, collecting long-term data, organizing research discussions and seminar series, and leading cross-site synthesis activities. The BNZ LTER staff and investigators provide research support, logistics, and training for incoming graduate students. We will expand this support with the addition of an annual graduate orientation and site-wide research symposium to better connect students with investigators to promote collaboration. Graduates students collaborate in all aspects of BNZ LTER from proposal development to research. In 2005, the graduate student community hosted a student synthesis to investigate nitrogen retention in relation to disturbance at LTER sites across North America. This synthesis project involves students from three other LTER sites and incorporates data from 9 LTER watersheds. We will continue to support current within-site and cross-site graduate collaborations and encourage the incorporation of synthesis into new graduate research, for example through LTER network-wide synthesis initiatives proposed for the 2006 All-Scientist Meeting.

Outreach to Communities, Agencies, and the General Public

We work closely with the Alaska Boreal Forest Council (ABFC), a non-profit group that seeks to develop consensus among scientists, resource managers, legislators, recreationists, commercial interests, and other stakeholders in the sustainable use of the boreal forest. The LTER program provides the scientific expertise for this citizen outreach program and relies on the ABFC for its expertise and energy in public outreach. This collaboration has enabled the LTER program to participate in public information programs, public round-table discussions, surveys of the use of forest products, and other outreach efforts to a much greater extent than if we were to try to organize it independently.

We collaborate with the Alaska Native Science Commission (ANSC) in their program to address the environmental and ecological concerns of Native Alaskans. We participate annually in a community meeting that ANSC organizes, with each year focusing on a different region of Alaska. We provide information on the long-term ecological changes that we observe and we listen to and discuss with Native leaders their concerns about environmental changes that affect their subsistence and cultural activities.

We work closely with several state and federal agencies (Alaska Division of Forestry, Alaska Division of Natural Resources, Alaska Fire Service, ADF&G, Tanana Chiefs Conference (a Native resource management agency), National Park Service, etc.) through joint research programs, discussions of management issues, jointly organized seminars, training programs for agency staff, and participation on Citizens' Advisory Committee for the Tanana Valley State Forest. The active role that these managers have played in our LTER synthesis is indicative of the close working relationship that we have developed with resource managers in Alaska.

Due to the growing national and international concern about climate warming, we are regularly interviewed by radio and television stations (NBC, CBS, ABC, public television and radio), newspapers (e.g., New York Times, local papers), journals (e.g., Science, Discovery Magazine, National Geographic), and film crews. For example, our experimental burn in 1999 was featured on a NOVA program about fire.

Ties to other Long-Term Research Programs

Our closest ties within the LTER network are with the Arctic LTER site at Toolik Lake. Chapin, Hinzman, Mack, Schuur, and Romanovsky have worked extensively at Toolik and maintain collaborations with ARC LTER researchers. We also maintain strong ties with other forested LTER sites and are strengthening ties with sites engaged in social-ecological research.

We work closely with the National Park Service to help them design their Long-Term Monitoring (LTEM) program in Alaska and participate in one another's research symposia. We also work closely with U.S. Fish and Wildlife Service research programs in the Arctic Wildlife Refuge and the Kenai National Wildlife Refuge, with ecological monitoring programs on military bases in interior Alaska, and with researchers engaged in ecological consulting.

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