Accomplishments:
What are the major Goals of the project?

The objectives of the Arctic Long-Term Ecological Research (LTER) Project for 2017-2023 are to use the concepts of biogeochemical and community "openness" and "connectivity" to understand the responses of arctic terrestrial and freshwater ecosystems to climate change and disturbance. These objectives will be met through continued long-term monitoring of changes in undisturbed terrestrial, stream, and lake ecosystems in the vicinity of Toolik Lake, Alaska, observations of the recovery of these ecosystems from natural and imposed disturbances, maintenance of existing long-term experiments, and initiation of new experimental manipulations. Based on these data, carbon and nutrient budgets and indices of species composition will be compiled for each component of the arctic landscape to compare the biogeochemistry and community dynamics of each ecosystem in relation to their responses to climate change and disturbance and to the propagation of those responses across the landscape.

What was accomplished under these goals?
Major Activities:

Terrestrial

- Collected annual datasets for multiple LTER experimental plots including long-term warming, shading, and nutrient addition treatments in multiple plant communities: variables included thaw depth, vegetation relative abundance, NDVI, and soil N mineralization rates
- Worked with TFS GIS to determine where to locate new greenhouses for new warming experiments, measured soil pH to help with site selection, set up pilot greenhouses and modified as needed for prototype
- Re-sample the plots from 2015 harvest to re-assess soil bulk densities and reworked food web analysis using adjusted bulk density.
- Sampled soil food webs at Anaktuvuk burn site
- Sampled soils from *E. vaginatum* and *B. nana* rhizospheres to compare soil food webs associated with dominant sedge and shrub species.
- Used field experiments, laboratory incubations, and isotope-tracing techniques to examine how vegetation type (*Be*tula nana and Eriophorum vaginatum) and fertilization (short-term and long-term) influenced decomposition of native SOM after labile C addition.
- Used dual-labeled E. vaginatum and B. nana enriched (13C and 15N) litter in both laboratory and field experiments to assess fate of leaf litter C and N fate in arctic soils including changes in organic matter chemistry, microbial use and incorporation of plant litter, and movement into different soil pools.
- Used a cross-biome study to test whether experimental warming affects the temperature sensitivity of microbial extracellular enzymes involved in soil organic matter decomposition.
- Collected NDVI data for two LTER fertilization Experiments
- Calibrated the Multiple Element Limitation (MEL) model to four major tundra types based on archived data and are beginning long-term factorial simulations of responses to projected warming, precipitation, and CO2.

- Contributed ARC data to meta-analysis examining how community responses to environmental changes at local scales can stabilize ecosystem function across meta-communities (Wilcox et al. 2017)
- Assisted with multiple associated research projects including plant and soil harvest of a 20-yr species removal experiment (with S. Bret-Harte), survey of biogenic silica in LTER experimental plots and Anaktuvuk burn site (with J. Carey), continued monitoring Imnavait watershed C, energy and water budgets and thaw depth (with S Bret-Harte, E Euskirchen),
- Academic year: working on updating data in the database and standardizing variables and metadata across multiple years

Land-Water

- Collected and analyzed inorganic and organic water chemistry in several long-term study lakes (E5, E6, Toolik Lake) and in a series of lakes and streams in the Toolik Lake and Kuparuk drainage (25 sites total).
- Measured flow of water into Toolik Lake and in several streams in the "inlet series" of lakes and streams of the Toolik Lake basin using automated water-level gauges calibrated with hand measurements of discharge.
- Measured bacterial production weekly in Toolik Lake and 3 times per summer in the series of lakes draining into Toolik Lake.
- Collected and analyzed water samples in groundwater and stream water in the Imnavait Creek basin
- Conducted thaw depth survey twice each summer in Imnavait watershed and the Tussock Watershed just south of Toolik Lake.
- Collected water samples for analysis of chemistry and bacterial activity to perform experiments on the effects of photo-oxidation on water chemistry and biological activity (in coordination with R Cory's DOM-Photochemistry CAREER project)
- Used a suite of complementary approaches, including solution-state 1H-NMR and fluorescence spectroscopy, to characterize the chemical composition of pore-water DOM collected from two landscape positions (hillslope, riparian) and two soil horizons (organic, mineral).
- Assessed the mobilization and exchange potentials of DOM flowing through organic soils versus along the mineral-permafrost interface using bromide, a conservative salt tracer.
- Microbial and biogeochemical sampling in lakes and streams in conjunction with B Crump's LTREB

Streams

- First year of post-fertilization monitoring in the Kuparuk River, following the conclusion of our 34-year fertilization experiment in 2016
- Continued long-term nutrient and biotic monitoring of Kuparuk River and Oksrukuyik Creek, including: Sestonic and benthic nutrient sampling (3 dates), monitoring growth of young-of-the-year Arctic Grayling (Thymallus arcticus) throughout the summer, and Bi-weekly sampling of benthic macroinvertebrates in the Kuparuk reference reach
- Bi-weekly nutrient samples from the reference reaches of the Kuparuk, Oksrukuyik,

Roche Moutonnee Creek, and Trevor Creek, from late May through early October.

- Weekly or bi-weekly benthic nutrient sampling in the reference reaches of the Kuparuk, Roche Moutonnee, and Trevor Creek from early June through late September.
- Bi-hourly nutrient sampling over 72 hours in the reference and fertilized reaches of the Kuparuk River, on three different occasions.
- Assisted Abbott, Zarnetske and Aanderud's synoptic nutrient and microbial DNA sampling in the Kuparuk River, Oksrukuyik Creek and Trevor Creek watersheds, on two occasions.
- Clearing backlog of unprocessed Kuparuk River invertebrate samples: ~ 812 samples have been taken from the reference and fertilized reaches during 2001 to 2017, 54% fully processed and 13% partially processed.

Lakes

- Continued long-term physical, chemical, and community sampling, process-level measurements, and modeling of lake ecosystems including Toolik Lake, the Inlet Series lakes, and sentinel lakes on landscapes of different ages
- Monitored experimental lakes recovering from fertilization to examine transition from more open (nutrients added) to more closed (nutrient addition stopped) ecosystems
- Periodic and opportunistic sampling of lakes undergoing change due to disturbance (e.g., fire and thermo-karst)
- In selected lakes, measured pelagic and benthic primary production, pelagic bacterial production, and sampled micro-zooplankton, bacteria, water column DNA, and benthic invertebrates.
- Continued long-term monitoring of fish communities, including comprehensive mark-recapture studies in the Fog lakes and some of the I Lakes, associated annual measurements of vital rates (e.g., growth, survival, condition), and estimates of population trends.
- On a subsample of fish, measured diet, analyzed trophic position and pelagic versus littoral contributions to diet using isotopes, and collect fish otoliths to age the fish.
- Increased focus on Lake and stream processes occurring late summer and early fall, the time period that climate warming is predicted to have the greatest effect
- New comparison of four lakes; two isolated lakes (Fog lakes) on a younger-aged surface, with low watershed inputs (biogeochemically more closed), low DOC concentrations, and have a closed, char-dominated community v. two lakes (I-lakes) in a highly inter-connected stream-lake system, are DOC rich, and have diverse and more mobile, grayling-dominated (with lake trout) communities.
- Assist with sampling and set up for separate grant from NSF to impose long-term whole lake warming; LTER data serves as pre-manipulation baseline for these lakes.

Specific Objectives:

Continue to maintain long-term experiments

Set up new experiments and measurements (see major activities above)

Continue synthesis to develop a long-term, integrated perspective on tundra landscapes.

Significant Results:

The Arctic LTER maintains long-term experimental manipulations in lakes, streams, and tundra plots. It is our policy to allow other researchers to make use of these experiments after review and approval. The data from these studies help advance LTER science, leverage off of existing LTER data, and are added to the LTER data base. In this section we report on findings from studies making use of LTER experiments and LTER supported personnel, facilities, and logistics.

Terrestrial Arthropods: We maintain long-term fertilizer, greenhouse, and shade-house plots in various tundra types. As part of Ashley Asmus' PhD research with Laura Gough, we determined that arthropod responses to nutrient addition differ depending on the degree of change of the plant community and the duration of the experiment, with shorter term responses following predictions that arthropod abundance and biomass should increase with greater plant productivity but longer-term results suggesting no overall change in arthropod abundance (Asmus 2017 and Asmus et al. On-line Early).

Belowground response to fertilizer and warming: Jennie McLaren also examined our fertilized tundra plots and concluded that (1) long-term responses of tundra to nutrient addition cannot be predicted from short-term responses; (2) belowground responses to nutrient addition are decoupled from aboveground responses; (3) the paradigm of strong nitrogen limitation of arctic ecosystems needs to expand to include potential phosphorus limitation, especially belowground; and (4) different arctic ecosystems do not respond similarly to nutrient additions.

Working in our greenhouse plots, Megan Machmuller et al. found that experimental warming does not alter the temperature-sensitivity of soil enzymes, an observation consistent across biomes. However, geographic location had considerable implications for the temperature sensitivity of soil enzymes. In combination, these results provide mechanistic support for the idea that warming will enhance the rate of soil carbon loss from soil, with the greatest effects in colder, high-latitude regions that have the highest temperature sensitivity of soil carbon decomposition.

Machmuller et al. also examined the effect of fertilization on soil C stocks and found that it varied considerably with time, initially causing a substantial soil C loss, followed by soil C accumulation, and no detectable effect after 35 years of in situ fertilization. Our study identifies several potential mechanisms leading to this temporal response. We found that N additions stimulated priming only in E. vaginatum soils, characterized by lower nutrient concentrations and microbial biomass. We found no evidence of priming in soils fertilized for 35 years. Rather, we found that long-term fertilization reduced microbially accessible C pools, microbial biomass, and SOM respiration. Our results suggest that, in the short-term, the magnitude of SOM priming is dependent on vegetation and soil N concentrations, but this effect may not persist if shrubs increase in abundance under climate warming. In combination, our study demonstrates how plant-soil-microbe interactions can influence the direction, magnitude, and timing of the Arctic C-climate feedback. This work has led to a manuscript in advanced stage: Machmuller, MB, LM Lynch, MF Cotrufo, EA Paul, F Calderon, GR Shaver, and MD Wallenstein. In Prep. Plant-soil-microbe interactions lead to the recovery of soil C stocks with long-term nutrient fertilization.

Machmuller et al. also added a low-molecular-weight C source (LMW-C) to soil under *Eriophorun vaginatum* and *Betula nana* and did not find evidence of priming, defined as an increase in the decomposition of native SOM stocks, from soils underlying either vegetation type. However, LMW-C conversion to CO_2 was twice as high in soils under *E. vaginatum* than

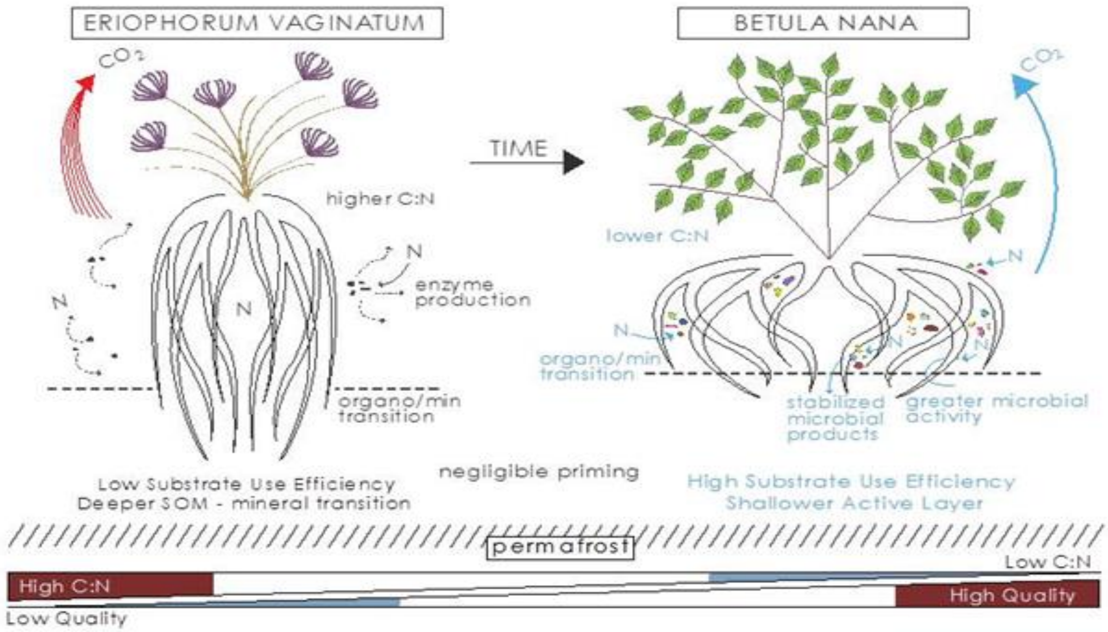

Figure 1. Conceptual model depicting the fate of LMW-C as influenced by vegetation type and soil chemistry. Plant traits (e.g. litter chemistry, root architecture, depth to mineral horizon) influence soil chemistry and lead to divergent microbial functions. Higher microbial substrate use efficiencies in soils underlying *B. nana* contribute to soil organic matter formation. Arrow sizes indicate the magnitude of CO_2 efflux.

under *B. nana*, and LMW-C stabilization efficiencies were 150% greater in soils under *B. nana.* than under *E. vaginatum.* Our results highlight the resilience and extraordinary C storage capacity of these soils, and suggest shrub expansion may partially mitigate C losses from decomposition of old SOM as Arctic soils warm (Fig. 1).

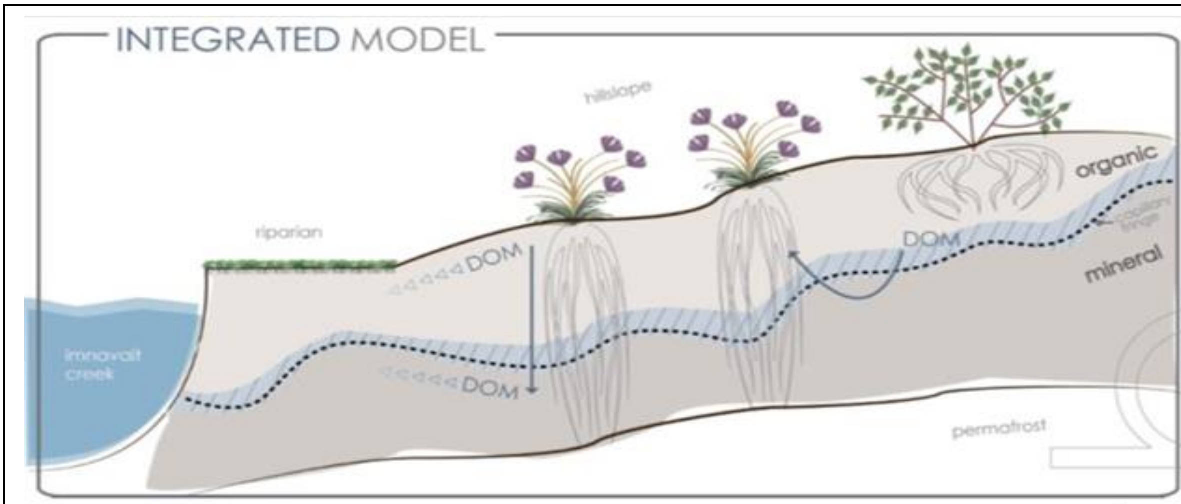

Figure 2. Conceptual model depicting flow-path mechanisms of dissolved organic matter (DOM) delivery to adjacent water bodies. Relatively rapid flow paths shunt DOM through the porous upper organic layer, but macro-pore flow and mass transport also deliver pore water directly to the stream along the impermeable permafrost boundary. Typical point measurements may be insufficient in characterizing Arctic hillslope flow paths.

Compounds mobilized through the porous organic horizon were associated with plant-derived molecules, while those flowing through mineral soils had a microbial fingerprint. Landscape position also influenced the structural diversity of DOM, which increased during downslope transport from hillslope to riparian soils. While the chemical composition of DOM varied across the landscape, the potential for relatively rapid lateral flow across Arctic hillslopes and along the mineral-permafrost interface suggests DOM mobilization is an important mechanism of C loss from Arctic soils (Fig. 2). This work has resulted in a manuscript in advanced stage: Lynch, L, T Covino, C Boot, M Machmuller, F Cotrufo, C Rithner, D Hoyt, and M Wallenstein. In Prep. From soils to streams: Tracking the fate of dissolved organic matter through Arctic soils.

Soil food webs: In a follow up to the 2015 harvest of plots fertilized for 35-years (plus controls), John Moore et al. resampled and corrected estimates of soil bulk density. These new estimates of bulk density had carry-on effects on estimates of the effects of fertilizer on soil food webs and soil metabolism (Table 1).

Table 1: 35-yr LTER fertilizer experiment: effects on soil food webs and metabolism:

	Upper O-Horizon (0-5 cm)		Lower O-Horizon (5 cm-mineral)		Mineral (Upper 5 cm)		
	Control	N+P fert	Control	N+P fert	Control	N+P fert	
Microbes ($g\ C\ m^{-2}$)							
Bacteria	0.02 ±0.003	0.03 ±0.002	0.12 ±0.03	0.24 ±0.09	0.51 ±0.17	0.70 ±0.19	Depth p<0.0001
Fungus	1.34 ±0.36	3.39 ±0.85	7.16 ±1.68	17.42 ±6.29	28.28 ±11.81	59.57 ±11.56	Trt P=0.0979; Depth p<0.0001
Consumers ($mg\ C\ m^{-2}$)							
Herbivores	0.12 ±0.3	0.03 ±0.01	0.16 ±0.03	0.06 ±0.02	0.13 ±0.05	0.05 ±0.02	Trt p=0.0388
Bacteriovores	0.42 ±0.18	2.36 ±1.72	7.36 ±3.95	3.34 ±1.39	12.90 ±7.67	4.76 ±1.23	Trt p=0.0541; Depth p=0.0965
Fungivores	13.55 ±1.25	30.40 ±4.27	12.36 ±4.91	24.75 ±8.48	2.02 ±1.30	1.24 ±0.70	Trt p=0.0543; Depth p=0.0003
Microbivores	0.01 ±0.01	0.00 ±0.00	0.05 ±0.05	0.18 ±0.12	0.00 ±0.00	0.00 ±0.00	Depth p=0.0693
Predators	2.01 ±0.65	1.94 ±0.64	2.47 ±0.83	2.93 ±0.88	3.39 ±2.45	1.99 ±1.10	Trt NS; Depth NS
Mineralization							
Respiration ($g\ C\ m^{-2}\ yr^{-1}$)	4.71 0.06±	11.30 ±0.08	22.05 ±0.30	52.03 ±1.16	80.55 ±1.96	170.72 ±2.05	
N-MIneraliz. ($g\ N\ m^{-2}\ yr^{-1}$)	0.46 ±0.01	1.12 ±0.01	2.17 ±0.03	5.15 ±0.12	7.95 ±0.20	16.94 ±0.21	

Results indicate that fungus increases with N+P fertilization and that microbial activity in general (fungus + bacteria) is higher in deeper layers of the soil. Both phytophagous nematodes (herbivores) and bacteriovores both decrease with N+P fertilization but fungivores increase. Microbivores are most active in the lower organic layer. Predators are unaffected by

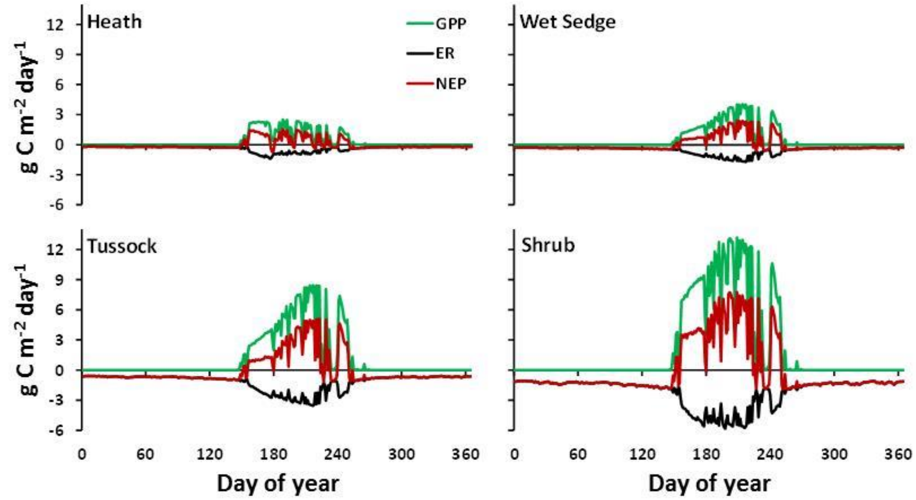

Figure 3. Simulated carbon metabolism of the dominant tundra types around Toolik Lake. All four simulations were run with the same weather, CO2, and deposition data and are calibrated to an annual steady state with climate. GPP - ecosystem photosynthesis; ER - ecosystem respiration (plotted as a negative to indicate loss from the ecosystem); NEP - net

treatment or depth. Both respiration and N mineralization increase with N+P fertilization.

Comparative modeling of tundra types: The Arctic LTER has long term data on C and nutrient budgets for the major tundra types near Toolik Lake. LTER REU student Erin Gleeson (Rhodes College), under the supervision of Ed Rastetter, used these data to calibrate the Multiple Element Limitation (MEL) model to heath, wet sedge, moist acidic tussock, and shrub tundras. The carbon metabolism varies widely among the tundra types in the Toolik region (Fig. 3). Heath tundra is found on ridge tops and glacial kames, has dry, well-drained soil with little organic matter accumulation, and has low productivity. Wet sedge tundra is found in flooded hollows and stream and lake margins, has deep, water-logged soils, and also has low productivity. Moist acidic tussock tundra covers most of the land surface in the Toolik region, has a thick organic soil, but is not continuously waterlogged, and has high productivity. Shrub tundra is found in water tracks and more deeply thawed soils, and has the highest productivity. With the continued involvement of Erin Gleeson, now a senior at Rhodes College, we are developing climate-change scenarios to simulate the responses of these four tundra types to climate warming over the next 100 years. We will be running factorial simulations to examine responses to increasing CO_2, warming, and changes in precipitation, and will relate those responses to biogeochemical openness of these tundra types. We will also analyze downslope losses of nitrogen, phosphorus, and organic matter to evaluate changes in the connectivity of the land surface to streams and lakes.

Thaw-depth monitoring: Despite arctic warming, thaw depth measurements using steel probes show variable results. The summer of 2017 had an average thaw depth that was deeper than the long-term average at both Toolik Lake and Imnavait Creek, our two long-term monitoring sites (Fig. 4). However, only at Imnavait Creek is there an indication that thaw depth is significantly increasing over time as expected from climate warming ($R^2 = 0.64$ of thaw depth with time at Imnavait versus $R^2 = 0.06$ at Toolik). This difference in response to climate in two similar watersheds only about 15 km apart has only emerged in the last several years of record, and we don't understand why. One possibility is that our grids of measurement are relatively small considering the entire landscape, and we may be capturing spatial variation that is confounding any long-term trend.

To investigate the spatial variation in thaw depth at larger scales, we are beginning a new initiative with Drs. Ann Chen and Bayani Cardenas at the University of Texas to use synthetic aperture radar data from satellites (InSAR) to examine this problem. InSAR measures the "rise and fall" of the ground surface due to soil water freezing in the fall and thawing in the spring, because ice occupies more volume than liquid water.

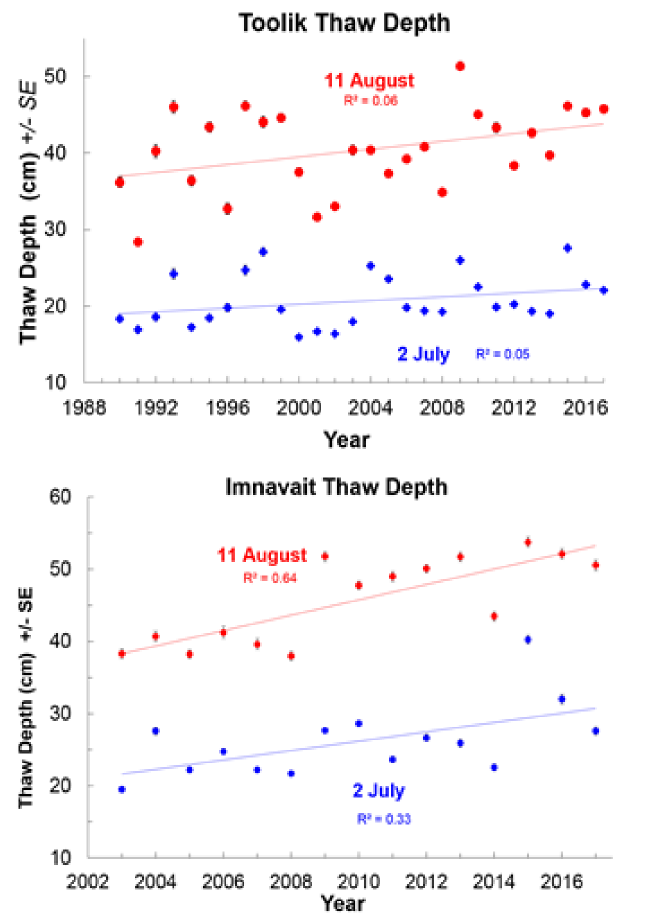

Figure 4. Thaw depth trends at Toolik and Imnavait

A pilot study by Dr. Chen demonstrated that InSAR data acquired between 2006 and 2010 can characterize the seasonal active layer freeze-thaw cycle to detect changes over time, and qualitatively map the spatial distribution of groundwater storage. The preliminary results show no statistical difference in the magnitude of the annual freeze-thaw cycle over the 2006-2010 period, but there was a clear difference in how the InSAR signals matched with ground-based LTER measurements of thaw depth. At Toolik the satellite and ground-based estimates of thaw depth matched fairly well (Fig. 5 left), while at Imnavait there was a definite offset between the two estimates (Fig. 5 right).

These differences between the Toolik and Imnavait watersheds will be investigated by combining ground-based and satellite measurements in detail in the coming years (supported in part by the LTER and in part by a NASA grant recently recommended for funding). Specifically, we will follow the pattern of change in land surface deformations due to freeze-thaw cycles between these two watersheds. The InSAR technique is quite sensitive, and has the advantage of much greater spatial coverage in much shorter time than measurements done by hand.

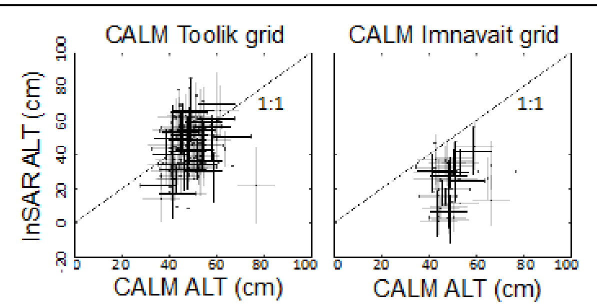

Figure 5. Comparison of satellite (InSARALT) and ground-based (CALM ALT) thaw depth at Toolik and Imnavait.

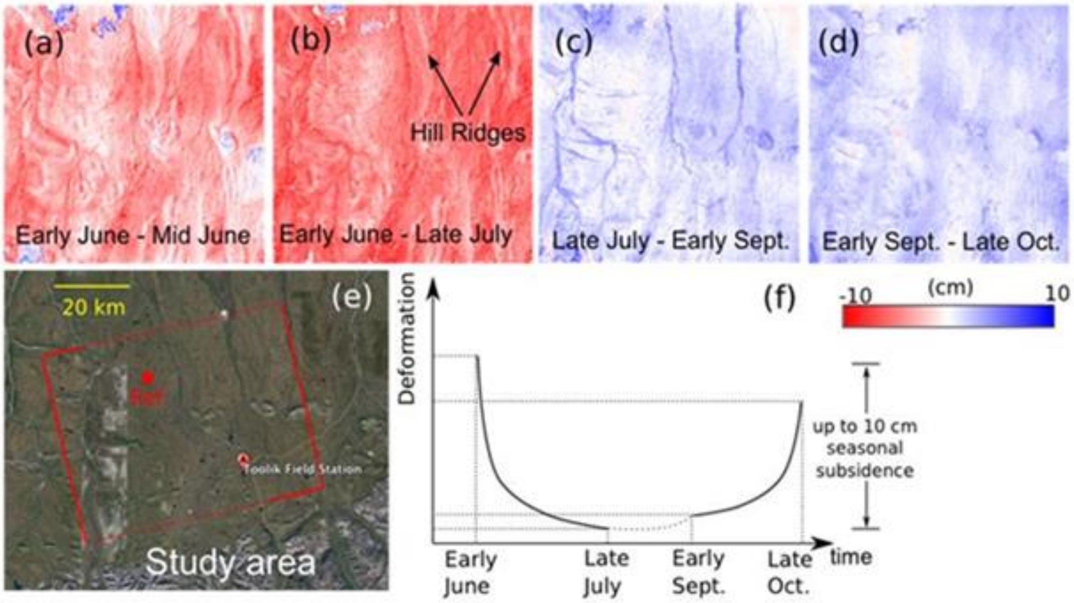

Figure 6. Vertical surface displacement due to annual freeze-thaw cycle near Toolik Lake. Vertical subsidence (red) and uplift (blue) were inferred from InSAR data. The 4 panels at the top show subsidence in early June to middle June and early June to late July (the maximum observed subsidence, darkest red). Panels (c) and (d) show the ground surface uplift (blue) as the soils start to freeze and expand in early and late fall. The spatial coverage of the InSAR data is outlined in red in panel (e). All deformation is relative to a reference point marked with a red star in panel (e), which was was chosen at the location where the minimum seasonal deformation was observed. Panel (f) illustrates a conceptual InSAR-based deformation model for characterizing the seasonal active layer thaw-freeze cycle. *(Chen et al. unpublished*)

The seasonal deformation pattern shows a strong correlation with the local watershed and river network morphology (Fig. 6). For example, the minimum seasonal subsidence (~1 cm) is observed at the hill ridges where the soil is the least saturated, and the maximum seasonal subsidence (> 5 cm, darkest red) is observed in the river valleys where the soil is fully saturated. This pattern is reversed during freezing and uplift, with the highest values (darkest blue) found in the water-saturated river valleys. Coupling these data with ground-based measurements of thaw depth, soil water saturation, and hydraulic properties will increase our understanding of how and how fast permafrost soils are thawing in response to climate change.

Responses to stream fertilization: Data analysis continues to reveal additional influences of long-term phosphorus addition on the Kuparuk River ecosystem (Fig. 7). By analyzing the nutrient content of the dominant bryophyte and algal communities, we have observed variability in the nutrient use efficiency of these communities in response to phosphorus addition. We compared the C:N:P ratios of the three main benthic communities in the Kuparuk: 1) the epilithic algal community, historically present in all reaches; 2) communities dominated by *Schistidium agassizii*, a bryophyte historically present in low densities in all reaches; and 3) communities dominated by *Hygrohypnum spp.*, bryophytes which displayed an explosive response to fertilization and now dominate the fertilized reach, but are only sporadically found in unfertilized reaches. These C:N:P ratios were compared to the Redfield

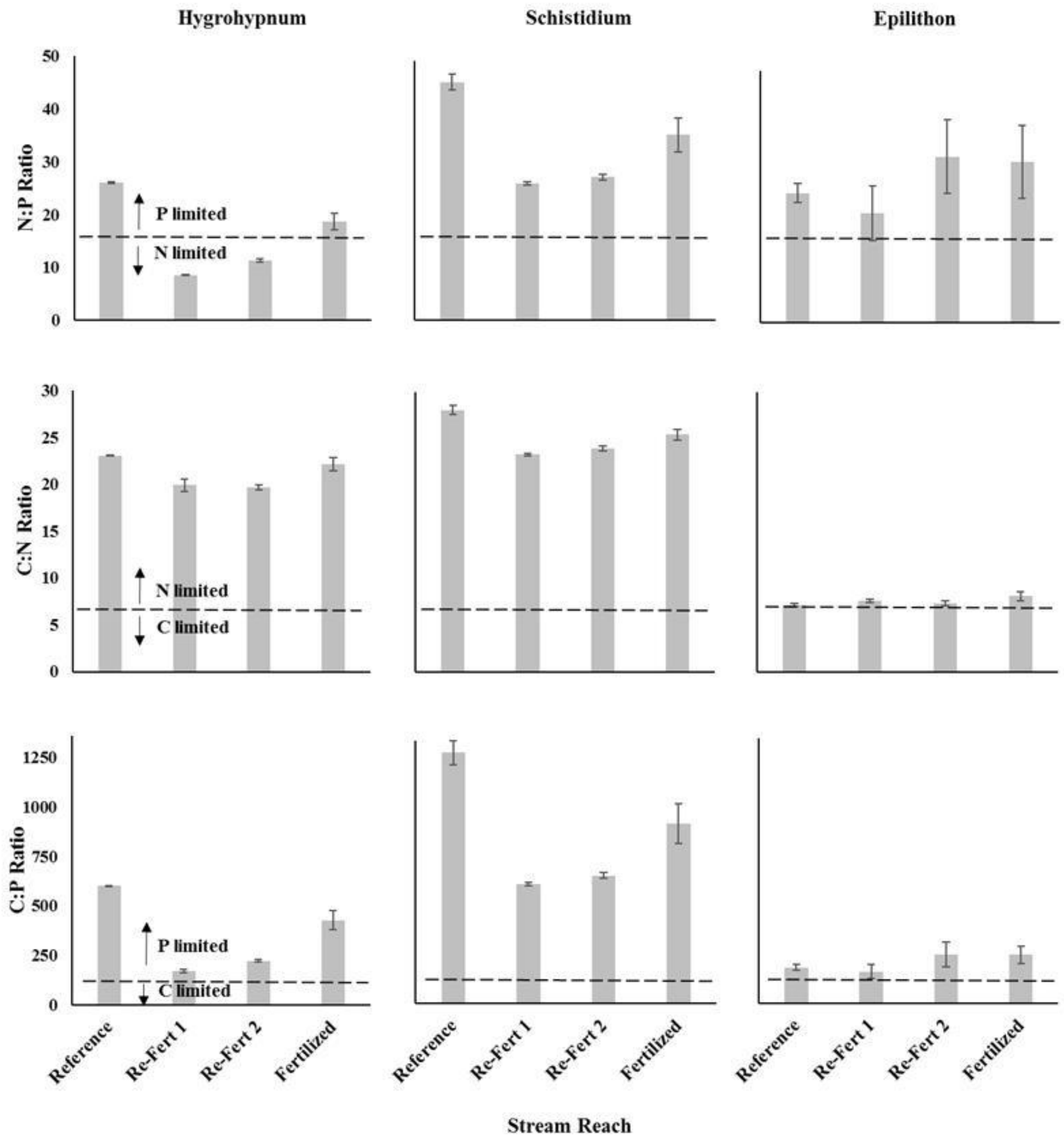

Figure 7. Nutrient content ratios of the three main benthic community types in the Kuparuk River in late July - early August, 2015. Stream reaches progress from upstream to downstream across each x axis. Phosphorus was added at the top of the Re-Fert 1 reach. Nutrient limitation thresholds are based on the Redfield ratio of 106:16:1 C:N:P.

ratio of 106:16:1, which provides conceptual thresholds of nutrient limitation in algae and can serve as a preliminary basis of comparison for other taxa (Fig. 7).

The epilithic community responds roughly as expected: C:N:P ratios remain relatively close to the Redfield ratio in all reaches (with the notable exception of N:P in the downstream reaches), indicating a consistent nutrient use efficiency regardless of nutrient availability. In contrast, the nutrient use efficiency of the bryophyte communities is more variable, both within and between the two community types. In all reaches, *Schistidium* communities display higher C:N and C:P ratios than *Hygrohypnum*, indicating greater nutrient use efficiency. This observation is consistent with historic data on the physiology of these bryophytes. However, both communities display a reduction in nutrient use efficiency upon P addition, regardless of their initial efficiency in unfertilized conditions. This may reflect a lag time between nutrient uptake and the physiological adaptation of adjusting production to match nutrient availability. Full interpretation of these results is ongoing. We intend to extend this investigation both backward into the available historic data, and forward into the post-fertilization years through continued sampling of bryophytes and epilithon.

Lake community responses to warming: In arctic lake ecosystems, changes in seasonality associated with climate warming (e.g., temperature, growing season duration) may alter invertebrate prey biomass through influences on physiology and phenology (Klobucar et al. In re-review). However, despite warmer thermal regimes, photoperiod will remain unchanged. Here, we use a multi-faceted approach to address prey availability to predators in these lake ecosystems, under a changing climatic regime. In a laboratory mesocosm experiment, we measured biomass of snails (Lymnaea elodes) and zooplankton (Daphnia middendorffiana) across three time periods (early, mid, and late season), and across three temperature and photoperiod treatments (control, increased temperature, increased temperature*photoperiod). We observed variable responses by snails and zooplankton across trials and treatments. In the early season, snail life stages (e.g., egg and juvenile development) were accelerated under warmer temperatures. In mid-season, we observed significantly increased Daphnia abundances, while in the late season, Daphnia appeared to be limited by photoperiod. We used generalized additive models (GAMs) and generalized additive mixed effects models (GAMMs) related long-term

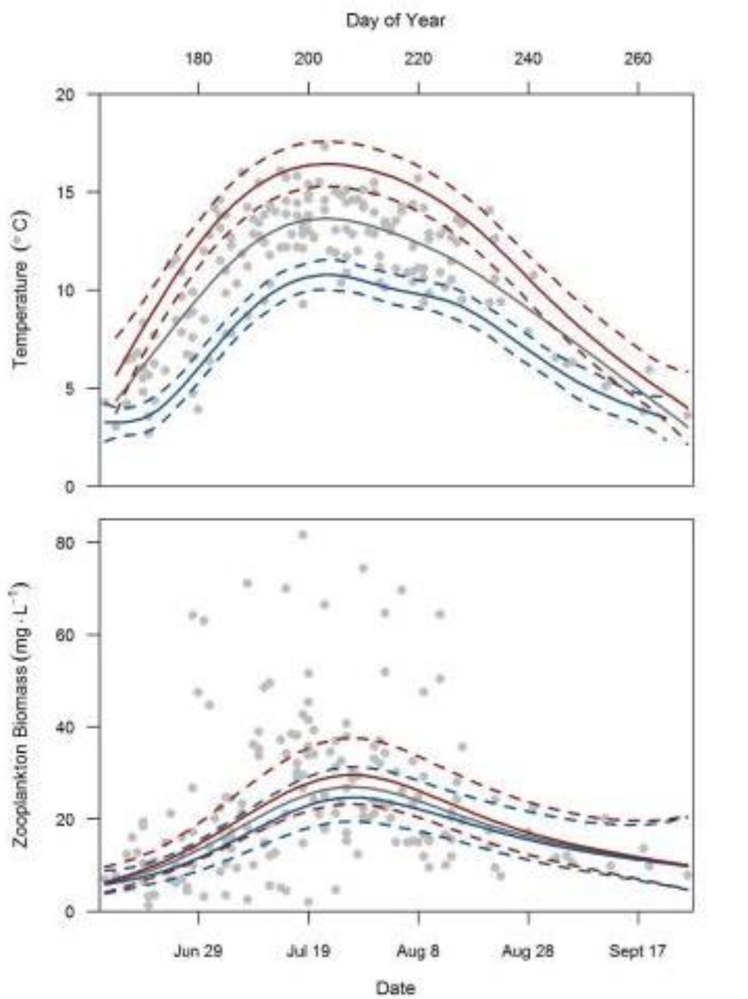

Figure 8. Modeled responses of zooplankton to changes in temperature. Bottom: Generalized mixed effects additive model predictions ($R^2 = 0.25$, edf = 3.64) of standing stock zooplankton biomass in Toolik Lake, Alaska, for a warm year (red) and cold year (blue) as a function of day of year ($p < 0.001$) and lake temperature ($p = 0.19$) at 3 m with random effect of sample year. Dashed lines are ± 2se. Gray points are all observed measures of zooplankton biomass from 1987 – 2015 (n = 175).

trends (1983 – 2015) in zooplankton biomass across a range of temperature regimes observed in nature (Fig. 8). Our models suggest zooplankton biomass increases nearly 20% in warmer years. However, these estimates could be conservative due to increased consumptive demand by fishes. Overall, our results provide multi-faceted evidence of the importance of interactive effects of temperature and seasonality. We demonstrate the need to better understand nutrient dynamics and species-specific mechanisms to predict invertebrate prey biomass and availability in a warmer climate. These results have important implications for fishes in terms of food availability.

Lake recovery from fertilization: We continue to monitor the recovery of two lakes that were fertilized for 13 years and that have not been fertilized for 4 years. Both lakes have nearly returned to pre-fertilization limnological conditions with the exception of the deeper lake where bottom water oxygen concentrations are still lower than the pre-fertilization condition. The extremely large population of arctic char that resulted from the increase in productivity had finally appeared to start a rapid decline, presumably because carrying capacity has been dramatically exceeded.

COLLABORATING PROJECTS:

The Arctic LTER Streams initiative collaborates with and helps to support (with data and field assistance) the following stream-related projects:

FISHSCAPE II: Adaptability of a key arctic freshwater species to climate change
M. Urban, L. Deegan (NSF-OPP)

The main goal of this project is to predict the adaptability and persistence of a key Arctic species, the Arctic grayling (*Thymallus arcticus*) to changing climate and hydrology. In 2017, we tested three main hypotheses: (1) landscape structure determines movement within and among watersheds; (2) populations adapt to stream characteristics at local and regional scales; and (3) the relative adaptability of populations will determine their persistence under future climate change. In order to assess fish movement patterns, we PIT-tagged Arctic grayling and installed 14 PIT-tag antenna arrays along three study watersheds: The Kuparuk River, Oksrukuyik Creek, and I-Minus. We also installed stream-monitoring devices to collect data on river temperature and flow intermittency. Additionally, we collected and fertilized Arctic grayling eggs, and hatched and reared Arctic grayling in a common garden experiment to test for local adaptation among genetically distinct populations. Finally, we collected Arctic grayling tissue samples from headwaters to the coastal plain for genomic analyses to look for genome-wide signatures of selection on a regional scale. Preliminary PIT-tag findings suggest that different Arctic grayling populations exhibit distinct movement patterns, which reflect local environmental conditions. Preliminary common garden data suggest that larval grayling experience faster growth but higher mortality in warmer versus cooler water temperatures. Further PIT-tag, common garden, and genomic analyses will inform predictions for Arctic grayling persistence under future climate change.

Temperature effects on growth, development, and % P in Baetid mayfly populations in arctic, temperate, and tropical streams along an elevation gradient
C. Atkinson

Increases in temperature associated with climate change may impact aquatic biota differentially depending on the temperature variability they currently experience. I conducted in situ growth transplants in small streams using mayflies in the family Baetidae across an 800-1200m elevational gradient in the Alaskan Brooks Range (AK), Colorado Rockies (CO), and Ecuadorian Andes (EC). Here I asked what are the effects of temperature on growth, development, and %P of closely related species of mayflies across elevation and latitude? Populations that inhabit high-altitude environments experience lower temperatures and shorter activity periods than their low-altitude neighbours and offer an excellent opportunity to assess how survival is facilitated in environments where growth is constrained. I hypothesized that insects from arctic and temperate streams, which experience greater seasonal and diel temperature fluctuations, would show the strongest response to temperature gradients as a result of elevation than phylogenetically-related organisms from tropical regions, where temperatures are annually stable. I measured growth rates in *Baetis spp* near Toolik in Alaska, *Baetis bicuadatus*, *Baetis tricaudatus* in Colorado, and *Andesiops spp*. mayflies in Ecuador along a 800-1300 m elevational gradient. Average temperatures ranged from 7-15°C across 6 sites in Alaska, 5-17°C across 7 sites in Colorado, and 8-14°C across 4 sites in Ecuador. I quantified the effect of different temperature variables (e.g., mean, mix, max, delta T, and accumulated degree days > 0°C) on mayfly specific growth rates (SGR, mg day^{-1}). I also quantified the effect of body size and estimated development stage on growth rates. At the end of each growth experiment, I also measured NH_4-N excretion rates as an estimate of physiological rate across the gradient. Furthermore, I analyzed mayflies along the gradient in Alaska, Colorado, and Ecuador for body % phosphorus (P) to test the growth rate hypothesis, which predicts that organisms with higher maximum growth rates will also have higher body phosphorus due to increased ribosomal RNA. Growing fast requires rapid protein synthesis, which requires many ribosomes that are high in P. As expected, growth rates were higher in streams with warmer temperatures in Alaska and Colorado. However, mayfly growth did not vary significantly across the elevation or temperature gradient in Ecuador suggesting that other factors determine growth in the tropics. Further, Ecuadorian mayfly excretion rates were positively related to temperature, but no pattern was seen in Alaskan or Colorado streams. Furthermore, body %P was not significantly related to mayfly growth rates in Alaska or Colorado, but mayfly body %P was positively correlated to mayfly growth in Ecuador. These somewhat contrary results highlight the potential interacting factors that may be in play to dictate invertebrate growth across ecosystems, which need to be further explored. This can have strong implications for community and functional processes in aquatic systems (e.g. fecundity, nutrient recycling).

Dissolved Organic Matter in Arctic and Boreal Streams

J. Zarnestke, B. Abbott

Dissolved organic carbon (DOC), nutrients, and other solute concentrations are increasing in rivers across the Arctic. These increases are widely attributed to permafrost degradation, but it is unknown whether they stem from enhanced solute sources or diminished solute sinks, hindering prediction of how climate change will alter energy and nutrient availability in terrestrial and aquatic ecosystems. Additionally, the relative importance of discrete and diffuse drivers of solute increase (e.g., active-layer deepening versus thermo-erosion) remains unknown. To address these unknowns, we are combining high-frequency water flow and chemistry sensors at catchment outlets with occasional spatially extensive sampling through upstream subcatchments. We are interpreting this synoptic data in a new ecohydrological framework to reveal the spatial structure of solute sources and sinks. In this context, we synoptically sampled carbon and nutrient chemistry three times over the last two years (August 2016, June 2017, and August 2017) in 119 subcatchments of three distinct LTER catchments (Trevor, Oksrukuyik, and Kuparuk). Subcatchments ranged from 0.1 to 80 km^2, and included three distinct types of Arctic landscapes – mountainous (Trevor), tundra (Kuparuk), and glacial-lake (Oksrukuyik) catchments. With multiple years of data, we are beginning to quantify the stability of spatial patterns in synoptic water chemistry through time and thaw conditions. We also collected and are starting to analyze high-frequency time series of DOC, nitrate, oxygen, electrical conductivity, and dissolved oxygen from the catchment outlets across the thaw season to identify timing of solute delivery and strength of in-stream retention of carbon and nutrients.

To date, the results show that that variance in solute concentrations between subcatchments collapsed at spatial scales between 1 to 20 km^2 (Fig. 9a) indicating a continuum of diffuse- and point-source dynamics. Across seasons (early to late thaw season), we see the role of catchment characteristics (e.g., reactivity, topography, vegetation, surficial geology) playing out in the spatial stability of solute sources and sinks. For DOC, we see that there is stability in the dominant source-sink function of subcatchments across seasons in both Kuparuk and Trevor, but that the source-sink structure fundamentally reorganizes in Oksrukuyik, which we associate with differences in timing in lake productivity and turnover (Fig. 2b, 2c). For nitrate, we see instability in the spatial source-sink function of subcatchments in all three watersheds, indicating major ecosystem shifts such as distributed DOM mineralization along deeper, longer flowpaths to the stream. Our estimates of the spatially distributed mass balance for solutes suggest relatively conservative transport of DOC and most major ions in all watersheds (i.e., the catchment outlets converge to the flow-weighted mean of the tributaries).

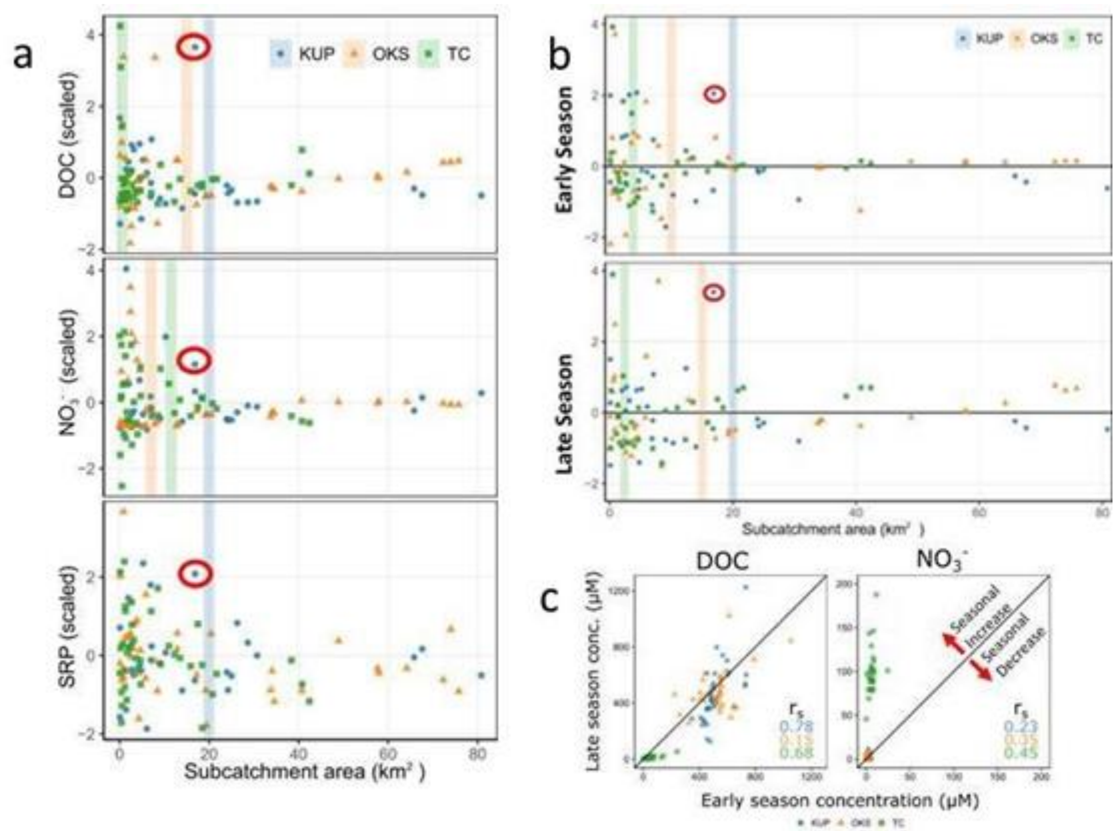

Figure 9. Flow-weighted DOC concentration variance collapse across Kuparuk (KUP, blue symbols), Oksrukuyik (OKS, orange symbols), Trevor (TC, green symbols). The vertical colored bands represent statistical changes in spatial variance among subcatchments based on change point analysis implemented for each catchment separately. Red circled data points in each plot is the Imnavait Creek subcatchment outflow to the Kuparuk. a. Preliminary comparison of 2016 late thaw season (August) DOC, nitrate (NO_3^-), soluble reactive phosphorous (SRP) showing variability collapse is predominantly at a scale of less than 20km^2, and b. Preliminary comparison of 2017 early (June) and late (August) thaw season, showing stability in DOC variance for Trevor and Kuparuk, but a significant expansion in spatial variance for Oksrukuyik.

However, there are interesting patterns of net nitrate production or uptake depending upon the watershed, with nitrate production via nitrification in Kuparuk, nitrate uptake in Trevor, and more conservative nitrate behavior in Oksrukuyik. In all watersheds, there appear to be strong in-stream retention of phosphorus. Also, worth noting in the context of attempting to upscale point and subcatchment studies to larger scale processes and patterns, we consistently find that Imnavait Creek, a major subcatchment to the Kuparuk has outlier conditions for DOC and nutrient conditions relative to all sampled subcatchments in the region. This presents an opportunity to leverage the decades of investigations in Imnavait to investigate why its solute source function is so different from other streams in the region.

Synoptic sampling allows direct observation of ecohydrology at intermediate scales to bridge site and landscape scale studies. For example, these large synoptic assessments are providing a network-scale confirmation of previous limited reach-scale inorganic N and P studies in these Arctic catchments. They are also helping to provide larger-scale context for the smaller scale LTER research efforts, such as those of land-water interactions of Imnavait Creek and lake ecosystems of Oksrukuyik. Overall, these investigations are developing new approaches to analyzing synoptic data for change detection and quantification of ecohydrological mechanisms in ecosystems in the Arctic and beyond.

Key outcomes or other achievements:

Covered under Significant Results

What opportunities for training and professional development has the project provided?

- The LTER core budget supported three REU students in 2017, one examining terrestrial processes (Erin Gleeson), one examining lake processes (Thomas Hafen), and one helping with lab analysis and data management (Nicholas Warren).
- Research Experience for Teachers: Supported 5 Teachers (Bucko, Wren, Kershner, Cruse, Lopez) and the LTER Education Representative (Morrison) assisted in data collection and processing of plant and fauna sampling at Toolik field station for 10 day at Toolik Field Station. Research was led by Adrian Rocca and John Moore.
    - 1 teacher (Lopez) worked with PI Beth Neilson on her hydrology research at Toolik Field Station for 10 days in early July.
    - All 5 teachers have been working to develop curriculum related to their summer research experience at Toolik Field Station and we anticipate classroom implementation by June 2018.
- **Meetings:** Ed Rastetter, John Moore, Amanda Morrison traveled to the Toolik Annual Meeting in Portland, OR in February 2017 on behalf of the Arctic LTER. Both engaged in education related meetings as well as the site meetings.
- **LTER Schoolyard Ecology:** Amanda worked to make connections with other LTER Education Representatives in an effort to work together on various projects – Schoolyard Book series, Research Experiences for Teachers group, and collaboration with other Alaska LTERs in an effort to collaborate with the North Slope Borough. Amanda attended monthly LTER Education meetings throughout the year.

How have the results been disseminated to communities of interest?

Yes through journal publications and press reports listed below under products

What do you plan to do during the next reporting period to accomplish the goals?

Terrestrial: In the next field season, we will continue to monitor plant community composition and timing of plant green-up in our long-term experimental plots in multiple plant communities including moist acidic tussock, moist non-acidic tussock, dry heath, wet sedge, and shrub. We will establish new artificial warming experiments in two plant communities to create new opportunities to understand the response of tundra communities to increased air temperatures. We will continue interacting with collaborating projects as detailed in the proposal and continue to assemble datasets for web publication as well as results for dissemination.

Land-water Interactions. During the winter months we will continue to analyze the chemistry of the samples collected in the first summer of the research. We will update the data products files, and begin assembling results into publications. In the next field season we will continue with maintaining the long-term data collections from our LTER monitoring sites, and we will continue with the research and sample collection according to the program goals and the specifics outlined in the proposal.

Streams: We will continue to monitor discharge, nutrients, benthic algae, benthic macroinvertebrates, fish, and whole-stream metabolism during the open-water season in the primary long-term river study sites: Kuparuk River and Oksrukuyik Creek. We will continue to monitor the state (cover and nutrient content) of the bryophyte community in the reach of the Kuparuk River that was enriched with phosphorus from 1983 until 2016, to follow the trajectory of ecosystem recovery after the enrichment ceased in 2018. We will continue to explore the use of eDNA techniques to identify spatial patterns of key fish species in streams in the region and we will conduct additional synoptic sampling events in selected watersheds (mountain, tundra, and tentatively coastal plain) to assess spatial patterns of solute variability in the context of river network structure and the landscape context.

Lakes. During the winter months we will continue to analyze limnological and fish data and analyze zooplankton and invertebrate samples collected in the first summer of the research. We will update the data products files, and begin assembling results into publications. In the next field season we will continue with maintaining the long-term data collections from our LTER monitoring sites, and we will continue with the research and sample collection according to the program goals and the specifics outlined in the proposal.

Products:

Within the Products section, you can list any products resulting from your project during the specified reporting period, such as:

Journal articles:

Asmus, A., A. Koltz, J.R. McLaren‡, G.R. Shaver, and L. Gough. Online Early. Long-term nutrient addition alters arthropod community structure and seasonality in arctic tundra. Oikos. DOI: 10.1111/oik.04398

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Books:

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Asmus, A.L. 2017. Arthropod food webs in arctic tundra: trophic interactions and responses to global change. Ph.D. Dissertation. University of Texas Arlington. 142 pp

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Other conference Presentations/papers:

Arnold, T.{undergraduate}, S.L. Klobucar, G.P. Thiede, and P. Budy. Investigating morphometric differences across and among Arctic Char populations in lakes on the North Slope, Alaska. Poster Presentation. Joint Meeting of the Utah Chapter and Colorado-Wyoming Chapters of the American Fisheries Society, February 2017, Grand Junction, CO. ***Awarded best student poster***

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Cory, R.M., A. Trusiak, C. P. Ward, G. W. Kling, M. M. Tfaily, L. Pasa-Tolic, V. Noël, J. R. Bargar. Interactions between iron and organic matter may influence the fate of permafrost carbon in the Arctic (2018). American Geophysical Union Fall National Meeting. New Orleans, LA.

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Ludwig, Sarah M, Susan Natali, Ed Rastetter, Gus Shaver, Laura Graham. 2017. Shifting the Arctic Carbon Balance: Effects of a Long-Term Fertilization Experiment and Anomalously Warm Temperatures on Net Ecosystem Exchange in the Alaskan Tundra. AGU Fall Meeting 2017, Oral Presentation.

Machmuller, Megan , Laurel Lynch, Francesca Cotrufo, Gus Shaver, Francisco Calderon, Eldor Paul, Matt Wallenstein. Quantifying the fate of C inputs to Arctic tundra soils from roots to rivers. Department of Energy PI Meeting, April 2017.

Mack, M.C., Melvin, A., Walker, X. J., and E. A. Schuur. Wildfire, legacy carbon combustion, and the centennial carbon balance of permafrost ecosystems, Annual Meeting of the American Geophysical Union, New Orleans, LA, December 2017

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Neil, T., E. Grunewald, M. Briggs, M.A. Kass, A.D. Huryn, M. Gooseff, P. Hendrickson, J. Lane. A conceptual model for seasonal thaw dynamics of an aufeis feature inferred from surface geophysical methods. Geological Society of America, Seattle, WA, 23-27 October 2017.

Nicholaides, K. D., M. O'Connor, M. B. Cardenas, B. T. Neilson, and G. W. Kling. 2017. The Effects of Different Scales of Topographic Variation on Shallow Groundwater Flow in an Arctic Watershed. C21A-1111, American Geophysical Union Fall National Meeting. New Orleans, LA.

O'Connor, M., M. B. Cardenas, B. T. Neilson, K. D. Nicholaides, G. W. Kling. 2017. Groundwater Dynamics and Export from Active Layer Aquifers Overlying Permafrost. C33F-04, American Geophysical Union Fall National Meeting. New Orleans, LA.

Pavelsky, T.M., and J.P. Zarnetske. (2016) Rapid Declines in Aufeis Means Major Changes for Many Arctic Rivers. American Geophysical Union Fall Meeting, San Francisco, CA.

Pressler, Y., A.M. Koltz, A.L. Asmus, R.T. Simpson, L. Gough, G.R. Shaver and J.C. Moore. Recovery and recoupling of above- and belowground food webs after an unprecedented arctic wildfire. Ecological Society of America, Annual Meeting, Portland, OR, August 2017.

Stuart, Julia M., Mack, Michelle C., Holland Moritz, Hannah, Fierer, Noah, McDaniel, Stuart F., and Lewis, Lily R. Plant, Microbiome, and Biogeochemistry: Quantifying moss associated N fixation in Alaska. Poster presentation delivered at the American Geophysical Union fall meeting, New Orleans, LA, December 2017

Ward, C. S., Nalven, S. G., Crump, B. C., Kling, G. W., and R. M. Cory. 2017. Photochemical alteration of organic carbon draining permafrost soils shifts microbial metabolic pathways and stimulates respiration. 24th Biennial Conference of the Coastal and Estuarine Research Federation, Providence, RI, November 5-9, 2017.

Zarnetske, J.P., B.W. Abbott, W.B. Bowden, F. Iannucci, N. Griffin, S.P. Parker, G. Pinay, Z. Aanderud. (2017) Repeat synoptic sampling reveals drivers of change in carbon and nutrient chemistry of Arctic catchments. American Geophysical Union Fall Meeting, New Orleans, LA.

Zarnetske J.P., B.W. Abbott, W. Bowden, S.P. Parker, F. Iannucci, J. Benes. (2017) Using spatial variability in carbon and nutrient chemistry to identify drivers and detect change in arctic watersheds. Society for Freshwater Science Annual Meeting, Raleigh, NC.

Other publications:

News articles or publications about your work at Toolik:

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https://www.capenews.net/falmouth/news/alaskan-tundra-research-an-inspiration-in-the-classroom/article_27cf4f89-4b9b-5b4c-b6cf-ab3bc41ed2b4.html?utm_medium=social&utm_source=email&utm_campaign=user-share

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https://www.emsl.pnnl.gov/emslweb/news/sunlight-stimulates-microbial-respiration-organic-carbon
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http://msutoday.msu.edu/news/2017/arctic-river-ice-deposits-rapidly-disappearing/

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Golden, H.E. 2017. "Arctic Research and Exploration: The Fishscape Team explores the ecology of Arctic aquatic landscapes." Science journal blog. https://heidigoldenarcticresearch.wordpress.com

Lindsey, K. 2017. "North Slope 'fish spa' might hold answers to survival in a warming Arctic." Anchorage Daily News. September 11, 2017. https://www.adn.com/alaska-news/science/2017/09/11/north-slope-fish-spa-might-hold-answers-to-survival-in-a-warming-arctic-2/

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Waldman, S. 2017. Climate change is transforming Arctic rivers. Scientific American. April 19, 2017. https://www.scientificamerican.com/article/climate-change-is-transforming-arctic-rivers/?WT.mc_id=SA_TW_ENGYSUS_NEWS

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Walter, K. 2017. Arctic river ice deposits vanishing. R&D Magazine. April 19, 2017. https://www.rdmag.com/article/2017/04/arctic-river-ice-deposits-vanishing
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- AGU News Room (https://news.agu.org/press-release/arctic-river-ice-deposits-rapidly-disappearing/)
- AAAS EurekAlert (https://eurekalert.org/pub_releases/2017-04/agu-ari041817.php)
- Phys.org (https://phys.org/news/2017-04-arctic-river-ice-deposits-rapidly.html)
- Environmental News Network (http://www.enn.com/sci-tech/article/51054)
- ScienceDaily (https://www.sciencedaily.com/releases/2017/04/170418111451.htm)
- EOS (https://eos.org/scientific-press/arctic-river-ice-deposits-rapidly-disappearing)
- La Informacion (https://www.lainformacion.com/medio-ambiente/naturaleza/RIOS-ARTICO-DERRITEN-AHORA-HACE_0_1018399592.html)
- Cronica Social (http://www.cronicasocial.com/noticia.aspx?idN=677618)
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Nash, JM. 2018. An unfrozen north. High Country News. February 19, 2018. http://www.hcn.org/issues/50.3/an-unfrozen-north

Technologies or techniques:
Patents:
Inventions:
Licenses:
Websites:

http://arc-lter.ecosystems.mbl.edu/
http://www.k-state.edu/ecoforecasting/SCALER/
http://www.usu.edu/fel/research/arctic-lake-ecosystems/

Other Products:

Richardson, A.D., K. Hufkens, T. Milliman, D.M. Aubrecht, M. Chen, J.M. Gray, M.R. Johnston, T.F. Keenan, S.T. Klosterman, M. Kosmala, E.K. Melaas, M.A. Friedl, S. Frolking, M. Abraha, M. Alber, M. Apple, B.E. Law, T.A. Black, P. Blanken, D. Browning, S. Bret-Harte, N. Brunsell, S.P. Burns, E. Cremonese, A.R. Desai, A.L. Dunn, D.M. Eissenstat, S.E. Euskirchen, L.B. Flanagan, B. Forsythe, J. Gallagher, L. Gu, D.Y. Hollinger, J.W. Jones, J. King, O. Langvall, J.H. McCaughey, P.J. McHale, G.A. Meyer, M.J. Mitchell, M. Migliavacca, Z. Nesic, A. Noormets, K. Novick, J. O'Connell, A.C. Oishi, W.W. Oswald, T.D. Perkins, R.P. Phillips, M.D. Schwartz, R.L. Scott, O. Sonnentag, and J.E. Thom. 2017. PhenoCam Dataset v1.0: Vegetation Phenology from Digital Camera Imagery, 2000-2015. ORNL DAAC, Oak Ridge, Tennessee, USA. https://doi.org/10.3334/ORNLDAAC/1511

Participants:
What individuals have worked on the project?
PIs

First Name: Edward
Last Name: Rastetter
Email address: erastetter@mbl.edu
Most senior project role: PI
Nearest person month worked: 3
Contribution to LTER Project: coordinate project, prepare these reports, simulation modeling, chairs ARC LTER Executive Committee
Funding Support: Marine Biological laboratory

First Name: Laura
Last Name: Gough
Email address: lgough@towson.edu
Most senior project role: co-PI
Nearest person month worked: 2
Contribution to LTER Project: coordinate terrestrial research program, serves on ARC LTER Executive Committee
Funding Support: Towson University

First Name: George
Last Name: Kling
Email address: gwk@umich.edu
Most senior project role: co-PI
Nearest person month worked: 2
Contribution to Project: responsible for coordinating the "land-water research" activities, serves on ARC LTER Executive Committee
Funding Support: University of Michigan

First Name: William
Last Name: Bowden
Email address: wbowden@uvm.edu
Most senior project role: co-PI
Nearest person month worked: 2
Contribution to LTER Project: Leads the Streams component, serves on ARC LTER Executive Committee
Funding Support: University of Vermont

First Name: Phaedra
Last Name: Budy
Email address: phaedra.budy@usu.edu
Most senior project role: Co-PI
Nearest person month worked: 2

Contribution to LTER Project: supervises fish and limnological measurements on lakes, serves on ARC LTER Executive Committee
Funding Support: The Ecology Center at Utah State University

Faculty Associates

First Name: Anne
Last Name: Giblin
Email address: agiblin@mbl.edu
Most senior project role: Faculty Associate
Nearest person month worked: 2
Contribution to LTER Project: supervises biogeochemical measurements in lakes, serves on ARC LTER Executive Committee
Funding Support: Marine Biological laboratory

First Name: Byron
Last Name: Crump
Email address: bcrump@coas.oregonstate.edu
Most senior project role: Faculty Associate
Nearest person month worked: 1
Contribution to LTER Project: Supervises biogeochemical and microbiological measurements in lakes and streams, serves on ARC LTER Executive Committee
Funding Support: Oregon State University

First Name: Linda
Last Name: Deegan
Email address: ldeegan@whrc.org
Most senior project role: Faculty Associate
Nearest person month worked: 1
Contribution to LTER Project: primary coordinator of LTER Streams' fish population monitoring efforts.
Funding Support: Woods Hole Research Center

First Name: John
Last Name: Moore
Email address: john.moore@colostate.edu
Most senior project role: Faculty Associate
Nearest person month worked: 2
Contribution to LTER Project: Hosts our teachers program and studies soil food webs
Funding Support: Colorado State University

First Name: Alex
Last Name: Huryn
Email address: huryn@ua.edu
Most senior project role: Faculty Associate
Nearest person month worked: 1
Contribution to LTER Project: He is the primary coordinator of LTER Streams' monitoring of benthic macroinvertebrates.
Funding Support: University of Alabama

OTHER PROFFESSIONALs

First Name: James
Last Name: Laundre
Email address: jlaundre@mbl.edu
Most senior project role: Other Professional
Nearest person month worked: 12
Contribution to Project: lead technician supervising work on LTER terrestrial research, data management, web site maintenance,
Funding Support: this grant

First Name: Jason
Last Name: Dobkowski
Email address: jdobkow@umich.edu
Most senior project role: Other Professional
Nearest person month worked: 12
Contribution to Project: lead technician supervising work on LTER Land-water research
Funding Support: NSF (this grant)

First Name: Frances
Last Name: Iannucci
Email address: fiannucc@uvm.edu
Most senior project role: Other Professional
Nearest person month worked: 12
Contribution to Project: lead technician supervising work on LTER streams research
Funding Support: LTER, University of Vermont

First Name: Daniel
Last Name: White
Email address: dwhite@mbl.edu
Most senior project role: Other Professional
Nearest person month worked: 12

Contribution to Project: lead technician supervising work on LTER lake research
Funding Support: this grant

First Name: Bonnie
Last Name: Kwiatkowski
Email address: bkwiatkowski@mbl.edu
Most senior project role: Other Professional
Nearest person month worked: 6
Contribution to Project: Technician working on LTER data management, simulation modeling
Funding Support: this grant,

First Name: Ruby
Last Name: An
Email address: rubyan@uchicago.edu
Most senior project role: Other Professional
Nearest person month worked: 3
Contribution to Project: summer technician working on LTER terrestrial research
Funding Support: this grant

First Name: Christopher
Last Name: Cook
Email address: chlcook@umich.edu
Most senior project role: Other Professional
Nearest person month worked: 6
Contribution to Project: Technician working on LTER Land-Water interactions
Funding Support: NSF (this grant)

First Name: Alexandria
Last Name: Kolenda
Email address: akolenda@umich.edu
Most senior project role: Other Professional
Nearest person month worked: 4
Contribution to Project: technician working on LTER Land-Water interactions
Funding Support: NSF (this grant)

First Name: Kyle
Last Name: Zollo-Veneck
Email address: kylezollo@gmail.com
Most senior project role: Other Professional
Nearest person month worked: 4

Contribution to Project: summer technician working on LTER lakes research
Funding Support: LTER (this grant)

(teachers)

First Name: Amanda
Last Name: Morrison
Email address: Amanda.j.morrison@colostate.edu
Most senior project role: Other Professional
Nearest person month worked: 2
Contribution to LTER Project: Coordinates educational activities for the Arctic LTER
Funding Support: Colorado State University

First Name: Celeste
Last Name: Cruse
Email address: ccruse@famouth.k12.ma.us
Most senior project role: Other Professional
Nearest person month worked: 1
Contribution to Project: Falmouth, MA Middle School teacher gaining research experience on schoolyard fund supplemented by the MBL; Assisted in food web data collection and in pluck field and lab work; curriculum development
Funding Support: Marine Biological Laboratory

First Name: Sarah
Last Name: Bucko
Email address: sbucko@psdschools.org
Most senior project role: Other Professional
Nearest person month worked: 1
Contribution to Project: Fort Collins, CO High School teacher gaining research experience; Assisted in food web data collection and in pluck field and lab work; curriculum development
Funding Support: USDA (NIFA CAP)

First Name: Catherine
Last Name: Kershner
Email address: cat.kershner@k12northstar.org
Most senior project role: Other Professional
Nearest person month worked: 1
Contribution to Project: Fairbanks, AK Middle School teacher gaining research experience as part of LTER schoolyard activities; Assisted in food web data collection and in pluck field and lab work; curriculum development

Funding Support: NSF

First Name: Rebecca
Last Name: Wren
Email address: rwren@psdschools.org
Most senior project role: Other Professional
Nearest person month worked: 1
Contribution to Project: Fort Collins, CO Middle School teacher gaining research experience; Assisted in food web data collection and in pluck field and lab work; curriculum development
Funding Support: USDA (WAMS)

First Name: Matthew
Last Name: Lopez
Email address: matthewl@susd12.org
Most senior project role: Other Professional
Nearest person month worked: 1
Contribution to Project: Tucson, AZ teacher; Assisted in hydrology field work and data collection; curriculum development
Funding Support: NSF (STEM-C)

Postdoctoral associates

First Name: Rodney
Last Name: Simpson
Email address: Rodney.simpson@colostate.edu
Most senior project role: Postdoctoral associate
Nearest person month worked: 2
Contribution to Project: Sampling and processing, Analysis and synthesis
Funding Support:

Graduate students

First Name: Stephen
Last Name: Klobucar
Email address: stephen.klobucar@gmail.com
Most senior project role: Graduate Student
Nearest person month worked: 12
Contribution to Project: Research and publications, supervising technicians in field and lab.
Funding Support: The Ecology Center at Utah State University

First Name: Karl
Last Name: Romanowicz
Email address: kjromano@umich.edu

Most senior project role: Graduate student
Nearest person month worked: 3
Contribution to Project: Karl Romanowicz started working in Dr. George Kling's lab in 2017 and spent the 2017 field season at Toolik Lake beginning his PhD studies.
Funding Support: University of Michigan

First Name: Adrianna
Last Name: Trusiak
Email address: atrusiak@umich.edu
Most senior project role: Graduate student
Nearest person month worked: 3
Contribution to Project:
Adrianna Trusiak started in Dr. Rose Cory's lab in Fall 2014, and worked in part on the LTER project during the summers of 2014-2017 at Toolik Lake.
Funding Support: University of Michigan

First Name: Tyler
Last Name: King
Email address: tylerking@aggiemail.usu.edu
Most senior project role: Graduate student
Nearest person month worked: 3
Contribution to Project:
Tyler King started in Dr. Beth Neilson's lab at Utah State University and has worked in part on the LTER project during the summers of 2015-2017 at Toolik Lake.
Funding Support: Utah State University

Undergraduate students

First Name: Erin
Last Name: Gleeson
Email address: gleee-18@rhodes.edu
Most senior project role: Undergraduate Student
Nearest person month worked: 3
Contribution to Project: Erin was a Junior at Rhodes College and one of three REUs supported by the LTER grant in 2017. She worked with Dr. Rastetter to develop calibration of the MEL model and helped with various projects in the field at Toolik Lake
Funding Support:

First Name: Thomas
Last Name: Hafen
Email address: thafen12@gmail.com
Most senior project role: Undergraduate Student

Nearest person month worked: 5
Contribution to Project: Thomas was a Junior at Utah State University and one of three REUs supported by the LTER grant in 2017. He assisted Dr. Budy with field work and laboratory analysis
Funding Support:

First Name: Nicholas
Last Name: Warren
Email address: ntwarren@uvm.edu
Most senior project role: Undergraduate student
Nearest person month worked: 2
Contribution to Project: Nicholas was a senior at the University of Vermont an one of three REUs supported by the LTER. He assisted Dr. Bowden as a lab technician and with data management.
Funding Support:

First Name: Will
Last Name: Sutor
Email address: fsutor@uvm.edu
Most senior project role: Undergraduate Student
Nearest person month worked: 1
Contribution to Project: Will was an additional summer RA for Arctic LTER Streams during the summer field season. He primarily assisted Meghan Christie with field work in the senior RA's absence.
Funding Support:

Name: Meghan
Last Name: Christie
Email address: meghan.j.christie.17@gmail.com
Most senior project role: Undergraduate Student
Nearest person month worked: 3
Contribution to Project: Megnan was the summer RA for Arctic LTER Streams. She assisted the senior RA in field operations, and acted as the lead RA in the senior RA's absence.
Funding Support: LTER

First Name: Rachel
Last Name: Kaplan
Email address: Rachellinneakaplan@gmail.com
Most senior project role: Undergraduate Student
Nearest person month worked: 3

Contribution to Project: Rachel assisted with laboratory analysis for the LTER and helped with field work when needed
Funding Support: LTER (this grant)

First Name: Tara
Last Name: Larkin
Email address: tara.larkin@aggiemail.usu.edu
Most senior project role: Undergraduate Student
Nearest person month worked: 3
Contribution to Project: Tara assisted with laboratory analysis of zooplankton, invertebrates, and fish diets
Funding Support: The Ecology Center at Utah State University

First Name: Ryan
Last Name: West
Email address: ranwest1@gmail.com
Most senior project role: Undergraduate Student
Nearest person month worked: 3
Contribution to Project: assisted with laboratory analysis (zooplankton, invertebrates, fish diets)
Funding Support: The Ecology Center at Utah State University

What other organizations have been involved as partners?

Type of Partner Organization, Name, Location, Partner's contribution to the project

University, Towson University, Towson, MD 21252, home institution L. Gough
University, University of Michigan, Ann Arbor, MI 48109, home institution G. Kling
University, University of Vermont, Burlington, VT 05405, home institution W. Bowden
University, Utah State University, Logan UT 84322, home institution, P. Budy
University, Oregon State University, Corvallis, OR 97331, home institution B. Crump
University, Colorado State University, Fort Collins, CO 80523, home institution J. Moore
Research, Woods Hole Research Center, Falmouth, MA 02540, home institution, L. Deegan
University, University of Alabama, Tuscaloosa, AL 35487, home institution A. Huryn

Have other collaborators or contacts been involved?

Faculty associates on collaborating grants:

Aanderud, Zach: zachary_aanderud@byu.edu, Brigham Young University,
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Atkinson, Carla: carla.l.atkinson@ua.edu, University of Alabama,
Boelman, Natalie: nboelman@ldeo.columbia.edu, Columbia University,
Bret-Harte, M. Syndonia: msbretharte@alaska.edu, University of Alaska, Fairbanks
Buckeridge, Kate: kmbuckeridge@gmail.com, Lancaster University, UK

Cardenas, Meinhard: Cardenas@jsg.utexas.edu, University of Texas, Austin
Carey, Joanna: jcarey@babson.edu, Babson College
Griffin, Kevin: griff@ldeo.columbia.edu, Columbia University
Mack, Michelle: michelle.mack@nau.edu, Northern Arizona University
McLaren, Jennie: jennie.mclaren@gmail.com, University of Texas, El Paso
Natali, Susan: snatali@whrc.org, Woods Hole Research Center
Rowe, Rebecca: Rebecca.Rowe@unh.edu, University of New Hampshire
Urban, Mark: mark.urban@uconn.edu, University of Connecticut
Wallenstein, Matthew: matthew.wallenstein@colostate.edu, Colorado State University
Zarnetske, Jay: jpz@msu.edu, Michigan State University

Postdoctoral scientists on collaborating grants:

Golden, Heidi: heidi.golden@uconn.edu, University of Connecticut, fish population monitoring, and implementation of new environmental DNA sampling
Hewitt, Rebecca: Rebecca.hewitt@nau.edu, Northern Arizona University, Deep Roots and Snow-shrub projects.
Machmuller, Megan: megan.machmuller@colostate.edu, Colorado State University, response of below-ground processes to warming and fertilization
Thiede, Gary: gary.thiede@usu.edu, Utah State University, Lake and streams fish populations

Graduate students on collaborating grants:

Baker, Kristina: bakerkri@oregonstate.edu, Oregon State University, monitoring Toolik Lake
Christman, Natasha: christmn@oregonstate.edu, Oregon State University, Lake warming project
Drew, Jackson: jwdrew@alaska.edu, University of Alaska, species removal experiment

Dunleavy, Haley: haley.dunleavy@nau.edu, Northern Arizona University, root-associated enzyme activity in warming, fertilization, snow fence, and the species removal experiment.
Lynch, Laurel: laurellynch@gmail.com, Colorado State University, DOE & NSF soil microbial process projects
Min, Elizabeth: ekm2130@columbia.edu, Columbia University, Team Vole
O'Connor, Michael: mtoconnor12@gmail.com, University of Texas, Austin, hydraulic properties of the active layer and modeling water flow

Pressler, Yamina: yamina@rams.colostate.edu, Colorado State University, soil food webs projects
Roy, Austin: anroy4@gmail.com, University of Texas, El Paso, Tem Vole
Steketee, Jessica: jess.steketee13@gmail.com, University of New Hampshire, Team Vole
Suchocki, Matthew: msucho1@students.towson.edu, Towson University, Team Vole

Other professionals on collaborating projects:

Frei, Becca: beccafrei@gmail.com, Brigham Young University, "Dissolved Organic Matter in Arctic and Boreal Streams" project.
Huish, Allie: allie.huish.lax@gmail.com, Utah State University, Lake warming project

Ludwig, Sarah: sludwig@whrc.org, Woods Hole Research Center, NASA & ABoVE C cycling projects and MBL-UChicago seed grant
MacKenzie, Cameron: cmackenzie@atwaterresources.com, Water Resources, Fishscape project.
Minions, Christina: cminions@whrc.org, Woods Hole Research Center, NASA & ABoVE C cycling projects
Spann, Sedona: Sedona@nau.edu, Norther Arizona University, root-associated enzyme activity in warming, fertilization, snow fence, and the species removal experiment.

Undergraduates, REUs on collaborating grants:

Griffin, Natasha: natasha.a.griffin@gmail.com, Brigham Young University, "Dissolved Organic Matter in Arctic and Boreal Streams"
Salter, Morgan: Colorado State University, Soil processes
Wilcots, Megan: mew2210@columbia.edu, Columbia University, Team Vole
Yappa, Felix: Colorado State University, Soil processes

Impacts

What is the impact on the development of the principal discipline(s) of the project?

A key indicator of impact is the number and diversity of citations from the ARC LTER. In our proposal we reported that we had over 35,000 citations of the 579 journal publications since 1975 that include contributions from ARC LTER scientists and their collaborators with an overall h-index of 101. In addition, ARC LTER scientists had produced 7 books, 95 book chapters, 35 PhD theses, 66 Master's theses, and 15 honor's theses. This past year we added 35 papers to our publication list, 1 book chapter, and 2 PhD theses. Our project website is regularly used as a source of data, with data downloads averaging 5-10 per week.

The ARC LTER attracts collaborators from all over the world to work at Toolik Lake, make measurements on our long-term manipulations of tundra, streams, and lakes, and make use of our monitoring program and data. Largely because of this leveraging on LTER capabilities, the area around Toolik is the most thoroughly described and studied arctic landscape in the world. Research results from Toolik Lake are often used in comparative studies at other sites. Many of the ideas that drive research in other arctic landscapes were developed from research at Toolik Lake. Examples include the Danish Greenland Ecosystem Monitoring (GEM) programs at Zackenberg and Nuuk, which used the ARC LTER design as a model for their establishment 20 years ago, and which have continued to call on ARC personnel for collaboration and advice (e.g., Hobbie et al. 2017); The International Tundra Experiment (ITEX) is another example, currently using our experience in Alaska to design an international program in ecotypic and within-species genetic adaptations. Examples of impacts outside the Arctic include research to document C losses from surface waters as a component of regional and global C budgets, first pointed out by Kling and colleagues working at Toolik Lake in the 1990s, and the Kuparuk river fertilizer experiment and N isotope experiments, which were the inspiration for the continent-wide STREON experiment.

What is the impact on other disciplines?

None to report

What is the impact on the development of human resources?

This year we provided support and training for five K-12 teachers who applying what they learned in their class rooms. We also supported two REU students from our core funding. In addition the summer research assistants gain training and field experience that they often take with them in the pursuit of higher degrees.

What is the impact on physical resources that form infrastructure?

The Arctic LTER has set up many long term experimental plots, streams, and lakes. We encourage the use of these resources by researchers outside the LTER after review and approval and provide our web site as a data repository (automatically uploaded to EDI site).

What is the impact on institutional resources that form infrastructure?

The Arctic LTER project has played a primary role in the development of Toolik Field Station into the Flagship Arctic Research Station that it now is, including lodging, laboratories, and other services to a wide array of research projects including ARC LTER. The solid foundation of research established by the ARC LTER was a major factor in the choice of Toolik Lake as a NEON site.

What is the impact on the information resources that for infrastructure?

ARC LTER is one of 7 sites using the LTER Drupal Ecological Informational Metadata System (DEIMS) which is based on the open source Drupal content management system (https://www.drupal.org/project/deims). This system provides web presentation/data discovery, dataset management and for the upload of datasets to the LTER network data portal (now the Environmental Data Initiative (EDI) data portal).

The Arctic LTER information manager (IM) actively contributes to the continued development of DEIMS via software enhancements, issue resolutions and discussions with other LTER IMs.

The Arctic LTER web site (http://arc.lternet.edu) currently has 592 datasets from LTER and collaborating projects. All datasets, including metadata and data, are available through the Arctic LTER web site or through the LTER network data portal.

At present 11 associated project's metadata and data are hosted on our web site. (http://arc.lternet.edu/data-collabrating-projects)

What is the impact on society beyond science and technology?

Arctic tundra has inherent value as one of the major biomes of the world, with a unique assemblage of animals and plants. Warming could result in a dramatic decrease in tundra area or the complete loss of the biome as the climatic boundary favorable to tundra moves northward beyond the shores of the Arctic Ocean. It is therefore vital to understand how this ecosystem is responding to current changes in climate.

One of the defining characteristics of arctic tundra is that it is underlain by permafrost. It is estimated that permafrost soils store between 25 and 50% of all the organic carbon currently in soils globally and contains substantially more carbon than is currently in the atmosphere. As the climate warms, the seasonal thaw depth of tundra soils increases and the organic matter currently in deep-freeze storage becomes susceptible to microbial activity. This activity releases the stored carbon to the atmosphere as CO_2, but also releases nutrients into the soil, potentially stimulating plant growth. The net contribution of tundra to atmospheric CO_2 depends on the balance between CO_2 released by microbes in the soil and CO_2 taken up by vegetation and stored in plant biomass. The LTER is striving to understand this balance.

Finally, because the Arctic is warming faster than the rest of the world, it serves as a harbinger for changes to come in ecosystems further south. All ecosystems share a core set of ecological processes like production of plant biomass through photosynthesis, decomposition of dead biomass by microbial activity, cycling of vital elements, among many more. Understanding how these processes change in a rapidly warming Arctic can help in predicting and interpreting future changes in other biomes.

Changes/Problems

Nothing to report