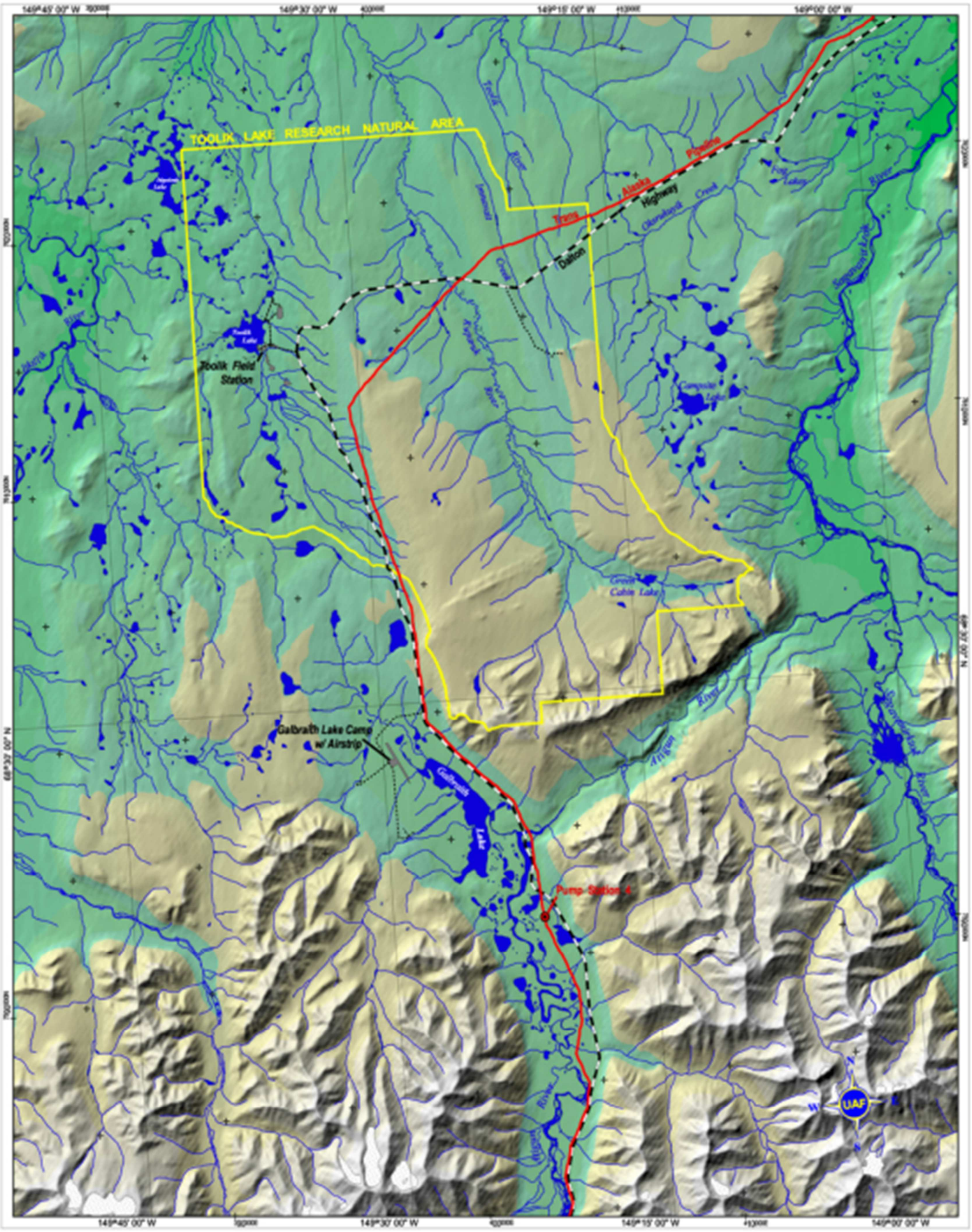


ARCTIC LTER SITE REVIEW
JUNE 18-19 2013

THE ARCTIC LTER PROJECT AT TOOLIK LAKE, ALASKA
NSF SITE REVIEW 2013

TABLE OF CONTENTS

THE ARCTIC LTER PROJECT AT TOOLIK LAKE, ALASKA
NSF SITE REVIEW 2013

1. INTRODUCTION

The Arctic LTER Site

The Arctic LTER field research site (front cover, Fig. 1) is located in the northern foothills of the North Slope, that part of northern Alaska that drains to the Arctic Ocean. The site was chosen in 1975 when the newly opened oil pipeline Haul Road (later renamed the Dalton Highway) made access possible. The Dalton Highway is the only road on the North Slope that connects with the rest of Alaska.

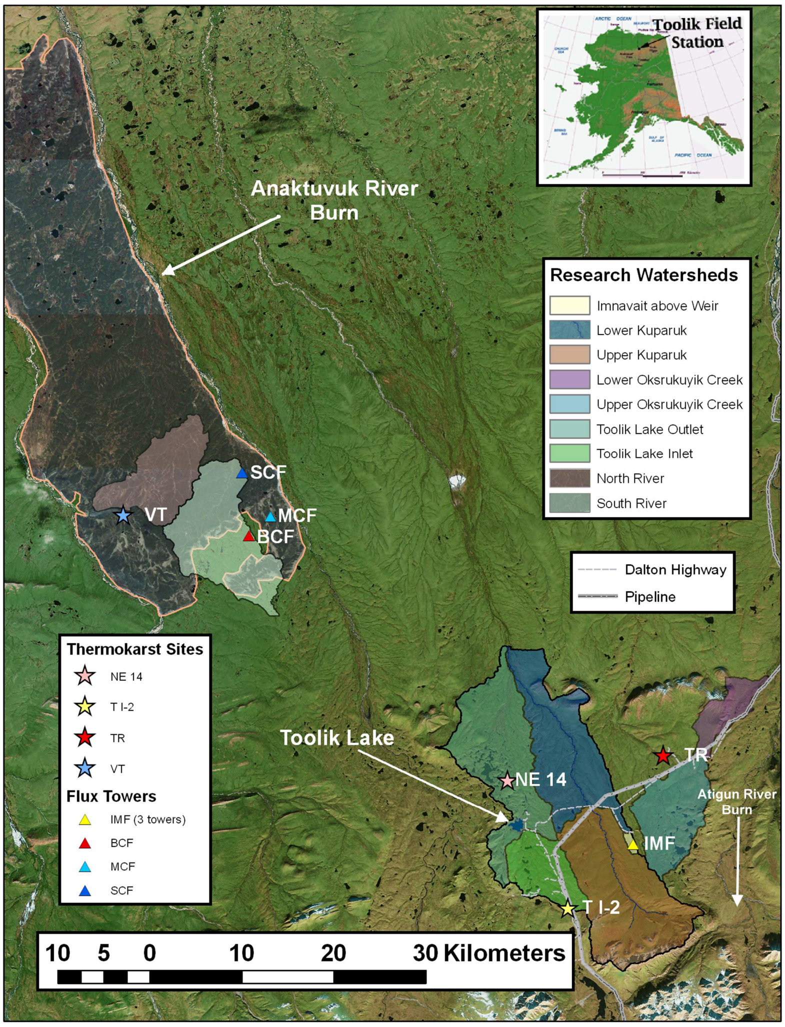


Fig 1. Major research sites and place names. The main Arctic LTER research site includes the drainage basin enclosing the two branches of the headwaters of the Kuparuk River (including Toolik Lake and its drainage basin, the upper Kuparuk River, and Imnavait Creek). The ARC LTER research also includes 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.

<u>Key to thermokarst and flux sites</u>:

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.

The Arctic LTER 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 1). Additional sites include the 1000 km^2 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 30-50 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 conseq(uence 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).

History of Research

The North Slope of Alaska has a substantial history of ecological research (described in greater detail in our new site synthesis book, Hobbie and Kling in press). Expeditions began in the First International Polar Year (1882) including establishment of a year-round observatory at Barrow. Various natural history collections were made for the next 65 years. After World War II, a Naval Arctic Research Laboratory (NARL) was established at Barrow (1947-1980). This was a large, well-supported facility with laboratories and dormitories, an air force of five planes, remote camps on an ice floe and on a mountain lake, and some small ships. In 1970-73 the Tundra Biome project of the International Biological Program (IBP, terrestrial and aquatic) was housed at NARL. The overall themes of IBP were (1) to develop a predictive understanding of the Arctic ecosystem, (2) to obtain a database for modeling and comparison, and (3) to use environmental knowledge for problems of degradation, maintenance, and restoration of ecosystems. All of the major ecosystem components such as primary producers, decomposers, herbivores, predators, climate and microclimate, and soils, were studied at an aquatic site and a terrestrial site. Process studies were emphasized, as were system budgets for C, N, and P.

The Dalton Highway opened in fall 1974, instantly creating access to a much wider array of tundra and freshwater ecosystems than were available at Barrow. Researchers were quick to take advantage of this opportunity, and Toolik Lake was chosen as a site for lakes research in June 1975. Research on nearby streams and tundra began in 1976. Most of this early work was funded by NSF-OPP and NSF-DEB. As the number and activities of these projects grew, Toolik Field Station (TFS) emerged as a logistics base, managed by the University of Alaska. Throughout the 1980s a number of smaller projects, mostly with NSF funding, began to use TFS. One large multiinvestigator project, the DOE-supported R4D project (1983-91), worked at nearby Imnavait Creek to study landscape response to disturbance.

The Arctic LTER

The Arctic LTER project began in 1987. The overall goal of the project is to understand all of the ecosystems that comprise the landscape around Toolik Lake, their structure, function, and interactions, to allow prediction of effects of change. The specific focus of our work evolves continuously and changes with each cycle of funding, as understanding and grows and new opportunities are recognized. In past funding cycles we have focused on the following:

- 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.

Now at the midpoint of our fifth funding cycle, our current specific goal is:

- LTER V (2011-2017): Understanding 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 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. 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?*

Overview of the following sections of this document

The following sections of this document describe the Arctic LTER project results and activities in the current funding period, since 1 December 2010. The initial sections provide examples of the research currently under way at Toolik Lake and at the home institutions of the collaborating P.I.s of the current ARC LTER project. These will be discussed in greater detail and with additional examples during the ARC LTER Site Review June 18-19. Following these examples we provide additional information on project management and on information management, and our education and outreach activities. We end with a list of “Current Challenges”, highlighting a few issues where progress is slow or activities have changed from what was originally proposed.

The project’s research activities are summarized in the following tables. Major field sites are listed in Table 1. Core monitoring and process studies are summarized in Table 2. The long-term, whole-ecosystem manipulations are summarized in Table 3. The current cooperating projects are listed in Table 4.

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

Core study watersheds and watershed-scale comparisons used to integrate the LTER	
Toolik Inlet Watershed	*A 48 km^2 watershed of streams and lakes that forms the largest input of water and materials into Toolik Lake, located on the 10-60,000 yr aged surface*
Upper Kuparuk Watershed	*146 km^2 watershed predominantly underlain by older Sagavanirktok-aged surfaces (~300,000 yr), extreme headwaters on 60,000 yr aged surface*
Imnavait Watershed	*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*
South River Watershed	*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 (TLNRA), 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 300,000 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 (~60,000) 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*

(Table 1 continued on next page)

Table 1, continued

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, ~60,000-100,000 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*

Table 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*

Climate, C, N, Energy Budgets, and Hydrology of LTER Core Watersheds		
Location and type of measurement		***Frequency***
Toolik Lake, Toolik Inlet, surrounding Landscape	*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*
Upper Kuparuk Watershed	*Stream gauge, temperature at Dalton Highway crossing*	*as above*
Imnavait Creek	*Climate Station, stream weir, and multiple soil temp/moisture data loggers, 3 eddy flux towers along hillslope*	*as above*
Anaktuvuk River Burn	*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*

(Table 2 continued on next page)

Table 2 (continued)

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*
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, chla 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 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 exclosure 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 µM 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 2014 or 2015*

Table 4. *Collaborating projects funded in 2012 or 2013.*

AGENCY	***P.I.'s***	***Topic***
NSF OPP	*Shaver, Rastetter, Bret-Harte, Walter, Euskirchen, Kling, Kane, Zimov*	*Arctic Observatory Network: Carbon, Water, and energy fluxes in a small catchment, Imnavait Creek, Alaska, and at Cherskii, Siberia*
NSF OPP	*Shaver*	*Canopy structure and carbon balance of tundra vegetation at Toolik Lake, Svalbard, Zackenberg (Greenland), and Abisko (Sweden)*
NSF OPP	*Shaver, Boelman, Bowden, Bret-Harte, Giblin, Kling, Luecke, Mack, Rastetter, Rocha*	*Impacts of the Anaktuvuyk River Wildfire*
NSF-EF	*Shaver, Rastetter, Rocha*	*Long-term, regional impacts of fire on the North Slope of Alaska*
NSF DEB	*Gough, Moore,*	*Herbivory and soil food web*
NSF-MSP	*Moore*	*Opportunities for teachers in ecological research*
NSF OPP	*Boelman, Gough, Wingfield*	*Changing seasonality and plant-insect-bird relationships*
NASA	*Boelman, Vierling, Griffin, Eitel*	*Long term shifts in arctic C storage*
NSF OPP	*Oberbauer.*	*Arctic Observatory Network: Phenology and growth of plants in an international warming experiment*
NSF-OPP	*Weintraub, Steltzer, Sulliuvan,*	*Changing seasonality and tundra biogeochemistry*
NSF-OPP	*Wallenstein*	*Microbial allocation of carbon (CAREER award) Enzymes in the Environment (RCN)*
NSF OPP	*Hu et al.*	*Paleoecology and tundra fire regimes*
NSF OPP	*Bowden et al*	*Changing thermokarst regime in permafrost regions of Alaska*
NSF OPP	*Bowden et al.*	*Changing seasonality and stream and soil processes in an arctic landscape*
NSF EFs	*Bowden et al.*	*Stream Consumers and Lotic Ecosystem Rates*
NSF-OPP	*Deegan, Huryn, Peterson*	*Changing seasonality and biotic linkages in arctic streams*
NSF LTREB	*Crump and Kling*	*Microbial community structure in stream-lake systems*
NSF OPP	*Cory and Kling*	*Photochemical and Microbial processing of C*
NSF-OPP	*Nielsen, and Kane*	*Heat fluxes in streams*
NSF OPP	*MacIntyre*	*Circulation and respiration in ice-covered lakes*
NSF-OPP	*Godsey, Harms, Gooseff*	*Coupling of hydrology and biogeochemistry on hillslopes*

2. TERRESTRIAL RESEARCH

*The major research goal of the **Terrestrial subgroup** is to develop a predictive understanding of the distribution of tundra ecosystems in the landscape; the controls over their structure, functioning, and biogeochemical cycles; and their interactions with each other and with the local and regional environment. We focus our efforts on investigating the plant and soil communities of the common tundra types with a relatively recent focus on consumers both above- and belowground. We are investigating three questions presented in our LTER proposal, and in this summary we present each question and highlight one major finding to date. Additional details associated with these and other recent findings (and relevant citations) can be found in the Terrestrial section of our current LTER annual report.*

Proposal Questions:

***1.** How does climate control ecosystem states, processes, and linkages?*

Finding: ***After 20 years of artificial warming, moist acidic tundra soils experienced no net change in carbon or nitrogen stocks, despite dramatic plant and soil community shifts.***

As tundra soils warm, decomposition and nutrient cycling rates increase, promoting greater net primary productivity (NPP) of the vegetation and in many cases a shift in the plant community towards dominance by deciduous shrubs. These vegetation changes have occurred in our long-term manipulations and have been documented across the arctic landscape in the past decade in response to regional warming. Previous work at the ARC LTER in moist acidic tundra (MAT) has shown dramatic changes in vegetation and associated ecosystem processes when nutrient limitation is alleviated experimentally (e.g., Chapin et al. 1995, Shaver et al. 2001, Mack et al. 2004). In a project led by Ph.D. student Seeta Sistla and her advisor Josh Schimel, we found that 20 years of summer warming resulted in no net change in soil carbon or nitrogen stocks relative to control plots (Sistla et al. 2013 Nature). As shown in the table below (red values indicate significantly greater values in greenhouse plots than controls, blue values the opposite), the most responsive soil layer was the mineral, in which carbon and nitrogen patterns did differ, but these were not substantial enough to alter the entire soil profile. The soil food web also changed in the

	Surface organic		Deep organic		Mineral	
Soil characteristic	Control	Greenhouse	Control	Greenhouse	Control	Greenhouse
Microbial biomass N (μg N soil g-1)	605 ± 106	563 ± 127	285 ± 63	307 ± 90	5.78 ± 1.55	13.0 ± 3.86
Fungal:bacterial biomass	181 ± 53	220 ± 53	858 ± 305	163 ± 69	115 ± 37	76 ± 70
SIR microbial biomass (μg C-CO2 soil g^{-1} day^{-1})	6011 ± 733	4584 ± 664	1604 ± 434	1848 ± 351	59.9 ± 7.26	83.0 ± 4.28
C-mineralization (μg C-CO2 soil g^{-1} day^{-1})	31.83 ± 1.6	27.15 ± 11.6	12.37 ± 2.2	15.46 ± 3.4	0.43 ± 0.05	0.64 ± 0.04
Extractable organic C (mg C m^{-2})	111.07 ± 18.3	138.11 ± 37.1	610.94 ± 192.3	917.60 ± 57.2	1343.14 ± 160.2	1092.11 ± 97.1

all values reported as means ± one se

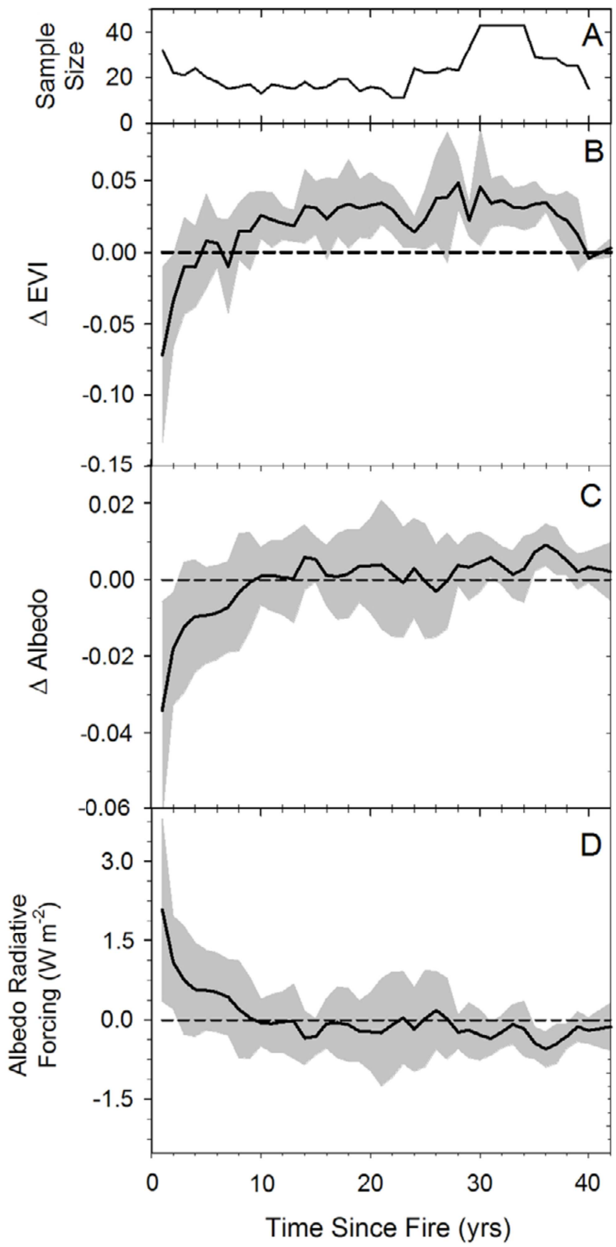
greenhouse plots, more in the surface layers than in the mineral.

Because plant biomass and NPP were greater in greenhouse plots than control, these results suggest that after 20 years of warming, MAT may be able to retain similar amounts of carbon and nitrogen as under ambient air temperatures. The interactions between vegetation and soils is complex because of differences in snow trapping and litter deposition associated with deciduous shrub dominance that alter the microclimate and soil inputs under the plants. These results together suggest that over the scale of two decades, this tundra ecosystem may be more resilient to warming than previously thought. In our current LTER funding we are focusing on lower-level nutrient additions that were begun in 2006 that allow us, in concert with the study above and others, to determine how temperature and nutrients interact in these soils. In 2012 we conducted a biomass harvest of several of these experiments, which allow us to examine nutrient limitation in more detail by determining threshold levels of nutrient availability that may push MAT towards deciduous shrub dominance. We will continue to monitor these experimental treatment plots to gather more insights that can be used to understand how the current regional increase in shrubs in the Arctic is likely to affect carbon and nitrogen cycling at the landscape scale.

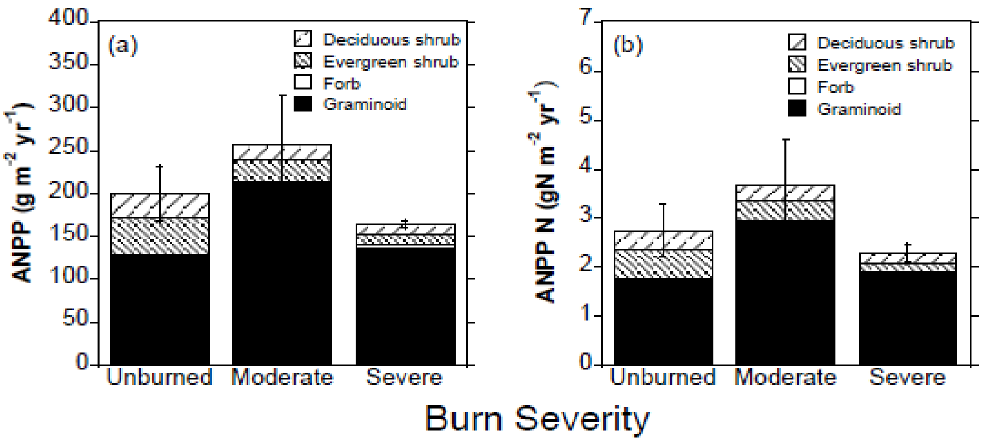
***2.** How do disturbances change ecosystem states, processes, and linkages? Here we are comparing two fundamental classes of disturbances, pulse (e.g., fire, thermokarst failures) and press (e.g., climate change, permafrost thaw).*

Finding: ***Despite huge losses of soil carbon during tundra fires, recovery of vegetation and its productivity can be rapid,, particularly following fires of moderate severity.***

The 2007 Anaktuvuk River wildfire burned 1039 km^2 of tundra about 40 km north of Toolik Lake (Fig. 1). One result of this fire was a huge emission of soil carbon of approximately 2.2 Tg C, effectively reversing the annual uptake (sink) of the entire global arctic tundra biome over the last 10 years of the 20th century (Mack et al. 2011 Nature). All of the abovground vegetation was burned, and there were major increases in energy inputs to the system (radiative forcing) and other changes such as large increases in depth of soil thaw. However, recovery of the vegetation canopy and surface energy exchanges turns out to be quite rapid in tundra fires, such that within 5-10 years they tend to become significant sinks for C. (the figure at right, from Rocha et al. 2012 Env Res. Letters, shows mean anomalies and 90% confidence intervals of "greenness" or EVI, albedo, and albedo radiative forcing in a survey of Alaska tundra wildfires since 1979)



In 2011, the ARC LTER conducted a detailed soil and plant biomass harvest at the Anaktuvuk River burn site including areas that had not been burned, or were moderately or severely burned. The results suggest that the vegetation, particularly the graminoids (dominated by the tussock-forming sedge *Eriophorum vaginatum),* was able to regrow from belowground rhizomes relatively quickly, with ANPP of the moderately burned tundra slightly greater than in tundra that had not been burned (figure below from Bret-Harte et al. in press Proc Roy Soc London B). However, lichens and mosses are showing little sign of recovery, and shrub wood was lost in the fire, therefore the biomass of the vegetation is substantially lower in the burned areas than unburned.

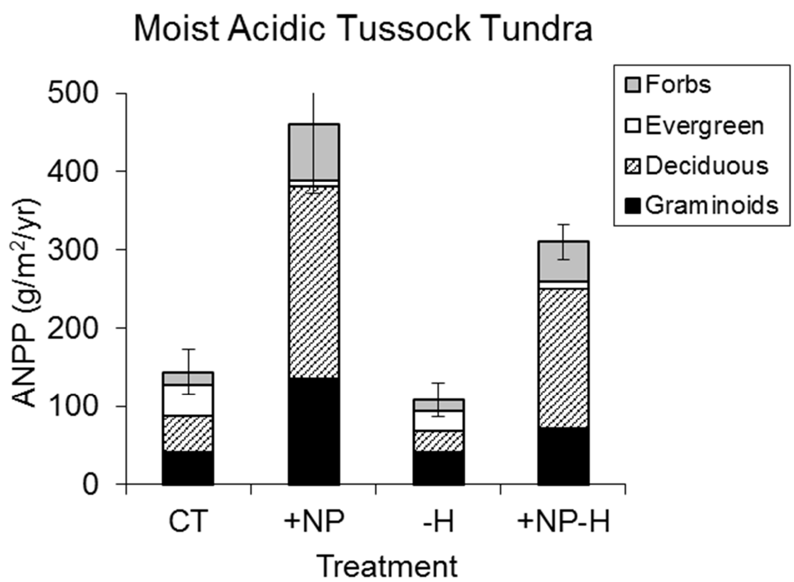


These results support findings in other parts of Alaska where tundra fires have occurred more frequently. We will continue to monitor the recovery of the burned areas in collaboration with aquatic research teams from the ARC LTER to determine how changes in the vegetation and soils contribute to observed changes in streams and lakes as well.

3. *How do climate and disturbance* <u>*interact*</u> *to control biogeochemical cycles and biodiversity at catchment and landscape scales?*

<u>*Finding*</u>*:* ***Consumer species, responding directly and indirectly to climate changes, may alter the disturbance regime and potentially exacerbate or slow responses of tundra ecosystems to warming.***

Recently attention is being paid to the role of terrestrial consumers in potentially offsetting changes in vegetation as described above, particularly the role of herbivory in restricting increases in shrub abundance in Scandinavian tundra. At the ARC LTER we took advantage of our long-term factorial manipulation of nutrient availability and mammalian herbivores to test the Exploitation Ecosystem Hypothesis (sensu Oksanen et al. 1981) both above- and belowground. We predicted that as resources increased, additional trophic levels should be supported, and thus the role of herbivory would intensify unless secondary consumer pressure also increased. In MAT, we were surprised to determine that after 10 years of manipulation, the absence of mammalian herbivores (-H treatments below) reduced ANPP, suggesting that caribou and small mammals stimulate ANPP in both ambient and increased nutrient plots and therefore exacerbate the changes caused by increased soil nutrients (Gough et al. 2012 Ecology). In contrast, the same experiment conducted in less productive dry heath tundra resulted in the



greatest ANPP in plots that received nutrients and were protected from herbivores, aligning with our predictions. Interestingly, below-ground herbivores (root-feeding nematodes) followed a similar pattern across the two communities as well.

These results suggest that mammalian herbivores may offset or exacerbate changes in plant productivity and species composition resulting from warming and associated increases in soil nutrients. The ARC LTER continues to examine these interactions through a new collaboration with Dr. Rebecca Rowe, University of New Hampshire, who is beginning to examine the small mammal communities in the vicinity of Toolik Lake. This is the first time in over 20 years that such studies will be conducted in this region. In addition, the arthropod community is also being studied near Toolik in collaboration with the ARC LTER, and in 2013 will be sampled within long-term nutrient addition experiments.

3. LAND-WATER INTERACTIONS RESEARCH

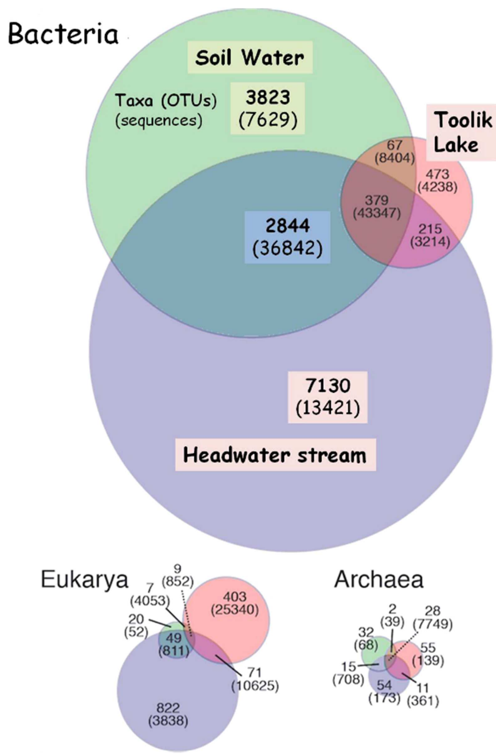
The major research goal of the ***Land-Water subgroup*** *is to understand the linkage between ecological processes in terrestrial and aquatic environments, and to determine the controls on these linkages and processes that operate moving from small to large spatial and temporal scales. To answer these questions we have used basic ecological research guided by a concepts of "biogeochemical cycling" and ecosystem interactions between land and surface water. We are investigating three questions presented in our LTER proposal, and in this summary we present each question and highlight a major finding to date. Figures and graphs associated with these findings can be found in the Land-Water section of our current LTER annual report.*

Proposal Questions:

1. *How does climate control ecosystem states, processes, and linkages?*

Finding: ***Landscape-level connections between lakes and streams affect patterns of chemistry and biology among sites, and we found that downslope transport and inoculation of soil bacteria strongly influence stream and lake microbial community composition.***

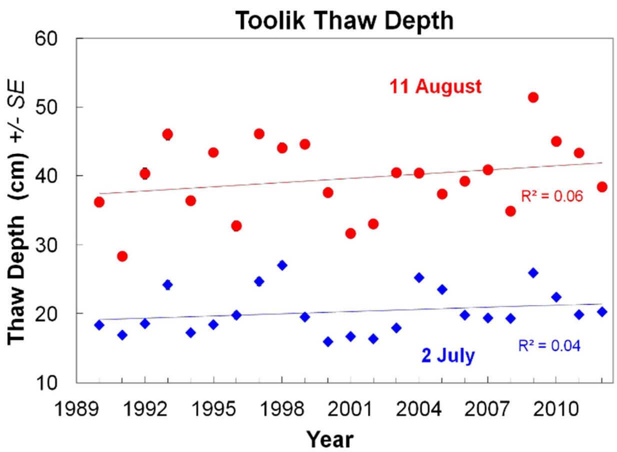
We showed previously that these landscape patterns are due to consistent differences in how the processing of materials (inorganic and organic) occurs among all lakes and among all streams. Starting in 2011 we expanded on this research to show that processing of materials in soil waters by microbes strongly affects the chemistry of water as it moves from uplands to lowlands and streams and lakes. In collaboration with Dr. Byron Crump we used 454 pyrosequencing to show that the genomics of microbes follow the same pattern where bacteria and Archaea species (OTUs) found in Toolik Lake were initially observed in upland soils and small headwater streams (Crump et al. 2012, ISME 2012:1). This is the first report of decreasing downslope diversity along a set of hydrologically-connected ecosystems, but what was most surprising was the pattern of overlap in species distributions. For example, in Toolik Lake 58% of the bacterial taxa and 43% of the archaeal taxa were first observed in upland habitats. In addition, the 39 most common bacterial taxa in Toolik Lake were also found higher on the landscape in the soils or headwater stream. Because most of these common bacterial taxa in the lake were classified as "rare" in the upslope environments (<0.1% of sequences), it is clear that the rare taxa transferred into the lake must undergo species sorting processes (e.g., competition and predation) in order to form the resultant lake community. These results suggest that terrestrial environments serve as critical reservoirs of microbial diversity, and that the patterns of diversity in surface waters are structured by initial inoculation from upslope habitats. One implication of this conclusion is that environmental changes on land (e.g., permafrost thaw from climate warming) that affect microbes will propagate to surface waters, and understanding freshwater microbial diversity and dynamics can only be accomplished by also studying the diversity and dispersal of terrestrial communities. Our planned next steps are to study the "function" of these taxa from different environments in the lake, and which taxa dominate the activity of the microbial community.

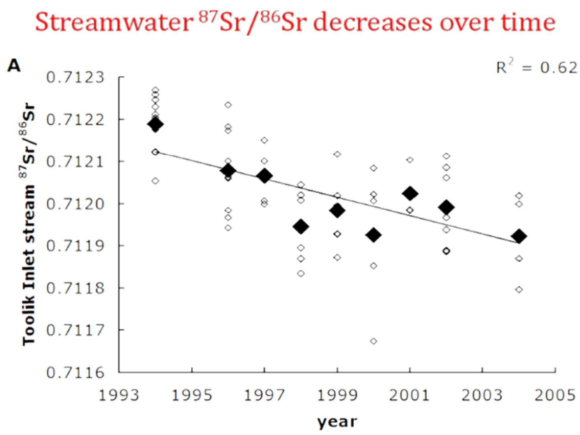


***2.** How do disturbances change ecosystem states, processes, and linkages? Here we are comparing two fundamental classes of disturbances, pulse (e.g., fire, thermokarst failures) and press (e.g., climate change, permafrost thaw).*

Finding: ***Despite arctic warming, thaw depth has not increased at Toolik, and yet the lake's chemistry has changed dramatically.***

Despite the long-term warming trend for many Arctic locations, at Toolik Lake there is no significant warming over the last 20 years and there is still no long term trend in thaw depth. However, we have observed trends in the chemistry of Toolik Lake over time that can only be explained by a change in thaw depth of some part of the basin. The alkalinity of Toolik Lake has doubled since measurements began in 1975, and we have observed that the in-lake processes that generate alkalinity cannot explain this increase. We know that carbonate content of the soils increases with depth, and also the $^{87}Sr/^{86}Sr$ in soils of the basin decreases with depth. If the increased carbonate alkalinity in Toolik Lake is due to a deeper thaw allowing water to flow more deeply into the soil, then we would expect that the Sr isotope ratio would decrease over time. This decrease in $^{87}Sr/^{86}Sr$ has been observed in the Toolik Inlet stream water over the last 10 years (Keller et al. 2010, Chemical Geology 273:76). The implication is that the flowpath of water in the Toolik Lake basin has progressively deepened and is now in contact with previously frozen soils with different chemical composition. It is likely that the thaw bulb under streams and lakes has deepened the most, which would account for the lack of observed changes in thaw depth of the uplands.



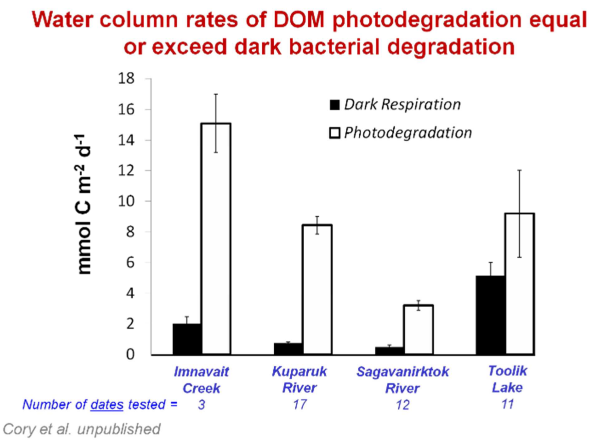


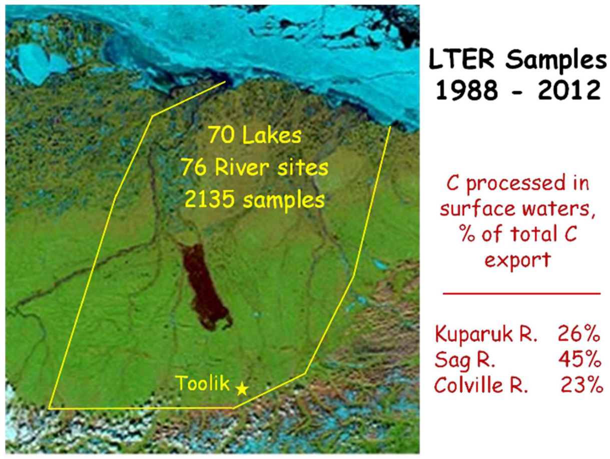
***3.** How do climate and disturbance interact to control biogeochemical cycles and biodiversity at catchment and landscape scales?*

Finding: **Processing of dissolved organic matter (DOM) by photochemistry in surface waters on the North Slope of Alaska can be substantial and important to landscape carbon cycling.**

We used LTER support in coordination with Dr. Rose Cory to investigate the relative importance of photochemical and biological (microbial) processing of DOM in surface waters. We first found that carbon from previously frozen soils ("permafrost carbon") released during thermokarst disturbances was labile to bacterial oxidation, and that when exposed to sunlight this carbon was oxidized 40% more compared to samples held in the dark (Cory et al. 2013, PNAS 1214104110). The general assumption is that dark bacterial degradation is more important than photochemical degradation of DOM when integrated over the water column, but when we scaled our findings to the entire water column of lakes and streams, we found just the opposite. In the rivers studied the rates of photochemical oxidation of carbon were higher than rates of bacterial oxidation, and in the lake studied the photo and bio rates were similar. Essentially sunlight is "outcompeting" bacteria for labile DOM substrates that can be oxidized partially to a degraded form of DOM or oxidized fully to CO_2. One obvious implication of this new finding is that studies reporting DOM degradation rates in arctic rivers based on bacterial respiration alone are missing most of the carbon processing.

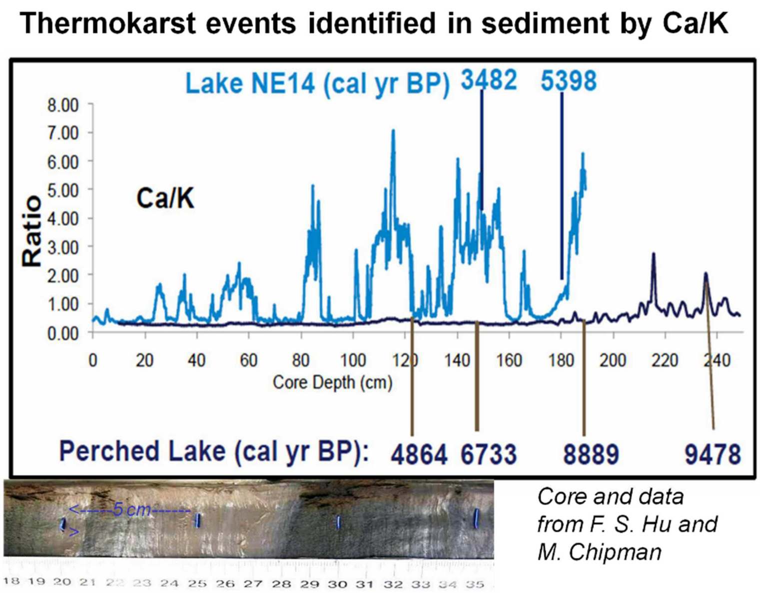
Once we had this finding of the importance of photochemical processing of DOM we used long-term LTER data on 70 lakes and 73 rivers sampled on the North Slope of Alaska from Toolik Lake to the Arctic Ocean to scale up to larger areas. Despite the relatively rapid extinction of light in these DOC-stained surface waters, the coupled photo-bio processing was roughly ¼ to almost ½ of all the DOC that was exported from major North Slope catchments (Kuparuk, Sagavanirktok, and Colville Rivers). This result highlights the fact that we must integrate surface water studies of carbon cycling with those in terrestrial systems in order to more completely understand the fate of soil carbon in the Arctic.





*<u>Finding</u>: **Thermokarst activity near Toolik appears to be a common feature through time of at least some landscapes.***

In coordination with Dr. Feng Sheng Hu a sediment core analyzed from Lake NE14 northwest of Toolik showed a record of thermokarst activity impacting the lake over the last several thousand years. We used a proxy for thermokarst activity in the catchment (Ca/K ratio in the sediments) to show that there was dramatic variation in the thermokarst activity in the catchment and the deposition of mineral materials from this activity into the lake. This variation indicates that at least in this catchment the thawing of permafrost and soil collapse and transport into the lake has been a regular feature over time. However, thermokarst failures are not ubiquitous on the landscape, because in another lake (Perched Lake) there was no such record of Ca/K spikes over time. Our plan is to continue this research by focusing on tying our current-day studies of DOM processing on the landscape to the record of organic matter deposition and diagenesis in the sediment core in order to better link our research on ecosystem processes (carbon cycling in this case) to past changes on the landscape, and to better inform our predictions of how the Arctic may respond to climate warming in the future.



4. STREAMS RESEARCH

The major goal of the ***Streams subgroup*** *is understand how the structure and function of stream ecosystems are being altered by presses and pulses associated with climate change in the arctic. While surface air temperature has apparently not changed much in the Toolik region, there are other indicators of climate change that affect streams directly. Among these are warming permafrost that increases the likelihood of thermokarst formation and alteration of flowpaths to streams as well as an increase in the frequency and duration of droughts that may affect the viability of Arctic grayling populations, the primary fish species in these rivers. We are studying these dynamics through a combination of long-term monitoring, manipulative experiments, and collaboration with other projects that are addressing fundamental stream processes in the arctic environment.*

Proposal questions

1. How does climate control ecosystem states, processes, and linkages?

Finding: ***Climate warming creates new opportunities for nutrient delivery and processing in permafrost-dominated arctic streams.***

In previous research we found that climate warming is not likely to expand the size of the hyporheic zone at a given point in time. However, a more likely scenario is that some part of the hyporheic zone will become active earlier in the season and will remain active later in the season. These headwater arctic streams freeze solidly or nearly so each year and then thaw during the summer. Thus, the major impact of future warming may be to extend the length of the season during which the hyporheic zone and the biogeochemical processing therein remain active in these seasonally frozen rivers.

Recently we have noted a potentially important consequence of extended, thawed conditions late in the season. If conditions are sufficiently warm for water to continue to move in the soil then they are also sufficient warm for there to be substantial microbial mineralization in the soil. During the growing season, nutrients produced by microbial mineralization are taken up by plants, with little apparently left over to migrate to streams in soil water. However, late in the season the plants have senesced and so plant uptake is negligible and nutrients in soil water can move to streams. Until recently we have not investigated what happens during the late season, when we have assumed biological activity is nearing a minimum. However, recently we have found that, just as predicted, concentrations of some nutrients, notably nitrate, do increase significantly during the late fall (Fig. 1). An asynchrony between microbial mineralization of nutrients and plant demand for nutrients is only one of three possible explanations for this late-season *increase in nitrate. In future work we intend to explore these different explanations.*

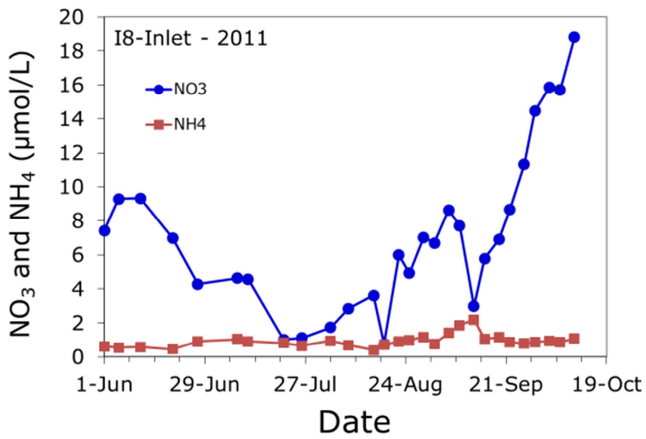


Figure 1. Concentration of nitrate and ammonium in the Kuparuk River in 2011. Vegetation is fully dormant by late August.

2. How do disturbances change ecosystem states, processes, and linkages?

*<u>Finding</u>: **Important pulse disturbances like fire and thermally-induced erosion events may have important local but relatively short-term effects compared to the long-term and subtle press of altered nutrient regimes.***

Recently we have had the opportunity to study the effects on arctic ecosystems of two types of large pulse disturbances: fire and thermokarst. In both cases measurable differences occur in the delivery of nutrients, carbon, and sediments to streams and lakes. Some of the effects on lakes are described elsewhere in this report (Land/Water Interactions and Lakes sections). The effects of fire and thermokarst on streams are subtle and complex. It is clear from our recent research that the immediate disturbance caused by fire and thermokarst can create acute loading of sediments, nitrogen, and dissolved organic carbon. But it is less clear whether there are long-term, chronic effects that may have more important impacts on stream ecosystems.

The core-experiment in the Arctic LTER Streams research is a long-term monitoring program of two undisturbed rivers (Kuparuk and Oksrukuyik). This long-term monitoring program includes the longest, continuous, experimental manipulation of stream chemistry. Over the 30 years since this experiment was initiated, it has given us the opportunity to witness major surprises, such as the introduction of aquatic mosses (Fig. 2) and has allowed us to do several manipulative experiments (e.g. the "Recovery" experiment) on top of the core phosphorus addition experiment, by simply moving the location of the phosphorus addition point. We are in the early phases of a new experiment that will allow us to test questions about recovery of altered stream ecosystems and the way that different types of autotrophic resources (epilithic biofilms, filamentous algae, and mosses) affect ecosystem metabolism and secondary production of benthic macroinvertebrates.

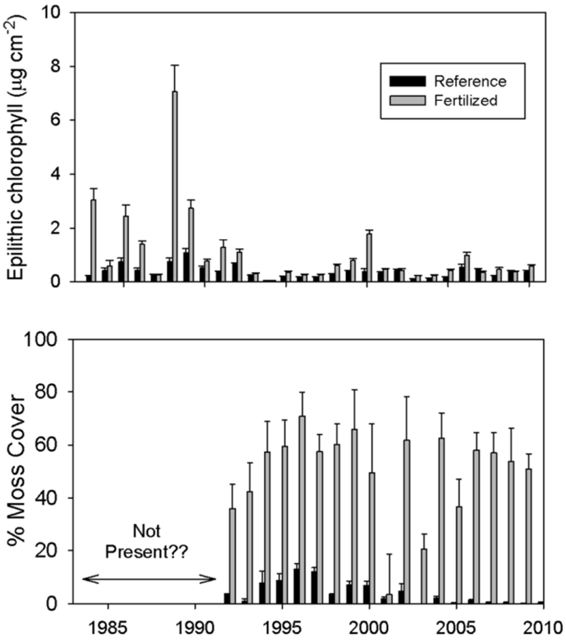


Figure 2. Epilithic algal chlorophyll (biomass, top) and aquatic moss abundance (% cover, bottom) in the Kuparuk River from 1983 to 2010. Darker bars are from the reference reach and lighter bars are from the fertilized reach. Moss did not appear in the experimental reach until ~1990.

3. How do climate and disturbance interact to control biogeochemical cycles and biodiversity at catchment and landscape scales?

*<u>Finding</u>: **Climate change may lead to more frequent and longer droughts that decrease river flow to a point that creates isolated reaches that impede the successful migration important fish species.***

Changes in climate expected for the Toolik region and the Arctic will have mostly negative repercussions for grayling. Increased water temperature within spawning, feeding and over-wintering habitats will affect grayling directly by increasing metabolic costs and oxygen consumption. Changes in seasonal patterns of precipitation and timing of freezing and thawing directly affect river discharge in arctic tundra streams and may have particularly important impacts on the population dynamics of Arctic grayling within these streams. The ability of this species to survive stems in part from the manner in which different age classes respond to alternating discharge regimes. In previous years we have found that in years with low river discharge, the young grow well but adult growth is often poor. Conversely, in years with high river discharge, the adults grow well but growth of the young is usually poor. This pattern of alternating good and poor growth between age classes has created a biological safety net for the species, guaranteeing that one or the other age class will have a successful growing season regardless of river discharge during any particular year. However, this safety net does not take into account repeated and extended periods of drought, causing portions of the river to go dry, restricting habitat availability and impeding migratory patterns.

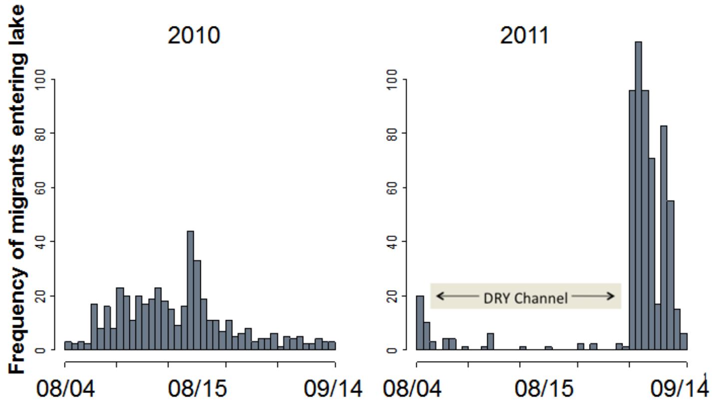


Figure 3. Timing of grayling migration to the headwater lake in 2010, an adequate flow year, and 2011, a dry year.

Since the early 2000s the precipitation trend in the Kuparuk river basin has been toward dryer dry periods and wetter wet periods. In addition to water loss through increased evaporation as temperatures warm, in the future water may percolate downward as permafrost thaws, further reducing water levels in critical grayling habitats. Although grayling young may do well in low flow conditions, the adult grayling fare poorly. Our recent research shows that dry periods that interrupt river connectivity to critical overwintering lakes in the headwaters of the Kuparuk River have become more common in recent years. This not only impedes the fall migration (Fig. 3), but is physically taxing on the adult grayling by restricting their livable habitat and forcing them into less than optimal thermal conditions. Grayling are highly territorial and, as documented, can actually lose weight when forced into situations of high population density in the river (Fig. 4). Furthermore, our data suggest that freeze-up has been occurring later than previously recorded, which means that grayling may remain active in the headwater lake, for a longer period of time, at higher temperatures and densities. Under these conditions the fish will become stressed and may expend considerable energy in territorial behavior that is needed for over-winter survival. Should the grayling enter the headwater lakes significantly earlier than freeze-up, a large portion of the population might beco me so stressed that they do not survive the winter. A grayling population may be able to rebound from a few consecutive years such stresses due to the resilience of the species, but eventually the population could be pushed beyond recovery. This is an area of active research within our group.

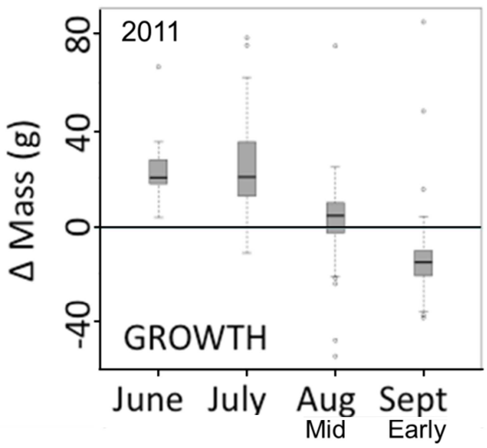


Figure 4. Change in mass of individual grayling during summer 2011. Note the downturn in growth and then loss of mass in August and September, coincident with the dry period in 2011 shown in Fig. 3.

5. LAKES RESEARCH

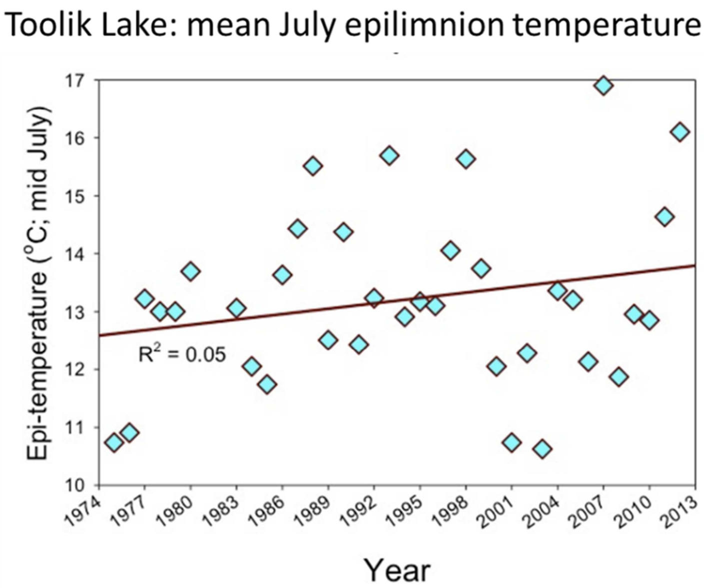
The major research goal of the ***lakes subgroup*** *is to understand how climate controls lake states, processes, and linkages to land; how these connections are altered by disturbance; and, how climate and disturbance interact to control biogeochemical cycling and associated productivity and food web dynamics in lake ecosystems. To answer these questions requires both comparative and experimental approaches. First, we combine long-term monitoring of changes in biogeochemistry, populations of key species, and community composition at Toolik and 14 other sentinel lakes. We use these data coupled with bioenergetic modeling to augment our understanding of the effect of climate variability and change on the structure and function of Arctic lakes. Second, we are continuing our assessment of the response of lakes to low-level nutrient additions and the recovery of fertilized lakes after the addition of nutrients has ended. These experiments mimic the disturbance to lake nutrient budgets from thermokarsts and possibly long term warming. In our current experiment we are fertilizing both a shallow fishless lake and a deeper lake with fish and comparing the results to similar reference lakes. This year (2013) marks the final year of the 13-year fertilization, and after a final assessment we will initiate the recovery stage of the experiment in 2014. In this summary, we highlight a few major findings of the research conducted to address the three questions presented in our LTER proposal. Additional information associated with these findings can be found in the Lake section of our current LTER annual report as well as Chapter 8 of the Arctic LTER Synthesis Book.*

Proposal Questions:

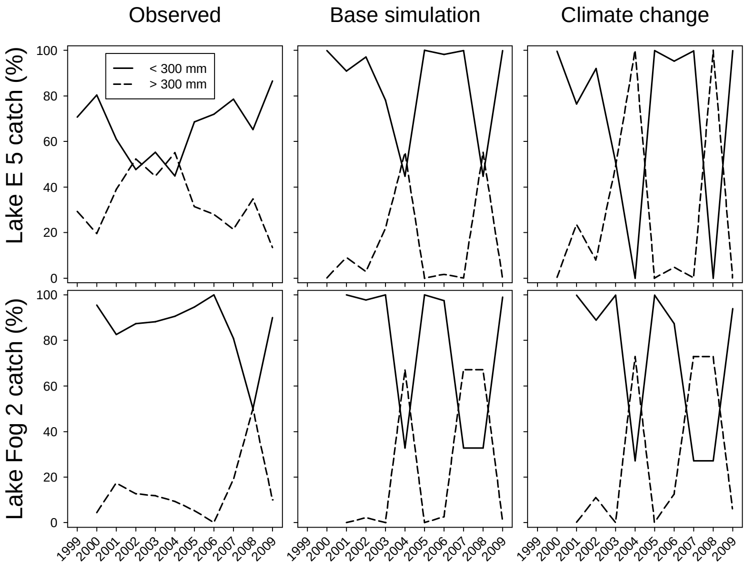
1. *How does climate control lake states, processes, and linkages to land, and how do disturbances change ecosystem states, processes, and linkages*

<u>*Finding:*</u> ***There has been only a modest signal of increasing temperatures in lake ecosystems; however, the increasingly frequent warm, dry summers have substantial effects on secondary productivity and on fish growth and population dynamics.***

Although air temperatures on the North Slope have risen since the 1950's, annual variation in lake water temperatures is substantial (mean annual epilimnetic air temperatures in Toolik Lake range from 10-17 °C), and to date there has been no significant increase overall. Mid-summer temperatures at 2 m, however, are now generally warmer on average as compared to earlier years. In contrast, the increase in frequency of warm, dry summers (MacIntyre et al. 2006, 2009) has resulted in increased stratification and epilimnetic temperatures in warmer years with concordant increases in zooplankton densities and reduced fish growth (Johnson 2009). The lakes also appear to experience some degree of synchrony as indicated in particular by the ubiquitous response to the warm summer of 2007.



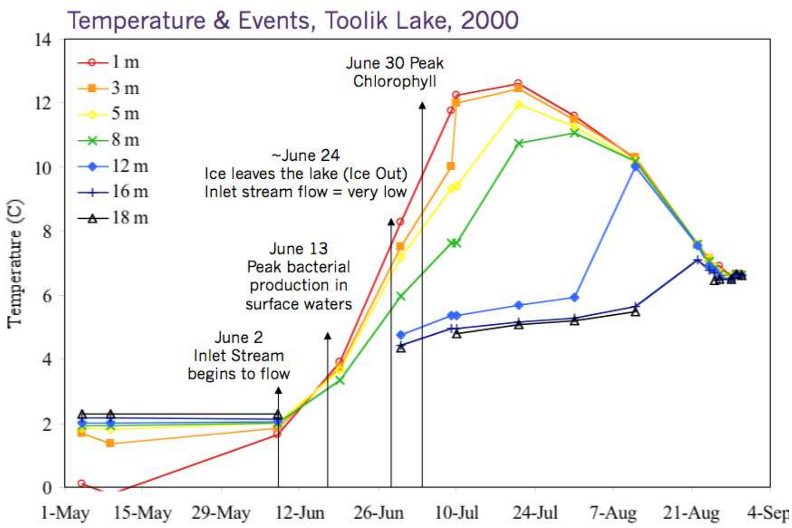
+



Above: Population size structure as indicated by the proportion of the catch for large (> 300 mm) and small (<300 mm) Arctic char. Observed (left panel) size-structure, matrix model, predicted size-structure of current conditions (middle panel), and matrix model, future predicted population structure under a warmer climate scenario (right panel) are shown for each year in the available time series.

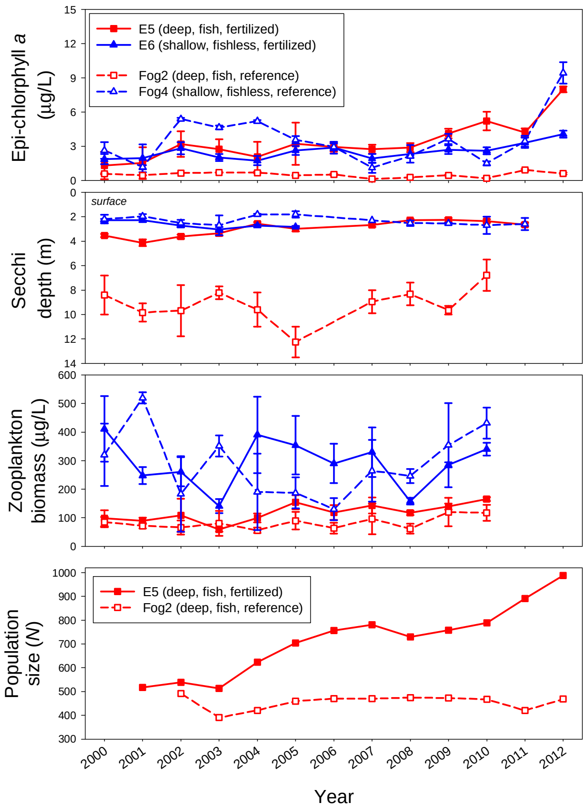
In our current work we have determined that Arctic char populations are regulated by strong intra-specific interactions that determine size structure, and net annual fish growth is determined by the number of ice-free days (Budy and Luecke, in review). Assuming no food limitation, an increase in predicted consumption rates (28-34%) under climate change scenarios led to much greater growth rates (23-34%). Higher growth rates predicted under climate change resulted in even greater predicted amplitude of cycles in population structure (shown to the left), as well as an increase in reproductive output and a decrease in generation time. Collectively, these results indicate that char are extremely sensitive to small changes in time of ice-off. We hypothesize that years of significantly longer growing season, which are predicted to occur more often under climate change, produce elevated growth rates of small char and thus act as a "resource pulse". As modeled, these warmer years of longer growing season result in a shift in vital rates that may then allow a sub-set of small char to "break though" into the large char morph or cohort, thus setting the cycle in population structure.

We are also interested in temporal patterns in microbial activity and have found a consistent seasonal cycle of change (Crump et al. 2003). This cycle (see figure) demonstrates a typical pattern related to temperature in Toolik Lake and most of the lakes in the region. The lake is frozen over from October to may, and then in May-June the snow on the tundra melts and the inlet stream starts to flow. A week or two later bacterial production peaks under the ice, presumably feeding on organic matter leached by melting snow from leaves and other material on the frozen tundra surface. One estimate states that half of the annual bacterial production in this lake occurs during this period, below the ice in very cold water. Then later in June ice leaves the lake and the stream flow decreases. Longer warmer days cause the lake to stratify and the phytoplankton "blooms" or rather reaches its modest peak (this is an ultraoligotrophic system).



2. & 3. How do disturbances change ecosystem states, processes, and linkages, and, how does climate and disturbance interact to control biogeochemical cycling and associated productivity and food web dynamics in lake ecosystems. We address both these questions with our long-term lake fertilization experiments.

<u>Finding:</u> ***In low intensity "press" fertilization experiments, the response is lagged and occurs over different time steps depending on trophic level. Nonetheless, in deep lakes with fish, we have observed a clear and significant pelagic response to fertilization at all trophic levels, and energy flowed directly from phytoplankton to zooplankton, to fish. The ecosystem response indicated certain thresholds had to be met or exceeded to stimulate a consistent response at the next trophic level, a response that took more than 10 years to be fully seen.***



Time series of lake response to fertilization relative to reference systems (not fertilized). The fertilization began in 2001 and will continue through 2013.

Associated with increased air temperatures from climate change are a suite of disturbances that are increasing in frequency and magnitude and include tundra fires and thermokarst failures. Thermokarst failure associated with permafrost thaw and fire delivers a large dose of nutrients and sediment to lake ecosystems, a disturbance we aimed to mimic in our current long-term "press" fertilization experiments. In previous high-intensity "pulse" experiments, primary productivity increased 3-10 fold, but quickly returned to pre-fertilization conditions (summarized in Chapter 8, Luecke et al, in press). In contrast, low hypolimnetic oxygen concentrations had not returned to pre-fertilization conditions up to 12 years post fertilization. The secondary productivity response was mixed and taxon-dependent, and the fish response was dependent on the fish community composition present (e.g., sculpin - none; lake trout – positive growth).

<u>Deep lakes with fish:</u> In our current "press" fertilizations the trajectory of response has been quite different. In the fertilized, deep lake with fish (E5), primary productivity (using chl *a* concentrations here as an index; µ g/L) increased approximately 700% relative to the start of experiment and approximately 650 % relative to the reference lake. However, chl. *a* demonstrated two lagged increases, the first after two years of fertilization and an even greater increase after the 8th year of the fertilization. In the fertilized lake, water transparency and hypolimnetic oxygen concentrations declined concordantly with the oxygen lagging 1-2 years behind stepped increases in primary productivity (see photos above). Increased primary productivity resulted in increased zooplankton biomass, but not until the 4th year of the fertilization (figure, previous page, unpublished data). By the end of the 9th year, zooplankton biomass had increased in the fertilized lake by approximately 68% relative to the beginning of the experiment and by 87% relative to the reference lake. Greater zooplankton and benthic invertebrate abundance (see below) in the fertilized lake increased fish abundance by approximately 94% relative to the beginning of the experiment and by approximately 92% relative to the reference lake. The fish response appeared to be initiated after

three years of fertilization, after which abundance increased nearly each year. In addition, the fertilization appeared to temporarily stabilize the fish population at high densities of small char.

Lake Fog2 – REF   Lake E5 - FERT

Chl *a* – 0.8 mg/m^3 Chl *a* – 4 mg/m^3

Finding: ***The lake ecosystem response to fertilization varied among fishless, shallow lakes and deep lakes with fish. In shallow, fishless lakes, fertilization stimulated increased benthic productivity. In contrast, in deep lakes with fish, fertilization had direct effects on the pelagic food web (increased productivity at all trophic levels) but also had indirect effects on the benthos in the form of phytoplankton sedimentation and nitrogen recycling in the benthos.***

Shallow, fishless lakes: In these lakes, the benthic response to fertilization was much greater, and the zooplankton demonstrated considerably inter-annual variation, likely in response to differences in mean, annual temperatures (Lake E6). In addition, the effect of a thermokarst failure that occurred near the beginning of the experiment in the reference lake may have been as or more influential than low-level, press fertilization. For example, in the fertilized lake, chl. *a* demonstrated no significant response to fertilization while chl. *a* increased 288% in the reference lake.

Deep lakes with fish: We observed very little benthic response to fertilization in deep lakes with fish. However, based on isotopic analyses of the food web, fertilizer persists and is used in the benthos. A ^{15}N tracer was added from 2002-2005, and by 2012, or seven years after the tracer was no longer being added, pelagic zooplankton and fish were still showing the mark of the tracer. In contrast, the ^{15}N signature of littoral invertebrates (e.g., snails) was only slightly elevated relative to before the tracer was added. These results indicate that benthic nitrogen is being recycled, perhaps by fish that consume benthic chironomids. In these oligotrophic lakes, phytoplankton sedimented from the epilimnion provide a labile substrate for bacteria and are likely readily consumed by omnivorous benthic invertebrates.

Benthic response: We found over the 12-year course of the experiment, that lake sediments became increasingly net-heterotrophic after nutrient enrichment began. Both respiration and GPP increased through 2007, but subsequently there has been a reduction in both. While the results are still preliminary, a first analysis suggests that fertilization may induce a diatom community shift similar to the recent shifts observed in paleolimnologic studies carried out in other remote arctic locations; however, unfertilized lakes still need to be analyzed to complete the comparison.

6. SYNTHESIS

In addition to the research of the terrestrial, land-water, streams, and lakes groups the ARC LTER supports and encourages a wide range of ***SYNTHESIS*** *activities including within-site synthesis, multisite and PanArctic synthesis, and network-level synthesis. These activities are important for several reasons. First, they are a useful way to help collaborating projects integrate and interpret their results in the context of the core ARC LTER long term datasets, detailed site descriptions, and biogeochemical budgets. This consistently leads to a much more powerful and rigorous analysis and application of the results from more narrowly-focused individual projects than would be possible if they did not have access to ARC LTER results. Second, multisite and PanArctic synthesis allows us to determine whether results from Toolik Lake can be extrapolated to other sites and ecosystems—to test what is general and what is specific about our research at Toolik Lake. Third, these activities are our principal means of participating in the LTER Network, promoting the science of long term ecological research.*

Within-Site Synthesis

*Finding**: A Warming Arctic: Ecological Consequences for Tundra, Streams and Lakes***

Our overall site synthesis book is now in press at Oxford University Press. Production of this book was a major synthesis effort, bringing together core ARC data with results of collaborating projects including some projects that had been working at Toolik Lake since before the ARC LTER was actually established. In 10 chapters with 56 coauthors, this book provides a history of research at the site, describes the climate, geology, and distribution of ecosystems on the landscape, and integrates past research on tundra, streams, lakes, and land-water interactions in separate chapters for each component. A final chapter brings together these results in the context of a changing climate, introduces the possibility of climate-related changes in disturbance regime and predicts future changes in the ecosystems and the landscape. In sum, this book summarizes past work of the ARC LTER and lays the foundation for our current three 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?

*Finding**: Changes in C balance in burned tundra are sufficient to become a dominant driver of regional C balance if the frequency and/or area burned increase in the future.***

Our research on the Anaktuvuk River (AR) wildfire involves all four ARC LTER research groups (lakes, streams, terrestrial, and land-water interactions), allowing us to combine our findings into an overall picture of how the whole landscape is affected by wildfire, and to estimate its implications for C balance of the entire North Slope. For example, in the first summer (2008) following the 2007 fire we can compare the direct effects of combustion on C stocks with changes in terrestrial Net Ecosystem Exchange of C (NEE) during recovery from the burn, and changes in losses to aquatic systems. All of these can be compared with model-predicted changes C balance due to climate change alone. Table 1 (below) shows that:

1. Long term climate warming in otherwise undisturbed vegetation leads to only a small annual increase in C sequestration per m^2 (<1 g $C/m^2/y$; model-based estimates from D. McGuire et al.). Although these increases are large when scaled up to large areas such as the North Slope or the entire Arctic, they are small by comparison with the large changes in burned tundra.

2. Combustion during the fire itself led to losses of about 2 kg C/m^2. Over the entire burned area this was about 2 E+12 g C, more than 1000 times the C sequestration that might be expected in an undisturbed area the same size in one year due to climate warming alone and more than 10 times the annual increase in C sequestration expected due to climate warming over the entire North Slope.
3. During the first summer of recovery from the burn, severely burned tundra lost ~60 g C/m^2 while unburned tundra sequestered ~80 g C/m^2, an overall difference of 140 g C in ~100 days. NEE of moderately burned tundra differed from unburned tundra by ~80 g C. over the same period. Scaled to the area of the AR Burn and accounting for variation in burn severity, the AR Burn in one summer (2008) lost about as much C as the entire North Slope would be expected to gain due to climate warming alone over a full year.
4. Carbon losses in streams of burned watersheds increased greatly in 2008, relative to losses in unburned watersheds. Although these losses are significant to the functioning of the streams themselves, they were much smaller than the C losses due to combustion or to changes in NEE on land. The increase in aquatic losses was about the same magnitude, but in the opposite direction, as the increases due to climate warming.

Table 1. Components of change in landscape C balance following the 2007 Anaktuvuk River Burn. .

AREA	**Yearly NEE**	**Change in C balance (NEE) in 1 yr due to:**			
		Climate warming	**Combustion (2007)**	**Recovery/regrowth (summer 2008)**	**Aquatic loss (summer 2008)**
One m^2	-15 g C	<-1 g C	2.02 E+3 g C	80-140 g C	1-2 g C
AR Burn (1039 km^2)	-15.6 E+09 g C	<1.04 E+09 g C	2.16 E+12 g C	1.25 E+11 g C	1-2 E+09 g C
N Slope (188,000 km^2)	-2.8 E+12 g C	<-1.88 E+11 g C			

The C balance of the terrestrial and aquatic ecosystems continues to change through the summer of 2013. Since 2010 the burned lands have become net sinks for C, rather than sources, while C losses to streams in burned catchments may have increased. We are continuing to monitor these changes and are developing models that will allow us to evaluate the contribution of wildfire to the regional C balance under a range of scenarios of fire frequency, severity, and area burned as well as scenarios of climate change.

PanArctic synthesis

<u>Finding</u>: ***At the level of whole vegetation canopies, the light response of Net Ecosystem Exchange of C (NEE) follows the same rules throughout the Arctic, including in canopies dominated by very different kinds of plants. Thus the light response of NEE can be predicted anywhere in the Arctic using a single parameterization of a single model***.

In a major synthesis effort (Shaver et al. 2013, in press) we showed that ~75% of the variation in canopy level Net Ecosystem Exchange (NEE) throughout the Arctic can be accounted for in a single regression model that predicts NEE as a function of Leaf Area Index (LAI), air temperature, and Photosynthetically Active Radiation (PAR). The model was developed in concert with a survey of the light response of NEE in arctic and subarctic tundras in Alaska, Greenland, Svalbard, and Sweden. Model parameterizations based on data collected in one part of the Arctic can be used to predict NEE in other parts of the Arctic with accuracy similar to that of predictions based on data collected in the same site where NEE is predicted. The principal requirement for the data set is that it should contain a sufficiently wide range of measurements of NEE at both high and low values of LAI, air temperature, and

PAR, to properly constrain the estimates of model parameters. Canopy N content can also be substituted for leaf area in predicting NEE, with equal or greater accuracy, but substitution of soil temperature for air temperature does not improve predictions. Overall, the results suggest a remarkable convergence in regulation of NEE in diverse ecosystem types throughout the Arctic. One significant conclusion is that data and relationships derived from research at Toolik can be extrapolated with confidence throughout the Arctic. (Figure 1 below).

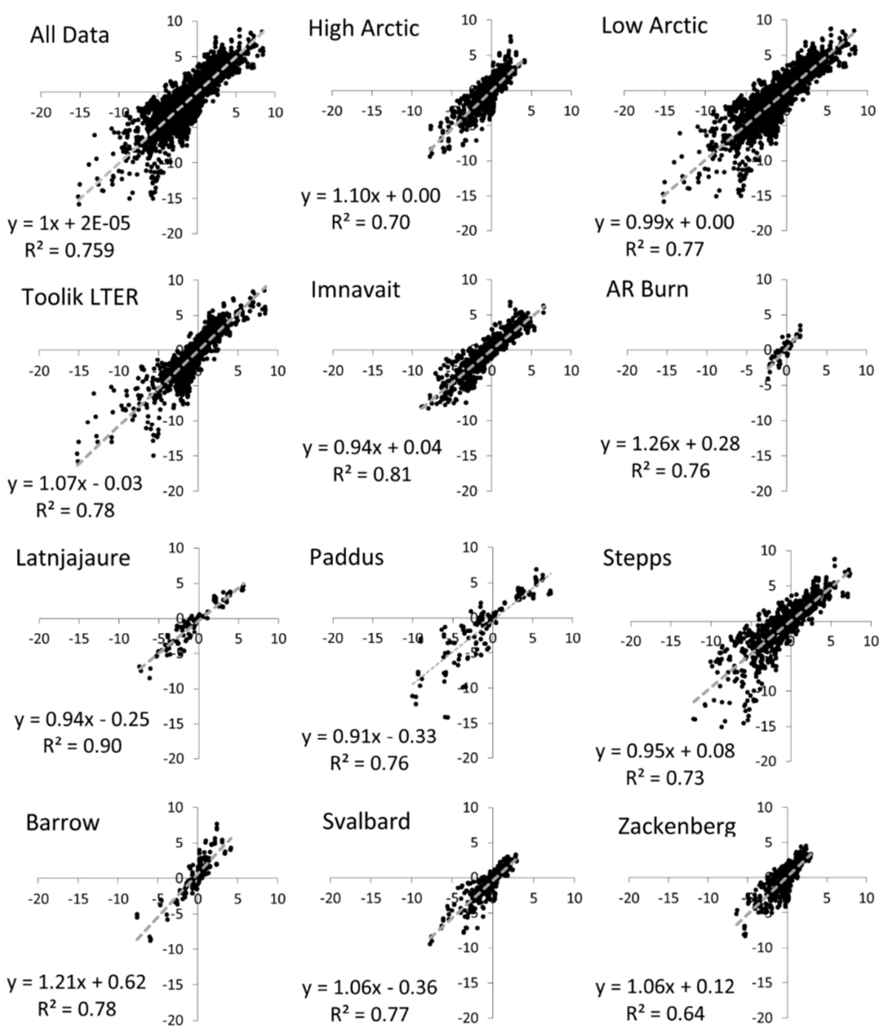


Figure 1 Predicted versus measured NEE using the entire data set ("All Data") in the regression to determine model parameters. Predicted values of NEE using these "All Data" regression parameters are plotted on the horizontal axes, with measured values on the vertical axes. Units of both axes are $\mu mol\ CO_2\ m^{-2}\ s^{-1}$. The upper left plot includes all 4834 predicted and measured values; other plots include predicted and measured values within the various data subsets (Table 2). The trendline, equation, and r^2 value in each plot describe the correlation between predicted and measured values within each data subset. From Shaver et al 2013, accepted

Network level and global synthesis

The ARC LTER participates in a wide range of network and global synthesis efforts. Examples of these activities include:

- A new book, *Energetic Food Webs: An Analysis of Real and Model Ecosystems* (Moore and DeRuiter 2012) uses the food webs of tundra soils at the ARC LTER to illustrate and evaluate the theory developed in this book.
- The LTER Network has long supported and participated in a series of Network-level analyses of ecosystem patterns and properties, published in high-impact journals. Our latest contribution to this series is the paper by Gough et al. (Oecologia, 2012), in which the importance of clonal

growth form is evaluated as a determinant of changes in community composition and diversity following fertilizer addition in grasslands across the LTER Network.

- The LTER Network also periodically produces major reviews of the status and opportunities for long term ecological research, usually as special issues of journals. Our most recent contributions include a paper in the April 2012 special issue of BioScience (Knapp et al. 2012), in which the past, present and future roles of long term experiments in the LTER Network are described and compared.

7. PROJECT MANAGEMENT, BUDGET, SITE 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". This structure has proved highly effective for planning and project management, especially manipulations of lakes, streams, and tundra.

An Executive Committee (EC) consisting of the lead PI (currently Shaver), representatives of each research group (currently Gough (terrestrial), Bowden (streams), Budy (lakes), and Kling (land-water)), and one additional person (currently Giblin) meets at least twice a year, once in the fall (usually by conference call) 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 and choose a theme for the winter meeting. 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. Additional conference calls are scheduled as needed. At least one member of the Executive Committee attends every LTER Network Science Council meeting.

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.

The winter meeting in Woods Hole is attended by all collaborating investigators, research assistants, postdocs, 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.

Finally, for 2012-2015 the ARC LTER takes its turn as a member of the LTER Network Executive Board, which meets several times a year by conference call, once a year at NSF, and once a year at the Network SC meeting; currently the site is represented at these meetings by the Lead PI, Gus Shaver.

Budget: Our approach to budgeting is practical and intended to maximize our ability to maintain core experiments and data collection while maintaining extensive collaborations with individual investigators and projects. Most of the project's core budget ($980,000 per year) is divided equally among the four major research groups: Terrestrial, Land-Water, Streams, and Lakes. Each of these groups receives support for one full-time Senior Research Assistant, one Summer Field Assistant, and one month of PI salary for that group's representative on the EC. Each group also receives a supplies and travel budget. Smaller amounts are retained in the core budget to cover costs of our annual meeting in Woods Hole, education activities (Schoolyard and REU support), and core Information Management tasks. In the current funding cycle we have also set aside about $10-15,000 per year to promote new collaborations, especially with social scientists, and each year we make available $5-10,000 to support site-level and network-level synthesis activities.

Additional activities and expenses are covered using annual supplemental funds. The uses of those funds are determined each year by NSF. Decisions about what we apply for are made by polling collaborating PIs and then prioritized by the EC.

Field site management: The land where most of the LTER research is carried out (front cover, Fig 1) 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 of Alaska 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). The labs, dorms, kitchen, and other buildings at TFS are owned by either NSF or UAF, and the majority of the funding for TFS operations comes through a cooperative agreement between UAF and NSF's Office of Polar Programs (OPP). Most of the rest of the funding also comes from NSF-OPP when 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 the 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 and monitoring. 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 and supplying a small amount of travel and logistics funds, in anticipation of their eventually obtaining independent funding (examples include current projects led by R Cory and G Kling, by B Nielsen, and by L. Gough and J. Moore, all of which began with small amounts of travel and logistics funding provided by ARC LTER). 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, Natalie Boelman, Byron Crump, Rose Cory, and Mike Weintraub have all followed this route).

Collaborations among ARC LTER collaborators are strongly encouraged as well as cross-site and Network-level collaborations; these are supported with both supplemental and core project funds. Examples include within-ARC synthesis projects like our food web analysis and catchment-level budget analyses (to be discussed at the site review); other examples include LTER Network collaborations and reviews (e.g., Knapp et al. 2012) as well as collaborations with other networks such as the International Tundra Experiment (ITEX: Elmendorf et al. 2012a, 2012b).

Anticipated changes, 2013-2017: Our management system has worked well since 1987 and we plan no major changes. There are two issues, however, that we must deal with in the next three years. The first is the rotation of project leadership: several of the EC members including the Lead PI have been with the project for decades and will be retiring in the next 6-12 years. We must begin planning now for these transitions. We have already begun to replace EC members with the appointments of Gough (terrestrial) and Budy (lakes) in 2012. Second, we must continue to attract new investigators with new skills and interests to the project, not only as retirement replacements but also to ensure continued intellectual vitality and growth. 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 in all EC meetings and, when possible, Network meetings such as the annual SC meetings. We have developed a plan and schedule for selection of the next lead PI. Second, 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.

A third key management issue is how to improve coordination and collaboration with other projects and groups based at TFS, and with TFS itself. There is a particular need to anticipate interactions with major monitoring and experimental networks such as NEON and AON, both of which will be active at Toolik Lake in the next decade and will be collecting and storing long term data sets. There is a major scientific opportunity here as well as a risk of conflicts, overlaps, and inefficiencies. Our current thinking is that the principal current need is to form a Scientific Steering Group, including key personnel from both ARC LTER and TFS but independent of both, to help coordinate these interactions among projects.

8. 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 identify themselves via the LTER Network's data access system or the LTER Network Information System (NIS) 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, with four major components to the ARC LTER information system linked to the terrestrial, streams, lakes, and landscape interactions research components. A Senior RA, Jim Laundre, is the overall project information manager with responsibility for overseeing the integrity of the ARC information system. Information management is a primary responsibility of all four full-time RAs associated with each of the research components. While each of the four core RAs maintains the data in their area, all are in frequent communication on overall data compatibility and metadata standards (currently two work at the MBL in Woods Hole, one is 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. For most of the past year we have also employed, with annual supplemental funding, an information management RA specifically charged with validating and uploading our data base to the new "PASTA" system at the LTER Network Data Portal (https://portal.lternet.edu). Overall guidance is provided by the ARC 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 downloaded once a user is registered with the Network Data Access System (http://metacat.lternet.edu/das/). 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.

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 many do so to meet NSF requirements for data archival (alternatives are available, such as the National Snow and Ice Data Center, NSIDC). In addition to datasets on our web server the ARC LTER also participates in the LTER Network's ClimDB, HydroDB, EcoTrends, and the developing VegDB information systems. These centralized databases provide access to meteorological, hydrological, and long-term change data from all the LTER sites. We have recently begun transferring our data sets into the new "PASTA" system developed for the LTER NIS; this transfer is nearing completion as of late May 2013.

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 created 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" and is PASTA ready. The xml file is uploaded to the LTER Network Office metacat server and the new LTER Network Data Portal (https://portal.lternet.edu) 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 (Section 11 below), 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. The ARC LTER project is still responsible for collection and management of weather and other data collected from experimental plots and as part of LTER research. Toolik Field Station weather data is available from the TFS web site (http://toolik.alaska.edu/edc/index.php). Also available on the TFS web site is a new weather data query and plotting capability. The TFS Environmental Data Center has added 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/datacatalog.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 m^2) 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 km^2), 1:5000 (25 km^2), and of the Kuparuk River basin at 1:25,000 and 1:250,000.
- The *Toolik Field Station GIS* (http://toolik.alaska.edu/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, 2013-2017: Several changes are planned to our overall Information Management strategy and practices. We plan to continue organizing and making available older "legacy" data sets in line with LTER NISAC recommendations. We are currently completing the transition of our metadata from EML Best Practices level 2/3 (no attribute EML) to the new PASTA system (as of late May, all of the old data sets are still available using METACAT; ~200 data sets are available in PASTA). Bringing the metadata up to PASTA standards requires review and where appropriate consolidation into multi-year files. Differences in methods and personnel will require that some years' data 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 Drupal Environmental Information Management System (DEIMS): This multiple site LTER effort is aimed at using the Drupal Content Management System to deploy a data model based on Ecological Metadata Language (EML) and to develop a common set of tools for use at LTER sites.. 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, currently we have a beta site at http://arc-dev.core.cli.mbl.edu.

As described above, Toolik Field Station started an environmental monitoring program in 2006 and has taken over some of the basic weather and environmental measurements, e.g., precipitation chemistry; all of these data are regularly added to the ARC data base. 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.

9. EDUCATION AND OUTREACH

The ARC LTER project maintains 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. With the exception of our Schoolyard and REU programs these are all independently funded but each of these high-impact activities 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 to and logistics costs at Toolik Field Station.

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) a weekly lecture series on a wide range of scientific topics, and (2) 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. Each year 1-4 LTER personnel visit Barrow to lecture in the "Saturday Schoolyard" series and in the public schools. Both activities have been very well-received by the Barrow community and we have received many requests to continue them. Both the public lectures and the in-school activities are managed in Barrow by The Barrow Arctic Science Consortium (BSASC; https://www.facebook.com/pages/Barrow-Arctic-Science-Consortium/329805053000). BASC also supplements our investment in these Schoolyard activities with additional funds.
2. The *Polar Hands-on Laboratory* is offered each year by Logan Science Journalism Program of the Marine Biological Laboratory (http://hermes.mbl.edu/sjp/index.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. Every summer, 10-20 journalists from all media (print, radio, film, electronic, freelance) participate in a 2-week course at the MBL in Woods Hole; following this and depending on the funding available, 2-12 of these journalists then come to Toolik Lake for intensive, hands-on experience with field data collection and practical environmental science. After leaving TFS, the journalists then produce articles and stories about our science, and our life as scientists, in a wide range of media.
3. *Opportunities for K-12 Teachers* include the chance for teachers to visit TFS and participate in our summer field research. Each summer we host 2-10 K-12 teachers with funding from a range of sources including the NSF-OPP "Polar Trec" program (http://www.polartrec.com/about). ARC LTER typically provides travel and logistics support. The main aim here is to provide teachers with experiences in scientific research that will inform their teaching and will provide them with access to data, methods, and other materials that they can use in their classrooms. In 2010 and 2011 we also supported one teacher, Eve Kendrick from Tuscaloosa Alabama, with supplemental RET funds. Eve worked with the Streams group, returned to Alabama to develop a series of lesson plans in Stream

ecology, and in spring 2013 she traveled to the village school in Anaktuvuk Pass, Alaska to present these lessons and improve them by discussion with local hunters and fishers.

4. *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.
5. *Education of undergraduate and graduate students in arctic research* is our fifth educational activity. 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.
6. *Outreach to the general public, locally and nationally* includes occasional talks given in Alaskan Native communities such as Anaktuvuk Pass, Kaktovik, and Barrow. As part of our attempt to build a social science component, Gary Kofinas and students from the University of Alaska have interviewed local citizens about their perceptions of climate change and how it has affected their subsistence life styles. Local hunters are particularly interested in the impact of our research on wildlife, and we try to keep them well-informed of our activities through the land use permitting process. Finally, we are particularly pleased to have published a new book on the natural history of northern Alaska, *Land of Extremes* by Alex Huryn and John Hobbie, 2012); the book is intended for tourists as well as scientists to use as they travel through northern Alaska including the area around Toolik Lake.
7. *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 BLM, Alaska Fish and Game, and with the North Slope Borough 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 the North Slope Borough have increased in frequency lately as our research increasingly involves helicopter travel through areas where subsistence hunting takes place. 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 several 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.
8. *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, 2013-2017: Overall, we are quite happy with this education and outreach program and expect to continue all components in 2013-2017. One change we are considering is a switch from BASC as the local host of our Schoolyard program in Barrow to another Native Alaskan organization that may be able to provide additional support for the program. Another possible change is the hosting of Alaskan high school students, including residents of North Slope villages, at Toolik Field Station; we have been exploring this possibility in discussions with state and local organizations but still need to overcome problems of adult supervision (chaperones) as well as choosing the students. The main need is to continue working to secure independent sources of funding for each of these components.

10. CURRENT CHALLENGES AND CHANGES FROM PROPOSAL

As might be expected in a large and complex project with a 6 year funding cycle and a constantly changing array of collaborations, by the middle of the funding period not everything is going exactly as originally planned. Here we list a few issues where our activities have deviated from our 2010 proposal plans or where we see particular obstacles or opportunities to progress. These include:

1.) Development of a Social Science Component of ARC LTER research: We stated in our proposal that we would try to establish, by 2017, a fifth research component focused on Social-Ecological Sciences, specifically the subsistence life styles and economies of Native Alaskan communities on the North Slope and the impacts of climate change on those life styles. At the time we wrote the proposal we were expecting rapid growth in funding for this research, and the LTER Network was actively promoting network-level opportunities in this area. Our plan was to fund most of this expansion with Annual Supplemental funds and by developing new collaborations through new programs such as the planned "Integrated Science for Society and the Environment (ISSE)".

Since 2010 none of these funding sources have appeared, and the general level of excitement and promotion of Social Science within the LTER Network level has declined precipitously. We are continuing, however, with a small program of research centered on effects of climate change on local communities, in collaboration with Gary Kofinas of University of Alaska Fairbanks and the BNZ LTER project. We have set aside a small amount of funds for this each year (~$15K). Clearly, we need to be more active in recruiting new researchers to this field. However, at present there appears to be a distinct loss of momentum for this research at the Network level, and we see few new sources of funding emerging in the near future. For now, we plan to continue our low level of current research and to be ready to respond if and when new opportunities arise.

2.) Schoolyard LTER: Our Schoolyard program at Barrow has been very well-received by the local community, and we have maintained essentially the same program of lectures and school activities over most of the past 15-20 years. In the last 3-5 years, however, the organization that has served as the local organizer of these activities has lost significant funding and personnel. Our Saturday Schoolyard lecture series is still continuing and popular, but our in-school activities and field data collection activities have been greatly diminished. We are investigating a change to a different local organizer to maintain these activities, since it is logistically difficult (and expensive) to send ARC LTER personnel to Barrow frequently to interact with the community.

3.) "Off Pad" Logistics: Our logistical support for food, lodging, and laboratories at Toolik Field Station is excellent and improves every year. Increasingly, however, there is a need for logistical support "off the pad", or outside the limits of TFS itself. Much of this support is most efficiently used if it is shared among collaborating project (e.g., boardwalks, field shelters, remote power supplies, radio communications gear), and under present circumstances this sharing is not easily worked out. A particular problem is permitting of facilities that are shared, on land that is owned by a range of Federal, State, and Local authorities. Procedures for streamlining the permitting and sharing of logistics for "Off Pad" research are very much needed, including a committee of stakeholders to manage this.

4.) Interactions and links with other TFS-based research projects and data bases including the NEON and AON networks and TFS: The culture of collaboration in research at Toolik Lake is very strong but continues to evolve. From the 1970s through the 1990s, research at Toolik Lake was strongly dominated by the ARC LTER project and its predecessors, including a small number of large, multi-investigator projects that collaborated closely with each other (including cooking and cleaning). The early growth of Toolik Field Station itself was largely in support of the LTER project and its predecessors and close collaborators. Over the past decade and a half, however, the number and size of projects and the range of research and education activities based at TFS has increased greatly. Many but by no means all of these activities or projects are linked to LTER through joint field work, the shared sampling of long term experimental plots, and the sharing of laboratory facilities and field and laboratory equipment. The ARC LTER continues to maintain all of its long-term data and to make these generally available, and it has begun adding "legacy" data sets and data from collaborating projects to its Information Management system. At the same time, a growing number of projects are coming to work at TFS with little or no connection to the ARC LTER and with a wide range of expectations about potential collaborations with ARC LTER. Occasionally there are conflicts or redundancies in research plans or expectations about availability of research sites or data.

This tremendous recent growth of research and other activities based at TFS is both a challenge and an opportunity for the ARC LTER, to promote even greater collaboration and integration of research. At present, though, there is no clear authority for managing the interactions among projects other than the land use permitting process of the principal landowner, the US Bureau of Land Management; this process is very slow and is not designed to facilitate integration of research projects. TFS is trying to help by developing a vetting process as part of a project's application to use the facilities at TFS. The problem is only going to get worse, though, as additional large, long term monitoring programs come online, like the NEON site to be developed at Toolik Lake in the next 2-3 years. To help manage these interactions, to forestall conflicts before they occur, and ideally to increase the opportunities for collaboration and synthesis among large and small projects, the ARC LTER is currently working toward the creation of an independent Scientific Steering Committee for all of the research projects working at and near Toolik Lake.

11. ARCTIC LTER PUBLICATIONS December 2010-present. Detailed information on publications since the start of the ARC LTER in 1987 is available at the ARC LTER web site, http://dryas.mbl.edu/arc/

SUMMARY	Since Dec 2010	Since 1975
Total Journal Articles	**75**	**522**
Number of Unique Journals	*45*	*129*
Contributing Authors	*357*	*1012*
Total Books	**3**	**7**
Total Book chapters	**7**	**88**
Total Student works	**18**	**104**
Ph.D Theses	*5*	*32*
Masters Theses	*5*	*65*
Senior Research projects	*8*	*13*
Number of universities/colleges	*8*	*32*

Journal Name	**Since Dec 2010**	**Since 1975**
Nature and Nature Climate Change	3	9
Science	0	8
Proceedings of the National Academy of Sciences	2	5
Ecology, Ecological Monographs, Ecological Applications	4	55
Hydrobiologia	0	31
Limnology and Oceanography	0	20
Canadian Journal of Fisheries and Aquatic Sciences	0	18
Freshwater Biology	0	18
Global Change Biology	7	18
Ambio	0	17
Journal of Ecology	1	17
Oecologia	2	17
Bioscience	3	13
Journal of the North American Benthological Society	0	13
Ecosystems	2	11
Applied and Environmental Microbiology	0	9
Vereinigung Verhandlungen International Limnologie	0	9
Arctic, Antarctic, and Alpine Research	3	8
Geophysical Research Letters	1	8
Global Biogeochemical Cycles	0	8
Journal of Geophysical Research	0	8
Oikos	1	8
Hydrological Processes	3	7
Arctic and Alpine Research	0	6
Biogeochemistry	2	6
Arctic	0	5
Ecology Letters	2	5
Holarctic Ecology	0	5
Journal of Geophysical Research: Atmospheres	0	5
New Phytologist	3	5
Papers in journals with >5 ARC LTER papers since 1975	36	150
SUM	**75**	**522**