

PROJECT SUMMARY

Intellectual Merit: The arctic region has warmed significantly over the past 30 years and arctic lands and freshwaters are already changing in response. The changes include a general “greening” of the arctic landscape, changes in species distributions and abundance, and changes in geophysical and biogeochemical processes and cycles at local and regional scales. Since 1975, the ARC LTER project and its predecessors have studied these changes by long-term monitoring of tundra and freshwater ecosystems in relation to climate changes, by experimental manipulations of whole tundra, lake, and stream ecosystems, and by comparisons among climatically different sites in northern Alaska and throughout the Arctic. Increasingly, however, it is apparent that climatic warming in the Arctic is accompanied by dramatic changes in disturbance regime, including disturbances related to thawing of permafrost, a surprising increase in wildfire, and changes in the seasonality and synchrony of ecosystem processes. These disturbances, in addition to having major impacts on biogeochemistry, populations, and communities, also lead to major changes in surface energy balance, surface temperatures, water balance, and heat transfer into the permafrost that lies beneath the tundra, lakes, and streams. The result is much more dramatic and rapid change in communities and element cycles than is predicted in response to warming alone. In the long term, warming-related changes in disturbance regime may be more important than the direct effects of warming on arctic tundra and freshwater ecosystems, and on the entire Arctic. Over the next six years the ARC LTER project will address these issues in an integrated landscape framework, viewing the Arctic landscape as a spatially linked system including tundra, streams, and lakes and leading to long-term predictions of change at hillslope, watershed, and regional scales. Our long-term goal, to develop a predictive understanding of the landscape of Northern Alaska including tundra, streams, lakes, and their interactions, remains the same but we will refocus our efforts for the next six years to include a new emphasis on changing disturbance regimes and their interactions with climate change. This refocusing will involve some shifts in our efforts, away from long-term experiments manipulating individual climatic, biotic, and biogeochemical drivers, and toward increased effort on characterizing disturbances including thermokarst, fire, and changing seasonality, and on new research focused on landscape linkages and physical disturbance. New areas of research will include changes in surface energy exchange and heat flux into permafrost, and a program on climate change impacts and responses by local Native Alaskan communities. We will maintain the same core project management and organization including the four research subgroups (terrestrial, lakes, streams, and landscape interactions) we have used successfully and productively in the past.

Broader Impacts: The **scientific impacts** of this research are much broader than improvement of our ability to predict ecosystem structure, function, and change in Northern Alaska. First, the role of disturbance in long-term change is of broad theoretical and empirical interest in ecology and is closely related to controls on “resilience”, “tipping points”, and “thresholds” in populations, communities, ecosystems, and complex landscapes. The landscape near Toolik Lake, Alaska is an excellent model system for analysis of these issues at multiple spatial and temporal scales. Second, our work at Toolik Lake will provide a multidimensional view of how responses of tundra and freshwater ecosystems to environmental change can feed back, both positively and negatively, on the factors driving the change. This, again, is of broad importance both theoretically and from the perspective of global climatic change. In **education**, we will maintain a multifaceted program including a Schoolyard project of lectures and inquiry in the largely Native Alaskan town of Barrow, Alaska, we will teach field courses in Arctic Ecology and in Polar Science for Journalists, and we will continue to actively support undergraduate and graduate research and degree programs. Research of the ARC LTER will benefit **society** as a case study of a landscape where local, subsistence land use is still common and important, and where climate change and its impacts are felt directly in the delivery of key ecosystem services.

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Section 1: Results of Prior LTER Support

Project History: Ecological research at the ARC LTER site began in 1975, with acceptance into the LTER Network in 1987. The overall aim has always been: ***to develop a predictive understanding of the arctic landscape near Toolik Lake including tundra, streams, lakes, and their interactions.*** The specific focus evolves continuously and changes with each renewal cycle, as understanding has grown and as new opportunities are recognized:

- LTER I (1987-1992): Descriptions of tundra, stream, and lake ecosystems; Long-term change versus short-term controls on ecosystem components
- LTER II (1992-1998): Ecological variability and long-term change; top-down versus bottom-up controls on tundra, streams, and lakes
- LTER III (1998-2004): Prediction of the future characteristics of arctic ecosystems and landscapes; controls on ecosystems by physical, climatic, and biotic factors
- LTER IV (2004-2010): Understanding changes in the Arctic system at catchment and landscape scales through knowledge of linkages and interactions among ecosystems.

The ARC LTER research is strongly collaborative and typically involves multiple projects and investigators working on sites and especially on long-term, whole-system experiments that are established and maintained by the LTER project. In these collaborations the ARC LTER typically provides site maintenance as well as access to sites and experiments, maintenance and access to long-term data bases, and often the system-level conceptual framework and background data that allow a much richer interpretation of results of individual studies than would be possible in single-investigator research.

Publications: Supplementary Documentation, Table 1, lists 139 peer-reviewed journal publications, 21 book chapters and one book, 24 MS or PhD theses, and over 50 “other” publications including newspaper and magazine articles, radio and video pieces, and internet blogs that have been produced based in whole or in part on ARC LTER research since 2004. The published or accepted journal papers appear in 50 different journals including Science; Nature (2); PNAS (2); Ambio (15); Ecology, Ecological Monographs, or Ecological Applications (11); Limnology and Oceanography (10); Journal of Geophysical Research or Geophysical Research Letters (8); Freshwater Biology (8); Oecologia (5); Arctic, Antarctic, and Alpine Research (5); Global Change Biology (4); Journal of Ecology (4); Ecosystems (4); Water Resources Research (4); Ecology Letters (3); Oikos (3); Biogeochemistry (3); Canadian Journal of Aquatic and Fisheries Science (3); Verh. Internat. Verein. Limnol (3); and 28 other journals with one or two papers each.

Data sets and data set use: Supplementary Documentation, Table 2, shows that the ARC LTER data base contains ~1400 data sets (72 MB). In 2009 there were 4563 hits on the data sets from outside the MBL and 393 downloads using the LNO Data Access Server. ARC LTER data sets have been used in a wide range of collaborations and multisite comparisons within and outside of the LTER network (e.g., Walker et al 2005, Callaghan et al. 2005, Knapp et al. 2008, Wookey et al. 2009, Clark et al. 2007, Cleland et al. 2008, Suding et al. in press, Pennings et al. in press, Wrona et al. 2006).

Education and Outreach: Since 2004 the ARC LTER has supported training of 28 REU students (10 with LTER supplemental funding), 12 Master's and 12 PhD students (an additional 21 MS and PhD students are in progress), 6 foreign PhD students, a Science Journalism program, an Arctic Ecology field course, and a Schoolyard program at Barrow, Alaska (most participants are Native Americans) including a weekly lecture series and a field observation program.

Use of Supplementary Funding: Annual supplemental funding has been used to support 10 (of 28 total) REU students since 2004 and has supported the Barrow Schoolyard Program (lecture series and student field observations) in collaboration with the Barrow Arctic Science Consortium (BASC). Supplemental Funds also supported travel for 9 students to an

international meeting on Land-Water Interactions in Arctic Landscapes at Abisko, Sweden, individual trips by investigators and students to meet with collaborators in Europe, and a field sampling trip for an investigator and a high school teacher to Thule, Greenland. Equipment purchases with supplemental funds include a spectroradiometer, a fluorometer, a Hydrolab multiprobe, an epifluorescence microscope, and a PIT tag reader and antenna system. A special supplement from the NSF-NEON program was used to purchase stream nutrient monitoring equipment and two methane/CO₂ flux tower systems. Finally, supplemental funding was used to develop a new Social Science component of the ARC LTER, in which we have documented native people's perceptions of recent climate change and its impacts on their ability to use the land for subsistence activities including hunting and fishing.

Terrestrial Research Accomplishments: the current goal of "*understanding changes in the Arctic system at catchment and landscape scales through knowledge of linkages and interactions among ecosystems*" has led to a wide range of individual terrestrial research projects including:

- *Carbon-nutrient interactions:* In long-term fertilizer experiments, we found a net loss of C over 20 years despite a doubling of C inputs as NPP over that time, indicating that ecosystem respiration may be much less tightly linked to recent photosynthesis than we previously believed (Mack et al. 2004).
- *Species effects:* In tussock tundra the removal of dominant species may result in little or no long-term change in community biomass, NPP, or N uptake, due to compensatory growth by remaining species (Bret-Harte et al. 2004, 2008); species do, however, differ in the relative importance of different N sources for plant uptake; the majority of plant N uptake now appears to come via mycorrhizal associations (Hobbie and Hobbie 2006, Yano et al. 2009).
- *Herbivory and trophic interactions:* Patterns of herbivory in tundra can be changed with nutrient availability in fertilizer experiments (Gough et al. 2007, 2008); the stability of soil food webs is related to productivity and to their diversity and symmetry (Rooney et al. 2006, Moore et al. 2005, de Ruiter et al. 2005).
- *Carbon balance of small plots and large landscapes:* A single parameterization of a model of Net Ecosystem Exchange of C (NEE) explains 80% of the variation in NEE in response to light and temperature in a wide range of tundra types without requiring any information on species composition, suggesting that canopy CO₂ exchange follows much the same rules in tundras dominated by different plant functional types (Shaver et al. 2007, Street et al. 2007, Williams et al. 2006, Douma et al. 2007). The same model also describes well the NEE at eddy flux towers (Rastetter et al. 2010).
- *Response to Disturbance:* In the Anaktuvuk River Burn we have monitored changes in surface C and energy balance over two full summers. At both the plot scale and the tower scale and across a range of burn severity from unburned to severely burned, NEE is predicted by canopy "greenness" and leaf area (Rocha and Shaver 2009). Surface albedo was much reduced by burning, leading to increased thawing of permafrost and increased thermokarst activity.
- *Global and PanArctic Synthesis:* Terrestrial research results are important components of several PanArctic syntheses including the Arctic Climate Impacts Assessment (Callaghan et al. 2005), the International Tundra Experiment (Walker et al. 2006), the Circumpolar Arctic Biodiversity study (Wookey et al. 2009), and the International Polar Year (Post et al. 2009). G. Shaver is currently on the Steering Committee of the International Study of Arctic Change. In the LTER network we participated in the synthesis of shrub encroachment data across the US (Knapp et al. 2008), and in the assessment of nutrient effects on biodiversity (Clark et al. 2007, Cleland et al. 2008, Suding et al. 2005, Pennings et al. 2005).

Streams Research Accomplishments: During the current funding period we maintained our long term monitoring initiatives and focused on stream linkages with the landscape. We considered various controls on those linkages and began to consider how climate change might influence

them. These efforts led to a number of new findings and positioned us for the research proposed here. In particular, we accomplished the following:

- *Long-term response to nutrients:* We found that short-term, low-level fertilization of beaded streams with N and P increased the rate of organic matter decomposition and the abundance and biomass of macroinvertebrates (Benstead et al. 2005). We found that recovery from fertilization, especially reduction in the cover and biomass of the aquatic mosses, took much longer than expected (Benstead 2007). Thus, established communities are able to withstand short periods of low nutrient availability.
- *Hyporheic processes:* We found that the hyporheic zone currently does not occupy the full extent of the existing thawed zone and is unlikely to deepen as the climate warms (Edwardson et al. 2003, Greenwald et al. 2008, Zarnetske et al. 2008). We found that the depth of the hyporheic zone is strongly controlled by stream geomorphology (Zarnetske et al. 2007). We concluded that changing seasonality (lengthened season) will have a greater impact on the role of hyporheic processing in arctic streams than will deepening of the thawed zone (Bowden et al. 2008).
- *Thermokarst development:* We found that thermokarst failures have become more numerous in the foothills region of the Brooks Range (Gooseff et al. 2008) and deliver significant quantities of sediment and nutrients to stream ecosystems (Bowden et al. 2008).
- *Fish ecology:* Buzby and Deegan (2004) found that survival of Arctic grayling – a keystone species in our streams – was surprisingly unresponsive to fundamental environmental drivers (temperature, discharge, winter severity), suggesting that these keystone species employ life strategies that may sacrifice short-term gains for long-term success. Deegan et al. (2005) found that these fish have physiological adaptations (metabolism and swimming ability) that are essential for survival in this harsh environment.
- *Stream diversity:* We found that arctic streams could be classified into useful ecological groups based on simple environmental metrics of temperature, disturbance regime (discharge), and phosphorus concentration (Huryn et al. 2005, Parker et al. 2006).
- *Innovative new methods:* We established that the widely-used whole-stream approach to estimate metabolism from diurnal patterns of temperature and dissolved oxygen can be applied in the arctic with minor modification (Cappelletti 2006). Morse et al. (2007) found that it is possible to accurately estimate oxygen reaeration rate from a simple measurement of sound pressure level versus older, time-consuming and expensive methods based on gas chromatography. We also found that simpler pulse-addition nutrient enrichment experiments provided information about nutrient uptake rates in streams that was comparable to more time-consuming continuous addition experiments (Payn et al. 2007, Gooseff et al. 2008). We demonstrated the feasibility of using ground penetrating radar to assess the depth and extent of the thaw basin under arctic streams (Bradford et al. 2005, Brosten et al. 2006, 2009a and b).
- *Contributions to field:* The streams group contributed significantly to important syntheses including LTER-led examinations of ecosystems processes (Katz et al. 2003) and climate change (Hobbie et al. 2003). We contributed to global as well as local syntheses of knowledge about high-latitude lakes and streams (McKnight et al. 2003 and Slavik et al. 2004, respectively). Working with a large, national collaborative group we found that the ratio of C:N in detrital organic matter is an important control on N retention in streams that span a latitudinal gradient from temperate to arctic regions (Dodds et al. 2004).

Lake Research Accomplishments: Investigations of landscape interactions and controls on lake ecosystems show that landscape age plays a major role in determining lake water chemistry, while lake size structures and controls the biological community (Luecke et al. *in prep*). Other key results from long-term monitoring and experiments of a range of lakes near Toolik include:

- *Climate change impacts:* Summer epilimnetic temperatures show no significant increase from 1980-2009, although the frequency of warm, dry summers increased. Three exceptionally warm summers caused greater stratification and larger differences in stratification and mixing dynamics compared to colder years (MacIntyre et al. 2009). This was especially pronounced in shallow lakes, allowing greater interaction between sediment and water column processes (MacIntyre et al. 2006).
- *Controls on Primary Productivity:* We discovered that current measurements and models of lake primary productivity may be 50% underestimates of the true productivity in the mid-depths of lakes (Evans et al. 2008). This underestimate is due to the large but unaccounted for effect of internal waves on phytoplankton position in the water column, in conjunction with temporal variations of clouds and sunlight hitting the lake.
- *Ecosystem responses to fertilization:* Lakes E5 (deep) and E6 (shallow) continue to respond to low-level N+P fertilization with increased pelagic primary production. Benthic chlorophyll has also been enhanced, especially in the shallow lake where light penetration to the sediments supported photosynthesis. Rates of benthic nitrogen fixation were suppressed by fertilization in both deep and shallow lakes (Gettel 2006). Zooplankton populations were greater in fertilized lakes, particularly in warmer summers (Burkart 2007).
- *Controls on secondary production:* Increased lake stratification in warm summers resulted in higher epilimnetic temperature, increased zooplankton density, and reduced fish growth (Johnson 2009). In the 2007 warm summer, excretion by zooplankton accounted for almost all the nitrogen and phosphorus needed by phytoplankton in six lakes, while phytoplankton in lakes dominated by copepods became nitrogen limited (Johnson et al. *submitted*).
- *Fish population structure and dynamics:* Arctic char populations in lakes E5 and Fog2 were regulated by interactions of cannibalism and competition. Large recruitment events were documented in 2002 in Fog2 and 2005 in E5. In both events significant recruitment only occurred after densities of piscivore-sized char were greatly reduced; this internal population dynamic masked any potential impact of lake fertilization on char growth or survival.
- *Fish distribution:* Grayling movement patterns indicate that shallow lakes may serve as important habitats for growth of juveniles. Isotopic labeling of a grayling population in lake NE12 indicates that smaller fish moved at greater rates between lakes than did larger fish.
- *Nitrogen dynamics:* Nitrogen fixation makes an important contribution to the N budget of these ultra-oligotrophic lakes (Gettel 2006). Fixation in the water column ranges from 0.12 to 1.5 mg N m⁻² d⁻¹ and is higher than reported from many other oligotrophic lakes. Benthic fixation ranges from 0-2.6 mg N m⁻² d⁻¹ and is largely autotrophic. Benthic fixation is reduced by even small amounts of grazing at ambient snail densities (Gettel et al. 2008).
- *Lake-Landscape biogeochemistry:* Alkalinity in Toolik Lake and other lakes in the region has more than doubled since measurements were first made in the 1970s, likely due to thaw-depth increases and weathering in the catchment (described below).
- *Synthesis:* Lakes Pls produced book chapters on polar limnology (Vincent et al. 2008a,b), microbial processes (Hobbie et al. 2007; Hobbie and Laybourn-Parry 2008), spatial variability (Kratz et al. 2005); zooplankton (O'Brien et al. 2006); climate (Quesada et al. 2006); and in the Encyclopedia of Inland Waters (Giblin 2009; Kling 2009, MacIntyre 2009).

Landscape Interactions Research Accomplishments: Our Landwater research has used monitoring and experiments to study the spatial connections and controls on carbon, nutrient, and organism distribution and movement, resulting in the following major findings:

- *Landscape-level ecosystem controls:* Expanding on previous findings that interactions between land, lakes, and streams are critical for determining biogeochemical processing in arctic landscapes (Kling et al. 2000), we showed that organism distribution in soil waters, streams, and lakes is under a similar, landscape control (Crump et al. 2003, 2007).

- *Landscape linkages*: The seasonal timing of hydrologic connectivity affects a range of ecological processes, including downslope nutrient transport, C/N cycling, and biological productivity along the toposequence (Stieglitz et al. 2003). On tundra hillslopes, downslope N movement is slow but still important for the landscape N budget and a critical linkage among patches of the landscape mosaic (Yano et al. 2009, 2010, Rastetter et al. 2004, 2005). Spring snowmelt interacting with surface soils controls the load and timing of nutrient export from both small and large catchments (McNamara et al. 2008).
- *Controls on secondary production and decomposition*: Aquatic bacterial production is driven strongly by rapid changes in community composition as environmental conditions vary (Judd et al. 2006). Communities held at different temperatures had varying rates of production, indicating populations with different temperature optima and shifts in productivity and composition occurring on ecologically relevant time scales of days (Adams et al. in press).
- *Microbial community composition and activity*: There are distinct and consistent patterns of microbial activity at key points in terrestrial and aquatic ecosystems across the landscape – communities can shift quickly over time, and activity is driven by inputs of leaf litter or dissolved organic matter (Zak and Kling 2006; Judd et al. 2006).
- *Warming impacts on permafrost*: Despite no evidence of increasing thaw depth near Toolik Lake in 20 years, observed changes in the strontium isotope geochemistry of lakes and streams over time can only be explained by a melting of permafrost and thus systematic changes in thaw depth in the basin due to global warming (Keller et al. 2007, *in revision*).
- *Spatial patterns of distribution*: Bacterial distribution in surface waters is driven by a combination of species sorting (e.g., competition) and residence time of lake and stream waters (Crump et al. 2007). Recent data show that even within Toolik Lake there are distinct spatial patterns of species distribution, and spatial variation in bacterial activity across the lake on a single day equals the seasonal and annual variation at a single site.
- *DOM processing and disturbance*: Tundra fires increase soil water concentrations of PO₄, total proteins, and extracellular enzyme activity of phenol oxidase and peroxidase. While burning does not change the lability of soil DOM for soil and stream bacteria, the combined effects photo-oxidation of soil water from burned tundra does increase the DOM lability for stream bacteria, likely due to shifts in bacterial community composition (Judd et al. 2007).

Social Science Research Accomplishments: In 2007, 2008, and 2009 we used annual supplemental funds to add a social science component to our overall research design. This was done in collaboration with BNZ LTER investigators as the two Alaskan LTER sites are in areas where traditional, subsistence use of the land is still common and important. We began in 2007 by establishing a community-based monitoring program with the village of Kaktovik on the Beaufort seacoast, and added an inland community, Anaktuvuk Pass, in 2008 (these are the closest villages to Toolik Lake). The research is focused on gathering data on Inupiat native perceptions of human-environment relations and recent climate change. Another objective is to compile available harvest, socio-economic, and demographic data for these North Slope communities to study changes in subsistence uses since 1960. We are also documenting subsistence use of the land near Toolik Lake (some of these data are available on the Toolik Field Station web site). In 2009 this developed into a new, multisite LTER effort led by G. Kofinas of the University of Alaska, called “*Maps and Locals (MALS): A Cross-Site LTER Comparative Study of Land-Cover and Land-Use Change with Spatial Analysis and Local Ecological Knowledge.*”

Overall Project Synthesis: In addition to the individual synthesis products described above, a complete draft of the book, “*A Warming Arctic: Ecological Consequences for Tundra, Streams and Lakes*” (Hobbie and Kling, eds.) has been written, and is now being edited for publication by Oxford University Press.

SECTION 2. PROJECT DESCRIPTION

Introduction: Tundra and freshwater ecosystems of the Arctic cover more than 7M km², about 6 percent of Earth's land surface. The climate of this cold, northern landscape is now warming rapidly, with manifold impacts on populations, communities, ecosystems, and people already apparent (ACIA 2005, Hinzman et al. 2005, Post et al. 2009). It is clear that changes in the arctic landscape in response to warming have the potential for strong positive and negative feedbacks on the drivers of climate change, especially through changes in C cycling, hydrology, and surface energy exchange (e.g., Chapin et al. 2005, Peterson et al. 2006, McGuire et al. 2009, Schurr et al. 2009). These changes are occurring in a region that provides a unique suite of ecosystem services to both arctic peoples and the global human population. In the United States, the arctic and boreal regions of Alaska are the only places where traditional, subsistence use of the land is common and extensive, where the largest wilderness areas are currently preserved, and where mineral, fossil energy, and biological resources are abundant but largely unexploited (Chapin et al. 2006, Chapin et al. 2008).

A predictive understanding of how structure and function of arctic ecosystems are regulated by climate and other state factors, and how they might change in the future, is essential to future management and adaptation of socioecological systems in the Arctic. This understanding has been a central goal of ARC LTER research since its inception in 1987. A second goal has been to use the landscape near our research site at Toolik Lake, Alaska as a model system for basic research in terrestrial and aquatic ecosystem ecology. Our past research has taken advantage of the relatively low species diversity, strong physical gradients in the environment, and unique features like permafrost to study fundamental questions such as top-down versus bottom-up controls over ecosystems, biodiversity and ecosystem function, spatial linkages in heterogeneous landscapes, and temporal and spatial scaling of ecosystem controls and responses. We now propose to renew our research for another 6 years, this time with a focus on how responses to climate change interact with a changing disturbance regime to determine the overall, linked landscape response.

Overall Goal, Organizing Questions, and Synthesis: We focus on climate change, disturbance regimes, and their interaction in arctic landscapes because the subject is timely with respect to both the current state of the changing arctic landscape and the current state of ecological theory (discussed below). For the years 2010-2016, our **Overall Goal** is to understand changes in the arctic system at catchment and landscape scales as the product of: (i) Direct effects of climate change on states, processes, and linkages of terrestrial and aquatic ecosystems, and (ii) Indirect effects of climate change on ecosystems through a changing disturbance regime.

Much of the research of the ARC LTER is done in collaboration with separately-funded projects (currently >30) that share LTER sites, experiments, data bases, facilities, and personnel. One of the key management challenges of the ARC LTER is to create a project structure that optimizes opportunities for synthesis among such a large, diverse, multidisciplinary group. To provide this structure we organize our research into four main components, focused on (a) terrestrial ecosystems, (b) streams, (c) lakes, and (d) landscape interactions (Fig 2-1). All four components address the same **Organizing Questions:**

1. *How does climate control ecosystem states, processes, and linkages?*
2. *How do disturbances change ecosystem states, processes, and linkages?*
3. *How do climate and disturbance interact to control biogeochemical cycles and biodiversity at catchment and landscape scales?*

Synthesis is further promoted by collocation of terrestrial, stream, lake, and landscape interactions research in the same watersheds and by coordinated sampling of different components of the watersheds. A mass balance approach to watershed and landscape

biogeochemistry is used to develop predictive models and to evaluate results of individual studies in the context of the whole land-water system. Finally, we have begun to develop a fifth research component, focused on subsistence land use and impacts of climate change on Native American village communities of Northern Alaska. This structure facilitates our ability to address broad, integrating questions such as:

- I. *How do changes in arctic catchments and large landscapes feed back on changes in climate, disturbance, and human use of arctic lands?*
- II. *How do climate and disturbance regime shape the function of the North Slope of Alaska as a regional socio-ecological system?*

Site description: Climate and Setting - In 1975 the NSF Office of Polar Programs began to fund aquatic ecology research on the rivers and lakes in the vicinity of Toolik Lake, in the northern foothills of the Brooks Range, Alaska. Toolik Lake (68°N, 149°W) was chosen because of its size, depth, and accessibility; the road along the oil pipeline had just opened (Shaver 1996). In 1976 terrestrial ecologists began projects at the site and in 1987 the Arctic LTER project was funded. Today the Toolik Field Station of the University of Alaska Fairbanks (<http://www.uaf.edu/toolik/>) operates year round, supporting >100 scientists at a time during the busy summer months and over 6,000 user days each year.

The main Arctic LTER research site includes the entire Toolik Lake watershed and the adjacent watershed of the upper Kuparuk River, down to the confluence of these two watersheds (Fig 2-2). Additional sites include the 1000 km² Anaktuvuk River (AR) Burn site 40 km NNW of Toolik Lake and thermokarst disturbances within helicopter range of Toolik Field Station (thermokarsts are slumps in the landscape caused by local thawing of ice in permafrost). This area is typical of the northern foothills of the Brooks Range, with no trees, a complete snow cover for 7 to 9 months, winter ice cover on lakes and streams, and no stream flow during the winter. Tussock tundra vegetation of sedges and grasses mixed with dwarf shrubs and low evergreens is the dominant vegetation type but there are extensive areas of drier heath tundra on ridge tops and other well-drained sites as well as areas of river-bottom willow and lowland wet-sedge communities (Walker et al. 1994; <http://www.uaf.edu/toolik/gis/>). The climate at the site is typical of arctic regions, with a mean annual air temperature of about -7°C and low precipitation (45% of the 20-40 cm of precipitation falls as snow). During the summer the daily average air temperature is 7-12°C with the sun continuously above the horizon from mid-May to late July. Permafrost underlies the site to a depth of ~200 m. An active layer thaws each summer to a depth of 28-47 cm (Hobbie et al. 2003). The glacial tills that cover the hills near Toolik have three different ages, ~300,000 y, ~60,000 y, and 11,500-25,000 y (Hamilton 2003; see Table 2-1). These landscapes control surface water chemistry, with the oldest lakes and streams being very dilute with low amounts of inorganic ions and alkalinity (Kling et al. 1992, 2000). Soils are more acidic in the older surfaces and less acidic in the youngest surface because of differences in leaching of the carbonate-rich glacial till (Walker et al. 1989, 2003). One consequence is that a different vegetation covers these surfaces; for example there is little or no birch in the non-acidic tundra (Gough et al. 2000).

Monitoring and experimental sites: To facilitate synthesis across lakes, streams, terrestrial, and landscape interactions components, the ARC LTER research is focused on 4 contrasting whole watersheds including (i) the Kuparuk River Headwaters which contains few lakes, (ii) the Toolik Lake Inlet Watershed which contains many lakes, (iii) Imnavait Creek, a first-order stream within the Kuparuk watershed and (iv) the mostly burned South River watershed including subwatersheds of varying burn severity (Fig 2-2). Other intensively studied sites and their characteristics are listed in Table 2-1. Most of these are accessible by foot or boat from Toolik Lake or by driving along the Dalton Highway, but some (e.g., the AR Burn, thermokarst disturbance sites, and some mountain streams) require the use of a helicopter.

Conceptual framework for 2011-2016: Our new emphasis on disturbance is driven by a host of observations suggesting that climate-related disturbances are increasing throughout the Arctic including the North Slope of Alaska. The disturbances range from an apparent, dramatic increase in lightning strikes and frequency of tundra wildfires within the past 10 years (Jones et al. 2009; <http://fire.ak.blm.gov/>) to changes in lake mixing dynamics related to changing atmospheric pressure fields (MacIntyre et al. 2009). Many of the disturbances are related to climate effects on permafrost and hydrologic regime, including a wide range of thermokarst events (i.e., land-surface changes resulting from melting of ice in permafrost; Bowden et al. 2008, Hinzman et al. 2005) as well as droughts and floods that affect movement of animals and materials in streams and lakes (e.g., Lundberg and Moberg 2003, Buzby and Deegan 2004). Frequently, changes in climate disturb the timing or synchrony of linked ecosystem processes in ways that could not be predicted from knowledge of direct climate effects alone (e.g., Buckeridge and Grogan 2008, Post et al. 2009, Slavik et al. 2004). All these disturbances have important feedbacks on climate as well as human use of the land, in particular subsistence hunting and harvesting but also tourism and commercial resource extraction.

The conceptual framework for continuing our long-term research includes a series of implicit hypotheses about how climate change, disturbance, terrestrial and aquatic ecosystems, and people interact to determine overall landscape properties and feedbacks on the drivers of change. In this framework (Fig 2-3) we show climate variability and change as the primary driver altering landscape properties and processes. We also recognize the importance of other state factors including topography, geology, biota, and time (indeed, much of our long-term research on these state factors will continue), but for the next 6 years we intend to focus more closely on climate effects and feedbacks. Climate variability and change affect tundra, lake, and stream ecosystems directly, as well as the linkages among them and, importantly, the disturbance regime. *For our purposes the disturbance regime includes wildfire, thermokarst, and related periglacial phenomena, as well as extreme climatic and hydrologic events (floods and drought) and changes in seasonality, synchrony, and timing of key ecological processes.* Ecosystem structure and function, landscape linkages, and disturbance regime all interact and, together, determine watershed and hillslope properties (Fig 2-3). Key feedbacks in this conceptual framework include the feedbacks from watershed and hillslope properties to climate, in particular the feedbacks due to changes in carbon, water, and nutrient budgets (e.g., McGuire et al. 2009) and to changes in surface energy exchanges which regulate the energy fluxes back to the atmosphere and into the soil and underlying permafrost (e.g., Chapin et al. 2005, Randerson et al. 2006). Also important are the feedbacks due to changing patterns in human land use including subsistence hunting and fishing, tourism, and road-building, mining, and drilling (Gunn et al. 2009, Kofinas and Chapin 2009).

One key consequence of including disturbance in our conceptual framework (Fig 2-3) is the need to integrate the strongly “patchy” nature of disturbances like fire and thermokarst with the more broadly uniform distribution of climatic warming or changes in cloudiness, evaporation, and precipitation. For most of the past 30 years the ARC LTER project and its predecessors have studied the direct effects of climate change on arctic lands and freshwaters as if the changes in climate occurred uniformly across a landscape like that in Fig 2-1. This perspective can lead to predictions of “patchy” responses as (1) some ecosystems respond differently than others to the same climate change and (2) climate change affects biogeochemical linkages between neighboring ecosystems and thus interactions between neighbors may change. The perspective of Fig 2-1, however, is inadequate to explain the role that disturbances play in a changing regional landscape. Disturbances of the kind we now see in northern Alaska are strongly “patchy” (e.g., Fig 2-4), and typically cause much larger-magnitude and more rapid changes within the disturbed area than the relatively slow, direct responses to climate change factors like temperature. *Thus, given that our goal is to understand changes in the arctic*

system as the product of both climate change and disturbance effects, we must take a large-watershed or regional landscape approach to our research.

Finally, we suggest that an increase in disturbances may represent a “tipping point” (e.g., AC-ERE 2009) or “resilience threshold” (Carpenter and Folke 2006, Chapin et al. 2009) that drives the arctic landscape into a new state of interaction with the regional and global climate systems and with the people who use and benefit from the ecosystem services it provides. This change to a new state may occur in either or both of two ways. First, although the area of disturbed land or water may be relatively small, the magnitude of change on disturbed sites may be sufficient to alter the overall characteristics of much larger areas (Fig 2-4). For example, the 2007 Anaktuvuk River Burn covered 1000 km², about 10% of the area of the adjacent Kuparuk River watershed and only 0.5% of the total area of the North Slope of Alaska (Jones et al. 2009). This one fire released at least 1.7M tons of C to the atmosphere, most of it in just 2 weeks in mid September; this amount comprised ~30% of the total C stock within the annually-thawed active layer above the permafrost (M. Mack, unpublished data). This huge C loss is about 10 times the net annual loss of C from the entire Kuparuk watershed (Williams et al. 2000, Oechel et al. 2000) and, if added to the current net annual C loss from the entire North Slope, would increase that loss by ~45%. Clearly, an increase in the frequency, area burned, or severity of tundra wildfires may mean that changes in C balance on burned areas could become the dominant component of C exchange with the atmosphere, much more important than relatively small changes in C loss due to gradual climate warming.

The second way that increased disturbance may represent a “tipping point” is through community changes that occur on or are driven by disturbances (Chapin et al. 2006, 2008). For example, our own long-term experiments at Toolik Lake indicate that an increase in shrubs should occur with warming and increased nutrient turnover in the soil (Shaver et al. 2001, Bret-Harte et al. 2001, 2008). Other research has shown that an increase in shrubs or trees in tundra has the potential to cause significant regional changes in surface energy exchange with the atmosphere (Chapin et al. 2005). Several investigations have suggested that shrub abundance may be increasing in Northern Alaska (Tape et al. 2006, Wahren et al. 2005), at least in alder-dominated sites, but the changes appear to be slow at best in most areas. The one place where shrub abundance is clearly increasing rapidly is on disturbed sites (e.g., thermokarsts, overgrazed sites, or development-related disturbances), in both Alaska and Siberia (Walker et al. 2009). Here our hypothesis is that disturbances create opportunities for rapid community change that occur only slowly in undisturbed communities in response to climate change alone; thus an increase in area and frequency of disturbance should facilitate a regional shift to a new state of interaction with climate and people.

Research plan: Overview. Our overall goal for the next six years is derived from over 30 years of experimentation and observations based at Toolik Lake. During this time we have seen significant changes in climate and in both terrestrial and freshwater ecosystems (e.g., Hinzman et al. 2005, Post et al. 2009). Within the past decade, we have begun to see significant changes in the disturbance regime including increases in wildfire, thermokarst and related periglacial phenomena, and extreme climatic and hydrologic events. Our research plan is designed to take maximum advantage of this strong background, continuing many of our long-term experiments and observations while adding new, strategically selected activities within a revised conceptual framework (Fig 2-4) that represents the continued evolution of our thinking about the Arctic Landscape.

Our research plan depends strongly on continued collaborations with other projects based at Toolik Lake (Projects listed in Budget Explanation). Many of these projects have had several rounds of renewed funding and have collaborated with the ARC LTER since its inception. Typically these projects make measurements at sites that have been established and are maintained by the ARC LTER, including an array of long-term experimental manipulations.

The Principal Investigators of these projects are included as “Senior Collaborators” in this proposal. Much of the work of our Executive Committee and of the terrestrial, lakes, streams, and landscapes interactions groups involves creating an optimal interaction between the LTER and collaborating projects. Typically, the ARC LTER provides field and laboratory assistance to collaborating projects, as well as core data such as climate and microclimate on experimental plots and waters. *One important consequence of this arrangement is that it promotes collocation (in both space and time) of diverse kinds of sampling, which greatly facilitates synthesis and modeling.* Furthermore, most collaborating studies opt to archive their data in the ARC LTER data base, where the common descriptors (metadata) of data also facilitate synthesis. *A second consequence is that this arrangement places the ARC LTER at the center of efforts to integrate the results of multiple collaborating projects with core monitoring and observations maintained by the LTER.* The ARC LTER winter meetings and the interactions among collaborating projects fostered by LTER during the summer become key sources of new ideas, crosscutting research, and synthesis.

Sites, Monitoring and Process Studies, Experiments, and Disturbance Studies:

ARC LTER research will continue at four core watershed sites (Table 2-1, Fig 2-2) where the aim is to bring together terrestrial, lake, stream, and landscape interactions research in the context of comparisons among whole catchments. These four watersheds differ in landscape age and geomorphology, in the relative abundance of lakes (Upper Kupaaruk has few lakes and Imnavait Creek has none, while Toolik Inlet has many lakes), and in disturbance history (South River includes entire subcatchments with different burn severity). Each of the current four research groups will maintain their long-term monitoring and process studies and comparisons among lake, stream, and terrestrial ecosystems (Table 2-1).

The ARC LTER will continue to monitor diverse environmental factors and ecological processes necessary to understanding and prediction of biogeochemistry and landscape linkages at ecosystem and catchment scales (Table 2-2). The details of methods and protocols for chemistry and sampling are available at the Arctic LTER web site. We also will maintain our long-term commitment to whole-system experimental manipulations as a means of elucidating controls on ecosystem states and processes (Table 2-3). To accommodate our new research on disturbances, however, several of our older experiments will be discontinued or placed in “mothball” status, and others will be maintained but sampled less often. Research by each of the four ARC LTER components is described in the following sections on each component.

Response to 2007 Site Review: Overall, our 2007 Site Review was strongly supportive of our current project organization, management, design, goals, and past productivity, but made three suggestions for improvement directly related to our research plan. We accept all of them:

- 1) “Consider the use of a focusing mechanism, such as a common study watershed... Consider initiating focusing studies and experiments that take place in the same place [and] time”.
We will focus on **four common study watersheds**, chosen to facilitate comparisons between disturbed and undisturbed landscapes, and between watersheds with and without lakes. We will also use a common set of three **Organizing Questions** to facilitate integration among research components.
- 2) “Consider re-setting some priorities to allow more frequent sampling in some of the more critical experiments”. We will reset priorities by reducing our sampling effort in several long-term experiments in order to allow more time and effort on the focusing studies above.
- 3) “Consider initiating experiments that directly manipulate temperature (permafrost) and water availability ... Improve the understanding and incorporation of hydrologic and geomorphic processes as physical drivers of the hillslope, watershed, and landscape connectivity...”.
We consider our new work on sites disturbed by fire and thermokarst to be taking advantage of large “natural experiments” including changes in energy balance, hydrology, and geomorphology that would be impossible to simulate cost-effectively in an artificial way; to

take advantage of these “natural experiments” in our research we must expand our observations of hydrologic and geomorphic change. Where feasible, we will initiate new, focused, plot-scale experiments on key processes as described below.

Terrestrial Research: Rationale. Terrestrial ecosystems dominate the landscape of northern Alaska, covering most of the area and accounting for the majority of its productivity and element cycling (Williams et al. 2000, 2001, LeDizes et al. 2003). Terrestrial ecosystems interact directly with the atmosphere and with climate through exchanges of trace gases (CO₂, CH₄, others) and energy (sensible and latent heat, radiation). Much of our previous research has been devoted to understanding these exchanges and their controls by climate, soils, and species composition (e.g., Mack et al. 2004, Boelman et al. 2005, Gough et al. 2008, Bret-Harte et al. 2008). We also know that terrestrial ecosystems are changing throughout the Arctic (Goetz et al. 2006, 2007, Verbyla 2008, Walker et al. 2009), and we know that the consequences for future climate are significant (e.g., Chapin et al. 2005), but we know relatively little about the timing and trajectory of that change: *How can we use results of our long-term monitoring and experiments to predict future changes?* We also have begun to see increases in major disturbances (fire and thermokarst), which have immediate and dramatic effects on surface C, water, energy, and nutrient exchange: *At what point will the large changes in relatively small areas of disturbed land become the dominant mode of interaction between the whole arctic landscape and the atmosphere, and between land and freshwater ecosystems?*

Almost all of the water and elements that enter aquatic systems must pass through terrestrial systems first, thus making the link between terrestrial and aquatic systems one key to our research (Rastetter et al. 2004, 2005, Stieglitz et al. 2003, 2006): *How do terrestrial systems control inputs to aquatic systems?* A second key is the fact that terrestrial ecosystems of the Arctic are extremely variable in relation to topography (Fig 2-5), often differing by an order of magnitude or more in productivity or various measures of C or N cycling over distances of only a few meters (Giblin et al. 1991, Shaver et al. 1996). At the same time these terrestrial ecosystems are all in contact with the same soil water, which generally stays close to the surface because continuous permafrost prevents deep drainage as the water moves downslope (Fig 2-6, Yano et al. 2010). Because adjacent ecosystems along toposequences differ so dramatically in both species composition and biogeochemistry, yet are clearly linked by downslope soil water movement, the obvious question is: *How does the transport of elements in soil water between adjacent terrestrial ecosystems affect the function of those ecosystems, and how is this transport controlled?*

Long-term monitoring and experiments. Terrestrial research of the Arctic LTER includes experimental and descriptive studies of the effects of climate, biota, geology and geomorphology, and fluxes of water and nutrients on tundra ecosystems (i.e., all of the “drivers” in Fig 2-3). The research design incorporates these controls through a combination of comparisons among sites that differ in their biota and their topographic position, geology, and landscape age with long-term manipulations of climate and nutrient inputs (Tables 2-1, 2-2, 2-3). Over the past 30 years we have developed a suite of experiments in which contrasting tundras, dominated by different plant functional types and located on different surfaces, are subjected to identical manipulations of nutrient inputs (with N and P fertilizers), air temperature (plastic greenhouses), light (shading), and other treatments such as herbivore exclusion (Table 2-3). Comparisons among treatments within a tundra type lead to insights about the interactions of climate and nutrient fluxes in regulating species composition and biogeochemistry (e.g., Fig 2-7, Mack et al. 2004). Comparisons among sites tell us how geology and geomorphology affect ecosystem structure and function (Shaver and Chapin 1991, Shaver et al. 1996, Gough et al. 2000). Comparisons of plant functional types in response to this common suite of manipulations teach us how differences in species function affect overall ecosystem characteristics (Hobbie et al. 1999, Chapin and Shaver 1996, Shaver et al. 2001, Bret-Harte et al. 2008). Finally,

comparisons of decomposition and other soil processes among sites and experiments tell us how vegetation composition interacts with soils and how overall C and N cycles are regulated (Hobbie et al. 2002, Weintraub and Schimel 2003, Shaver et al. 2004).

Over the next six years, we will maintain most of our existing suite of long-term observations, experiments, and comparisons, with periodic harvests as in the past. Because these ecosystems continue to respond to treatments, with each harvest we gain new insights about ecosystem regulation and we expect to continue to do so as long as the experimental plots continue to change. We also will continue long-term monitoring of plant growth and flowering in relation to weather (Shaver et al. 1986). To track interannual changes in above ground biomass we now routinely make NDVI (“greenness”) measurements of all plots using a hand-held spectroradiometer (Shaver et al. 2007). This provides us with a complete data set from all of our long-term treatments. With complementary funding from related grants, we will continue process studies (Table 2-2). Simulation modeling and cross-site comparisons (across both the Arctic and the LTER network) will be a major, continuing effort.

New activities: Disturbance. *The new research on disturbance will require us to shift our personnel and other resources, placing a greater emphasis on disturbances, especially fire and thermokarst, and on linkages between landscape patches rather than on their internal regulation and responses.* We have already started work on fire and thermokarst in collaboration with separately-funded projects (Rocha and Shaver 2009, Bowden et al. 2008). New projects on “changing seasonality” in the Arctic will be starting in 2010 (listed in Budget Explanation). All of these projects share personnel and equipment with the ARC LTER; typically the LTER provides assistance with field sampling, with chemical analysis especially at the field station, and with data as they are added to the LTER data base. In sampling our long-term experiments we will make the same measurements as in disturbed sites.

We also will be increasing our efforts to scale up this knowledge of disturbances, with the overall goal of evaluating the relative importance of disturbance responses versus direct responses to climate change in determining change at the scale of the North Slope of Alaska, or of the entire Arctic. To do this we will be using new (to us) methods such as eddy covariance to measure CO₂ and energy fluxes in burned and unburned patches (Fig 2-8), as well as developing relationships between flux measurements and various measures of reflectance (greenness; e.g., Shaver et al. 2007, Rocha and Shaver 2009). We will also harvest terrestrial soils and vegetation to develop the kind of detailed C and nutrient budgets already constructed for many undisturbed and experimentally-manipulated sites near Toolik (e.g., Mack et al. 2004, Bret-Harte et al. 2008). Finally, we will be working closely with the landscape interactions group to develop budgets for downslope water and nutrient transport into streams and lakes (Fig 2-6).

Modeling and scaling: Simulation models developed in past research at Toolik Lake will be used to integrate the results of field experiments and observations and to develop and test predictions about long-term and large-area changes (e.g., McKane et al. 1997a, b, Hobbie et al. 1998, Rastetter et al. 2003, 2010, Williams et al. 2000, 2001). Two models of particular interest to the terrestrial group include the General Ecosystem Model (GEM, Rastetter et al. 1991) and the Multiple Element Limitation (MEL, Rastetter & Shaver 1992). In one application, we coupled GEM to a hillslope hydrology model (Stieglitz et al. 1999) to examine how the downslope movement of inorganic N influenced moist tussock tundra responses to changes in CO₂ and climate (Rastetter et al. 2004). We also recently adapted the MEL model to examine the effects of dissolved organic N losses on long-term responses to changes in CO₂ and climate (Rastetter et al. 2005). Finally, we have begun to develop versions of these models for analysis of the effects of plant community change and species effects on element limitation and biogeochemistry (Herbert et al. 1999, 2004, Rastetter and Ågren 2002), and of productivity on trophic structure and interactions (Moore et al. 2005, de Reuter et al. 2005).

We are developing new models and methods for understanding and prediction of C and energy exchanges. Using one model, (PLIRTLE; Shaver et al. 2007) we have shown that 80%

of the variation in canopy-level CO₂ exchange (NEE) among a wide range of tundra ecosystems in Alaska and Scandinavia can be explained using a single parameterization of the model. We are currently working on adapting this model to eddy-covariance data (Rastetter et al. 2010).

Links to conceptual framework and Organizing Questions. The three Organizing Questions provide a means to link research on terrestrial ecosystems to the overall LTER goals:

1. *How does climate control ecosystem states, processes, and linkages?* The terrestrial group contributes to answering this question by measuring states, processes, and linkages over time in undisturbed systems and in response to our long-term manipulations of air temperature, light, nutrients, and other factors. Over the 6 years of this project we will continue our periodic biomass and production harvests of contrasting vegetation types. We will continue to add new sites and vegetation types to our growing data base on canopy CO₂ exchange in relation to light, temperature, and soil properties (Shaver et al. 2007). We will continue to monitor downslope water and nutrient movement in a ¹⁵N labeling experiment at Imnavait Creek (Yano et al. 2010; Fig 2-6). All of these results will further expand our long-term data base and be used in our modeling and scaling efforts.
2. *How do disturbances change ecosystem states, processes, and linkages?* Disturbed sites to be studied include the Anaktuvuk River Fire, where we have already started work on unburned and moderately- and severely-burned sites, and thermokarst sites near Toolik Lake (Fig 2-2). One key aim is to complete detailed soil-vegetation harvests and descriptions of C and N stocks in all of these sites. We have already completed an initial post-burn survey of organic matter stocks along a burn severity gradient; we will do this twice more, once in 2011 and once in 2014-2016. We will also measure light response of CO₂ exchange in all these disturbed sites using the cuvette technique we have used successfully in a wide range of undisturbed tundras (Shaver et al. 2007). All of this work will be done in collaboration with projects also working on these sites, including a network of 6 eddy flux towers (three in the AR Burn, three at Imnavait Creek; Shaver, Bret-Harte, Rastetter, and Mack are PIs).
3. *How do climate and disturbance interact to control biogeochemical cycles and biodiversity at catchment and landscape scales?* This question will be addressed by the terrestrial group by developing and comparing large-area C and energy budgets for undisturbed landscapes, for the AR Burn, and for two thermokarst sites, including an active-layer detachment slide and a glacial thaw slump (Fig 2-2, Table 2-1). We have already begun to do this with the burn site (e.g., Fig 2-4), where we compared C losses in the 1000 km² fire with net C exchange in the adjacent 10,000 km² Kuparuk River drainage; (Oechel et al. 2000). Because we know that net C balance (NEE) is strongly correlated with reflectance indices (NDVI & EVI) measured by the MODIS satellite (Fig 2-8), we are developing the data base to calculate large-area C fluxes in disturbed and undisturbed landscapes; of course we need to continue monitoring the fluxes on the burn site in particular because they are still changing rapidly as the land surface recovers. We can make similar calculations for surface energy exchanges (such as albedo), also using the MODIS satellite (Fig 2-9). To make these comparisons for thermokarst sites, which cover much smaller areas than the AR Burn, we can use chamber measurements of C fluxes, and energy balance measurements made from micromet towers and handheld instrumentation. We will also need fine-scale maps of the thermokarst areas including plant cover and soils, which are being developed by collaborating projects (B. Bowden, M. Mack).

Streams Research: Rationale. We are just beginning to understand how climate warming affects the hydrology and geomorphology of arctic streams. As described in our conceptual framework (above), it is clear that seasonality in the Arctic is changing, with shorter, warmer winters, longer ice-free periods, and warmer growing seasons with lower discharge (Hinzman and Kane 1992, Rouse et al. 1997, Hobbie et al. 1999, Hodkinson et al. 1999, Serreze et al.

2002). Changes to the landscape including thermokarst formation (Gooseff et al. 2008, Bowden et al. 2008), geomorphic changes to stream networks (McNamara et al. 1998, 1999) and a possible increase in the incidence of fire (Jones et al. 2009) are important new disturbances that have unknown consequences for stream and river ecosystems (Fig 2-10, Martin et al. 2008), but at this point we do not fully understand these impacts.

Long-term monitoring in the ARC LTER has provided several important insights. For example, there has been a slow but discernable increase in concentration of total suspended sediments (TSS) and nitrate in the Kuparuk River (Fig 2-11). We expected and found that increased nutrient additions favor greater primary production but also found an unexpected shift in production from diatoms to bryophytes, but do not yet know if increasing sediment load reduces production. With future warming we predict changes in the timing of life cycles of the dominant macroinvertebrates in the streams. And we anticipate that hydrologic and geomorphic changes will alter system-level linkages by disrupting migrations and predator-prey coupling that control the survival and growth of Arctic grayling – a keystone species – ultimately affecting the resilience and function of arctic stream ecosystems.

In this section we describe our efforts to address these expectations. The ARC LTER and its collaborating projects provide a unique opportunity to coordinate research on arctic streams with related research on terrestrial and lake ecosystems. As noted earlier, several closely-related projects will be active during this renewal. Monitoring and experiments maintained by the ARC LTER will directly support these other projects, while the projects will provide data and insights that would be impossible to obtain in the ARC LTER alone. Our research uses the same watersheds focused on by the terrestrial, lake, and land-water components of the ARC LTER, which facilitates opportunities for synthesis at a landscape level.

Current Activities: We have studied the structure and function of streams on the North Slope of Alaska for over 25 years (Peterson et al. 1986, Peterson et al. 1993, Slavik et al. 2004). As a part of the ARC LTER and closely related NSF-funded research, we have characterized the benthic autotrophic (e.g., Miller et al. 1992) and invertebrate (e.g., Hiltner 1985, Hershey et al. 1988, Hinterleitner-Anderson et al. 1992, Huryn et al. 2005) communities and have developed and applied methods to measure key ecosystem processes such as nutrient dynamics (Peterson et al. 1985, Peterson et al. 1997, Harvey et al. 1998, Peterson 1999, Peterson et al. 2001), primary production (Bowden et al. 1994, Finlay et al. 1994, Arscott et al. 1998, Bowden 1999), secondary production (Deegan et al. 1992, Deegan et al. 1997, Deegan et al. 2005, Huryn et al. 2005, Benstead et al. 2007), and decomposition (Peterson et al. 1986, Bowden et al. 1999, Benstead et al. 2005). These previous efforts provide a strong foundation for our continuing and new research.

Overview of Proposed Research. *Our overarching hypothesis is that arctic headwater streams are poised to undergo – and may have already begun – a phase of adjustment to climate warming that will substantially alter the hydrologic, nutrient, and sediment regimes in stream ecosystems in ways that will significantly change their biotic structure and ecological functions.* It will take considerable effort to address this hypothesis fully. We propose to start by realigning some aspects of our ARC LTER streams monitoring program and initiating new experiments to explore some of the potential effects of long-term climate change on arctic stream ecosystems, as outlined below.

Long-term monitoring: In the past we have sampled a wide array of stream types (nearly 100 individual sites at 30 different locations, Fig 2-12) in tundra, mountain, glacial, and spring environments throughout the foothills region of the North Slope (e.g. Huryn et al. 2005). In 2011-2016, we will maintain our monitoring at two key, long-term sites: the Upper Kuparuk River and Oksrukuyik Creek (Fig 2-2 and Table 2-1). The monitoring record for the Kuparuk River is particularly important because it is a candidate NEON monitoring and STREON experiment site.

Legacy effects from long-term fertilization: The flagship stream experiment in the ARC LTER program is the phosphorus fertilization of the Kuparuk River, which has continued for 26

consecutive seasons in conjunction with our long-term monitoring efforts. Phosphate added to the river elevates the concentration by $\sim 0.3 \mu\text{M}$, creating a treatment reach 3-4 km downstream. An upstream reach serves as the Reference. Impacts of this low-level, long-term fertilization have been studied extensively (Peterson et al. 1985, Peterson et al. 1993, Slavik et al. 2004) including an unexpected proliferation of bryophytes (Fig 2-13) that substantively altered the community structure and ecological functions in the treatment reach (Bowden et al. 1999, Fig 2-14). In 1996 we moved the P addition point 0.8 km below its location for the previous 10 years, creating a "Recovery" reach. We predicted that the bryophyte community in the previously fertilized "Recovery" reach would crash but found instead that it persisted for 8 years before gradually declining to a very low level (Benstead et al. 2007). Although the number of bryophyte individuals is now very low, they are not absent. This creates the possibility that the "Recovery" might respond more quickly to a new influx of nutrients than was the case at first. We hypothesize that if we reintroduce phosphate to this reach, the residual population of bryophytes will respond quickly and re-establish dominance in this reach, with important impacts on nutrient retention, primary production, macroinvertebrate community structure, and fish production. If we are correct we would have to reassess what we mean by "recovery" of a reach and its "resilience" to nutrient additions; i.e., legacy effects from previous nutrient enrichment might have long-lasting and unexpected impacts on responses to future nutrient disturbances.

Hydrologic disruption of stream and lake foodwebs: Anticipated changes in climate and hydrology could reconfigure trophic linkages within streams and between streams and lakes (Fig 2-15). Experimental and observational studies have shown altered life-cycles or community structure of freshwater macroinvertebrates in response to climate warming over a decade or less (Hogg and Williams 1996, McKee and Atkinson 2000, Harper and Peckarsky 2006, Burgmer et al. 2007, Durrance and Ormerod 2007, Dingemanse and Kalkman 2008, Doi 2008). With anticipated warming we predict significant changes in timing of life cycles of the dominant macroinvertebrate taxa of the Kuparuk River. Specifically, we predict that earlier spring thaw and warmer temperatures will result in earlier hatching of overwintering eggs, more rapid rates of growth and development, and earlier emergence of adults. We predict that mature larvae and emerging adults will have a smaller body size than those emerging under cooler thermal regimes due to higher metabolic rates with warming (Vannote and Sweeney 1980). Finally, we predict changes in voltinism, or the number of generations produced per season. We propose to increase the temporal resolution of our standard macroinvertebrate sampling regime by sampling at 10 to 14 day intervals from late June through mid-August. Based on preliminary studies, this sampling regime will be adequate to test these hypotheses.

Grayling have developed a migration cycle keyed to the seasonal availability of water and the macroinvertebrate food resources on which they depend. Thus, climate changes that alter future hydrologic regimes and macroinvertebrate life-cycles, as noted above, could have important impacts on this keystone species. In the short summer season, shifts of a week or two in open water (which have already been measured in the Kuparuk River, Fig 2-16) are potentially significant because a small shift in the timing of insect production either earlier or later in the season could deprive the fish of the food needed for migration and overwintering survival (Deegan and Peterson 1992, Deegan et al. 1999, Kratz et al. 2003). We will examine the implications of changing climate on these key biotic linkages by new work on fish migration in the early spring and late fall, stream productivity and trophic transfer, and food webs in winter refugia. We will test whether seasonal patterns of secondary production become increasingly biased toward high levels in the spring and early summer. This should result in food limitation for Arctic grayling prior to migration to winter refugia. The importance of migrating grayling as a trophic subsidy to lakes will be determined by evaluating whether the timing of migration has changed in the last two decades in response to the extended open water season (fall and spring migration assessment using a counting weir at the lake outlet stream) and by analysis of food

webs (using stable isotopes combined with quantitative sampling), diet, and growth of lake trout in lakes with and without migrating grayling.

Stream structure and habitat quality in a changing arctic landscape: The disturbances to streams expected to occur with climate change may be abrupt (as with direct impacts of thermokarsts, Fig 2-10) or progressive (as with the potential increases we have observed in sediment and nutrient loading, Fig 2-11). As noted above, we expect to see an increased incidence of drought conditions, which could have important effects on the distribution and abundance of macroinvertebrates and juvenile plus adult grayling. Thus, we expect to see important changes to the structure and function of small stream ecosystems, as noted in our overall streams hypothesis. Our past research suggests that these changes are occurring now and we expect them to continue over the course of this project. We propose to collaborate with and extend closely related projects that will examine the influences of thermokarst on small streams and the influences of changing seasonality on in-stream biogeochemical processing and grayling migration patterns. At these stream sites we will collaborate to continuously measure discharge, electrical conductivity, and temperature (air, water, and 3 hyporheic depths) and will sample 2-3 times each year for nutrients, major ions, algae, insects, and fish (abundance, diet). Growth rates of insects and grayling will be measured with length/weight frequency analysis and RNA:DNA ratios (calibrated to known growth rates in the Kuparuk; Caldaroni et al. 2006, Chicharo and Chicharo 2008). Relationships between landscape attributes and stream reach structure and productivity will be determined using newly acquired survey data and existing GIS data maintained by the ARC LTER and Toolik Field Station GIS facility.

Links to conceptual framework and core questions. The streams research plan for 2010-2016 addresses our three Organizing Questions in the following ways:

1. *How climate controls ecosystem states, processes, and linkages?* The realignment of our monitoring initiatives will allow us to focus new efforts on trends emerging from our long-term data, such as increases in nutrient and sediment loading, that may be important as climate change continues in the Arctic.
2. *Effects of disturbance on ecosystem states, processes, and linkages?* We will address this question with our proposed experiments on recovery and resilience, shifts in macroinvertebrate life cycles, and changes to small streams. We will compare streams in the AR burn area with our long term stream monitoring sites and will quantify the effects of burn-induced thermokarst features on stream ecosystem structure and function.
3. *How climate and disturbance interact to control biogeochemical cycles and biodiversity at catchment and landscape scales?* We have used various modeling approaches in the past to understand how disturbance structures stream types (Huryn et al. 2005), to quantify nutrient cycling (Wollheim et al. 1999, 2001), and to synthesize whole-stream ecosystem dynamics (Wan and Vallino 2005, Wan et al. 2008). These models are directly relevant to synthesis activities described in other components of this proposal. Furthermore, the collaborating researchers in the ARC LTER streams group are also co-PIs on separate projects that have major modeling components (on hydrology and biogeochemistry of arctic stream networks and migration and foodweb dynamics, respectively) that are directly related to the ARC LTER streams research.

Lakes Research: Rationale. Although the North Slope of Alaska has seen a significant increase in air temperatures since the 1950's, and significant permafrost warming (Hinzman et al. 2005), the long-term trend of summer lake temperatures in the Toolik region does not show a significant increase from 1980-2009. What has changed is the frequency of warm, dry summers. This is important because lake physical processes show distinct differences when cool, wet summers are compared to warm dry summers (MacIntyre et al. 2009). Cool summers promote extensive water column mixing. These changes in physical processes are reflected in

the biology of lakes, but biotic responses also vary according to lake depth. For example, summer air temperatures of three of the previous six years (2004, 2007, 2009) have been extremely warm, with air temperatures at the main Toolik climate station exceeding long-term averages by almost 2°C. Monitoring of over 20 lakes in the region (Table 2-1) indicates that ecosystem processes and population characteristics of organisms in shallow lakes respond more dramatically to inter-annual differences in temperature than do the same processes and populations in deeper lake ecosystems (Fig 2-17, 2-18). Zooplankton populations increase more rapidly in shallow than in deep lakes during warm summers because shallow lakes tend to thaw earlier, providing additional time for zooplankton populations to expand during the ice-free period. Also, increased feeding rates and decreased egg development times for egg-carrying cladocerans (Burkart 2007) increase birth rates for these species. Epilimnetic temperatures in deeper lakes do not increase as dramatically during warmer summers due to the greater heat storage capacity of a more extensive water column, meaning that zooplankton populations vary less between warm and cool summers. Increased water temperatures also have an impact on fish populations. During warm summers, condition factors of lake trout and char populations decrease (Fig 2-19). The decrease in weight of these cold-water fishes appears to be due to higher fish respiration rates in warmer epilimnetic waters (Johnson 2009).

Increased soil warming in lake watersheds is expected to increase rates of nutrient delivery to arctic lakes. We have no direct evidence that this has occurred in the Toolik region, although the possibility of mobilizing P from soils exists (Keller et al. 2007), and preliminary data suggest that nutrients may have recently begun to increase in streams on the North Slope (see streams section, Fig 2-11). To better understand the impact of chronic low-level increase in nutrient delivery to lakes we began a nutrient addition to a deep (E5) and a shallow (E6) lake in 2001. This experiment was a follow up to high-level nutrient addition experiments carried out in the 1980s and 1990s. The addition was calculated to double the amount of nutrient inputs into both lakes. We hypothesized that pelagic production would show a greater response to nutrient enrichment in the deeper lake while the shallow lake would exhibit a greater increase in benthic production. Consistent with our predictions, during the first four years of the experiment we saw a large increase in primary production in E5 (Fig 2-23), the deeper lake, and a smaller increase in E6. Since then, production and chlorophyll concentrations have remained elevated in E5 compared to pre-fertilization levels, while increases in E6 are more modest and not always elevated above pre-fertilization levels (Fig 2-24, 2-25). Both lakes show considerable inter-annual variability that appears to be driven by water-column mixing dynamics and temperature (Evans et al. 2008). Benthic production increased in the shallow lake but only in some years, while benthic production in the deeper portions of E5 has gone to zero as light levels have declined (Gettel 2006, Giblin unpublished). Zooplankton responded more dramatically to nutrient addition in years when summer water temperatures were greater (Fig 2-18; Burkart 2007). These results show that the response of lakes in the Toolik region to low-level increases in nutrient loading is strongly influenced by both lake depth and climate fluctuation.

Long-term Monitoring: We will continue our long-term monitoring of Toolik Lake and an additional 14 lakes near the field station to augment our understanding of the effect of climate variability and change on the structure and function of arctic lakes (Table 2-2). These lakes vary in size, depth, and geology of their drainage basins. Information from this monitoring program has become more valuable over time and has improved our understanding of how climate change interacts with other factors such as lake size, nutrient status, and disturbance. The lakes and the proposed frequency of sampling are detailed in Table 2-4.

We will increase the information about the thermal structure and mixing dynamics of lakes by maintaining a series of thermistor chains in several lakes (NSF-funded project on lake physics; MacIntyre et al. 2009). The LTER program will work to place these data within the LTER data base. The better temporal resolution of water temperature using these in-situ

loggers will provide an additional means of assessing lake thermal structure within the context of ongoing climate change.

Whole-lake Experiments: We will continue assessment of the response of lakes to nutrient additions and the recovery of fertilized lakes after addition of nutrients has ended (Table 2-3). We propose to continue a low-level addition of N and P to lakes E5 (deep lake) and E6 (shallow lake) for the next three years. Results suggest that the biological responses depend on the significant year-to-year variation in light intensity, temperature, and food web interactions. The integrated ecosystem response to this long-term experiment will take a number of additional years to be fully expressed. The cumulative effects of such low-level “press” experiments are difficult to study due to multiple non-linear responses of biological processes; thus we propose to use the hierarchical-response framework (Smith et al. 2009) to interpret the results of this experiment. During this next phase of LTER research, we will reduce the frequency of sampling on Lakes E5 and E6 as we anticipate more modest annual changes in ecosystem properties (Table 2-4). At the end of the fertilization period we will take sediment cores from a variety of depths in both lakes to compare with cores taken prior to fertilization. We found major changes in all sediment parameters in our heavily fertilized lakes, and this will allow for a robust comparison of strong versus weak nutrient disturbances on lake dynamics.

We will also continue to examine the long-term recovery of two lakes, N1 and N2, from high-level fertilization experiments that ended more than a decade ago. Both these lakes experienced bottom water anoxia during the fertilization period. While phytoplankton and zooplankton biomass returned to pre-fertilization levels within a few years (O'Brien et al. 2004), bottom water oxygen and sediment nutrient release has not. This experiment may provide a better analog to a high-level nutrient disturbance such as occurs with a large thermokarst failure near a lake (e.g., Fig 2-4, Center). We will continue monitoring limnological conditions in Lakes N1 and N2 but at a lower frequency of sampling for the next six years. Near the end of the six years we will collect sediment cores to determine the rates of recovery and whether sediment stores of nutrients and iron have returned to pre-fertilization values.

New Activities: The tundra fire of late 2007 created a unique opportunity to examine the integration of landscape disturbances within a watershed on lake ecosystem processes. The assessment of terrestrial and aquatic ecosystems by the ARC LTER over the previous 20 years provides an opportunity for synthesis of the interactions between terrestrial and aquatic ecosystems in response to large landscape disturbances. Early in 2008, we sampled 5 lakes that captured a range of lake morphometry and burn conditions within the Anaktuvuk River Burn (Fig 2-2). Biological parameters, water chemistry, and sediment chemistry (with one exception) largely fell within the range of characteristics of lakes outside the burn area (Fig 2-20). We sampled these lakes again in 2009 and plan to track changes in these lakes over time as thermokarst development on the lake shores proceeds (Fig 2-22). Interestingly, Dimple Lake (Table 2-1) experiences intermittent meromixis and had laminated sediments (Fig 2-21). This is the only such lake we have found on the North Slope and it provided an ideal situation for other investigators to examine the 10,000 year fire history of the region (Hu et al. submitted).

Thermokarst within the burned watersheds and shoreline slumping adjacent to the lakes vary considerably among the five lakes and provide an opportunity to assess impacts of landscape disturbance on lake ecosystem function and community composition (Fig 2-22). We will continue to assess effects of the tundra fire on lakes in three ways. First, we will compare measurements of burn area lakes to the same physical, chemical, and biological measures collected in the other LTER lakes. Second, we have taken sediment samples to assess sedimentation, benthic respiration, and nutrient fluxes from the sediments; we hypothesize that the response of the benthos to these thermokarst inputs will greatly affect the response of the lake to the disturbance. This work is being largely carried out by C. Johnson as part of his IPY post-doc, but he is receiving advice, equipment, and sampling help from the LTER. Finally, we will examine the degree of thermokarst activity in the watersheds of burn area lakes and

conduct gradient analyses (Caston et al. 2009) to assess the impact that these fire-related disturbances have on lake ecosystem processes.

We will also investigate changes in the mixing regime by deploying thermistor chains in two of the lakes within the burn area. At least one of the lakes in the burn area does not mix every year (Fig 2-20). We anticipate that additional terrestrial inputs from thermokarst failures will decrease light transparency (Fig 2-4, Center), increase the frequency of meromixis, and reduce the ability of fish populations to thrive. Our proposed research will allow us to assess these interactions and form a more complete understanding of the linkages between terrestrial and aquatic ecosystems.

Thermokarst slumps also occur in unburned lake watersheds. In some cases thermokarst may increase nutrient inputs, and increased delivery of particulate material may reduce light and increase benthic oxygen demand in a dramatic pulse event that can last several years. In 2000 a thermokarst appeared on the shores of Lake Fog 4 just as monitoring began. We have no earlier data, but since that time the shore has stabilized and chlorophyll levels and zooplankton biomass have decreased (Fig 2-26).

Link to conceptual framework and core questions. The lakes research plan for 2010-2016 addresses our three Organizing Questions in the following ways:

1. *How does climate control ecosystem states, processes, and linkages?* We address this question through our long-term monitoring and survey work and our experiments. The monitoring and survey work establishes relationships between climate and other environmental drivers as well as short-term responses to weather and its annual and seasonal variation (Fig 2-3). We also measure directly the linkages with stream and terrestrial systems as part of input-output studies. Experimental manipulations expand our understanding of key controls on ecosystem processes and states and lead to predictions of future states in response to environmental changes.
2. *How do disturbances change ecosystem states, processes, and linkages?* We study disturbances directly by measuring their impacts in burned and thermokarst-impacted sites. Our experimental manipulations also represent controlled disturbances to nutrient supply, helping to isolate effects of and responses to individual components of change in complex disturbances like fire and thermokarst.
3. *How do climate and disturbance interact to control biogeochemical cycles and biodiversity at catchment and landscape scales?* We study the interactions of climate and disturbance at catchment and landscape scales by means of whole-watershed comparisons in a range of both disturbed and undisturbed lake catchments. By coordinating this research with the terrestrial, stream, and landscape interaction groups working in the same watersheds, we will achieve a synthesis of disturbance effects at the watershed and landscape scale.

Landscape Interactions Research: Rationale. In essence, the “Landwater” research begins where the terrestrial research ends, and works with the stream and lake groups to determine how the input of materials from upland or upstream systems (land to streams, streams to and from lakes) affects ecosystem structure and function. This conceptual integration is accomplished by **(1)** determining the controls on and production rates of C,N,P species into soil waters, **(2)** linking the processing and movement of these soil-water materials to surface waters through measurements and hydrologic modeling, and **(3)** assessing how the spatial configuration and interactions of lake and stream ecosystems on the landscape operate to set the bounds of aquatic ecosystem productivity and dynamics. In this renewal proposal, we will add a fourth component to address how disturbance from thermokarst failures and tundra fires alters the movement, processing, and impacts of C and nutrients entering aquatic ecosystems.

Background. Although the simple idea of a hydrological catchment as a study ecosystem has provided a clear framework of biogeochemical cycling within and between ecosystems for several decades, it has proved an extraordinary challenge to measure the outputs of energy and

biochemical elements and relate them back to the underlying processes controlling the structure and function of the terrestrial ecosystem – we still understand little about the complex dynamics producing and delivering materials from land to surface waters (e.g., Kling 1995, Michalzik et al. 2001, Stieglitz et al. 2003). Our initial research in landscape interactions focused on C cycling, and set the stage for current research directions. We found that the C loss from the entire Kuparuk basin via streams and lakes was $\sim 4 \text{ g C m}^{-2}$ of land surface per year, with almost one third of this loss as CO_2 and CH_4 released from surface waters directly into the atmosphere (Kling et al. 1991, 1992, Cole et al. 1994). We also learned that the production of DOC from plant roots alone is extremely high, from $1\text{-}4 \text{ g C m}^{-2}$ per day, whereas DOC catchment export is only $2\text{-}3 \text{ g C m}^{-2}$ per year! Our conclusion is that microbial processing of this C must be ~ 2 orders of magnitude higher than the net catchment export (Judd and Kling 2002; Kling, Nadelhoffer, Sommerkorn, Rastetter *unpublished*). Given this strong biogeochemical influence across landscape scales, we asked questions about the spatial and temporal patterns of soil C and nutrients and of microbial processing – i.e., where are the control points, what organisms are responsible, and how do interactions among ecosystems affect their structure and function.

Overview of current activities: (1) Land-water Linkages - In our LTER we have focused on hillslopes as the “missing scale” required to transfer detailed process information to larger and larger areas. The toposequence of a hillslope represents the major ecosystem types and landscape morphology of an entire catchment, yet can be studied in depth and cohesively (e.g., Giblin et al. 1991; Fig 2-5). In this context, we determined the detailed pattern of DOC concentration in soil waters on the Imnavait basin toposequence; Fig 2-27 shows early and late summer DOC peaks at mid-slope, slightly elevated concentrations at the footslope near the valley floor throughout the summer, and no evidence of major transport of DOC from upslope to downslope during the summer. Our interpretation of this pattern is that most DOC production and consumption occurs *in situ*, which is consistent with the idea presented above that large amounts of DOC processing occur before DOC leaves the catchment. Preliminary data suggest that the same patterns (and interpretation) occur for other dissolved materials such as N and P, and the next research step is to examine the specific processes and rates at the landscape points where concentrations are high or they change rapidly. This step will be accomplished by continuing to improve our hydrologic and biogeochemical models (Fig 2-28) by incorporating information on biogeochemical processing at key “control points” on the landscape. Although the mass of C or nutrients processed on the hillslope may be much greater than that transported downslope and into streams and lakes, the materials transported have both great impacts on the functioning of receiving surface waters (see Lake and Stream research), and can be substantial relative to the net C storage on land (Fig 2-28, lower left; Rastetter et al. 2004).

(2) Microbial processing across the landscape - Consideration of how the basic processes of production, respiration, and gas exchange are linked and interact across the landscape requires an integration of concepts in microbial and landscape ecology. For example, we must consider the congruence of ecotones and spatial boundaries of ecosystems with the rates of microbial activity, as well as the biogeographical diversity of microbes and the time scales that microbial populations adapt physiologically and change population frequencies. In our research we found that microbial community composition was distinct among tundra ecosystems (Judd et al. 2006; Zak and Kling 2006). In addition, microbial activity differs, with downslope wet-sedge tundra exhibiting the greatest extracellular enzyme activity. Thus it is apparent that topographic variation in plant litter biochemistry and soil drainage shape the metabolic capability of soil microbial communities, which, in turn, influence the chemical composition of DOM and the microbial composition across the tundra landscape.

In addition to discovering these patterns of community composition and activity, we tested an ongoing debate that revolves around how species composition and ecosystem function are related. We manipulated the composition of DOM fed to aquatic bacteria to

determine effects on both bacterial activity and community composition. Bacterial production, DOC-specific bacterial production, and DOC consumption were greatest in mesocosms fed soil water DOM, but the really novel finding was that adding upslope DOM to stream and lake bacterial communities resulted in significant changes in bacterial community composition relative to controls (Judd et al. 2006). In these experiments the bacterial community composition converged based on DOM source regardless of the initial bacterial inoculum. In other words, when lake bacteria were fed soil or stream DOM, the lake community assemblage shifted to resemble the species present in the soil or the stream. Clearly the soil and stream bacteria were already present in the lake in undetectable numbers, but when exposed to soil or stream DOM these populations had a metabolic advantage and grew to replace the originally-dominant lake bacteria. We have now confirmed this rapid shift in community composition and in turn bacterial production in experiments where both temperature and nutrients were manipulated (Adams et al. in press, Adams 2010). In similar experiments we also examined how photo-oxidation of DOM affected microbial activity and DOM processing along these dominant hydrological flow paths. Finally, the impacts of DOM photo-oxidation depended in part on DOM source, but were also influenced by the relatively rapid shifts in bacterial community composition to groups better able to consume photo-products or tolerate harmful radicals (Judd et al. 2007); this result has great implications for the fate of DOM produced by thermokarst failures or burning, as described below under New Activities. Overall, these results indicate that variation in DOM, temperature, or nutrients in soil and surface waters influenced bacterial community dynamics, and in turn different communities controlled rates of carbon processing in set patterns across the landscape. We must now combine this basic understanding with the role of natural variations driven by climate, hydrology, and disturbance to determine processing rates of C and nutrients on the landscape.

(3) Landscape-level ecosystem interactions - In earlier LTER research we showed that in a connected series of lakes and streams there was consistent and directional (downslope) processing of materials that produced spatial patterns in many limnological variables, and these patterns were coherent over time (Kling et al. 2000). That is, the interactions of material processing in both lakes and streams are critical for understanding the structure and function of surface waters, especially in a landscape perspective. In recent research we have expanded these ideas to show that the processing of DOM by microbes, and the species of microbes present, vary consistently as water moves through a network of streams and lakes in the Toolik catchment (Crump et al. 2003, 2007, Adams 2010). Both lake and stream systems shared certain bacteria species, and stream communities changed with distance from the upstream lake, suggesting both dispersal of species between lakes and streams as well as inoculation and dilution with bacteria from soil waters or hyporheic zones (Crump et al. 2007). At the same time, similarity in lake and stream communities shifted gradually down the catchment (Fig 2-29), although dispersal appears to influence bacterioplankton communities via advection less than the competition (species sorting) between different bacterial populations (Crump et al. 2007, Adams 2010). Overall these results reveal large differences in lake-specific and stream-specific bacterial community composition over restricted spatial scales (< 10 km), and suggest that geographic distance and connectivity influence the distribution of bacterioplankton communities across a landscape; however, at present we have no good way of predicting how rapid-pulse, patch-related disturbances such as fire and thermokarst will alter our view of controls on biodiversity and material processing; this lack of knowledge will be addressed in the proposed research by measuring similar processes we have in the past, but focusing on sampling the same sites that the Terrestrial, Streams, and Lakes Groups are using that highlight the key landscape disturbances of fire and permafrost alteration (e.g., Fig 2-30).

New activities. Our new activities will focus on the nature and impacts of disturbance on land-water linkages of C and nutrients, and on the processing rates and fate of these new materials

released from disturbed tundra. Preliminary data verify that the chemical nature of DOM extracted from burned and unburned soil cores and tussock tundra has a high degree of photolability (Fig 2-31). Burning produces more chromophoric C, indicated by higher fulvic acid and specific UV absorbance (SUVA) values (Fig 2-31). Given its limited prior exposure to sunlight, along with evidence for high chromophoric C content, we hypothesize that DOM from melting permafrost, thermokarst failures, and burned tundra will be more photo-labile than DOM currently found in arctic surface waters. Additionally, DOM rich in chromophoric C stimulates bacterial metabolism following photodegradation (Tranvik & Bertilsson 2001, Moran & Covert 2003), and as we found near Toolik this results in increased rates of DOM removal by bacteria (Cory et al. 2007, Judd et al. 2007; Fig 2-31). Preliminary data also suggest a greater export of DOM (as DOC) from burned catchments compared to unburned catchments (Fig 2-32), suggesting that the DOM exported is susceptible to coupled photochemical and biological oxidation. This is important for arctic C cycling, and it will influence whether this “new” DOM is respired to CO₂ and returned to the atmosphere, or transported to the ocean in a more degraded form.

To test this hypothesis of the role of newly supplied DOM from disturbances in arctic C cycling, we will combine our monitoring of disturbed sites with experiments on small patches of tundra, burning them to generate altered plant and soil C, and on soils collected from thermokarst failures. We will manipulate temperature, moisture, and light exposure to test how changes in climate interact with alteration of DOM processing by disturbances, and how this alteration is modulated by changes in bacterial community composition.

Link to conceptual framework and core questions

1. How does climate control ecosystem states, processes, and linkages? The Landwater group contributes to answering this by monitoring changes in soil water chemistry, hydrology, C and nutrient export, and microbial processing at three different scales: the 0.2 ha Tussock Watershed, the 2.2 km² Imnavait catchment, and the 65 km² Toolik Lake basin (Tables 2-1, 2-2). The data generated will support our long-term database of changes in water chemistry and summer thaw depth, and our modeling efforts on downslope nutrient movement.
2. How do disturbances change ecosystem states, processes, and linkages? In conjunction with the Streams and Lakes Groups, we will study sites disturbed by thermokarst failures (Lake NE-14, streams; Fig 2-30) and sites in the Anaktuvuk burn area using our Toolik Inlet and Imnavait catchments as controls (Fig 2-32). In addition, working with the Terrestrial Group we will manipulate tundra by burning small patches at various intensities to determine changes in C and N cycling and the quality and quantity of DOM released from burned plants and soils (Fig 2-31); these burned materials are in turn exported to surface waters.
3. How do climate and disturbance interact to control biogeochemical cycles and biodiversity? We will combine our monitoring of undisturbed control sites with measurements taken in thermokarst and burned areas – because both areas are exposed to the same climate, the differential is attributed to the impacts of disturbance and its interactions with climate variation. To better understand this interaction between the two controlling factors, we will perform experiments in control and disturbed mesocosms where temperature and moisture are also manipulated. Adding this information to the large-area C and energy budgets determined by the Terrestrial Group, we can begin to update our current models to predict how future warming and changes in hydrology will interact with disturbance to alter the transfer and processing of materials between ecosystems.

Human Dimensions Research: To date, Human Dimensions research of the ARC LTER has focused on rural villages and how changes in ecosystems have affected human livelihoods. We have engaged two communities of northern Alaska in our work, Kaktovik and Anaktuvuk Pass. With supplemental funding we have involved Anaktuvuk Pass in the production of a video that documents local ecological knowledge about changes in access to and harvesting of caribou.

We have also partnered with Kaktovik to document local observations of change and to participate in a project that measures subsistence sharing, using social network analysis. Over the next six years, we plan to build on these Human Dimensions activities, working with Alaskan village communities to understand their perceptions of climate change and its impacts on subsistence lifestyles, including their use of the land and their understanding of how the land and freshwaters are changing. The implications of tundra fires, permafrost melting, and thermokarst dynamics will also be a focus of this research. The ARC LTER studies are linked to similar research of the BNZ LTER, and both are led by Gary Kofinas of University of Alaska Fairbanks, who is also a BNZ investigator. This linkage provides an opportunity for comparisons of social-ecological conditions in interior Alaska, the North Slope, and Brooks Range areas.

The ARC LTER Human Dimensions research is also linked to an LTER network wide study, "*Maps and Locals (MALS): A Cross-Site LTER Comparative Study of Land-Cover and Land-Use Change with Spatial Analysis and Local Ecological Knowledge*," led by Kofinas, Pontius, and Sayre. Our LTER's focus in MALS analyzes maps from three points in time at two locations, an area of the Prudhoe Bay oil field and an area in the village of Nuiqsut, located southwest of Prudhoe Bay. Initial analysis of land surface change suggests a significant increase in thermokarst activity in the vicinity of roads and gravel pads. In MALS we will use our spatial analysis as a focus of discussion with villagers and oil field workers to document perceptions and explanations of change, and its implications to people.

Thus far we have used Annual Supplemental funds to support our ARC LTER Human Dimensions effort, along with funding from complementary research grants. In the next 6 years we will add to these funds to include one person's travel and field work. The eventual goal is to develop an independently-funded project linked to the ARC LTER research on the role of climate and disturbance in landscape change in northern Alaska. We have followed this route successfully in the past to support development of collaborating research projects on herbivory and soil food webs, the Anaktuvuk River Fire, and stream insect communities. Further development of the Human Dimensions component will require taking the following steps:

- Continue to develop partnerships with local communities and facilitate meetings of researchers and North Slope residents.
- Establish formal linkages between the BNZ and ARC LTER Human Dimensions research programs, to allow for effective comparative analysis.
- Explore and develop new methods for integrating local knowledge, social scientific data, and ecological data, and develop new collaborations with non-LTER researchers currently working in Human Dimensions research.
- Include Human Dimensions researchers in the development of new ARC LTER research, ensuring that new studies contribute more strongly to social-ecological questions.

Network-level and Cross-site Research: LTER Network-level and cross-site research has been an important part of the ARC LTER for over 20 years and will continue to be important in 2011-2016. In the past much of this work has been *ad hoc* in that it was not part of the plans laid out in renewal proposals but was developed as opportunities arose at All-Scientists meetings, coordinating committee/science council meetings, or special competitions for NSF or network office funds; e.g., projects that we have contributed to include Mulholland et al. 2001, Knapp et al. 2008, and the current LTER TRENDS project. We will continue to support participation in these activities by ARC LTER and collaborating personnel, and have included estimates of travel support and other costs in our budget request.

For 2011-2016, we are specifically committed to developing a robust collaboration, comparison, and synthesis of our research with that of the BNZ LTER site, which is focused on the Alaskan boreal forest landscape immediately South of us. Gus Shaver spent the winter of 2008-2009 at the University of Alaska and met regularly with BNZ scientists to discuss future collaborations. For several years we have invited BNZ scientists to attend our annual winter

meeting, and an increasing number of BNZ scientists visit Toolik Lake each summer for comparative research. Reviewers who read both of our proposals will notice that we are moving gradually to a similar set of research goals and questions focused on the role of disturbance and its landscape-scale importance. Over the next 6 years we will pick up the pace of this emerging two-biome comparison. We will continue to exchange field site and annual meeting visits and in Year 3 of this renewal we plan a meeting to explore cross-site comparisons and synthesis of our disturbance studies.

The LTER Network is now moving to develop an explicitly *network-level* research program and we are committed to participation in this program as it develops. The centerpiece of the program is called “*Integrated Science for Society and Environment*” (ISSE; Collins et al. 2006); as part of its development all LTER sites were asked to place their work in a common conceptual framework including Human Dimensions components and basic research on ecosystem structure and function. Disturbance regimes are at the core of this framework, and we had little difficulty translating our new conceptual framework (Fig 2-2) into the ISSE standard (Fig 2-33). As the ISSE program develops, the ARC LTER is prepared to participate as a part of the LTER Network that represents not only a unique suite of ecosystems in an extreme environment but also a unique suite of ecosystem services including extensive subsistence land use, the largest wilderness areas in the United States, and rapid changes in mineral and energy extraction industries.

We are also participating actively in three other network synthesis activities that will continue in 2011-2016: (1) “The Disappearing Cryosphere”, (2) “Future Scenarios”, and (3) “Microbial Biodiversity”. These are still in the planning stages but we are setting aside the time and funds to enable full participation.

Finally, the ARC LTER project plans to continue its participation in several other national and international research networks. These include the NEON, STREON and GLEON networks (www.neoninc.org/; <http://www.gleon.org/>) focused on stream and lake ecosystems and the International Tundra Experiment (ITEX) network, which has already led to several PanArctic syntheses of terrestrial plant growth and C cycling processes (e.g., Arft et al. 1999, Walker et al. 2006, Wookey et al. 2009, Oberbauer et al. 2008). The US National Environmental Observatory Network (NEON; STREON is a part of NEON) has already identified Toolik Lake as one of its 20 sites to be developed during 2011-2016. Emerging opportunities for synthesis and collaboration include the US Arctic Observatory Network (AON) and its international partners SAON, SCANNET, ISAC, and other IPY-related groups. ARC LTER investigators are already working with all of these networks to optimize our ability to contribute data and knowledge of the Arctic.

Synthesis: The ARC LTER research plan is designed to optimize the productivity of individual investigators and research groups while also providing significant opportunities for multidisciplinary synthesis and modeling (Fig 2-34). To achieve this, the project is strongly committed to a wide range of collaborations in which the ARC LTER plays a central coordinating role. Key aspects of that coordinating role include the maintenance of a set of core long-term observations, a data base, and experiments that serve to stimulate and attract a wide range of additional research done on ARC LTER sites. The ARC LTER also provides field assistance and laboratory support for many of its collaborators. Finally, the ARC LTER supports synthesis directly by providing regular opportunities for investigators to meet; in addition to our annual winter meeting and the intense interactions among investigators during the summer field season, we have reserved funding for small workshops and individual travel to support synthesis in each year of this renewal.

Operating in this way, the ARC LTER is able to address significant research questions that would not be possible for individual projects or smaller groups to approach, particularly those dependent on frequently-renewed funding. The diverse group of terrestrial and aquatic ecologists working in the same area and often in the same place allows us to evaluate the

regulation and role of individual populations and processes in the context of whole ecosystems, and it allows us to evaluate the importance of spatial linkages in heterogeneous landscapes and watersheds. The ARC LTER research design is the template that allows this to happen.

For the years 2011-2016, our **Overall Goal is to understand changes in the arctic system at catchment and landscape scales as the product of: (i) Direct effects of climate change on states, processes, and linkages of terrestrial and aquatic ecosystems, and (ii) Indirect effects of climate change on ecosystems through a changing disturbance regime.** This goal reflects the continued evolution of our understanding of the landscape of Northern Alaska, and of high-priority research needs in a constantly changing environment. To meet this goal we have redirected some project resources, but the core of our long-term research will continue; the main changes are intended to strengthen collaborations and synthesis among lakes, streams, terrestrial, and landscape interactions research by creating opportunities for comparisons and other research within the same landscapes and watersheds.

Modeling will continue to be a key synthesis tool. The ARC LTER has a long history of working with models at multiple scales of time and space (described above). At the catchment or watershed scale we provided much of the data used to develop models of hydrology, snow cover, and C-N-water interactions (e.g., Stieglitz et al. 2000, 2003) that are now used at other LTER sites (e.g., HJ Andrews). At the scale of hillslopes or large, heterogeneous landscapes we have collaborated in development of models of hydrologic connectivity, downslope movement of water and materials, Net Ecosystem Exchange of carbon (NEE), and ecosystem stoichiometry (e.g., Williams et al. 2000, Rastetter et al. 2004, Yano et al. 2010, McClelland et al. 2004, Wollheim et al. 2001, Kling et al. 2000, Stieglitz et al, 2003). The ARC LTER research design is intended to optimize model-data interactions as these models are developed further, with the aim of understanding the interactive effects of disturbance and climate change at these scales. Another focus of this effort is on understanding problems of temporal and spatial scaling, or how to use short-term, fine-scale measurements to make accurate long-term, large-area predictions (e.g., Williams et al. 2001, Rastetter 2003, Shaver et al. 2007). In addition to the collection of appropriate data sets at different scales and the coordination of multiple collaborating projects, the ARC LTER promotes these synthesis efforts by supporting small workshops and travel by LTER personnel to participate in these activities.

Results of ARC LTER research are also used in developing models of regional and PanArctic change, with the eventual goal of understanding and predicting **“How do changes in arctic catchments and large landscapes feed back on changes in climate, disturbance, and human use of arctic lands?”** We already know, for example, that changes in vegetation composition (shrubiness) have the potential to act as a positive feedback on regional climate warming (Chapin et al. 2005), and we know that increased freshwater inputs to the Arctic Ocean are already changing ocean salinity, chemistry, and potentially its interactions with the global ocean (Peterson et al. 2006, McClelland et al. 2004). ARC LTER research will contribute to further development of these models, in particular by documenting the role of disturbance in large-area landscape disturbance and change relative to the direct impacts of climate factors such as climate warming.

A final synthesis goal is to develop a model of the North Slope of Alaska that incorporates the Human Dimension explicitly, asking, **“How do climate and disturbance regime shape the function of the North Slope of Alaska as a regional socio-ecological system?”** In this effort we will collaborate with the entire LTER Network as part of the ISSE initiative (Collins et al. 2006; Fig 2-33). In this case we see the ARC LTER as a resource that can provide data and knowledge especially about the broader impacts of changes in a site with a unique suite of ecosystem services and human interactions, in a part of the United States where local, subsistence land use is still common and important and where climate change and its impacts are felt immediately and directly.

Fig 2-1. Research of the ARC LTER involves multiple landscape components and processes. For management purposes the research is divided into terrestrial, lake, stream, and landscape interactions components. Here, this structure is shown against a background of the foothills and mountains at Toolik Lake (modified from U.S. Postal Stamp Series Nature of America # 5); examples of research by each component are in the boxes. In 2010-2016 we will add a fifth component, focused on subsistence land use and impacts of climate change and on Native communities.

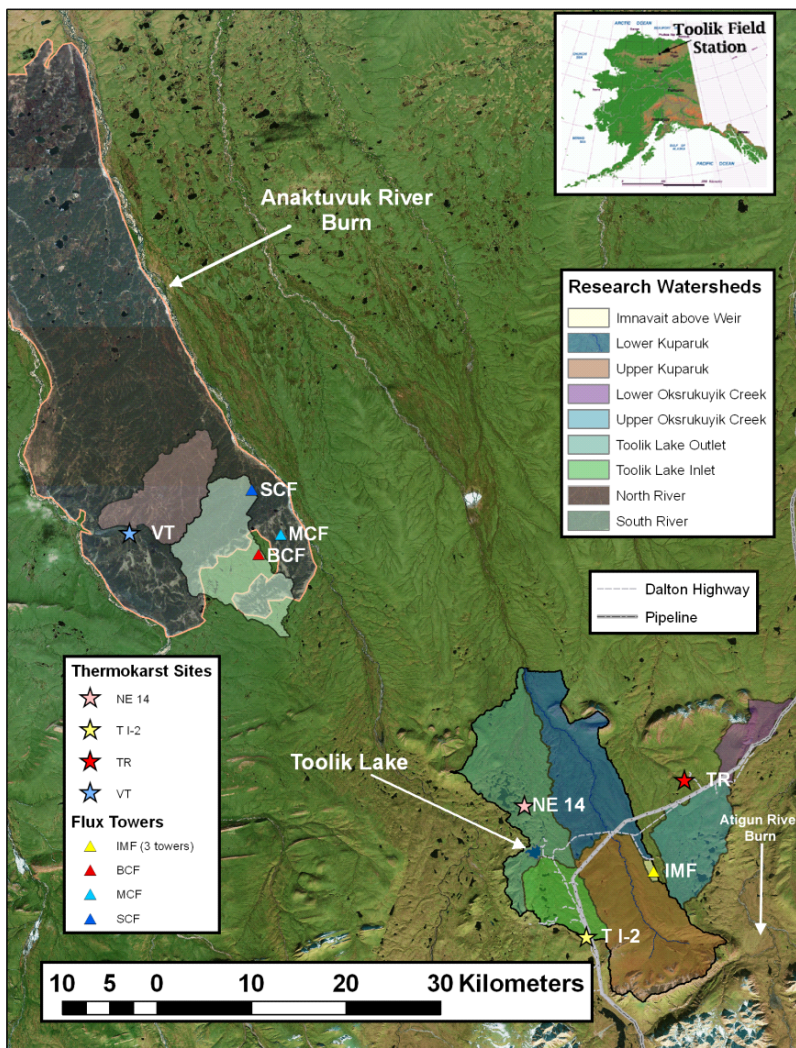
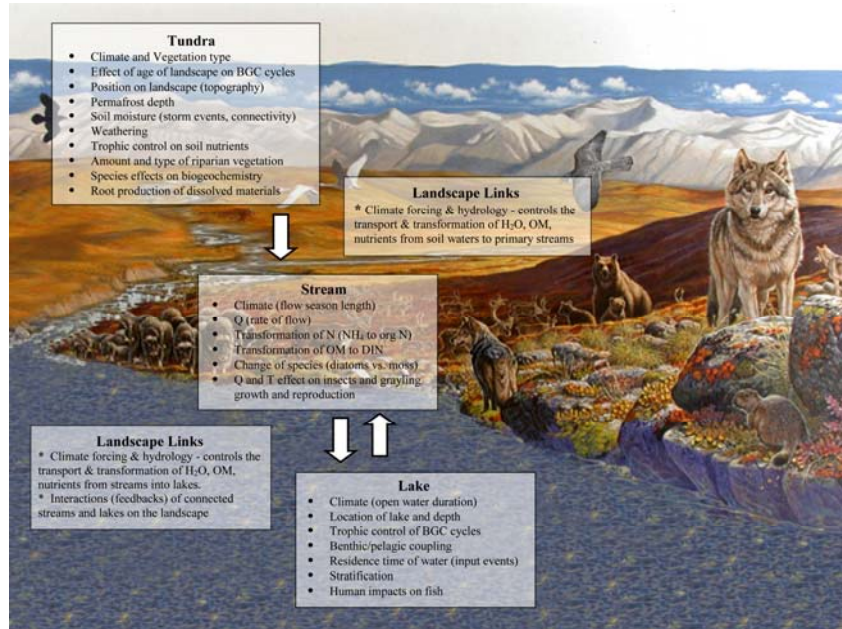


Fig 2-2. Major research sites and place names. The main Arctic LTER research site includes the drainage basin enclosing the two branches of the headwaters of the Kuparuk River (including Toolik Lake and its drainage basin, the upper Kuparuk River, and Imnavait Creek). The ARC LTER research also includes sections of Oksrukuyik Creek, lakes and springs in the mountains and foothills near Toolik Lake (not on this map), the 2004 Atigun River Burn (not shown) and the 2007 Anaktuvuk River Burn 40 km to the northwest.

Key to thermokarst and flux sites:

NE-14 = glacial thermokarst on lake shore; TI-2 = Toolik Inlet thermokarst; TR = Toolik River thermokarst; VT = Valley of Thermokarsts; IMF = Imnavait Creek flux towers (3); BCF=unburned control flux tower; MCF=Moderate burn flux tower; SCF=severe burn flux tower.

Table 2-1. Sampling sites of Arctic LTER research. For details of location and description see Fig 2-2 and <http://ecosystems.mbl.edu/ARC/>

Core study watersheds and watershed-scale comparisons used to integrate the LTER	
<i>Toolik Inlet Watershed</i>	A 48 km ² watershed of streams and lakes that forms the largest input of water and materials into Toolik Lake, located on the 10,000 yr aged surface
<i>Upper Kuparuk Watershed</i>	146 km ² watershed predominantly underlain by older Sagavanirktok-aged surfaces (125,000 to 780,000 yr), extreme headwaters on 50,000 yr aged surface
<i>Imnavait Watershed</i>	2.2 km ² watershed with weir on primary stream and weir on one of many distinct water tracks; >300,000 yr surface. Long-term ¹⁵ N tracer experiment
<i>South River Watershed</i>	115 km ² watershed of varying burn severity within 1000 km ² Anaktuvuk River Burn (mostly >300,000 yr aged surface)
Core disturbance sites	
Anaktuvuk River Burn	Multiple sites on 1000 km ² 2007 burn including numerous whole catchments of varying burn severity and thermokarst activity
Atigun River Burn	18 ha 2004 burn monitored yearly by REU students
TLNRA Thermokarsts	Various thermokarst features within and near the Toolik Lake Natural Research area, including gully thermokarsts (Toolik River, I-minus-2) and thaw slumps (lakes NE-14 and I-minus-1, and Imnavait Creek).
"Valley of Thermokarsts"	Numerous active layer detachments in 96 km ² sub-watershed of 2007 AR Burn
Terrestrial ecology and ecosystem comparisons	
Toolik Lake area including Toolik Inlet watershed	Multiple sites on Itkillik I and Itkillik II aged surfaces (10,000-60,000 yr old), including moist acidic and nonacidic tundras, wet sedge tundra, riparian tundra, and dry heath
Imnavait Creek	Toposequences on Sagavanirktok-age surface (~300,000 yr), ranging from dry heath to wet sedge and riparian shrub communities. ¹⁵ N tracer experiment
Anaktuvuk River Burn	Multiple sites on areas of varying burn severity including South River watershed
Stream ecology and ecosystem comparisons	
Upper Kuparuk River	4 th order, clear-water tundra stream; 25 km in length from origins to Dalton Hwy. crossing (146 km ² area); draining surfaces 60,000 to 780,000 yr old.
Oksrukuyik Creek	3 rd order, clear-water tundra stream; 12 km in length (73.5 km ² area); tributary of the Sagavanirktok River. Headwaters in Itkillik 1 (~50,000) surface and mid-reaches in ~300,000 yr old Sagavanirktok 1 surface
South River, North River	Streams within Anaktuvuk River Burn
Survey streams	Multiple streams in mountains and foothills representing Mountain, Glacier, Tundra and Spring stream types.
Lakes ecology and ecosystem comparisons	
Toolik Lake	25 m deep, 1.5 km ² , ultra-oligotrophic, receives inputs of Toolik Inlet watershed
Survey lakes, Toolik Inlet series	Multiple lakes differing in geologic setting, area, depth, and trophic structure including fish
Experimental and Control Lakes	Paired Shallow and Deep lakes including controls (Fog-2, Fog-4), fertilized (E-5, E-6) and recovering lakes (N-1, N-2)
NE-14	Active glacial thermokarst on shore of 24 ha lake
Perched, Horn, Dimple Lakes	Shallow and deep lakes with/without fish in Anaktuvuk River Burn. Perched and Dimple lakes in South River watershed
Landscape Interactions and hillslope and catchment processes	
Tussock Watershed	1 ha watershed with a primary stream and weir located on South shore of Toolik Lake, ~100,000 yr aged surface
Imnavait Watershed	Long-term ¹⁵ N tracer experiment, water-track hydrology and biogeochemistry, hillslope studies of water, C, N transport and cycling
Toolik Inlet Watershed (the "I-Series")	A series of streams and lakes that form the largest input of water and materials into Toolik Lake, located on the 10,000 yr surface
South/North River and Dimple Watersheds	Watersheds of varying area and burn severity within the 1000 km ² Anaktuvuk River Burn

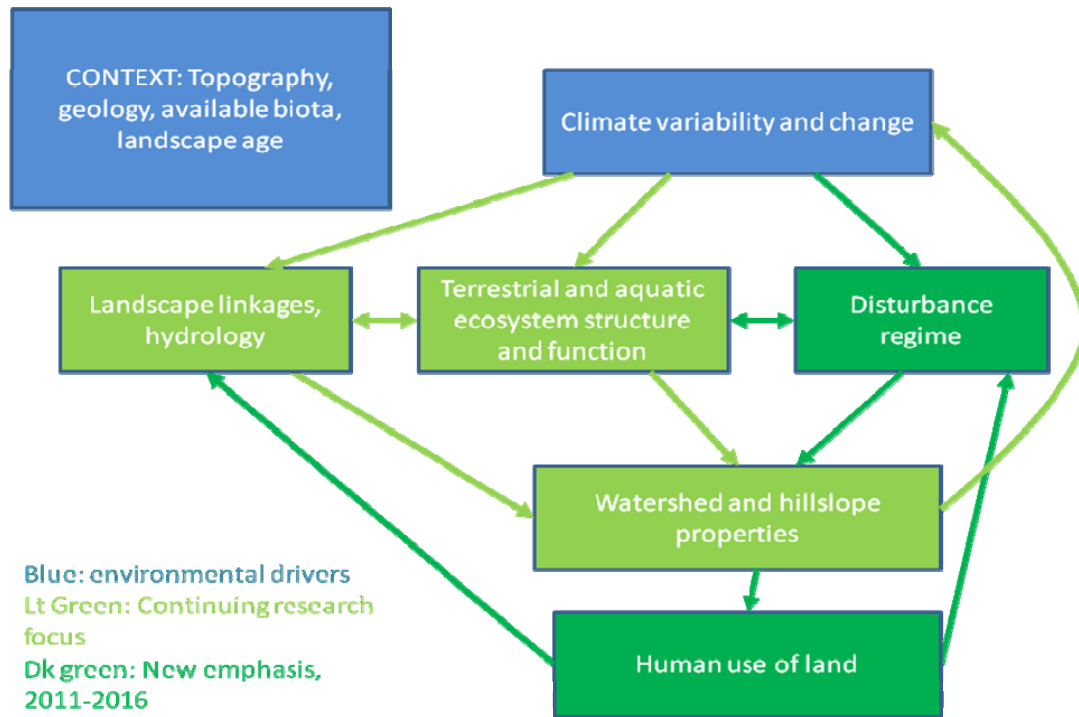


Fig 2-3. Conceptual Framework for 2011-2016. (see text for explanation).



Fig 2-4. Disturbances create patches of dramatically different biogeochemistry and environmental conditions that can dominate the C or energy balance and community dynamics of much larger areas. LEFT: 1000 km² Anaktuvuk River Burn (arrow) adjacent to the 9200 km² Kuparuk River watershed. CENTER: <1 ha thermokarst (arrow) on the shore of 25 ha Lake NE-14. RIGHT: Extreme low water in the Kuparuk River caused by occasional drought blocks fish migration to headwater lakes 10 km away.

Table 2-2. Core monitoring and process studies to be carried out by the ARC LTER personnel. Detailed protocols and methods at: <http://ecosystems.mbl.edu/arc/Datatable.html>

Type of measurement		Frequency
Climate, C, N, Energy Budgets, and Hydrology of LTER Core Watersheds		
<i>Toolik Lake, Toolik Inlet, surrounding Landscape</i>	Main climate station and several satellite stations, atmospheric deposition monitoring, inlet stream gauge, lake temperature, water level, and irradiance measures (aboveground and in the lake)	Daily, weekly, or continuous using data loggers; 3-6x per summer for nutrients; occasional early- and late-season visits
<i>Upper Kuparuk Watershed</i>	Stream gauge, temperature at Dalton Highway crossing	as above
<i>Imnavait Creek</i>	Climate Station, stream weir, and multiple soil temp/moisture data loggers, 3 eddy flux towers along hillslope	as above
<i>Anaktuvuk River Burn</i>	Multiple stream gauges and autosamplers, in South and North River watersheds, data loggers and 3 eddy flux towers in South River watershed	as above
Terrestrial ecology and biogeochemistry		
Vegetation growth and flowering	Permanent plots along Dalton Highway and control plots of long-term experiments at Toolik Lake	Annual flower counts, seasonal phenological observations
Vegetation NPP, C and N uptake, soil C and N stocks	Control plots of long term experiments at Toolik Lake; occasional resampling of older plots for long term changes	Major biomass harvests each year; sites depend on collaborating projects
Soil respiration, N mineralization	Long term plots in contrasting vegetation/soils at Toolik Lake	Annually at approximately the same time
Downslope water, ¹⁵ N movement	Imnavait Creek toposequence, monitoring of dissolved N, P, soil temperature, moisture, thaw and long-term movement of ¹⁵ N label	2x in 2011-2016
Disturbance effects on vegetation, soils	Anaktuvuk River Burn and thermokarst sites	Biomass, NPP harvests 2x in 2011-2016; C and N stocks
Stream ecology and biogeochemistry		
Transport in river, pelagic/benthic linkages, flow	Kuparuk River and Oksrukuyik Creek	3-4x per summer for nutrients, chlorophyll, moss, insects and fish;
Macroinvertebrate life cycles, seasonality	Kuparuk River and tributaries	Seasonal sampling of invertebrate life cycles and growth rates
Fish habitats and growth, changes in seasonality	Kuparuk River and tributaries	Seasonal sampling of growth rates, habitats, and food sources
Disturbance effects on stream communities, chemistry	Anaktuvuk Burn and TLRNA thermokarst sites. and surveys of other stream types. Flow, temperature, conductivity, alkalinity, SRP, TDP, PP, NO ₃ , NH ₄ , TDN, PON, DOC, POC, chlorophyll in seston and on rocks, insects, moss cover, fish (young, adult)	1-3 times per summer with collaborating projects
Lake ecology and biogeochemistry		
Long term changes in lake BGC and communities	Toolik Lake, Toolik Inlet series, and Survey Lakes. Alkalinity, nutrients, DOM, chlorophyll, zooplankton in seepage and drainage lakes; Regional fish survey; Thermal structure using thermistor chains	Community structure and chemistry 1-3X per year; continuous monitoring of temps in selected lakes
Linkage between stream inflow and lakes	Toolik Lake and Toolik Inlet series Chemistry, primary and bacterial production, and thermal structure measurements at times of wind or rain events	Weekly for chemistry, prim prods. Continuous for temperature Event-based for chemistry and production
Disturbance effects on lake communities and biogeochemistry	Dimple, Horn, Perched Lake in Anaktuvuk Burn, Lake NE-14	1-3x per year in with collaborating projects

(Table 2-2 continued on next page)

Table 2-2 (continued)

Landscape Interactions		
Soil water chemistry and transfer to primary streams	Toolik tussock watershed and Imnavait Creek. Soil water and stream nutrients and organic matter to estimate production in soils and flux out of primary catchments and “water tracks” (sites of occasional surface water flow)	Weekly for soils at ~30 sites; Weekly plus event-based for stream chemistry.
I-Series of connected lakes and streams flowing into Toolik	Toolik Inlet series of lakes and streams Water inorganic and organic chemistry, primary and bacterial production, chl _a to determine interactions of aquatic systems across the landscape	3x/year sampling of 12 lake and 15 stream sites
Effects of disturbance	South River, North River, and Dimple watersheds, Anaktuvuk River Burn, Lake NE-14 for thermokarst	Auto sampling of stream chemistry during summer; breakup sampling every 2-3 years, lake sediments

Table 2-3. Core long-term whole ecosystem experimental manipulations, 2011-2016. (discontinued experiments not shown)

Sites	Experimental treatment	Principal measurements	Status & sampling
Terrestrial			
5 contrasting vegetation types at Toolik Lake	Fertilizer, warming, shading, experiments	Vegetation greenness (NDVI), NPP, biomass, soil C/N/P stocks and turnover, soil communities	Started 1980-89; Continue treatments; one harvest of oldest plots in Year 3 or 4
Moist acidic and heath tundra, Toolik	Herbivore enclosure x fertilizer addition	As above	Started 1996; continue treatments; harvest with collab. projects TBD
Moist acidic tundra, Toolik	Species removal x fertilizer addition	As above	Started 1997; continue treatments; harvest with collab. projects TBD
Moist acidic tundra, Toolik	Multilevel NxP factorial fertilizer addition	As above	Started 2006; continue treatments; NDVI weekly each summer; harvest with collab projects TBD
Streams			
Kuparuk River	Seasonal constant phosphate addition to 0.3 μ M level final concentration	GPP, respiration, nutrient cycling, autotrophic communities, macroinvertebrate communities and production, fish ecology	Started 1979, continue sampling 3-4 x per summer
Kuparuk River	New moss re-establishment experiment in previously-fertilized recovery reach	GPP, respiration, nutrient cycling, autotrophic communities, macroinvertebrate communities and production, fish ecology	Start 2011; sampling 2-3 x per year
Lakes			
Lakes E-5, E-6 (control lakes Fog-2, Fog-4)	Nutrient addition once per week to increase nutrient loadings by 50%	Alkalinity, nutrients, DOM, chlorophyll, zooplankton in seepage and drainage lakes; Regional fish survey	Started 2000; continue sampling 3x per year
Lakes N-1, N-2	Fertilizer treatments discontinued	Monitor recovery as above	1-3x per year, 2011-2016
Landscape Interactions			
Moist acidic tundra, Toolik	New controlled burn (pending permit approval)	Opportunity to study recovery processes in greater detail than at AR Burn site—soil leaching losses, changes in soil chemistry, microbial activity	Start 2011 or 2012

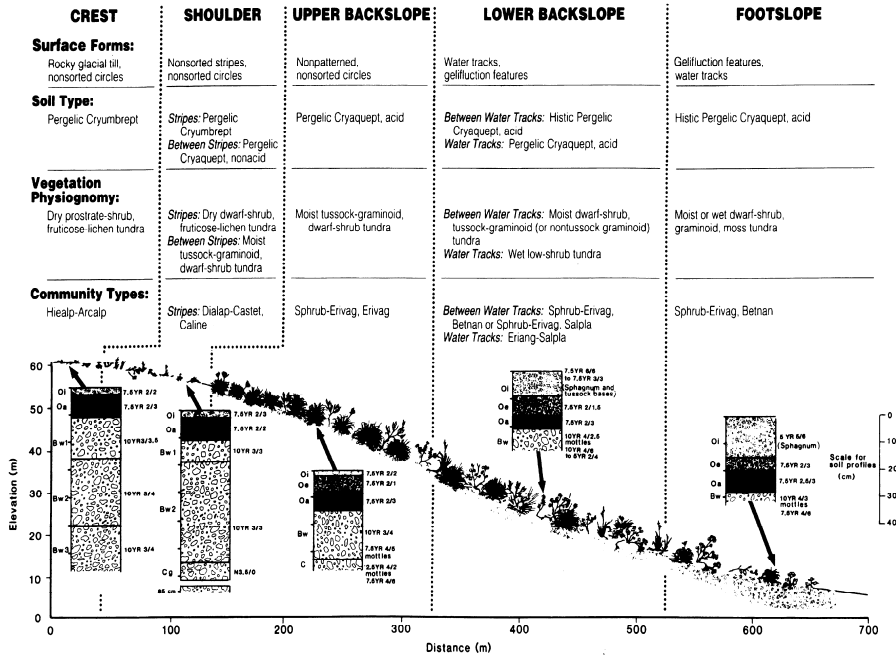


Fig 2-5. A typical toposequence of Sagavanirktok age (~300,000 yr), in the Imnavait Creek drainage (Walker et al. 1989). This is one of the toposequences to be studied by the Terrestrial and Landscapes Interactions groups, focusing on downslope water and element movement. It is underlain by permafrost at a depth of 30-150 cm.

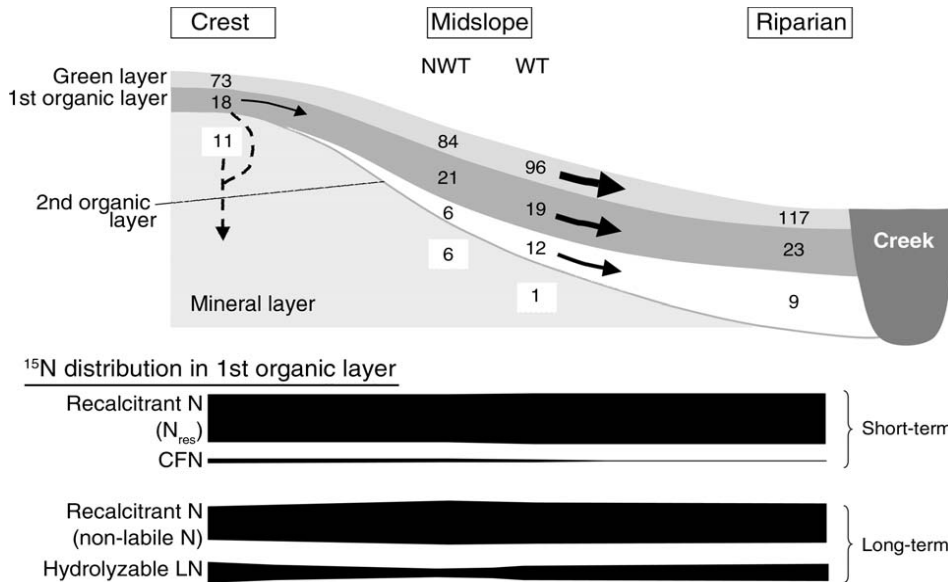


Fig 2-6. Conceptual model of short and long-term (1 week versus 2 years) ¹⁵N retention and movement along the hillslope of Imnavait Creek (field labeling experiment, Yano et al. 2010). Footslope sites were omitted for simplicity. Values indicate short-term recovery of ¹⁵N (percentage of added) within each moss or soil layer. Solid arrows indicate subsequent movement of ¹⁵N via water flow downslope, and dashed arrows show possible ¹⁵N leaching. Arrow width shows relative magnitude of ¹⁵N movement. The bars at the bottom show short- and long-term ¹⁵N distribution within the organic layer among N pools across the hillslope; bar width indicates contribution of each pool to ¹⁵N retention relative to other pools. N_{res} is residual N after chloroform-fumigation extraction; CFN is chloroform-fumigation extractable N; hydrolyzable LN is labile N (hydrolyzable NH₄, amino acids, amino sugars); non-labile N is total ¹⁵N recovered in the first organic layer (100%) – total hydrolyzable LN.

Fig 2-7. Twenty years of N+P fertilizer addition leads to a net LOSS of both C and N in moist tussock tundra despite doubling of NPP (and thus C inputs) and direct addition of 200 g m⁻² N. All plant biomass and litter pools increased.

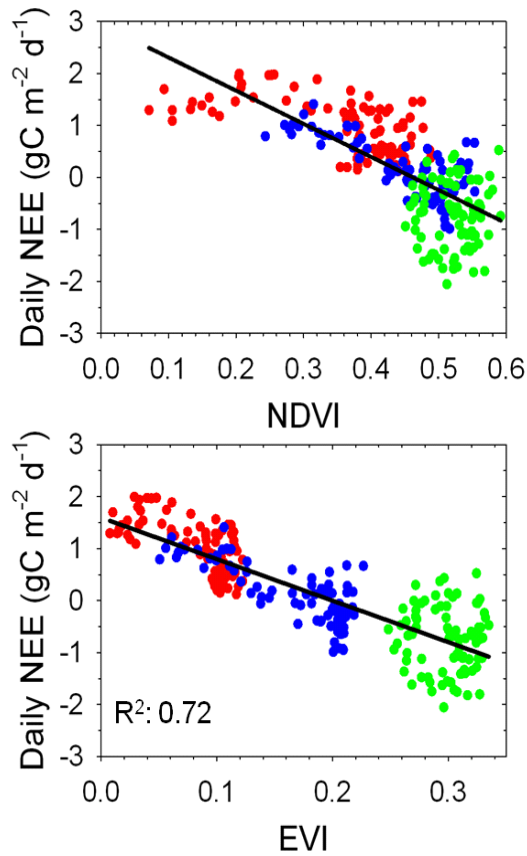
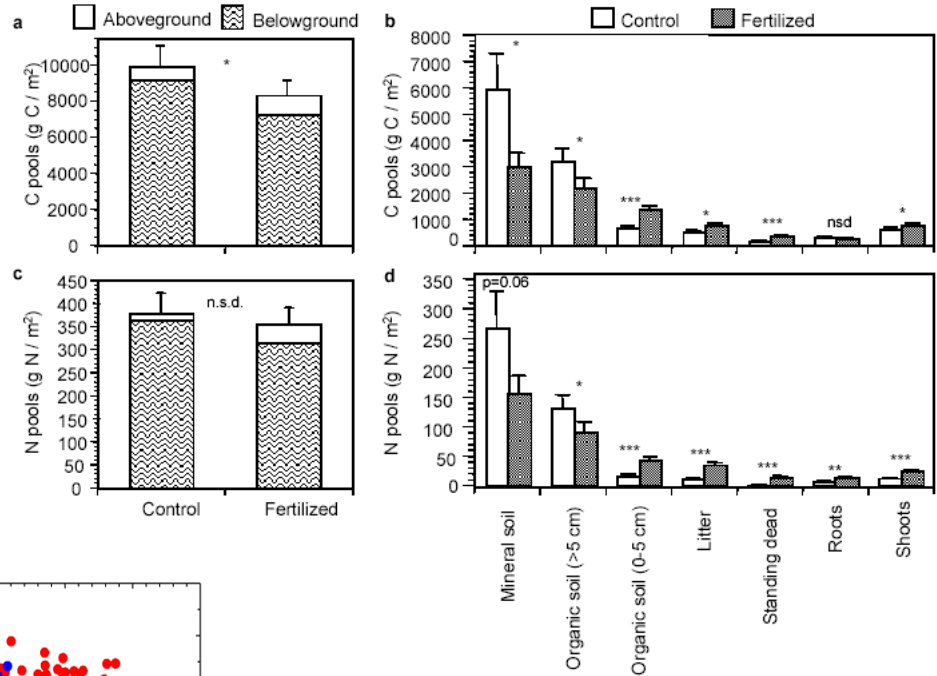
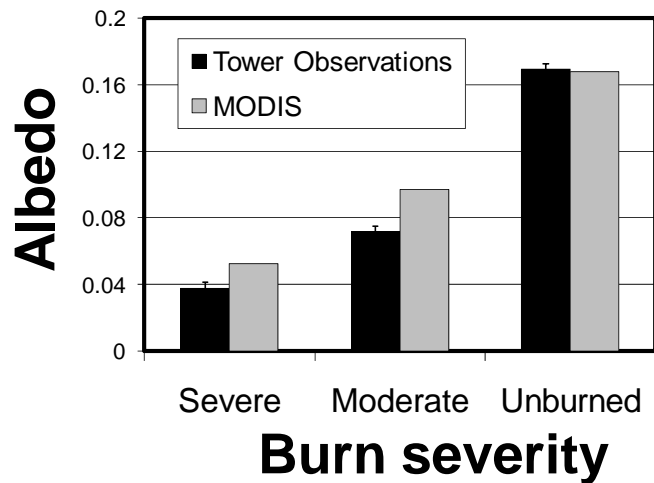


Fig 2-9. Albedo measurements from eddy flux towers at severe, moderate, and unburned tundra sites compare well with MODIS satellite albedo data from 1 km² area around each tower (Rocha and Shaver 2009)

Fig 2-8. On the Anaktuvuk River Burn, daily NEE (Net Ecosystem Exchange of CO₂) in unburned (green) and severely- (red) and moderately-burned (blue) sites is correlated with surface reflectance properties including commonly-used measures such as NDVI and EVI. These data, collected over the first two summers of recovery (2008-2009), suggest a continuous relationship in “greenness” versus NEE across burned and unburned tundra that may be used to develop a large-area model of Arctic C balance including large disturbances (A. Rocha unpublished data).



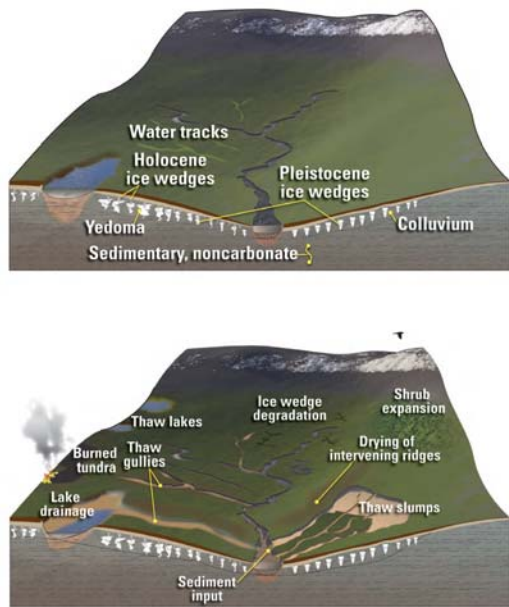


Fig 2-10. Schematic of the Arctic Foothills landscape, current (top) and projected (bottom). The projected landscape illustrates geomorphic and hydrologic changes, which are likely to occur as a result of climate change (reproduced from Martin et al. 2008).

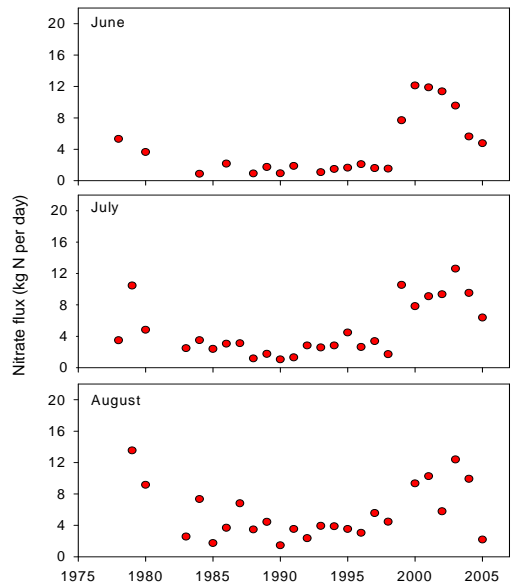


Fig 2-11. Average daily nitrate flux (kg N/day) in the Kuparuk River for the summer months in which water is flowing and biotic activity is high. Nitrate flux was high early in the record and especially for years after 1998. These years correspond to years that tended to be warmer, with less discharge, and with increasing incidence of thermokarst.

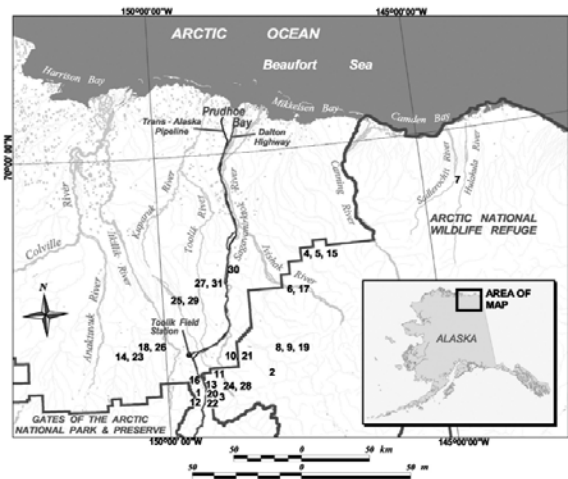


Fig 2-12. Stream locations (some with multiple sampling reaches) that have been studied in detail by the ARC LTER streams research group.

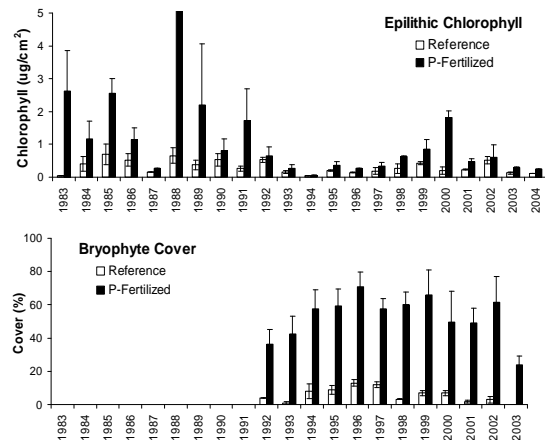


Fig 2-13. Epilithic chla (top) and % total bryophyte cover (bottom) in Reference and Fertilized riffles, Kuparuk R. Chla for 1987 and 1994 only include August values. In 1988, fertilized reach chla is inflated due to contamination by green algal filaments. Bryophyte cover was negligible prior to 1992. Means \pm 1 SE, updated from Slavik et al. 2004.

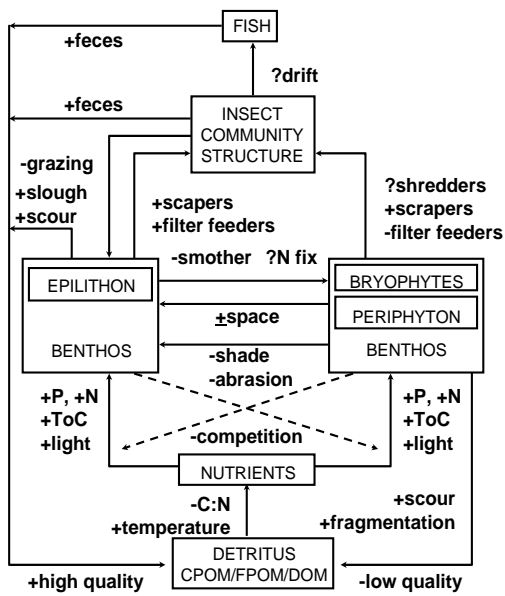


Fig 2-14. Influences of aquatic bryophytes on stream communities and processes. Bryophytes can significantly alter structure and function of stream ecosystems through physical, chemical, and biological means. From the Stream Bryophyte Group (Bowden et al. 1999).

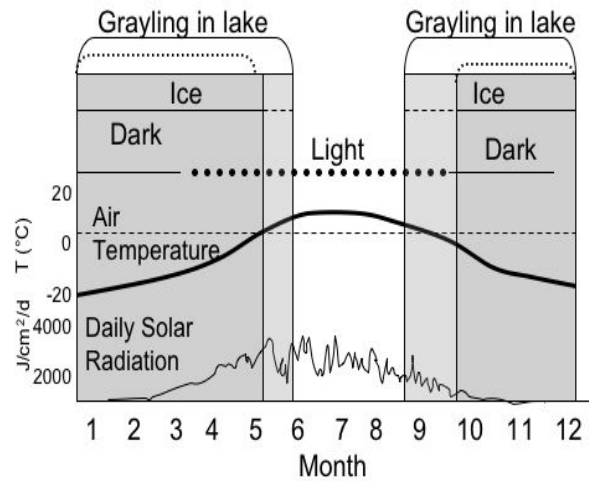


Fig 2-15. Climate of the foothills region related to grayling life history. Shaded area is duration of grayling residence in the lake; darker area is projected shorter occupancy of lake with a longer flowing water period in the river.

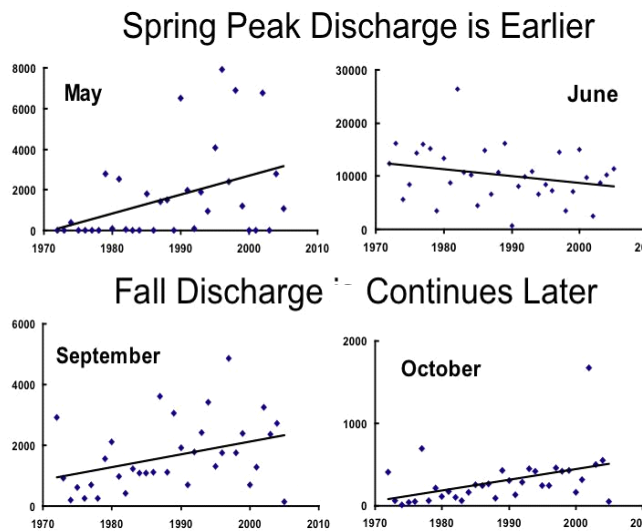


Fig 2-16. Shifting discharge in the Kuparuk River. Spring discharge is occurring earlier and fall discharge persists longer and is higher than was the case in the past (based on USGS data).

Fig 2-17. Variation in mean (+SE) chlorophyll a ($\text{mg m}^{-3} \times 100$), benthic gross primary production (GPP, $\text{mgC m}^{-2} \text{day}^{-1}$), and zooplankton biomass (mg m^{-3}) in small (<5 ha) and large (>5 ha) lakes near the Toolik Field Station.

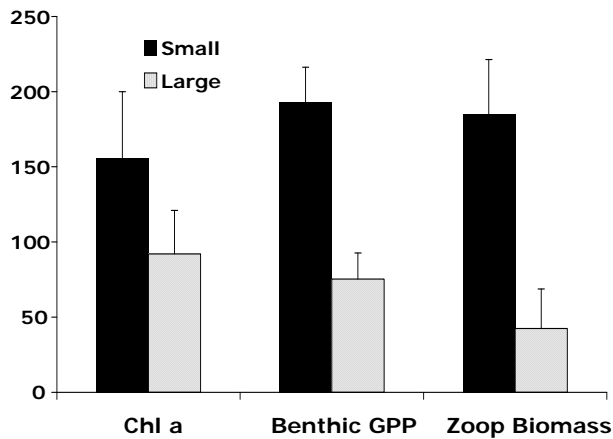


Fig 2-19. Slope of log length-weight regression versus epilimnetic temperature in lakes NE-12 (grayling and lake trout) and Lake Fog-2 (char).

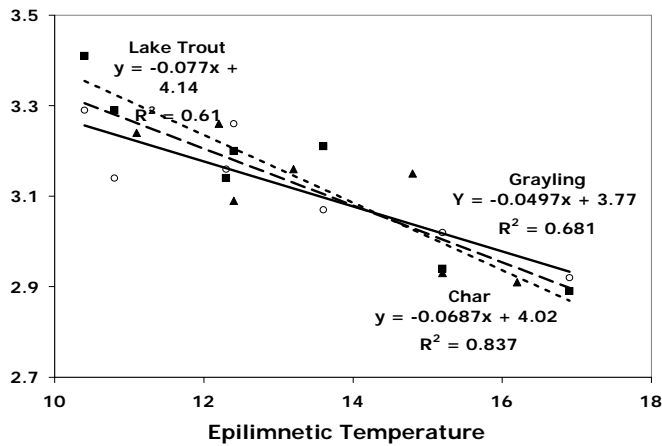


Fig 2-21. Laminated sediments from Dimple Lake in 2008. Dating indicated that the laminations are not annual patterns but may be related to longer-term periods of meromixis.



Fig 2-18. Effect of water temperature on zooplankton biomass in a deep (E5) and a shallow (E6) fertilized lake. The Y-axis is the ratio of zooplankton biomass in the fertilized lake to the reference lake.

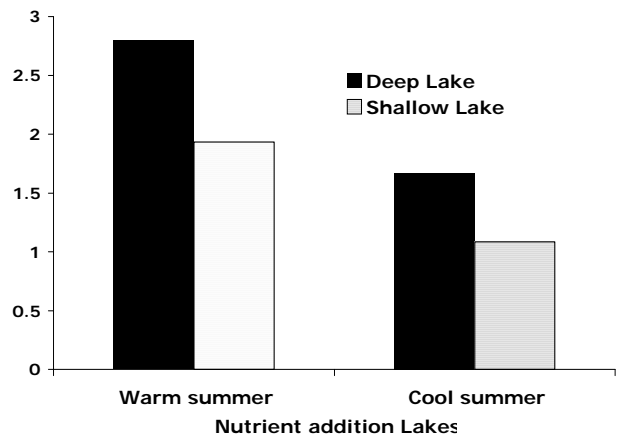


Fig 2-20. Depth profiles of temperature ($^{\circ}\text{C}$), dissolved oxygen (mg/L^{-1}), and conductivity (uS cm^{-1}) in Dimple Lake in spring 2008 and 2009.

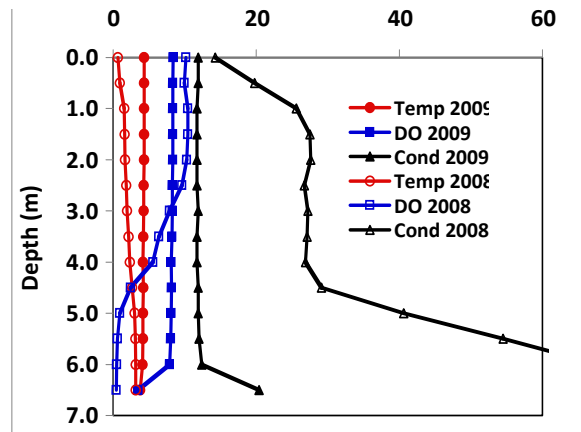


Fig 2-22. Photograph taken in July 2008 of shoreline of Horn Lake in the burn area. Thermokarst slumping results in sediment transport into the lake.



Table 2-4. List of lakes sampled and their characteristics (survey, nutrient addition, burn) for the ARC LTER.

Survey Lakes	Surface Area (ha)	Max Depth (m)	Sampling Frequency (per summer)
Toolik	149	25	10
E1	2.6	11	1
Fog 2	5.9	20.3	2
Fog 4	1.9	4.4	2
NE9b	.4	6	1
NE12	8.2	17.1	1
N1	4.3	14.2	1
S6	1.1	5.2	1
S7	.8	2.9	1
S11	.3	9.5	1
I Series	2.1-17	3.1-15	3
Nutrient Addition Lakes			
E5	11.3	12.7	5
E6	1.9	3.2	5
N2	1.6	9.7	2
Burn Area Lakes			
Dimple	10.6	9.0	3
Horn	35.8	5.0	3
Luna	4.75	2.5	3
Perched	15.1	12.0	3
North	32.9	2.0	3

Fig 2-23. Primary production over time in fertilized Lake E5 (ugC/L/hr). Fertilization started in 2001.

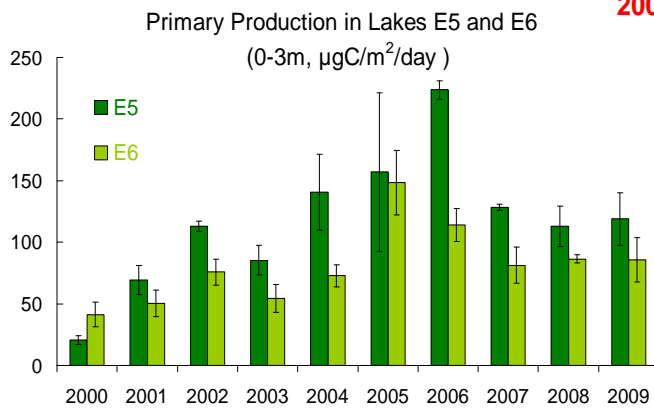
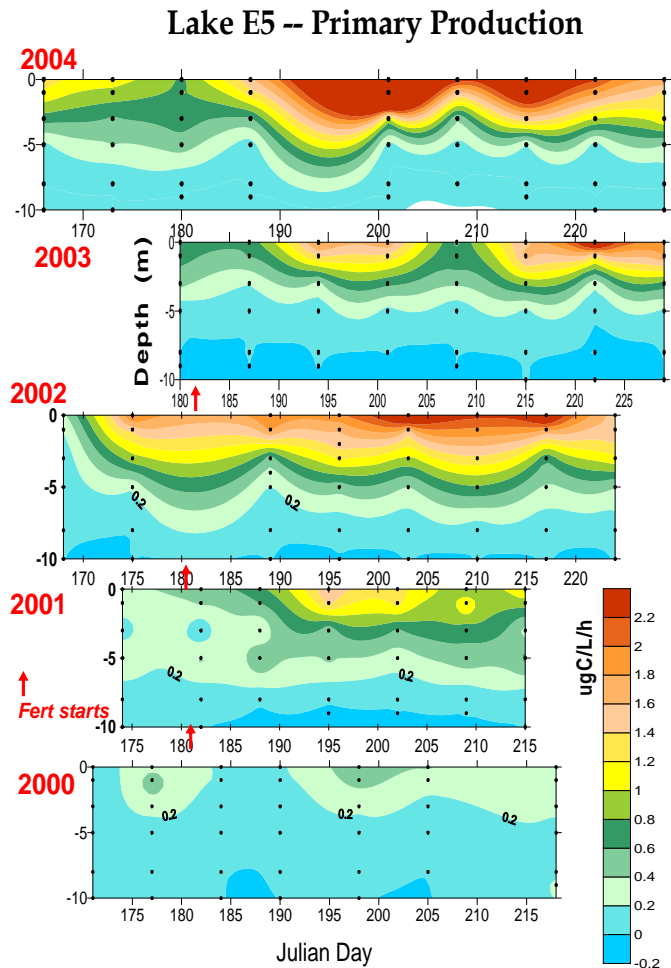


Fig 2-25 (below). Chlorophyll in fertilized lakes E5 (deep) and E6 (shallow). Values are depth-integrated, 0-3 m.

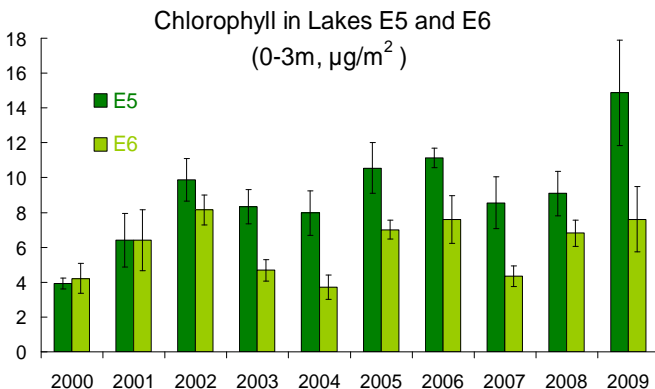


Fig 2-24 (left). Primary production in the fertilized Lakes E5 (deep) and E6 (shallow). Fertilization started in 2001. Values are depth integrated, 0-3 m.

Fig 2-26 (below). Chlorophyll a concentrations in Lakes Fog 2 and Fog 4 (0-5 m epilimnetic average) showing the potential impact of a thermokarst slump on the shoreline of Fog 4, resulting in higher chla concentrations.

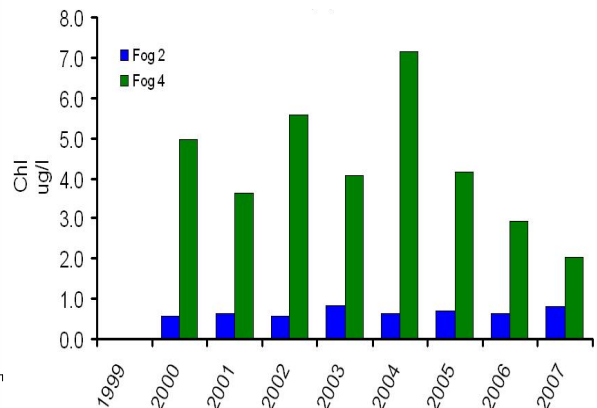
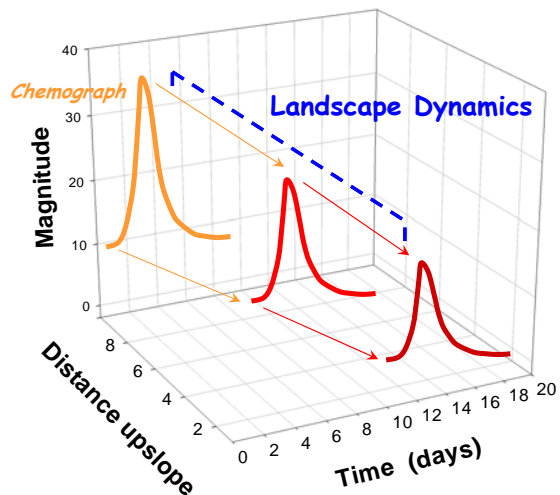


Fig 2-27. Landscape dynamics (*left*) represented by changes in patterns or processes (e.g., soil water chemistry) moving from upslope to downslope and through time. Plot at *right* shows DOC concentration in soil waters along the toposequence at Innavaik Creek through time – the stream is located at the bottom of the graph, and the hilltop is at the top of the graph.

Controls on biogeochemical processes and catchment export



Hillslope Patterns of DOC

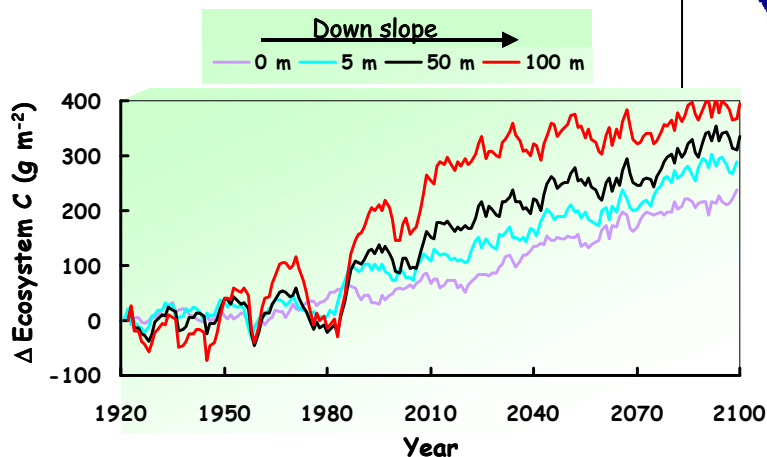
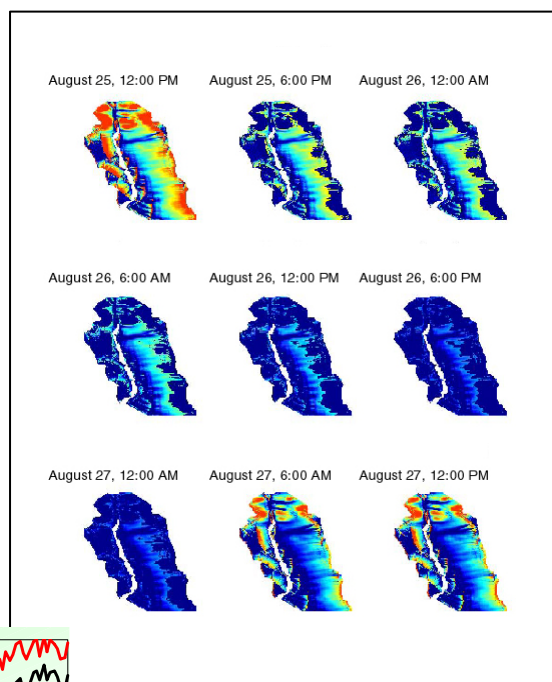
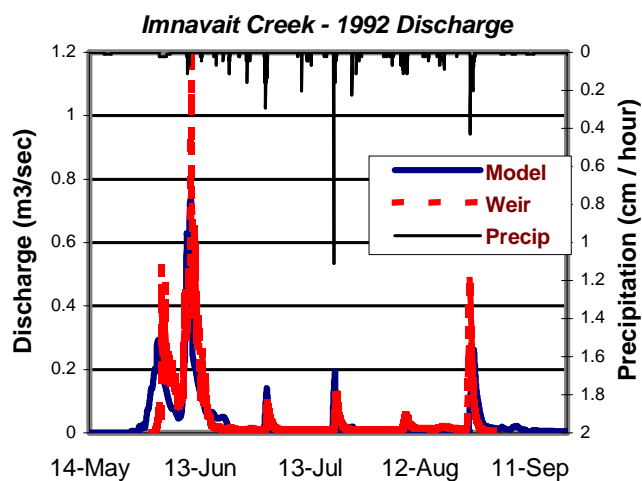
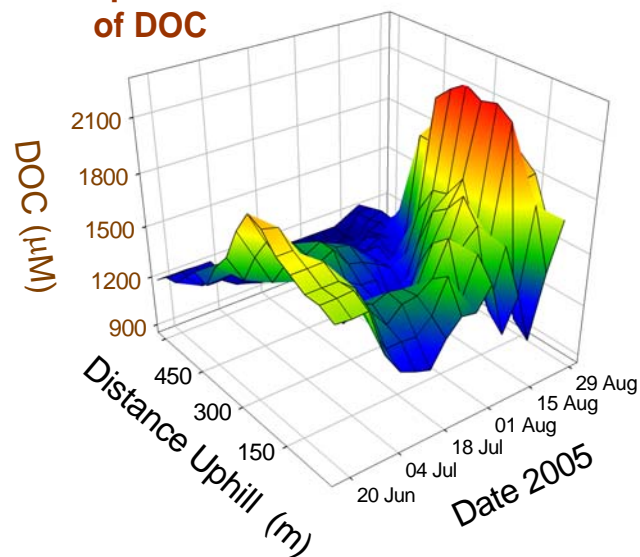


Fig 2-28. Modeled vs. measured discharge in Innavaik Creek (*upper left*). The sequence at *right* shows changes in soil moisture during a rain event over 2 days – such dynamic changes impact the production and transport of C,N,P downslope (Stieglitz *et al.* 2003), which in turn impacts ecosystem C storage (*lower left* – Rastetter *et al.* 2004).

Nearby sites have similar microbial communities

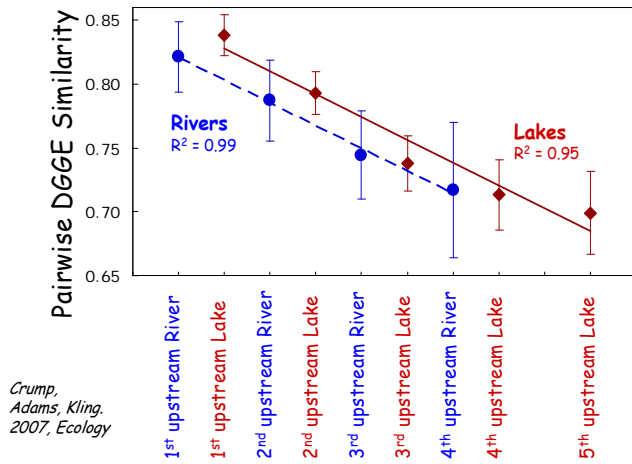


Fig 2-29. Pairwise similarity of DGGE patterns versus landscape separation. X-axis represents the number of upstream lakes or inlets separating two sites; 1st upstream lake or river means the comparison is between closest neighbors. 2nd and higher comparisons indicate a 2-lake separation on the landscape.

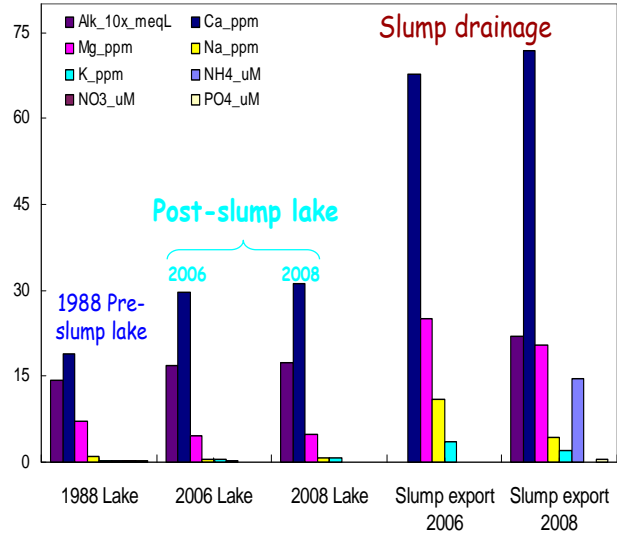


Fig 2-30. Evidence of thermokarst failure impacts on Lake NE-14, showing the pre-slump lake vs. the lake in 2006 and 2008, and the slump drainage water chemistry (see Fig 2-4, Center).

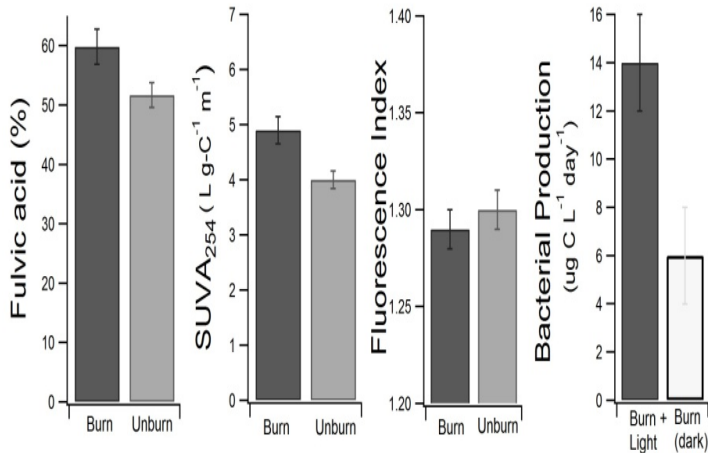


Fig 2-31, Above. Chemical characteristics of water soluble DOM from arctic tussock tundra (panels 1-3) and the effect of photodegradation of burned DOM on bacterial C production (panel 4); unpublished data from D. McKnight, R. Gabor, S. Barbro, J. Boyar, R. Cory, G. Kling.

Fig 2-32, Right. Differences in C and N loading and discharge between a burned catchment (S. River) and a control catchment, Toolik Inlet stream. Discharge drives loading, but when discharge is the same the burned catchment exports more total C and total N.

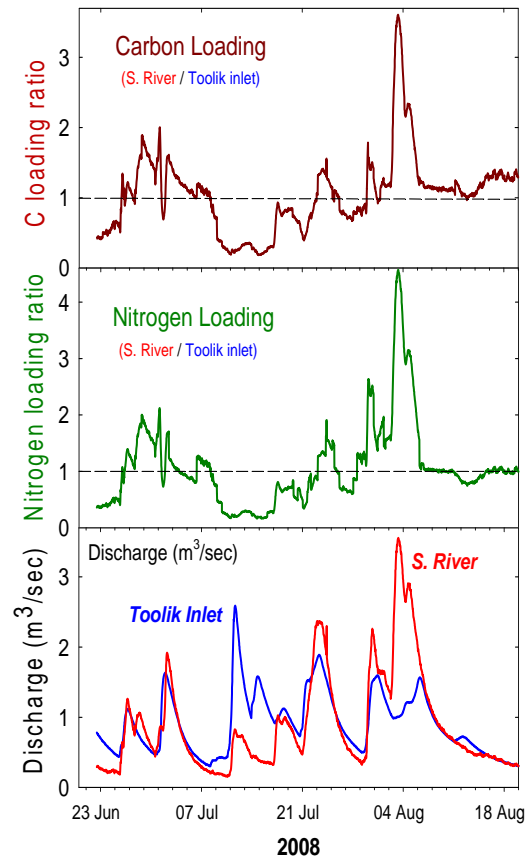


Fig 2-33. The proposed ARC LTER research translated into the framework of the LTER Network's planned Integrated Science for Society and the Environment (ISSE) research. Here the five core questions driving research that links the main components of the system are:

- Q1: How do disturbances in climate and surface energy balance affect structure and function of terrestrial and aquatic systems both directly through changes in temperature and indirectly through changes in biogeochemistry?
- Q2: How do changes in community composition feed back both positively and negatively on changes in nutrient cycling and availability in response to climate and disturbance?
- Q3: How do changing terrestrial and aquatic ecosystems affect the attractiveness of the arctic landscape to tourists, its ability to meet needs of subsistence users, and its suitability or profitability for commercial exploitation?
- Q4: How do local inhabitants and human populations outside the Arctic perceive or use these ecosystem services and how they change, and how do these perceptions affect their use or enjoyment of the arctic landscape?
- Q5: How do humans decisions, actions, and regulations affect disturbance regimes?

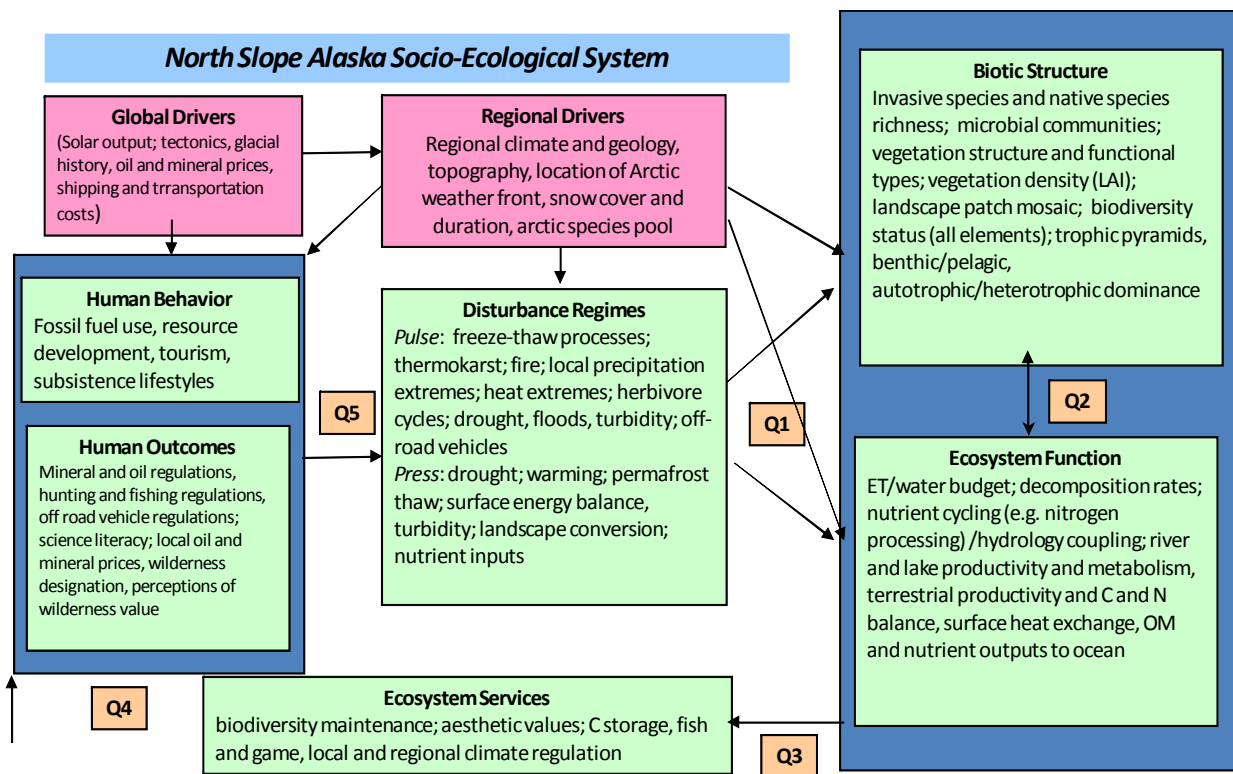
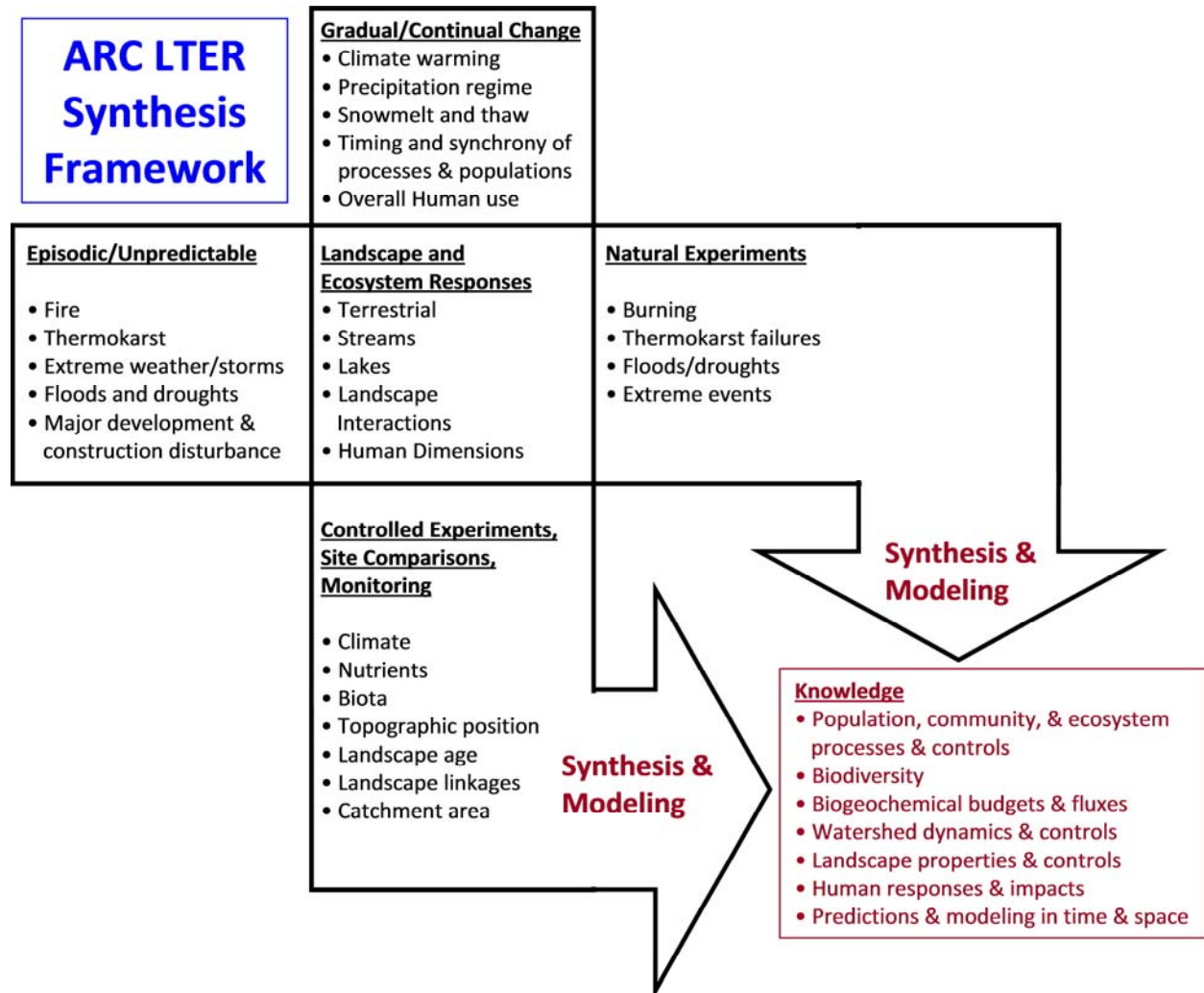


Fig 2-34. A framework for synthesis of ARC LTER research. The work of the five core research groups lies at the intersection between new work on disturbances (natural experiments) and ongoing, long-term experimental, comparative, and monitoring research. ARC LTER coordinates this work so as to optimize synthesis and modeling efforts, as well as supporting modeling efforts directly.



SECTION 3: PROJECT MANAGEMENT

Overall management structure: Arctic LTER research spans a broad spectrum of researcher backgrounds, skills, and interests. For efficiency and to promote effective planning we have organized into four groups, each focused on major components of the landscape, i.e., terrestrial, streams, lakes, and “landscape interactions” (Fig 3-1). This structure has proved highly effective for planning and project management, especially manipulations of lakes, streams, and tundra. Over the next 6 years we plan to add a fifth component, Human Dimensions.

An Executive Committee (EC) consisting of the lead PI (currently Hobbie), representatives of each research group (currently Shaver, Bowden, Luecke, and Kling), and one additional person (currently Giblin) meets at least twice a year, once in the fall and once during a winter plenary meeting of all project personnel. The purpose of the fall meeting is to review the previous summer's work, review the current state of the project's budget, and begin discussion of any changes in priorities, funding allocations, or new opportunities that might emerge in the coming year. At the fall meeting we also set the agenda for the winter meeting and choose a theme. At the winter meeting the EC meets before and after the plenary sessions to review the agenda, consolidate priorities and reconcile conflicts in plans developed by the four research groups, and again review the budget. Throughout the year, the EC responds to requests for information or collaboration, prepares annual reports and other communications, and interacts with the LTER Network office and with NSF. At least one member of the Executive Committee attends every Network Scientific Council meeting.

The winter meeting in Woods Hole is attended by all collaborating investigators, research assistants, and students. In addition to a review of the past year's science accomplishments, plenary discussions of project priorities are held and each of the four groups meets separately to develop plans for the upcoming summer. Each year we also invite to the meeting several current or potential collaborators as well as agency representatives (e.g., BLM). Ad hoc meetings of individual groups and of the whole project are also held during the summer, at Toolik Lake, and occasionally groups will meet during the winter.

Key project personnel include the four full-time, senior research assistants associated with each of the four research groups and a part-time assistant who works with the PI. These assistants work with the EC and the four research group leaders to do most of the day-to-day project management and coordination; they also serve as information managers within each group. One of them, Jim Laundre, is the project's senior Information Manager.

Field site management: The land where most of the LTER research is carried out (Fig 3-2) is owned by the US Bureau of Land Management (BLM), which grants permits to work there. Additional permits are required by the Alaska Department of Fish and Game for research on fish, and by the State and the North Slope Borough when working on their land. We work closely with these agencies to ensure that the permitting process runs smoothly, meeting with them each summer at Toolik Lake and (most years) at our annual winter meeting.

Toolik Field Station (TFS) is a facility of the Institute of Arctic Biology of the University of Alaska Fairbanks (UAF); it operates under lease of its land from BLM (only the 17-acre camp itself is covered). Much of the support for TFS comes through a cooperative agreement between UAF and NSF's Office of Polar Programs (OPP). Projects with NSF support, including the Arctic LTER, receive support for room, board, and laboratory costs based on the number of “user-days” at TFS. LTER scientists work closely with TFS management to ensure that research needs are met and to avoid conflicts among projects. During the summer a “Chief Scientist” meets daily with camp management to discuss immediate issues, and each summer general meetings are held with all personnel invited. LTER scientists also attend annual winter planning meetings as members of the TFS Steering Committee; M.S. Bret-Harte, an ARC LTER scientist at the University of Alaska, is Associate Scientific Director of TFS.

Collaborating projects, diversity, and interactions with LTER and other Networks:

Opportunities for collaboration were a primary consideration in designing the ARC LTER research, especially its long-term experiments. Collaborating projects include those that work directly on LTER sites and experiments, and projects that use TFS facilities and collaborate in synthesis papers. Often the LTER project will encourage a particular interaction by inviting visitors to work at Toolik Lake with supplemental or core research funds, in anticipation of their eventually obtaining independent funding (an example is the project by L. Gough and J. Moore, which began with annual LTER supplemental funding). The ARC LTER project has also been successful in attracting young investigators by encouraging those who were trained at Toolik Lake as postdocs and graduate students to return as investigators with their own funding (George Kling, Syndonia Bret-Harte, Laura Gough, and Byron Crump have all followed this route). Collaborating projects are listed in the Budget Explanation.

Cross-site and Network collaborations are strongly encouraged and are supported with supplemental and core funds. Recently we contributed to the cross-site shrub comparison (Knapp et al. 2008) and the LTER TRENDS Project. Over the past 20 years a growing exchange between TFS and Abisko Field Station in Sweden has developed, involving students and investigators from European Universities; this has led to several publications, theses, and meta-analyses of responses to tundra experiments (e.g., Cornelissen et al. 2007). In the past five years we have participated in several major international synthesis activities including the Arctic Climate Impacts Assessment (ACIA; Callaghan et al. 2005, Wrona et al. 2005). Working with the International Tundra Experiment (ITEX) we have developed two meta-analyses of plant growth and community responses to warming (Arft et al. 1999, Walker et al. 2006); a third meta-analysis, of plant phenology, is currently in development.

Collaborating investigators come from 16 institutions in 12 states and are ~30% female. We also use every opportunity to promote diversity with RA and student hiring; the majority of RAs and students working with the project are women. All job opportunities are advertised nationally and those hired come from at least 15 states. The Toolik Field Station works conscientiously to hire local people including Alaskan Natives to run the Station, and our Schoolyard program (Section 5) and the nascent Human Dimensions program (Section 2) are focused on Native involvement.

Anticipated changes, 2010-2016: Our management system has worked well since 1987 and we plan no major changes. There are four issues, however, that we must deal with in the next six years. The first is the rotation of project leadership: most of the EC members have been with the project for several decades and will be retiring in the next 6-12 years. Shaver will be taking over from Hobbie as PI in 2010, but we must begin planning now for the next transition. Leadership changes in the terrestrial and lakes groups will also occur. Within the next six years we must identify replacements for these leaders and bring them “up to speed” on management issues. Second, we must regularize and strengthen inputs from the social sciences at the level of the EC. Third, we must continue to attract new investigators with new skills and interests to the project, not only as retirement replacements but also to ensure continuing intellectual vitality and growth. Finally, TFS will become a NEON site by 2016, and we must work with NEON to ensure that this opportunity for the ARC LTER is developed effectively. We will address these issues in the following ways: First, we will increase participation in the EC by inviting additional, less-senior investigators to participate, and by including conference calls involving all investigators as part of regular EC meetings. Second, as the social science component of our project grows, by the end of this renewal period we will add it as a fifth research subgroup with EC membership. Third, to attract new investigators, each year we will support travel to Toolik Lake and to our winter meeting for 1-3 investigators with new or complementary skills and research interests. Fourth, we are already meeting with NEON to plan an effective NEON-LTER interaction. (Bowden, Hobbie, Bret-Harte, and Giblin are involved).

Figure 3-1. Organizational structure of the ARC LTER project. The Executive Committee manages the allocation of project resources among research, data, and education components in response to the needs of the collaborating investigators and projects. The EC also interacts with the LTER Network Office, with other networks, and with NSF; it responds to requests for information or collaboration, and it prepares annual reports and other communications.

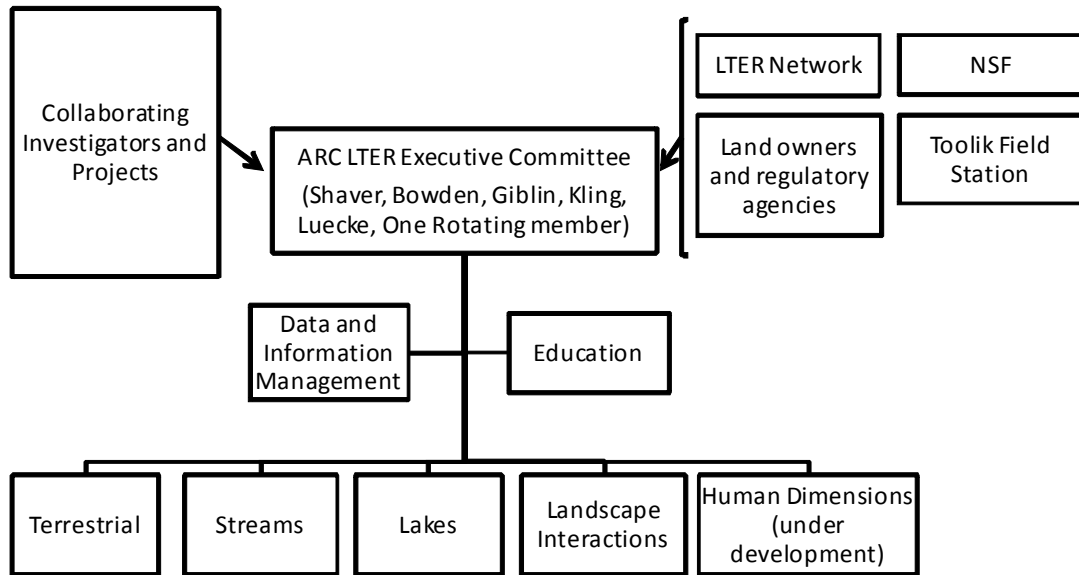
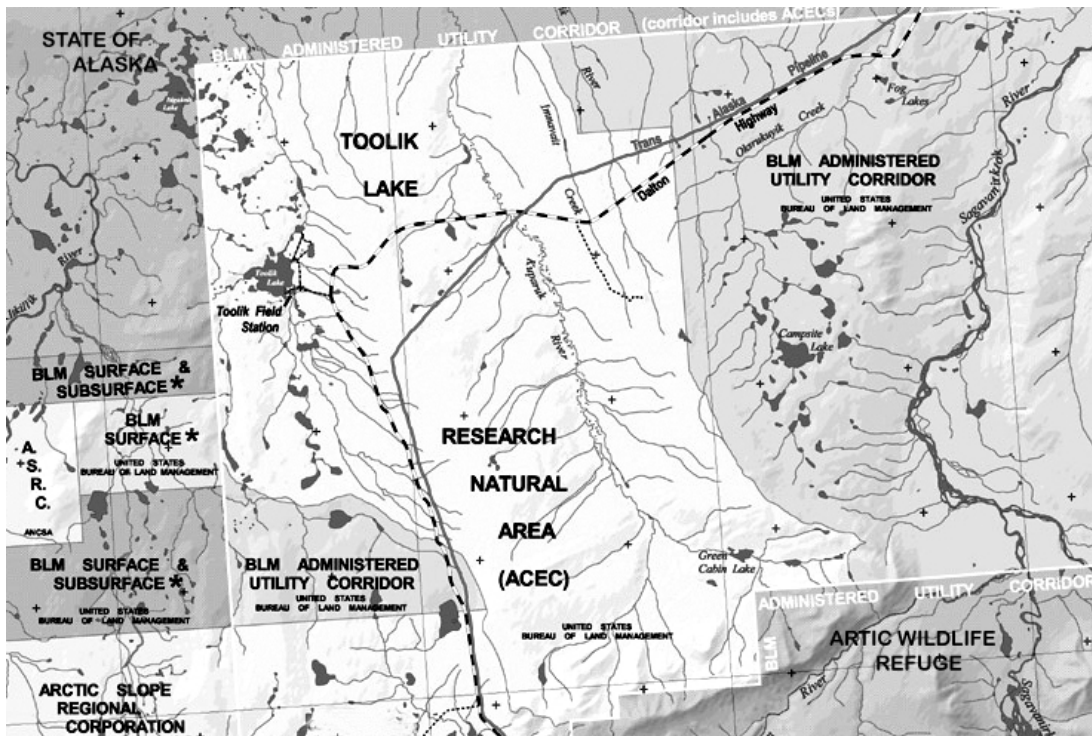


Figure 3-2. Land ownership near Toolik Lake Field Station (from Toolik Field Station GIS). All research in the area requires permits from landowners and regulatory agencies.



SECTION 4. INFORMATION MANAGEMENT AND TECHNOLOGY

Overall Strategy and Structure: Information management in the Arctic LTER has two principal aims. The first is to maximize data **access** both within the project and to other researchers. We try to maximize data access by rapidly adding new data sets to the data base (usually before publication) and by making all of the data sets available for downloading by anyone; the only requirements are: (1) users must register with the LTER Network's data access system and (2) NSF and the Arctic LTER project must be acknowledged in any use of the data. The second aim is to optimize data **usability** and **integration** for within-site synthesis and modeling, regional and long-term scaling, and multisite or global comparisons and syntheses. Careful planning at the research design stage is required to ensure that any single set of measurements is easily linked to other measurements; typically this includes working closely with collaborating projects so that their work on LTER sites and experiments is optimally integrated.

The structure of our information management system parallels the overall structure of the project (Section 3). A Senior RA, Jim Laundre, is the overall project information manager with responsibility for overseeing the integrity of the Arctic LTER information system. There are four major components to the information system, linked to the terrestrial, streams, lakes, and landscape interactions research components (Human Dimensions component to be added). Information management is a primary responsibility of all four full-time RAs (including Laundre) associated with each of these research components. While each of the four assistants maintains the data in their area, all are in frequent communication on overall data compatibility and metadata standards (two will work at the MBL in Woods Hole, one will be at University of Michigan, and one at University of Vermont). Each RA is deeply involved in the actual research design, day-to-day management, and data collection within their area. The four RAs work closely in the field with investigators, technicians, and students to ensure quality control and appropriate documentation. Overall guidance is provided by the Executive Committee while Laundre attends the LTER Network Information Manager's meetings and makes sure we are kept up to date and compatible with Network data standards.

Each year at our annual winter meeting in Woods Hole we review the status of the information system and ways of improving its accessibility and ease of use. At this meeting we focus in particular on the upcoming summer season and on how to design our research for optimum integration of diverse data sets. All project personnel including postdocs, graduate students, and occasional REU students participate in these discussions. See <http://ecosystems.mbl.edu/arc/dataprotocol/ArcticLTERIM.html> for details.

Availability of Datasets: Datasets of the Arctic LTER project are available from the Arctic LTER web site (<http://ecosystems.mbl.edu/arc/Datatable.html>) and can be download once a user is registered with the Network Data Access System (<http://metacat.lternet.edu/knb/>). We ask only that the LTER project and the principal investigator responsible for the data set be informed and that NSF and the ARC LTER be acknowledged in any papers published in which the data are used. Recent statistics of web site use are summarized in Table 4-1.

Data from the large-scale experiments and from routine monitoring are available online as soon as the data are checked for quality and, where necessary, transformed for presentation in standard units and scales. Many data sets, such as weather observations, stream flow, flower counts, and data that do not require a great deal of post-collection chemical or other analysis, are available within 3-6 months of collection. Other data, particularly from samples requiring chemical analysis in our home laboratories, may take up to two years before they appear on-line. We also request collaborating projects to contribute their datasets to our online database, and most do so. In addition to datasets on our web server the ARC LTER also participates in the LTER Network's ClimDB, HydroDB, and EcoTrends information systems. These centralized databases provide access to meteorological, hydrological, and long-term change data from all the LTER sites.

Format of Datasets: Investigators, technicians, and students who collect the data are responsible for data analysis, quality control, and documentation. This ensures that the data are checked and documented by those most familiar with the data. While investigators may use any software for their own data entry and analysis, we expect that all documentation and datasets that are submitted conform to the required ARC LTER formats. The metadata and data are submitted using ARC LTER's [Excel based metadata form](#). Comments are used extensively throughout the sheet to aid in filling out the data. Data validation lists are used to create drop down lists for units, measurement scale, and number types. For researchers who do not use Excel a rich text form is available with the data being submitted as comma delimited ASCII. Researchers are encouraged to include the metadata worksheet in their Excel workbooks to facilitate documentation. The worksheet was designed to be easily moved or copied. Submitted files are checked for conformance by the four senior RAs. Once files are accepted, they are placed in the appropriate data directories on the web. An Excel macro is used to parse the metadata form and generate html, xml, and data files needed for accessing the data via the web. The xml file conforms to the LTER network's "[EML Best practices](#)" level 4. The xml file is uploaded to the LTER Network Office metacat server via a harvest list. Uploaded files are then available from the [LTERNET data catalog](#) or any metacat server.

General site information and publications. General information about the ARC LTER project is provided on our web site (<http://ecosystems.mbl.edu/arc/>) including site descriptions, past proposals and other documents, a site bibliography including publications based on project research (Table 4-2), educational opportunities, contact information for site personnel, and links to related sites. This information is updated once a year or whenever major changes occur.

Toolik Field Station Environmental Monitoring Program: The Arctic LTER and its precursor projects have maintained an environmental monitoring program at Toolik Lake since 1975, including basic weather data as well as stream and lake observations. These data have always been made available to other projects and to Toolik Field Station (TFS) management but, as the number and diversity of projects at TFS have grown, it has become clear that it would be more appropriate for TFS to maintain these observations and make them available via the TFS web site. Increased support for TFS from NSF-OPP has also made it possible for TFS to make additional observations that the ARC LTER cannot afford by itself.

To accommodate these changes, since September 2006 TFS has gradually assumed responsibility for maintenance and data management of the main Toolik weather station, which LTER has been supporting since 1987. TFS and LTER personnel are working together to pass responsibility to TFS for other long-term, core-site data sets, such as precipitation chemistry and stream flow. This shared responsibility is working well, and importantly it allows LTER resources to be used for other activities. The LTER project still is responsible for collection and management of weather and other data collected from experimental plots and as part of LTER research. All weather data still reside on the LTER web site but are now available through a link from the TFS web site (<http://ecosystems.mbl.edu/arc/weather/TLKMAINcurrentweather.html>). Also available on the TFS web site is a new weather data query and plotting capability. The [TFS Environmental Data Center](#) plans to add additional components including plant phenological monitoring, bird observations, and other year-round observations of weather and natural history that cannot be made by LTER personnel who are not year-round residents.

Geographic Information Systems, Mapping, and Remote Sensing: Geographic information from the Toolik Lake region is extensive, detailed, and linked to several key global and regional data bases. Because much of this first-class information system was developed with funding independent from the ARC LTER project, we have focused our efforts on insuring access to this valuable database and on optimizing its usability for our needs. Where appropriate, we have contributed some funds and personnel support to guarantee this access and usability. Links to

the key databases are provided on the Arctic LTER web site at <http://ecosystems.mbl.edu/arc/database1.html>; these include:

- The *Circumpolar Geobotanical Atlas*, developed by Dr. Donald (Skip) Walker and colleagues at the Alaska Geobotany Center, University of Alaska (<http://www.arcticatlas.org>), features a nested, hierarchical series of maps of arctic ecosystems at scales ranging from 1:10 (1 m²) to 1:7,500,000 (the entire Arctic), with multiple data layers at each scale including vegetation, soils, hydrology, topography, glacial geology, permafrost, NDVI, and other variables. Much of the development of this hierarchical system is based on original work done by Walker and colleagues at Toolik Lake and Imnavait Creek, with multilayer maps of these areas at 1:10, 1:500 (1 km²), 1:5000 (25 km²), and of the Kuparuk River basin at 1:25,000 and 1:250,000.
- The *Toolik Field Station GIS* (<http://www.uaf.edu/toolik/gis>) was developed with support from NSF-Office of Polar Programs to help manage and support research based at the Field Station including LTER research. This GIS is maintained by a full-time GIS and Remote Sensing Manager and includes a multilayer GIS based largely on the Geobotanical Atlas data described above, combined with landownership information, roads and pipelines, and disturbances (e.g., Fig. 2-2, 3-2). Particularly important for our purposes is a detailed map of research sites including all of the LTER experimental plots and sample locations in the upper Kuparuk region. The GIS includes a map of Inupiaq place names with annotations of historic use of the land by the Inupiaq people, along with a dictionary of plant and animal names and common words.

Anticipated changes, 2010-2016: No major changes are planned to our overall Information Management strategy and practices. Our current approach was reviewed favorably in the 2007 Site Review, with no major changes recommended. We do plan to continue organizing and making available older data sets in line with LTER Network-level recommendations and requirements. Currently all our legacy metadata have been converted to Ecological Metadata Language (EML) but only at EML Best Practices level 2/3 (no attribute EML). Bringing the files up to level 4 requires review and where appropriate consolidated into multi-year files. Differences in methods and personnel will require that some years remain separate. For some datasets we will be using a relational database for storing and retrieving subsets of data. We will also be implementing a content management system framework based on the LTER Network Office implementation at the SEV and LUQ LTER sites using the open source content management software Drupal. This implementation will allow us to meet and exceed the new LTER Executive Board expectations for data accessibility, specifically concerns about core and non-core data sets. For more information see the 2009 LTER ASM workgroup “No dead end information” website, <http://asm.lternet.edu/2009/workgroups/no-dead-ends-lter-information-website>,

As described above, Toolik Field Station started an environmental monitoring program in 2006 and will be taking over some of the basic weather and environmental measurements, e.g., precipitation chemistry. Plans are also underway to work with the Toolik Field Station GIS manager to generate EML files for some of the basic site GIS files. This would include the research locations and layers with vegetation, topography, streams, and lakes.

As the research program at TFS grows we expect increased challenges as well as opportunities for information management. Two that are likely to affect our work in the next six years are (1) establishment of the Arctic Observatory Network (AON) including several projects at TFS, and (2) establishment of a National Environmental Observatory Network (NEON) site at TFS. Carbon, water, and energy-balance data sets from collaborating projects of the AON program are already available at <http://ecosystems.mbl.edu/arc/AON/AONdata.html>.

Table 4-1. Summary of web site and data base hits for 2009. Columns show monthly sums of hits outside of MBL on all Arctic LTER web pages and on data files only (excluding web-crawler hits). Data requests are also received via email to the Information Managers. These typically number 6-12 per year.

Month	Hits on Arctic LTER Web Site				Hits on Arctic LTER Data Files				DAS # Downloads
	All Hits		Outside MBL		All Hits		Outside MBL		
	Hits	Visitors	Hits	Visitors	Hits	Visitors	Hits	Visitors *	
1	26875	2021	26288	1966	331	110	329	109	6
2	33598	2369	32698	2347	449	116	446	114	5
3	31407	2456	30878	2422	363	114	356	110	5
4	20513	2018	20955	2025	229	105	228	105	18
5	25516	2239	25211	2220	281	106	281	106	70
6	20346	2033	19734	2009	361	104	361	104	55
7	16708	1745	16374	1713	386	126	384	125	68
8	29861	2179	29458	2138	429	80	429	80	56
9	25333	2156	27355	2147	472	98	470	96	32
10	30527	2657	30114	2624	329	117	329	117	61
11	34336	2349	33454	2308	249	73	208	68	13
12	24073	1847	32040	1853	1075	69	1,071	68	10

* Visitors come from 73 different countries.

Since January 2009 ARC has participated in the LTER Network Office Data Access Server (DAS) Project which provides end-user registration and tracking of data file usage. Approximately 400 files are currently using the DAS with plans to include all ARC data files in the DAS by the end of 2010.

Table 4-2. Publications of the Arctic LTER project

Publication type	1988-2009	2004-2009
Theses		
Ph.D.	18	12
Masters	37	12
Bachelors (Honors)	3	0
Books and Book Chapters	70	22
Journal Articles		
All refereed journals	340	139
Science	5	1
Nature	6	2
Proceedings National Academy of Sciences	2	2
Ambio	15	15
Ecology, Ecological Monographs, Ecological Applications	38	11
Limnology and Oceanography	13	10
Journal of Geophysical Research, Geophysical Research Letters	17	8
Freshwater Biology	15	7
Oecologia	12	5
Arctic, Antarctic, and Alpine Research	8	5
Journal of Ecology, Functional Ecology	11	5
Global Change Biology	12	4
Ecosystems	8	4
Water Resources Research	5	4
Ecology Letters	3	3
Oikos	8	3
Biogeochemistry	3	3
Canadian Journal of Aquatic and Fisheries Sciences	10	3
Verh. Internat. Verein. Limnol.	9	3
Other journals	76	56

SECTION 5. EDUCATION AND OUTREACH

The ARC LTER project will continue to maintain a multifaceted education and outreach program. Each component of our program is selected to optimize the particular education opportunities available to this project and its institutional resources. With a few carefully-selected activities, our strategy is to reach a diverse audience ranging from kindergarten through graduate students to the general public and to governmental and scientific planning agencies. Each of these high-impact activities is independently funded but receives support from the ARC LTER in the form of investigator, student, or RA participation, and through access to our field sites, laboratories, and data base. We also provide small subsidies from LTER research or supplemental funds especially for travel and logistics costs for participation by LTER students and investigators.

1. Our *Schoolyard LTER program* (<http://ecosystems.mbl.edu/ARC/schoolyard/index.html>) focuses on Barrow, Alaska, because it is the nearest large town to Toolik Lake and because a strong link to the local community is desirable for several reasons. The reasons include a historic involvement of the community of Barrow with science on the North Slope of Alaska and a strong community interest in and feeling of ownership and responsibility for North Slope Science. The community of Barrow is also interested in science because subsistence hunting and fishing is still a major activity there and many residents feel closely tied to the land and to scientific understanding of the landscape. The activities at Barrow include two main components: (1) an inquiry-based program that replicates some of our experimental and monitoring activities in tundra and lakes, which have been used as part of the K-12 science program in Barrow schools, and (2) a weekly lecture series on a wide range of scientific topics. Both activities have been very well-received by the Barrow community and we have received many requests to continue them. The Barrow Arctic Science Consortium (<http://www.arcticscience.org/schoolyardProject.php>) has supplemented our investment in these Schoolyard activities with additional funds and actively manages both the in-school activities and the public lectures. In addition, each year 1-4 LTER personnel visit Barrow to lecture in the "Saturday Schoolyard" series and in the public schools.
2. The *Polar Hands-on Laboratory* is offered each year by Logan Science Journalism Program of the Marine Biological Laboratory (<http://www.mbl.edu/sjp/polar.html>). Our aim in this program is to infuse professionals at communication with the public with the excitement of arctic research and with the principles of doing science. There is a tremendous multiplier here because we cannot bring the general public to our site, so our strategy is to develop ambassadors of our research that communicate through highly visible media to the broadest possible audience. The program has grown considerably over the past 5 years, as we have gone from a small program based in Woods Hole, in which 1-3 journalists visited Toolik Lake each year, to a full-blown field course for 10-15 science journalists. A wide range of newspaper, magazine, radio, and film media are represented (Table 5-2). Articles and other products are included in Supplementary Documents as part of our publications list.
3. *Courses in Arctic Ecology* for graduate and undergraduate students are held at the Toolik Field Station most summers, with ARC LTER investigators as faculty. These courses are exceptionally valuable because few if any courses provide opportunities for the learning of advanced techniques in the field in the Arctic, particularly in the United States. As with the Polar Hands-on Laboratory, these are "hands-on" courses with an emphasis on making measurements in the field and analyzing and discussing the results in the context of ongoing LTER research projects. For the past two years we have participated in collaboration with the [MBL-UAF Arctic Observatory Network project](#).
4. *Education of undergraduate and graduate students in arctic research* is our fourth educational activity (Table 5-1). Each year we support at least 2 REU students at Toolik Lake with LTER supplemental funds, and 2-10 others in association with collaborating NSF

grants. REU students are selected via a national search each year and come from a wide range of states and institutions. We promote the training of graduate students by supporting them with collaborating grants, and we continue to encourage foreign collaborators to send their students to us for a summer at Toolik Lake. To promote communication among these students, every summer we organize a weekly seminar series, "Toolik Talking Shop", and at the end of the summer we organize a poster session for REU students to show off and to "defend" their summer projects to an interested and friendly audience. Since 2005, each summer we have included 4-8 REU students in a group research project of monitoring of recovery from a small tundra wildfire near Toolik Lake. Most of our REU students have gone on to graduate school and often they are included as authors on publications. Graduate students, and occasionally REU students, are invited to our annual winter workshop in Woods Hole to present their results and to participate in planning for the following summer's research. These initiatives have helped us to increase the number of active graduate students by more than 2-fold over the past five years.

5. Outreach to federal, state, and local management agencies is an important component of our outreach program. Much of the research done at Toolik Lake is directly relevant to the problems of managing the huge expanse of publicly owned, wild land on the North Slope of Alaska. We provide regular briefings of BLM, ANWR, DNR, Alaska Fish and Game, and North Slope Borough officials; usually this consists of visits to their offices in Anchorage, Fairbanks, and Barrow, as well as tours of our research sites at Toolik Lake. We work particularly closely with the BLM and Alaska Fish and Game offices in association with the annual permitting process for our research. The Alaska Fish and Game office has used our data and advice in the past to set angling policies and fish catch regulations. Our contacts with Alaska DNR have increased in frequency lately as the DNR has been engaged in a reassessment of winter off-road travel policies. Each year we invite representatives from these agencies to attend our winter meeting in Woods Hole, to learn about our latest results and future plans. For the past 5 years, Toolik Field Station has also invited representatives of these agencies to speak at our weekly "Toolik Talking Shop" evening seminars for Toolik scientists and students, helping to make this a two-way channel of communication.
6. National and International Research Planning and Organization: We will continue our long-term participation in a wide range of national and international research planning and oversight organizations. In the past 5 years this has included participation in the steering or advisory committees for SEARCH (the Study of Environmental Arctic Change), ISAC (International Study of Arctic Change), and the ACIA (Arctic Climate Impacts Assessment), and we will continue to help with the long-term management and organization of the University of Alaska's Toolik Field Station. The planning activities are particularly important in development of broader scientific impacts of our research, and for applications of understanding developed from our research at the PanArctic, continental, and global scales.

Anticipated changes, 2010-2016: Overall, we are quite happy with this education and outreach program and expect to continue all components in 2010-2016. The program was praised in our 2007 site review and no changes were recommended. One addition to the program that is planned is increased interaction with smaller local villages including Anaktuvuk Pass and Kaktovik, where over the past two years we have opened discussions on climate change and its impacts on subsistence use of the land, as part of our LTER Network social science activities (Section 2). A second addition will be our participation in a new project led by John Moore of Colorado State University, "*Culturally relevant ecology, learning progressions and environmental literacy*". This project (NSF-DUE-0832173) will involve 3 other LTER sites, 22 K-12 school districts, and over 250 science and mathematics teachers across the US.

Table 5-1. Undergraduate and graduate students associated with the ARC LTER2004-2009

<i>Academic level</i>	<i># students</i>	<i>College or University</i>
Research Experience for Undergraduates	28 (17 female, 11 male)	Utah State, Brown University (2), Lawrence University, University of Michigan (4), Sterling College, University of Alabama, Gettysburg College, Lewis and Clark College, University of Vermont (2) Allegheny College, Middlebury College, University of Florida (2), Cornell University, University of California Santa Barbara (3), Michigan Technological University, Beloit College, Univ. of North Carolina, Western Washington University, Swarthmore College, Colorado College
Undergraduate research assistants	17 (7 female, 10 male)	Univ. of Florida (2), Univ. of California, Santa Barbara (4), Georgia Institute of Technology, University of Michigan, University of Northern Colorado/Northeastern University, University of Texas Arlington (2), University of Alabama, University of Texas Arlington (2), University of Vermont (2), Cal Poly, University of Alaska Fairbanks
Master's degree in progress	10 (6 female, 4 male)	Univ. of North Carolina, Greensboro(2), Univ. Florida (2), University of Michigan, University of Florida, University of Alaska, Fairbanks, University of Alabama, University of California Santa Barbara, University of Alaska Fairbanks
Master's degree recipients	12 (6 female, 6 male)	Brown University, University of North Carolina, Greensboro (3), University of Vermont (3), Utah State University University of Texas, Arlington, University of Maine, University of California at Santa Barbara, University of Michigan
Ph.D. degree in progress	11 (9 female, 2 male)	University of Alabama, University of Alaska Fairbanks, University of Florida (3), University of Vermont, Colorado State University (2), University of California Santa Barbara (2), University of Minnesota
Ph.D. degree recipients	12 (10 female, 2 male)	University of Michigan (4), Lamont-Doherty -Columbia University (2), Utah State University (2), Cornell University, University of Texas, Arlington, University of Alabama (2)
Foreign students	6 (5 female, 1 male)	Copenhagen, Roskilde (Denmark), Amsterdam, British Columbia, Tokyo Institute of Technology (2)

Table 5-2. Products and participants in the Science Journalism Program at Toolik Lake, 2004-2009.

<i>Media</i>	<i>Articles</i>	<i>Examples</i>
Newspaper: New York Times, Newark Star Ledger, Kansas City Star, Sacramento Bee, News and Observer, News Journal (Wilmington, DE), San Antonio Express Journal, Los Angeles Times, Courier Journal, Billings Gazette, Antarctic Sun, Santa Fe New Mexican, The Tennessean, Polar Field Newsletter	13	"Canary in the Mine,"(2005) by Mike Stark, <i>The Billings Gazette</i> ; "Flames Fill Alaskan Tundra" (2008) by Scott Canon, <i>Kansas City Star/McClatchy Newspapers</i> .
Magazines: YES, Chemical and Engineering News, Audubon, Nature, Muy Interesante, National Geographic News, Geo Times, Business Week, The Economist, New Scientist, Galileu, Smithsonian Magazine, OnEarth	8	"Alaska's biggest tundra fire sparks climate warning," (2009) by Tracey Logan, <i>New Scientist</i> "Tundra's Burning" (2009) by Jane Qiu, <i>Nature</i>
Radio: PRI's Living on Earth, BBC Radio, South Dakota Public Broadcasting, Connecticut Public Broadcasting, Pulse of the Planet	15	"Above the Arctic Circle" (2008) by Nancy Cohen, Connecticut Public Broadcasting Network; "Rekindling interest in science", Richard Hollingham BBC News
TV: NBC Weather Plus, National Geographic TV, Greenrock Productions (VJ Movement)	2	"Climate change may have sparked Arctic fire", Leslie Dodson. 2009. VJ Movement (Int'l news service)
Web-based journals: Salon.com	1	"Baked Alaska," (2004) by Rebecca Clarren, Salon.com.
Blogs	11 sites	"Arctic Dispatches" (2008) by Christine Dell'Amore, <i>Smithsonian Magazine</i>

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Table 7-1. ARC LTER Collaborating grants in effect, January 2010

1. NSF-OPP-0632139, "IPY: Collaborative Research on Carbon, Water, and Energy Balance of the Arctic Landscape at Flagship Observatories and in a PanArctic Network"; \$1,398,346 (Shaver, Rastetter, Hobbie)
2. NSF-OPP-0632264 IPY: Collaborative Research on Carbon, Water, and Energy Balance of the Arctic Landscape at Flagship Observatories and in a Pan-Arctic Network 03/15/2007 \$1,550,981. (Bret-Harte, Barnes, Walter, Euskirchen)
3. NSF-DEB-0639805 LTREB: Collaborative Research: What Controls Long-term Changes in Freshwater Microbial Community Composition? 01/15/2007; \$105,794. (Kling)
4. NSF-DEB-0639790 LTREB: Collaborative Research: What Controls Long-term Changes in Freshwater Microbial Community Composition? 01/15/2007 \$165,272. (Crump)
5. NSF-DEB-0640953 Turbulent Mixing, Internal Waves, and Intrusions: Temporal and Spatial Variability of Resource Supply and Metabolic Activity in Lakes 04/01/2007 \$535,554. (MacIntyre)
6. NSF-OPP-0714085 Arctic Lakes are Sieves: Will Global Warming Close the Pores? 09/15/2007 \$262,415. (MacIntyre)
7. NSF-OPP-0732664 IPY: Autotrophic Respiration in a Changing Arctic Climate: Mechanistic Responses and Ecosystem Consequences 03/01/2008 \$389,689 (Griffin)
8. NSF-OPP-0732955, "IPY: Improving the Public's Understanding of Polar Research Through Hands-On Fellowships for Science Journalists in the Arctic and Antarctic"; 3 weeks/year; \$365,289 (Neill, Ducklow, Shaver)
9. NSF-OPP-0732985 Collaborative Research: IPY: Arctic Great Rivers Observatory (Arctic-GRO) 07/01/2008 \$435,487. (Peterson)
10. NSF-OPP-0733074 IPY: Microbial winter survival physiology: a driver on microbial community composition and carbon cycling 09/15/2007 \$904,623. (Schimel)
11. NSF-OPP-0806254 Collaborative Research: Spatial and Temporal Influences of Thermokarst Features. 09/01/2008; \$163,277. (Kling)
12. NSF-OPP-0806271 Collaborative Research: Spatial and Temporal Influences of Thermokarst Failures on Arctic Surface Processes 09/01/2008 \$374,867. (Mack)
13. NSF-OPP-0806341 Collaborative Research: Spatial and Temporal Influences of Thermokarst Features on Surface Processes in Arctic Landscapes 09/01/2008 \$415,605. (Gooseff)
14. NSF-OPP-0806329 Collaborative Research: Spatial and Temporal Influences of Thermokarst Features on Surface Processes in Arctic Landscapes 09/01/2008 \$116,158. (Rastetter)
15. NSF-OPP-0806394 Collaborative Research: Spatial and Temporal Influences of Thermokarst Failures on Surface Processes in Arctic Landscapes. 09/01/2008 \$1,073,210. (Bowden)

16. NSF-OPP-0806451 Collaborative Research: Spatial and Temporal Influences of thermokarst features on Surface Processes in Arctic Landscapes 09/01/2008 \$254,239. (Schimel)
17. NSF-OPP-0807639, "Canopy Structure and CO₂ Exchange of Arctic Vegetation: Key Constraints on Change and Predictability of the Arctic System" ; \$997,782 (Shaver)
18. NSF-DUE-0832173 Targeted Partnership: Culturally relevant ecology, learning progressions and environmental literacy 10/01/2008 \$7,498,822. (Moore)
19. NSF-OPP-0852075 PostDoctoral Research Fellowship: Arctic lakes and Fire 08/01/2009 \$152,636. (C. Johnson)
20. NSF-OPP-0856853, "Fire In the Arctic Landscape: Impacts, Interactions And Links To Global and Regional Environmental Change"; 1 month/year; \$872,715 (Shaver plus associates Kling, Bowden, Giblin, Rastetter, Boelman, Rocha, Deegan, Mack, Bret-Harte)
21. NSF-OPP-0902106 Collaborative Research: How does changing seasonality affect the capacity of arctic stream networks to influence nutrient fluxes from the landscape to the ocean? 09/01/2009; \$549,581. (Bowden)
22. NSF-OPP-0902029 Collaborative Research: How does changing seasonality affect the capacity of arctic stream networks to influence nutrient fluxes from the landscape to the ocean? 09/01/2009 \$373,268. (Gooseff)
23. NSF-OPP-0902153 Collaborative Research: Shifting seasonality of Arctic river hydrology alters key biotic linkages among aquatic systems 07/01/2009 \$1,317,687. (Deegan)
24. NSF-OPP-0902126 Collaborative proposal: Shifting seasonality of Arctic river hydrology alters key biotic linkages among aquatic systems 07/01/2009 \$307,269. (Huryn)
25. NSF-OPP-0902038 Collaborative Research: The Changing Seasonality of Tundra Nutrient Cycling: Implications for Ecosystem and Arctic System Functioning 09/01/2009 \$313,386. (Schimel)
26. NSF-OPP-0902102 Collaborative Research: The Changing Seasonality of Tundra Nutrient Cycling: Implications for Ecosystem and Arctic System Functioning 09/01/2009 \$180,926. (Rastetter)
27. NSF-OPP-0902109 Effects of lengthening growing season and increasing temperature on soil carbon fluxes and stocks in Arctic tundra 09/01/2009 \$99,879. (Tang)
28. NSF-OPP-0908602 Collaborative Research: Effects of warming induced increases in shrub abundance and changing seasonality on migratory songbirds in Alaskan arctic tundra 09/01/2009 \$346,230. (Gough)
29. NSF-DEB-0908444 Collaborative Research: Effects of warming induced increases in shrub abundance and changing seasonality on migratory songbirds in Alaskan arctic tundra. 09/01/2009 \$600,005. (Boelman)
30. NSF-DEB-0909133 Collaborative Research: Effects of warming induced increases in shrub abundance and changing seasonality on migratory songbirds in Alaskan arctic tundra. 09/01/2009. \$332,086 (Wingfield)
31. NSF-OPP-0908936 Implications of Ecotypic Variation for the Response of Tundra Plants to Climate Change 08/01/2009 \$196,846 (McGraw, Fetcher)

32. NSF-OPP-0909441 Collaborative Research: A biotic awakening: How do invertebrates, microbes, and plants determine soil organic matter responses to release from nutrient limitation in arctic tundra? 09/01/2009 \$771,369. (Moore)
33. NSF-OPP-0909507 Collaborative Research: A biotic awakening: How do invertebrates, microbes, and plants determine soil organic matter responses to release from nutrient limitation in arctic tundra? 09/01/2009 \$225,550. (Gough)
34. NSF-DEB-0909747 DISSERTATION RESEARCH: Dynamics of labile organic matter fractions in arctic soils 09/01/2009 \$13,150. (Moore)
35. NSF-DEB-0919603 Collaborative Research: Arctic to the Amazon: Physical Processes Controlling Gas Exchange from Freshwater Ecosystems. 09/01/2009 \$399,567. (MacIntyre)

Supplemental Table 1: Publications of the ARC LTER 2004-2009

Journal articles:

- Adams, H. E., B. C. Crump, and G. W. Kling. in press. Temperature controls on aquatic bacterial activity and community dynamics. *Environmental Microbiology*.
- Benstead, J. P., A. C. Green, L. A. Deegan, B. J. Peterson, K. Slavik, W. B. Bowden, and A. E. Hershey. 2007. Recovery of three Arctic stream reaches from experimental nutrient enrichment. *Freshwater Biology*. 52:1077-1089.
- Benstead, J. P., L. A. L.A. Deegan, B. J. Peterson, A. D. Huryn, W. B. Bowden, K. Suberkropp, K. M. Buzby, A. D. Green, and J. A. Vacca. 2005. Responses of beaded Arctic stream to short-term N and P fertilization. *Freshwater Biology* 50:277-290.
- Biesinger, Z., E. Rastetter, and B. Kwiatkowski. 2007. Hourly and daily models of active layer evolution in Arctic soils. *Ecological Modelling* 206:131-146.
- Boelman, N. T., M. Stieglitz, K. L. Griffin, and G. R. Shaver. 2005. Inter-annual variability of NDVI in response to long-term warming and fertilization in wet sedge and tussock tundra. *Oecologia* 143:588-597.
- Bosch, N. S., T. H. Johengen, J. D. Allan, and G. W. Kling. In press. Nutrient fluxes across reaches and impoundments in two southeastern Michigan watersheds. . *Lake and Reservoir Management*.
- Bowden, W. B., M. N. Gooseff, A. Balsler, A. Green, B. J. Peterson, and J. Bradford. 2008. Sediment and nutrient delivery from thermokarst features in the foothills of the North Slope, Alaska: Potential impacts on headwater stream ecosystems. *J. Geophys. Res* 113, G02026, doi:10.1029/2007JG000470.
- Bradford, J. H., C. R. Johnson, T. Brosten, J. P. McNamara, and M. N. Gooseff. 2007. Imaging thermal stratigraphy in freshwater lakes using georadar. *Geophys. Res. Lett.* 34:L24405, doi:24410.21029/22007GL032488.
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- Bret-Harte, M. S., E. A. Garcia, V. M. Sacré, J. R. Whorley, J. L. Wagner, S. C. Lippert, and F. S. I. Chapin. 2004. Plant and soil responses to neighbour removal and fertilization in Alaskan tussock tundra. *Journal of Ecology* 92:635-647.
- Bret-Harte, M. S., M. C. Mack, G. R. Goldsmith, D. B. Sloan, J. DeMarco, G. Shaver , P. M. Ray, Z. Biesinger, and F. S. Chapin III. 2008. Plant functional types do not predict biomass responses to removal and fertilization in Alaskan tussock tundra. *Journal of Ecology* 96:713-726. DOI: 710.1111/j.1365-2745.2008.01378.
- Brosten, T., J. H. Bradford, J. P. McNamara, M. N. Gooseff, J. P. Zarnetske, W. B. Bowden, and M. E. Johnston. 2009. Multi-offset GPR methods for hyporheic zone investigations. *Near Surface Geophysics* 7:247-257.
- Brosten, T., J. H. Bradford, J. P. McNamara, J. P. Zarnetske, M. N. Gooseff, and W. B. Bowden. 2006. Temporal thaw depth beneath two arctic stream types using ground-penetrating radar. . *Permafrost and Periglacial Processes* 17:341-355.
- Brosten, T. R., J. H. Bradford, J. P. McNamara, M. N. Gooseff, J. P. Zarnetske, W. B. Bowden, and M. E. Johnston. 2009. Estimating 3D variation in active-layer thickness beneath arctic streams using ground-penetrating radar. *Journal of Hydrology* 373:479-486.
- Buzby, K., and L. A. Deegan. 2004. Long-term survival of adult Arctic grayling in the Kuparuk River, Alaska. *Canadian Journal of Fisheries and Aquatic Sciences* 61:1954-1964.
- Callaghan, T. V., L. O. Björn, Y. Chernov, F. S. Chapin, T. R. Christensen, B. Huntley, R. A. Ims, M. Johansson, D. Jolly, S. Jonasson, N. Matveyeva, N. Panikov, W. C. Oechel, and G. R. Shaver. 2004. Rationale, concepts and approach to the assessment. *Ambio* 33:393-397.

- Callaghan, T. V., L. O. Björn, Y. Chernov, F. S. Chapin, T. R. Christensen, B. Huntley, R. A. Ims, D. Jolly, M. Johansson, S. Jonasson, N. Matveyeva, N. Panikov, W. C. Oechel, and G. R. Shaver. 2004. Effects on the function of Arctic ecosystems in the short- and long-term perspectives. *Ambio* 33:448-458.
- Callaghan, T. V., L. O. Björn, Y. Chernov, F. S. Chapin, T. R. Christensen, B. Huntley, R. A. Ims, D. Jolly, M. Johansson, S. Jonasson, N. Matveyeva, N. Panikov, W. C. Oechel, and G. R. Shaver. 2004. Past changes in Arctic terrestrial ecosystems, climate and UV radiation. *Ambio* 33:398-403.
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- Callaghan, T. V., L. O. Björn, Y. Chernov, F. S. Chapin, T. R. Christensen, B. Huntley, R. A. Ims, D. Jolly, M. Johansson, S. Jonasson, N. Matveyeva, N. Panikov, W. C. Oechel, G. R. Shaver, J. Elster, H. Henttonen, K. Laine, K. Taulavuori, E. Taulavuori, and C. Zöckler. 2004. Biodiversity, distributions and adaptations of Arctic species in the context of environmental change. *Ambio* 33:404-417.
- Callaghan, T. V., L. O. Björn, Y. Chernov, F. S. Chapin, T. R. Christensen, B. Huntley, R. A. Ims, D. Jolly, M. Johansson, S. Jonasson, N. Matveyeva, N. Panikov, W. C. Oechel, G. R. Shaver, J. Elster, I. S. Jonsdottir, K. Laine, K. Taulavuori, E. Taulavuori, and C. Zöckler. 2004. Responses to projected changes in climate and UV-B at the species level. *Ambio* 33.
- Callaghan, T. V., L. O. Björn, Y. Chernov, F. S. Chapin, T. R. Christensen, B. Huntley, R. A. Ims, D. Jolly, M. Johansson, S. Jonasson, N. Matveyeva, N. Panikov, W. C. Oechel, G. R. Shaver, and H. Henttonen. 2004. Effects on the structure of Arctic ecosystems in the short- and long-term. *Ambio* 33:436-447.
- Callaghan, T. V., L. O. Björn, Y. Chernov, F. S. Chapin, T. R. Christensen, B. Huntley, R. A. Ims, D. Jolly, M. Johansson, S. Jonasson, N. Matveyeva, N. Panikov, W. C. Oechel, G. R. Shaver, S. Schaphoff, and S. Sitch. 2004. Effects on landscape and regional processes and feedbacks to the climate system. *Ambio* 33:459-468.
- Callaghan, T. V., L. O. Björn, Y. Chernov, F. S. Chapin, T. R. Christensen, B. Huntley, R. A. Ims, D. Jolly, M. Johansson, S. Jonasson, N. Matveyeva, N. Panikov, W. C. Oechel, G. R. Shaver, S. Schaphoff, S. Sitch, and C. Zöckler. 2004. Key findings and extended summaries. *Ambio* 33:386-392.
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- Castillo, M., J. D. Allan, R. L. Sinsabaugh, and G. Kling. 2004. Seasonal and interannual variation of bacterial production in lowland rivers of the Orinoco basin. *Freshwater Biology* 49:1400-1414.
- Cherry, J. E., L.-B. Tremblay, S. J. Déry, and M. Stieglitz. 2005. Reconstructing Solid Precipitation Snow Depth Measurements and a Land Surface Model. *Water Resources Research* 41:W09401, doi:09410.01029/02005WR003965.
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Supplementary Documents, Table 2: Data files available online from the ARC LTER web site.

Total number of data files (Reported file size is of the Excel files which include both metadata and data worksheets) ~1,400. Total size ~72 MB.

Weather Data

Type of data	No. files (Size, MB)	Aggregation	Description
Toolik Field Station Met	65 (112)	Yearly & multiyear	Air temperature, relative humidity, wind speed and direction, solar radiation, precipitation, barometric pressure, soil temperatures, lake temperature, lake depth, and evaporation pan measured at Toolik Lake since June 1988.
Plot level Weather Stations	82 (719)	Yearly	Soil and air temperatures in mesic acidic tussock, mesic non-acidic tussock and wet sedge in treated and untreated plots around Toolik Lake.
Sagavanirktok River	17 (7.5)	Yearly & multiyear	Soil, air temperature, solar radiation and summer precipitation collected 40 km north of Toolik.

Terrestrial

Type of data	No.	Aggregation	Description
Plant Biomass, Chemistry	39 (8.2)	Year & multiyear	Biomass harvests; includes several tundra types (heath, wet sedge, acidic and non acidic mesic tussock, shrub), treated and untreated plots and woody stem biomass. Percent carbon, nitrogen, phosphorus, leaf area, stem biomass and carbon flux were also measured for several of the harvests.
Plant Communities and species list	10 (5.7)	Year & Multiyear	Plant lists and percent cover from biomass harvests and from permanent plots.
Plant phenological and growth data	11 (6.6)	Year & multiyear	Leaf growth and phenology data from experimental plots from northern and central Alaska. <i>Eriophorum vaginatum</i> flowering abundance data are from observations at 34 sites, spanning 5.5 degrees latitude and 1050 m elevation.
Soil del C-13; Radiocarbon dates	27 (2.1)	Separated by year and sites	Percent moisture, percent organic carbon, bulk density, del C-13, del ¹⁵ N, and radiocarbon content at depth intervals in peat cores from the North Slope of Alaska.
Soil properties	13 (3.9)	Year & multiyear	Extractable NH ₄ -N, NO ₃ -N and PO ₄ -P, pH, total carbon, nitrogen and phosphorus, net nitrogen mineralization and thaw depth on soils of the experimental plots near Toolik.
Trace gas	14 (4.6)	Year	Ecosystem respiration, methane fluxes and net ecosystem production near Toolik Lake comparing effects of temperature, moisture and nutrients on tundra C balances.
Litter Decomposition	1	Multiyear	Long-term Intersite Decomposition Experiment Team (LIDET) data set for Toolik.
Precipitation Chemistry	3 (0.4)	Multiyear	Unfrozen wet only and bulk precipitation chemistry for summer months at Toolik Lake.