Preview of Award 1026843 - Annual Project Report

Cover

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PD/PI Name:	Gaius R Shaver, Principal Investigator William B Bowden, Co-Principal Investigator Phaedra Budy, Co-Principal Investigator Anne E Giblin, Co-Principal Investigator George W Kling, Co-Principal Investigator
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Accomplishments

*** What are the major goals of the project?**

For the years 2010-2016, *our **Overall Goal** is to understand changes in the arctic system at catchment and landscape scales as the product of: (i) Direct effects of climate change on states, processes, and linkages of terrestrial and aquatic ecosystems, and (ii) Indirect effects of climate change on ecosystems through a changing disturbance regime.*

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

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

Synthesis is further promoted by collocation of terrestrial, stream, lake, and landscape interactions research in the same watersheds and by coordinated sampling of different components of the watersheds. A mass balance approach to watershed and landscape biogeochemistry is used to develop predictive models and to evaluate results of individual studies in the context of the whole land-water system. Finally, we have begun to develop a fifth research component, focused on subsistence land use and impacts of climate change on Native American village communities of Northern Alaska. This structure facilitates our ability to address broad, integrating questions such as:

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

*** What was accomplished under these goals (you must provide information for at least one of the 4 categories below)?**

Major Activities:	Major activities of the ARC LTER include research, information management, and education, training, and outreach. Our research activities are summarized in the attached document, "Findings combined 2012", emphasizing specific objectives and findings (significant results) of the past year in each of our four core research areas (terrestrial, land-water interactions, streams, and lakes). Other activities of the ARC LTER are summarized below under “Key Outcomes”.
Specific Objectives:	Specific research objectives are described in the attached file, "Findings Combined 2012"
Significant Results:	Significant research results are described in the attached file, "Findings Combined 2012". Other results are described in the attached file, "Key Outcomes"
Key outcomes or Other achievements:	Key Outcomes are described in the attached file,"Key Outcomes"

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

Training and Professional Development: The ARC LTER has contributed to training and professional development at all levels including the following in this reporting period:

Students and postdoctoral fellows: Most of the students and postdoctoral fellows working at the Arctic LTER site in 2012 were actually employed by collaborating projects. ARC LTER personnel worked with them in the field and also provided mentoring opportunities through weekly seminar series, student poster sessions, invitations to our annual winter meeting and planning sessions. In 2012 these included:

13 undergraduate students including 2 REU students supported with LTER Supplemental funds.

22 graduate students (MS or PhD)

5 postdocs

New and "assimilated" investigators: The majority of collaborating PIs at the ARC LTER site began work there as students, postdocs, or as new investigators invited by the project. Each summer the ARC LTER invites 1-3 new investigators to work at the site, developing new lines of research and collaboration. Typically these new investigators will take 2-3 years to develop their own, independently funded research project. In 2012 we supported 1 new investigator, Rebecca Rowe of the University of New Hampshire, who will be returning in 2013 with LTER support. Another new investigator, Bethany Nielsen of Utah State University received support from ARC LTER and was successful in funding her own project which will begin in 2013.

Research Assistants: 11 research assistants were supported with ARC LTER funds in 2012, and 13 others were supported by collaborating projects but worked on LTER sites. Over the years we have realized that this is an important training and professional development component of our project, as each year about half of these research assistants go on to graduate school or to teaching positions. For example, one of our 2012 RAs, Laura van der Pol will be teaching grade school science with Teach For America in 2013.

K-12 Teachers: In 2012, 8 middle school and high school teachers from Michigan, Colorado, and Maryland came to Toolik Lake to participate in a major harvest of one of our long term tundra fertilizer experiments. In the process they learned techniques of biomass sampling, plant identification, soil sampling, invertebrate identification, and food web analysis.

*** How have the results been disseminated to communities of interest?**

Our principal means of dissemination to "communities of interest" has been through scientific publication (40 journal articles, 3 books, 4 book chapters, 19 published proceedings talks). In addition we have completed several interviews in radio and print news.

Public outreach activities include the public lecture series we sponsor as part of our Schoolyard LTER series in Barrow, Alaska, as well as the book, "Land of Extremes" by Huryn and Hobbie, which is intended as a natural history guide to northern Alaska that is accessible to lay tourists and hikers as well as professional scientists.

*** What do you plan to do during the next reporting period to accomplish the goals?**
No change.

Supporting Files

Filename	Description	Uploaded By	Uploaded On
Key Outcomes.pdf	Key outcomes	Gaius Shaver	04/05/2013
Findings Combined 2012Final.pdf	Findings combined Final	Gaius Shaver	04/23/2013

Products

Journals

Barrett, K, AV Rocha, MJ van de Weg, and GR Shaver. (6/1/12). Vegetation shifts observed in arctic tundra 17 years after fire. *Remote Sensing Letters DOI:10.1080/2150704X.2012.676741*. 8 729-736.

Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: DOI:10.1080/2150704X.2012.676741

Bennington, Cynthia C.; Fetcher, Ned; Vavrek, Milan C.; Shaver, Gaius R.; Cummings, Kelli J.; McGraw, James B. (7/1/12). Home site advantage in two long-lived arctic plant species: results from two 30-year reciprocal transplant studies. *JOURNAL OF ECOLOGY*. 100 (4), 841-851.

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Brzostek, Edward R.; Blair, John M.; Dukes, Jeffrey S.; Frey, Serita D.; Hobbie, Sarah E.; Melillo, Jerry M.; Mitchell, Robert J.; Pendall, Elise; Reich, Peter B.; Shaver, Gaius R.; Stefanski, Artur; Tjoelker, Mark G.; Finzi, Adrien C. (8/1/12). The effect of experimental warming and precipitation change on proteolytic enzyme activity: positive feedbacks to nitrogen availability are not universal. *GLOBAL CHANGE BIOLOGY*. 18 (8), 2617-2625.

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Cahoon, Sean M. P.; Sullivan, Patrick F.; Shaver, Gaius R.; Welker, Jeffrey M.; Post, Eric (12/1/12). Interactions among shrub cover and the soil microclimate may determine future Arctic carbon budgets. *ECOLOGY LETTERS*. 15 (12), 1415-1422.

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Crump, B. C., L. A. Amaral-Zettler, and G. W. Kling. (3/1/12). Microbial diversity in arctic freshwaters is structured by inoculation of microbes from soils.. *The ISME Journal*. 6 1629–1639.

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De Schrijver, An; De Frenne, Pieter; Ampoorter, Evy; Van Nevel, Lotte; Demey, Andreas; Wuyts, Karen; Verheyen, Kris (11/1/11). Cumulative nitrogen input drives species loss in terrestrial ecosystems. *GLOBAL ECOLOGY AND BIOGEOGRAPHY*. 20 (6), 803-816.

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Deslippe, Julie R.; Hartmann, Martin; Simard, Suzanne W.; Mohn, William W. (11/1/12). Long-term warming alters the composition of Arctic soil microbial communities. *FEMS MICROBIOLOGY ECOLOGY*. 82 (2), 303-315.

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Sistla, S.A, E.B. Rastetter, J.P. Schimel. (5/1/13). Responses of a tundra system to warming using SCAMPS: A stoichiometrically coupled, acclimating microbe-plant-soil model.. *Ecological Monographs.*. xx xx.

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Sistla, S.A, J. C. Moore, R. Simpson, L. Gough, G.R. Shaver, and J.P. Schimel. (5/1/13). Long-term warming restructures arctic tundra without changing net soil carbon storage.. *Nature*. xx xx.

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Sikes, DS, ML Draney and B Fleshamn. (4/1/13). Unexpectedly high among-habitat spider (Araneae)faunal diversity from the Arctic Long-Term Experimental Research (LTER) field station at Toolik Lake, Alaska, United States of America.. *Can. Entomol. 145:219-2*. 145 219-226.

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18. Griffin, K.L., D.J. Epstein, N.T. Boelman. Maximum photosynthetic electron transport decreases down slope in a small Arctic watershed, 2012. (in press at Arctic, Antarctic and Alpine Research) (DOI: http://dx.doi.org/10.1657/1938-4246-45.1) (4/15/13). Maximum photosynthetic electron transport decreases down slope in a small Arctic watershed,. *Arctic, Antarctic and Alpine Research*. xx xx.

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Hagen, Elizabeth M.; McCluney, Kevin E.; Wyant, Karl A.; Soykan, Candan U.; Keller, Andrew C.; Luttermoser, Kymberly C.; Holmes, Eric J.; Moore, John C.; Sabo, John L. (10/1/12). A meta-analysis of the effects of detritus on primary producers and consumers in marine, freshwater, and terrestrial ecosystems. *OIKOS*. 121 (10), 1507-1515.

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Merck, M. F., B.T. Neilson, R. Cory, G.W. Kling. (10/1/12). Variability of Instream and Riparian Storage in a Beaded Arctic Stream.. *Hydrological Processes*. 26 2938-2950.

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Oberbauer, S.F. S. C. Elmendorf, T. Troxler, R. D. Hollister, A. Rocha, S. Bret-Harte, A. M. Fosaa, T. T. Høye, G. H. R. Henry, F. Jarrad, I. S. Jonsdottir, K. Klanderud, J. A. Klein, U. Molau, C. Rixen, N. M. Schmidt, G. Shaver, R. Slider, Ø. et al. (4/20/13). Phenological responses of tundra plants to background climate warming tested using the International Tundra Experiment (ITEX).. *Proceedings of the Royal Society B*. x xx.

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Rocha, A.V. (4/1/13). Tracking carbon within the trees. . *New Phytologist*. 197 685-686.

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Street, L., Shaver, G.R., Rastetter, E. Van Wijk, M.T., Kaye, B., Williams, M. (11/12/12). Incident radiation and the allocation of nitrogen within Arctic plant canopies: implications for predicting gross primary productivity.. *Global Change Biology*. 18 2838-2852.

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Books

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Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; ISBN: 978-1-60223-181-8

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Book Chapters

de Ruiter, P.C. and J.C. Moore. (2012). Top-Down Control. *Sourcebook in Theoretical Ecology* Hastings, A. and Gross, L. (Eds.),. University of California Press.. 739.

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Jessica E. Cherry, Stephen J. Déry, Yiwei Cheng, Marc Stieglitz, Amy S. Jacobs, Fei-fei Pan (2013). Chapter 2. Climate and Hydrometeorology of the Toolik Lake Region and the Kuparuk River Basin: Past, present and future. *A Changing Arctic: Ecological Consequences for Tundra, Streams, and Lakes* John E. Hobbie George W. Kling, editors. Oxford University Press. Oxford. xx.

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W. Wyatt Oswald, Linda B. Brubaker, Feng Sheng Hu, George W. Kling (2013). Chapter 4. Late-Quaternary environmental and ecological history of the Arctic Foothills, northern Alaska. *A Changing Arctic: Ecological Consequences for Tundra, Streams, and Lakes* John E. Hobbie George W. Kling, editors. Oxford University Press. Oxford. xx.

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Gaius R. Shaver, James A. Laundre, M. Syndonia Bret-Harte, F. Stuart Chapin III, Anne E. Giblin, Laura Gough, William A. Gould, Sarah E. Hobbie, George W. Kling, Michelle C. Mac,k John C. Moore, Joel A. Mercado Díaz, Knute J. Nadelhoffer, Edward B. Rastette, Joshua P. Schimel (2013). Chapter 5. Terrestrial ecosystems. *A Changing Arctic: Ecological Consequences for Tundra, Streams, and Lakes* John E. Hobbie George W. Kling, editors. Oxford University Press. Oxford. xx.

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Thesis/Dissertations

Conference Papers and Presentations

Luecke, C., P. Budy, A. E. Giblin, and G. W. Kling. (2/17/13). *Response of shallow and deep lakes to low level nutrient addition in the sub-arctic region of northern Alaska.*. American Society of Limnology and Oceanography Science Meeting. New Orleans.

Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Hobbie, J. E., G. R. Shaver, and G. W. Kling. (8/4/12). *The integrated effects of warming are obvious in the physics, chemistry, and ecology of tundra at the arctic Alaska LTER site despite no significant warming trend since climate measurements began in 1989.*. 98th Ecological Society of America annual meeting. Minneapolis, MN..

Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Eugster, W., T. DelSontro, S. Sollberger, G. R. Shaver, and G. W. Kling. (4/7/13). *Daily to interannual variations of CH4 and CO2 fluxes from a deep lake in Arctic Alaska.*. EGU General Assembly, Geophysical Research Abstracts, Vol. 15, EGU2013-7629. Vienna.

Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Hobbie, J., and G. W. Kling. (7/8/12). *The Long-Term Record of an Arctic Alaskan Lake in a Warming Climate: No Ecological Change Yet But Experiments Yield Predictions.*. American Society of Limnology and Oceanography, Annual Science Meeting. Shiga, Japan.

Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Daniels, W., A. Giblin, P. Budy, G. Kling, and C. Luecke. (9/10/12). *Low-level nutrient addition drives hypolimnetic hypoxia in a deep arctic lake.*. Triennial All Scientists meeting of the NSF LTER program. Estes Park, CO.

Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Eugster, W., A.V. Rocha, G. W. Kling, G. R. Shaver, L. Merbold, D. Imer, J. Stieger, R. Hiller, N. C. Buchmann. (12/3/12). *Getting control over spatial variability in CH4, N2O and CO2 flux measurements – Examples from Switzerland and Alaska.*. American Geophysical Union meeting. San Francisco, CA.

Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Neilson, B.T (12/3/12). *"Determining Key Heat Fluxes Necessary for Instream Temperature Predictions"*. 2012 Fall Meeing, American Geophysical Union, Abstract H51M-02.. San Francisco, CA..

Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Neilson, B.T (12/3/12). *Roles of Heat Transport in Transient Storage Modeling.*. 2012 Fall Meeting, American Geophysical Union. San Francisco, CA.

Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Boelman, N.; Gough, L.; Wingfield, J. C.; (12/5/12). *Team Bird. Trophic matches in Northern Alaska: Existing synchrony among climate, vegetation, arthropods and migratory songbirds abstract #B52B-06*. American Geophysical Union, Fall Meeting 2011,. San Francisco, CA.

Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Moore, J.C., L. Gough, R.T. Simpson and D. Johnson (9/12/12). *Aboveground and belowground responses to nutrient additions and herbivore exclusion in arctic tundra ecosystems in northern Alaska. Poster*. LTER All Scientists Meeting. Estes Park, CO.

Status = OTHER; Acknowledgement of Federal Support = Yes

Smith, M., K. LaPierre, J. Barrett, S. Collins, S. Frey, L. Gough, K.L. Gross, R. Miller, J. Morris, L. Rustad and J. Yarie. (9/12/12). *Assessing ecosystem sensitivity to chronic resource alterations: a synthesis of long-term experiments (poster).*. LTER All Scientists Meeting,. Estes Park, CO.

Status = OTHER; Acknowledgement of Federal Support = Yes

Moore, J.C., L. Gough, R. Simpson, and D.R. Johnson. (12/22/11). *Aboveground and belowground responses to nutrient additions and herbivore exclusion in arctic tundra ecosystems in northern Alaska. poster*. American Geophysical Union, Annual Meeting 2011. , San Francisco, CA,.

Status = OTHER; Acknowledgement of Federal Support = Yes

Bond-Lamberty, BP, Calvin K, Rocha AV, Wang C (12/12/12). *Tree growth and mortality at the former Northern Old Black Spruce research site, B24A-06, Talk.*. AGU Fall meeting,. San Francisco.

Status = OTHER; Acknowledgement of Federal Support = Yes

Eugster W, Rocha AV, Kling GW, Shaver GR, Merbold L, Imer D, Stieger J, Hiller R, Buchmann NC. (12/13/12). *Getting control over spatial variability in CH4, N2O, and CO2 flux measurements-examples from Switzerland and Alaska, B42A-01, Invited Talk.*. AGU Fall Meeting,. San Francisco, CA.

Status = OTHER; Acknowledgement of Federal Support = Yes

Rocha AV, Shaver GR, Rastetter E, Jiang Y. (12/13/12). *An eddy covariance network to investigate post-fire carbon and energy dynamics in remote regions of Alaskan arctic tundra, AGU fall meeting, B51C-0571, Poster.*. AGU Fall Meeting,. San Francisco, CA.

Status = OTHER; Acknowledgement of Federal Support = Yes

Ueyama M, Ichii K, Iwata H, Euskirchen ES, Zona D, Rocha AV, Harazono Y, Iwama C, Nakai T, Oechel WC. (12/13/12). *Increase of surface energy fluxes due to warming climate in Alaska based on upscaling of eddy covariance measurements. B51C-0573, Poster.*. AGU fall meeting. San Francisco, CA.

Status = OTHER; Acknowledgement of Federal Support = Yes

Jiang Y, Rastetter E, Shaver GR, Rocha AV. (12/13/12). *Impact of fire disturbance on soil thermal and carbon dynamics in Alaskan tundra and boreal* *forest ecosystems, , B23F-0511, Poster.*. AGU fall meeting. San Francisco, CA.

Status = OTHER; Acknowledgement of Federal Support = Yes

Budy, P., C. Luecke, and G.P. Thiede. (8/15/12). *Resource allocation among arctic char in closed arctic lakes: implications for population structure and regulation. Poster presentation*. American Fisheries Society conference. St. Paul, MN.

Status = OTHER; Acknowledgement of Federal Support = Yes

Longo, W. M., S. Theroux, A.E. Giblin, and Y. Huang. (12/3/12). *Long chain alkenones in the Toolik Lake region of Alaska: characterization, abundance and in situ water column calibrations from three lakes. Abstract PP43B-2031. Poster presentation*. 2012 Fall Meeting, American Geophysical Union,. San Francisco, CA.

Status = OTHER; Acknowledgement of Federal Support = Yes

Luecke, C., P. Budy, A. Giblin, and G. Kling. (2/22/13). *Response of shallow and deep lakes to low level nutrient addition in sub-arctic region of northern Alaska.*. American Society of Limnology and Oceanography conference. New Orleans, LA.

Status = OTHER; Acknowledgement of Federal Support = Yes

Other Publications

Technologies or Techniques
Nothing to report.

Patents
Nothing to report.

Inventions
Nothing to report.

Licenses
Nothing to report.

Websites

Title: Arctic LTER

URL: http://dryas.mbl.edu/ARC/

Description: Gives overview of Arctic LTER site, location, personnel, prublications, research and other data.

Other Products

Product Type: Databases

Description: The ARC LTER data base is available at http://dryas.mbl.edu/arc/

Other:

Participants

Research Experience for Undergraduates (REU) funding

How many REU applications were received during this reporting period? 50

How many REU applicants were selected and agreed to participate during this reporting period? 2

What individuals have worked on the project?

Name	Most Senior Project Role	Nearest Person Month Worked
Sara Fortin	Non-Student Research Assistant	12
Katie Fisher	Undergraduate Student	3
Karen Word	Graduate Student (research assistant)	3
Wilfred Wollheim	Co-Investigator	2
Adam Wlosktowski	Graduate Student (research assistant)	2
Lisa Wininger	K-12 Teacher	1
John Wingfield	Co-Investigator	1

Name	Most Senior Project Role	Nearest Person Month Worked
Mathew Williams	Co-Investigator	1
Kyle Whittinghill	Postdoctoral (scholar, fellow or other postdoctoral position)	2
Colin Ward	Graduate Student (research assistant)	12
Katey Walter	Co-Investigator	2
Matthew Wallenstein	Co-Investigator	2
Genna Waldvogel	Technician	3
David Wafle	K-12 Teacher	1
Lee Vierling	Co-Investigator	1
Javier Vidal-Hurtado	Postdoctoral (scholar, fellow or other postdoctoral position)	2
Laura van der Pol	Technician	12
Mark Urban	Co-Investigator	1
Claire Treat	Graduate Student (research assistant)	2
Gary Thiede	Co-Investigator	1
Ted Tedford	Postdoctoral (scholar, fellow or other postdoctoral position)	2
Jianwu Tang	Co-Investigator	1
Shannan Sweet	Graduate Student (research assistant)	12
David Swartz	K-12 Teacher	1
Heidi Steltzer	Co-Investigator	2
Elena Sparrow	Co-Investigator	1
Lisle Snyder	Technician	4
Erika Smull	Undergraduate Student	3
Chelsea Smith	Technician	3
Ryan Sleeper	Undergraduate Student	3
Rodney Simpson	Postdoctoral (scholar, fellow or other postdoctoral position)	12
Gaius R Shaver	PD/PI	6
Chris Sferra	Technician	3
Greg Selby	Technician	6
Ted Schuur	Co-Investigator	1
Elissa Schuett	Technician	12
Joshua Schimel	Co-Investigator	1

Name	Most Senior Project Role	Nearest Person Month Worked
Deborah Scanlon	Technician	2
Steve Sadro	Postdoctoral (scholar, fellow or other postdoctoral position)	6
Caitlin Rushlow	Graduate Student (research assistant)	3
Rebecca Rowe	Co-Investigator	1
Matthew Rich	Graduate Student (research assistant)	3
Edward Rastetter	Co-Investigator	4
Marilyn Ramenofsky	Co-Investigator	1
Lisa Quatch	Undergraduate Student	3
Bruce Peterson	Co-Investigator	2
Colin Penn	Undergraduate Student	3
Andrea Pearce	Postdoctoral (scholar, fellow or other postdoctoral position)	12
Samuel Parker	Graduate Student (research assistant)	3
Brittany Papworth	Undergraduate Student	3
Bethany Neilson	Co-Investigator	2
Gretchen Murphey	Technician	3
Amanda Morrison	Graduate Student (research assistant)	3
Andrew Miano	Undergraduate Student	3
Madeline Merck	Graduate Student (research assistant)	12
Jennie McLaren	Postdoctoral (scholar, fellow or other postdoctoral position)	12
Michaela McGuigan	Undergraduate Student	3
James MCGraw	Co-Investigator	2
Oscar Marquina	Graduate Student (research assistant)	6
Camilo Majica	Undergraduate Student	2
Kimberly Maher	Graduate Student (research assistant)	3
Cameron MacKenzie	Technician	12
Michelle Mack	Co-Investigator	1
Sally MacIntyre	Co-Investigator	4
Chris Luecke	Co-Investigator	1
William Longo	Graduate Student (research assistant)	1
Toni Lewkowicz	Co-Investigator	12

Name	Most Senior Project Role	Nearest Person Month Worked
Jade Lawrence	Technician	2
Julia LaRouche	Graduate Student (research assistant)	6
James Laundre	Technician	12
Kelsey Lanan	Graduate Student (research assistant)	3
Kacy Krieger	Graduate Student (research assistant)	3
Jesse Krause	Graduate Student (research assistant)	3
Akihiro Koyama	Postdoctoral (scholar, fellow or other postdoctoral position)	6
Jennifer Kostrewski	Technician	12
Amanda Kolz	Graduate Student (research assistant)	12
Gary Kofinas	Co-Investigator	1
Stephen Klobucar	Graduate Student (research assistant)	3
George W Kling	Co PD/PI	2
Michael Kendrick	Graduate Student (research assistant)	6
Doug Kane	Co-Investigator	1
Jeff Kampman	Graduate Student (research assistant)	2
Torre Jorgenson	Co-Investigator	1
Jay Jones	Co-Investigator	1
Hansen Johnson	Research Experience for Undergraduates (REU) Participant	3
Fiona Jevon	Undergraduate Student	3
Alex Huryn	Co-Investigator	2
Mary Hunter-Laszlo	K-12 Teacher	1
Feng Sheng Hu	Co-Investigator	2
Kirsten Holfelder	Graduate Student (research assistant)	2
John Hobbie	Co-Investigator	1
Greg Hill	Technician	3
Lacey Harris-Coble	Research Experience for Undergraduates (REU) Participant	2
Carolyn Harris	Technician	6
Tamara Harms	Co-Investigator	2
Mary Grintals	K-12 Teacher	1
Kevin Griffin	Co-Investigator	2

Name	Most Senior Project Role	Nearest Person Month Worked
Zak Gratton	Undergraduate Student	3
Laura Gough	Co-Investigator	2
Michael Gooseff	Co-Investigator	2
Robert Golder	Technician	1
Heidi Golden	Graduate Student (research assistant)	6
Sarah Godsey	Co-Investigator	2
Anne E Giblin	Co PD/PI	1
Samuel German	Undergraduate Student	2
Rudi Gens	Co-Investigator	1
Gretchen Gann	Undergraduate Student	3
Steve Frolking	Co-Investigator	1
Adam Formica	Research Experience for Undergraduates (REU) Participant	2
Michael Flinn	Co-Investigator	2
Jack Finn	Co-Investigator	1
Eugenie Euskirchen	Co-Investigator	2
Colin Edgar	Technician	12
Jessica Drysdale	Technician	9
Jason Dobkowski	Graduate Student (research assistant)	12
Linda Deegan	Co-Investigator	2
William Daniels	Graduate Student (research assistant)	2
Byron Crump	Co-Investigator	3
Ben Crosby	Co-Investigator	1
Rose Cory	Co-Investigator	2
Melissa Chipman	Technician	2
Jasmin Castillo	K-12 Teacher	1
Allison Butler	Graduate Student (research assistant)	1
Martin Buehler	K-12 Teacher	1
Phaedra Budy	Co PD/PI	2
Kate Buckridge	Postdoctoral (scholar, fellow or other postdoctoral position)	6
Syndonia Bret-Harte	Co-Investigator	4

Name	Most Senior Project Role	Nearest Person Month Worked
William B Bowden	Co PD/PI	2
Natalie Boelman	Co-Investigator	4
Evelyn Boardman	Technician	3
Bradley Blank	K-12 Teacher	1
Louise Beveridge	Undergraduate Student	3
Josh Benes	Technician	8
Heather Bass	Undergraduate Student	2
Andres Baron	Graduate Student (research assistant)	1
Andrew Balser	Graduate Student (research assistant)	2
Jenny Baesemen	Co-Investigator	1
Ashley Asmus	Graduate Student (research assistant)	3
Garrett Arnold	Undergraduate Student	2
Jeff Adams	Co-Investigator	1
Ben Abbott	Graduate Student (research assistant)	2

What other organizations have been involved as partners?

Name	Location
University of Alaska	Toolik Field Station

Have other collaborators or contacts been involved? N

Impacts

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

Largely due to the research of ARC LTER and its collaborators, the area around Toolik is the most thoroughly described and studied arctic landscape in the world. Research results from Toolik Lake 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.

What is the impact on other disciplines?

Nothing to report.

What is the impact on the development of human resources?

Many of our students, postdocs, and research assistants end up making their careers in science, at all levels. The training we provide prepares them for these careers, and often their experience working with us is critical to the career choices they make after leaving our group. Each year about 6-12 people leave the ARC LTER and go on to careers in science. We are particularly proud of those who stay with us or return to work in arctic research; about half of our current collaborating PIs received some of their early training with us, working as students, RAs, or postdocs.

Our K-12 teacher training opportunities also have a strong positive impact, not only on the careers of the teachers who participate in the program but also on the quality of their teaching, and thus the impact of their teaching on future scientists.

What is the impact on physical 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 institutional resources that form infrastructure?

The Arctic LTER is a member of the US LTER network, and its scientists participate in several other networks including ITEX, STREON, GLEON, and Ameriflux. It is on the basis of thier expoerience and productivity as ARC LTER scientists that these scientists are also invited to participate in national and international infrastructure organizations including the NAS Polar Research Board, the SEARCH advisory committee, the International Study of Arctic Change, and the International Arctic Science Committee.

What is the impact on information resources that form infrastructure?

The ARC LTER has developed a data base that is now a major repository of information about Toolik Lake and arctic terrestrial and freshwater ecosystems. ARC LTER also contributes to the LTER Network Information System and to other data bases such as the National Snow and Ice Data Consortium (NSIDC)

What is the impact on technology transfer?
Nothing to report.

What is the impact on society beyond science and technology?
Nothing to report.

Changes

Changes in approach and reason for change
Nothing to report.

Actual or Anticipated problems or delays and actions or plans to resolve them
Nothing to report.

Changes that have a significant impact on expenditures
Nothing to report.

Significant changes in use or care of human subjects
Nothing to report.

Significant changes in use or care of vertebrate animals
Nothing to report.

Significant changes in use or care of biohazards
Nothing to report.

Key outcomes:

<u>Diverse Collaborations</u>: We are particularly proud of our success in developing productive collaborations with diverse investigators, institutions, and research programs and networks throughout the US, the Arctic, and the world. In 2012, in addition to the 5 signatory PIs, the field research done on the ARC LTER sites and in close coordination with and often direct support by ARC LTER personnel currently involves 47 collaborating PIs from 28 institutions in 22 states and 3 foreign countries. These collaborating researchers were supported by ~30 separately-funded research grants, mostly from NSF. The ARC LTER is clearly successful in attracting additional research that opens up new lines of inquiry (or delves more deeply into established topics) while effectively using the solid base of long term monitoring and experimental results and descriptive studies that have accumulated from this site since 1988. Virtually all of our publications based on field research done at Toolik Lake are written in collaboration with personnel from at least one other project. Our just-finished book in the LTER Oxford Press series, "*A Changing Arctic: Ecological Consequences for Tundra, Streams, and Lakes*", includes 58 authors from .

Additional collaborations with other groups extend the application of ARC's site-based research still further. These include collaborations within the LTER Network and with other networks such as the International Tundra Experiment (ITEX), the Ameriflux Network, and with the STREON and GLEON networks. In 2012, five of our 40 journal publications involved this type of collaboration. As further evidence of our success promoting the diverse use and application of ARC LTER results, in 2012 two papers were published using (and acknowledging) ARC LTER data that did not involve direct participation by ARC LTER personnel or collaborators.

<u>High research productivity</u>: Within the past year the core ARC LTER personnel and collaborators have published or submitted 3 complete books, 40 journal articles, 4 book chapters, and 19 presentations in proceedings volumes. The 40 journal articles have been (or will be) published in 31 different journals including high impact journals such as Nature, Nature Climate Change, PNAS, Ecology, Ecology Letters, and Global Change Biology (n=3).

<u>Progress in Information Management</u>: We have continued to make progress, continually upgrading our capabilities and the volume of information managed. Highlights include:

- Datasets online and downloads for 2012
  - There are about 1725 datasets available on the Arctic LTER web site. Some of these are small yearly files for each research site and measurement. Where it is appropriate we are in the process of combining these into yearly multisite files with common variable attributes. This will improve data access and usability.
  - 149 users downloaded 1593 data files. The most common reasons given for downloading the data files were research and student projects and dissertations.
- Improvements to sensor networks
  - Implemented Vista Data Vision - a data management system for storing measured data, offering web access, alarm service and reports.
  - Consolidated station data downloads on a virtual machine for easier management.
  - Expanded our existing network of wireless radios to include almost all of our data loggers.
- Improvements to data access at site and network level.
  - Development and implementation of the Drupal Ecological Information Management System (DEIMS) which is based on the open source Drupal Content Management System. A group of 6 LTER sites are developing DEIMS for use in information management, from the database backbone to the dynamic website portal. The Arctic LTER website will be available in late spring of 2013.

- Additional metadata and data checks were programed into our Excel metadata input form. Our Excel form includes sheets for both metadata and data which allowed us to easily develop scripts to check and output eml and data exchange files. We now produce eml exchange files to eml version 2.1 which is the versions required for the new LTER Network Data Portal for harvesting metadata and data into the LTER network PASTA system.

- Addition of non-LTER project data.
  - Three new non-LTER project data were added to our information system:
    - Spatial and Temporal Influences of Thermokarst Failures on Surface Processes in Arctic Landscapes (PI George Kling)
    - Mechanisms and feedback consequences of shrub expansion following long-term increases in winter snow depth in northern Alaska: a legacy for IPY (PI Jeff Welker)
    - Physical Limnology of Arctic Lakes (PI Sally MacIntyre). Note: These data have been received and will be online late spring 2013.

K-12 Education: K-12 Education is another key goal of the LTER Network. In ARC LTER, due to the remoteness of our site we cannot bring young students the field. Instead, we participate in K-12 education in several ways:

- Schoolyard program: Annual Supplemental Funds are used to support a public lecture program on science topics in the Native American community of Barrow. Each year one or two lectures are given by ARC investigators or collaborators, with about 15-20 others given by visiting scientists, federal and state agency representatives, or public health officials; occasionally a lecture on subsistence living is given by a Native hunter, fisher, or whaler. This has been a very successful program and the community is keenly interested in continuing it. One current problem with the program is that a companion program in which local K-12 students would make measurements on local tundra and ponds for comparison with similar measurements at Toolik Lake has been discontinued due to lack of funding. We are currently looking for additional funding or alternative arrangements that will restore this successful and well-received program
- Experiences for K-12 teachers at Toolik Field Station: Most summers we have 1-3 middle school or high school teachers working at Toolik with collaborating projects, typoically supported by NSF-OPP as part of their Polar TREC program. For the past two summers we have also supported teachers at Toolik in collaboration with a program run by Dr. John Moore of Colorado State University. In 2012, eight teachers (2 from Maryland, 3 from Michigan, and 3 from Colorado) spent two weeks at Toolik Field Station participating in a major harvest of one of the long term tundra fertilizer experiments, learning how to sample, sort, and weigh the samples, organize data, and calculate biomass, production, and soil food web properties.
- Research Experience for Teachers: With Annual Supplemental Funding Eve Kendrick, a middle school teacher from Alabama, worked for one summer (2011) with our streams group learning stream sampling methods and data analysis. In the following winter she developed lesson plans based on this experience in her school in Alabama. In the spring of 2013 she will travel to Anaktuvuk Pass, the nearest Native community to Toolik Lake (population ~350), where she will present the same lessons in the local schools.

Use of Supplemental Funds: LTER projects are requested to describe explicitly how they have used supplemental funds. In the ARC LTER project we have used these funds in the following ways:

- Research Experience for Undergraduates (REU): These funds ($13,000 per year) were added to our core budget at the start of the current project in 2010, covering stipend, travel, and living expenses for two students each year. In 2012 we supported Lacey Coble-Harris from Columbia University and Hansen Johnson from Bates College for a summer of field research at Toolik Field Station.

- Schoolyard LTER: These funds ($24,000 per year) were also added to our core budget at the start of the current project in 2010 and are used to support a series of public outreach lectures on science in the community of Barrow. In the past this program has included student visits to field sites near Barrow; we are working to restore this component of the program.
- Research Experience for Teachers (RET): We continued to use funds ($10,000) from our 2011 Supplement to support the work of Eve Kendrick, a middle school teacher from Alabama, as she developed and presented lesson plans based on her field experience in 2011. In April 2012 she will visit the village of Anaktuvuk Pass to present these lessons.
- Truck purchase: In 2012 we completed the purchase of a new crew cab pickup truck using equipment funds ($36,000) from our 2011 Supplement.
- Information management: The largest pool of funds ($30,000 in 2011, $100,000 in 2012) was used for a series of improvements to our data and information management system and for participation in LTER Network Information System activities. As we proposed, most of this is being used for salaries to hire additional people to bring our information system up to the latest network standards. As of April 2013, about $40,000 remain to be spent in this category; the remainder of these funds will be spent during 2013 in support of the work of an additional "data management" assistant (already hired and working).

<u>Year 2 Activities and Findings</u> The following pages describe, in a series of vignettes, the major activities and findings in Year 2 of the current ARC LTER project

<u>Part I – Terrestrial Research of the Arctic LTER</u>

The terrestrial research activities of the ARC LTER include (1) maintenance and monitoring of our long term experimental plots in contrasting tundra ecosystems, (2) cooperation with diverse projects in collaborative sampling and analysis of data from these long term plots, and (3) participation in a range of synthesis activities including overall site synthesis (with the ARC LTER's land-water, stream, and lakes groups) as well as diverse LTER Network and PanArctic synthesis and modeling activities. Highlights of Year 2 include the following:

Effects of wildfire on tundra landscapes: For the years 2010-2016, our overall project goal is to understand changes in the arctic system at catchment and landscape scales as the product of: (i) Direct effects of climate change on states, processes, and linkages of terrestrial and aquatic ecosystems, and (ii) Indirect effects of climate change on ecosystems through a changing disturbance regime. The terrestrial group is working to meet this goal by monitoring changes in carbon, water, and energy balance on the site of a major wildfire that occurred in 2007, the Anaktuvuk River (AR) Burn. This work is done in collaboration with several other NSF-funded projects including NSF-OPP-0807639, NSF-EF-1065587, and NSF-OPP-1107707.

For 2012 we have two major findings to report: **First**, five years of monitoring of C balance at the AR Burn sites shows continuing changes in both moderately and severely burned tundra (Figure 1 below). By the summer of 2010, Gross Primary Production (GPP or GEE) in both severely and moderately burned tundra was greater than in unburned tundra; and in the severely burned tundra the GPP was still increasing in 2012. Ecosystem respiration also continued to increase in the severely burned tundra in 2012, in contrast to the moderately burned tundra where ER remained similar to unburned tundra. As a result, both moderately burned and severely burned tundra sequestered about 50% more C in the summers of 2011 and 2012 than in unburned tundra (i.e., Net Ecosystem Production was more negative).

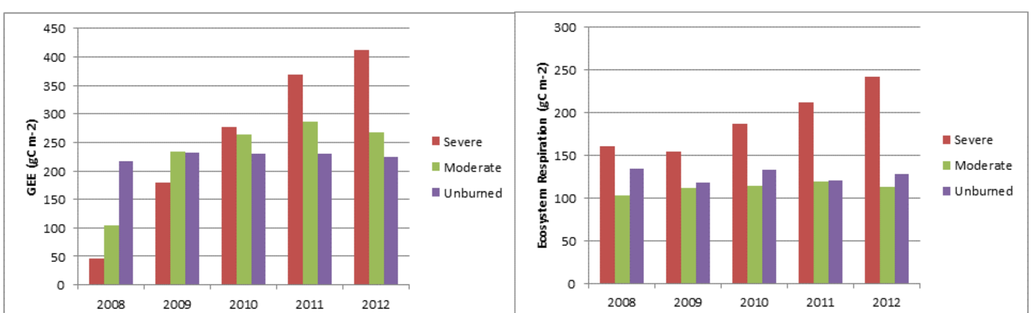


Figure 1: Cumulative summer total (June-August) Gross Primary Production, Ecosystem Respiration, and Net Ecosystem Production in Severely and Moderately Burned tundra at the AK Burn site, for each year following wildfire in 2007.

Second, the changes in C balance measured at eddy flux towers were compared with results of a direct harvest of vegetation and soils in burned and unburned tundra. The field sampling for this harvest was completed in the summer of 2011, with sample analysis and data workup in 2012 (Bret-Harte et al. 2013, accepted). Results of the harvest show that the greater GPP and overall C fluxes in the two burned sites occurred despite significantly lower total live plant biomass in the burned sites. (Figure 2 below)

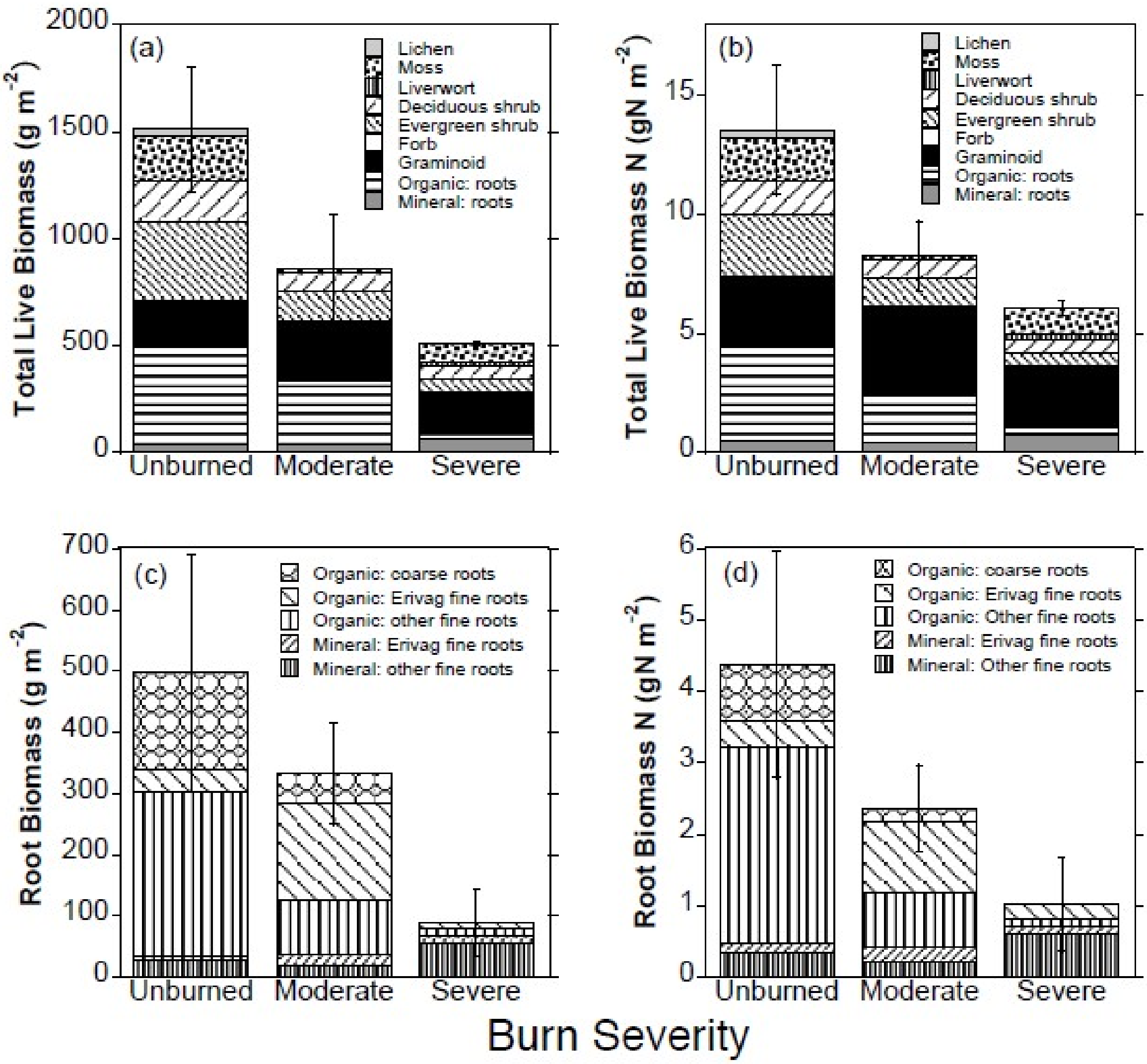
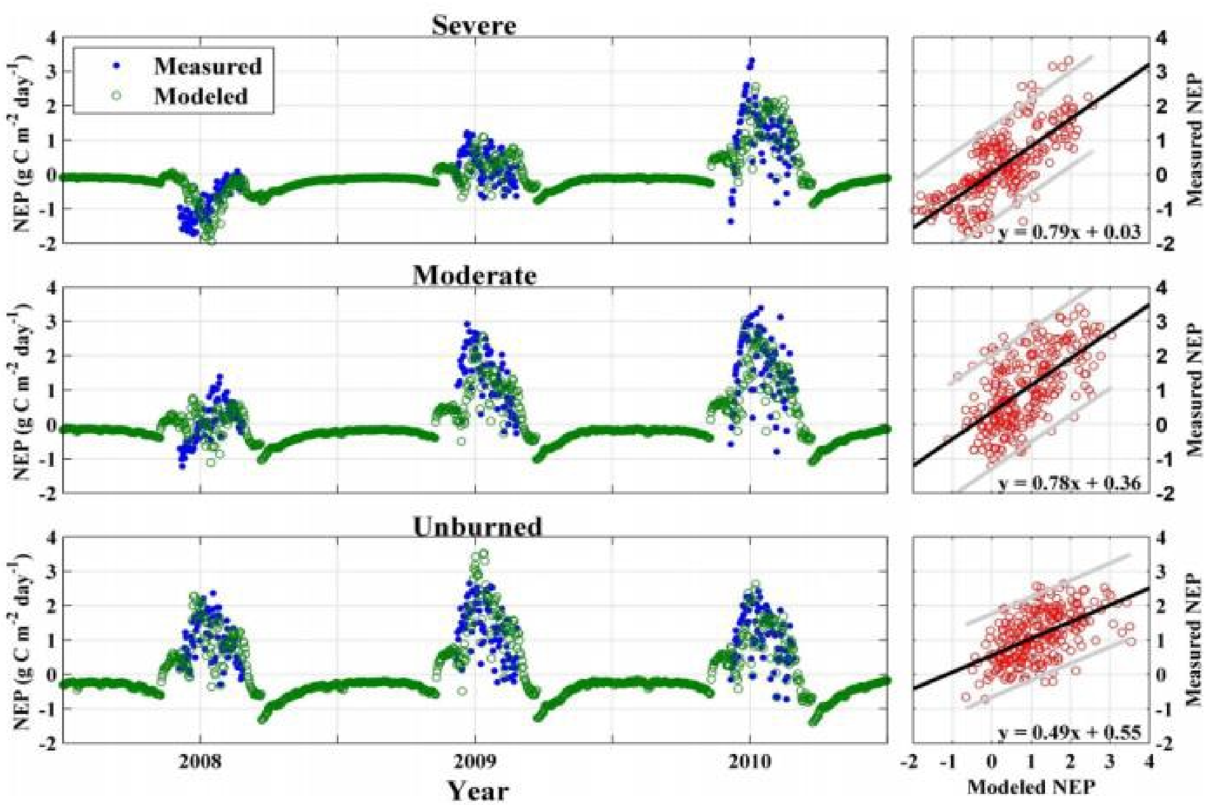


Figure 2. Biomass in burned and unburned tundra in 2011, the fourth summer of recovery from the AR Burn

Monitoring and modeling Arctic C balance: The ARC LTER is also collaborating with NSF-EF-1065587, and NSF-OPP-1107707 to develop long-term models of tundra C balance and its changes over time as both climate and disturbance regime change. We now have four years of data from our eddy flux towers at Imnavait Creek, and have compared the seasonal meteorological and flux data through May of 2011 in a publication in the ESA journal, Ecosphere (Euskirchen et al. 2012). In wet, moist, and dry ecosystems along a toposequence at Imnavait Creek the peak of carbon uptake occurs during July, with accumulations of ~90-150 g C m-2 between late May and August. These gains are generally lost through respiration during the snow covered months of September through mid-May, with releases of ~60-140 g C m-2 during this time period. The water use efficiency (WUE) of the ecosystems showed higher WUE in the warmer summer of 2009 compared to the cooler summer of 2008. The cumulative water balance of the ecosystems from mid-May to August was positive in all three ecosystems during all three summers, but was negative during the early spring of 2008 in conjunction with rates of evapotranspiration that were greater than rates of precipitation. These findings underline the importance of collecting data over the full annual cycle and across multiple types of tundra ecosystems in order to come to a more complete understanding of the carbon and water fluxes in the Arctic.

Our data also show that both the heath and wet sedge ecosystems at the ridge (dry) and fen (wet) site, respectively, are a sink for carbon during the summer, with the wet sedge tundra taking up slightly more carbon (~20 g C m-2) than the heath tundra (Euskirchen et al 2012). However, both ecosystems released significant amounts of carbon during the fall, winter, and spring months. These releases were generally larger than the summer uptake, indicating that both ecosystems appear to be net sources of carbon to the atmosphere in the three years that we've been monitoring them.

Yueyang Jiang, a postdoctoral scholar on NSF-EF-1065587, has initiated NEE modeling of these results with the Multiple Element Limitation (MEL) Model (Figure 3 below). Preliminary runs look promising, and model observations capture the temporal variability in the Net Ecosystem Exchange of CO_2 (NEE) associated with the recovery after fire, and the spatial variability in NEE associated with burn severity. Future work will continue to refine the model as more field data is collected.



Canopy structure and C balance of tundra vegetation: For the past 5 years the ARC LTER has collaborated with NSF-OPP-0807639 to determine the relationship between canopy structure and C balance of a wide range of tundra vegetation types, including work on our long term fertilizer, greenhouse, and shade plots. This collaboration is important to our long term goal of understanding how climate change and disturbance regime interact to determine structure and function of tundra ecosystems. In 2012 there were two major accomplishments, including (1) detailed analysis in the field of leaf properties, canopy structure and C balance of tall shrub canopies at Toolik Lake, and (2) completion of a PanArctic analysis of canopy structure and C balance.

In the field work in 2012, our most important finding was that photosynthesis in tall, dense shrub canopies follows the same relationships with leaf area as in the low-stature, low-leaf area canopies that are more typical of arctic tundra (Figure 4 below). This finding is important because it indicates that as the arctic tundra becomes taller, greener, and "shrubbier", we can make accurate extrapolations of our predictions of canopy photosynthesis based on the less dense, less leafy canopies in the ARC LTER experimental plots. A second important finding of our fieldwork in 2012 is that, as predicted by theory, diffuse sunlight penetrates tundra shrub canopies more effectively than direct sunlight. This means that on cloudy days with diffuse light, despite overall low light levels, photosynthesis in shrub canopies is consistently greater that would be predicted from the response of the same canopies to direct sunlight (Figure 4).

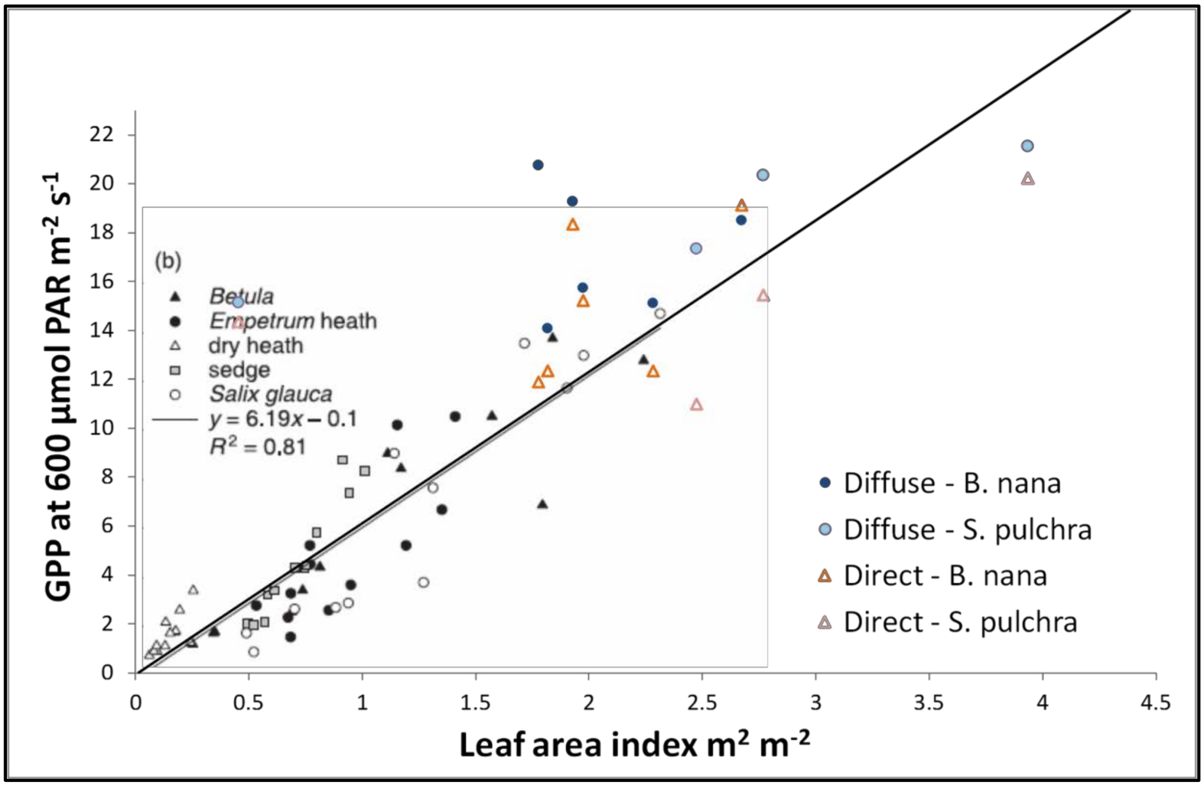


Figure 4. Blue and orange data points show whole-canopy photosynthesis at 600 micromoles of incoming photosynthetically active radiation in canopies dominated by the deciduous shrubs *Betula nana* or *Salix pulchra.* These data points have been superimposed over a previously published figure (Street et al 2007) showing the same relationship in lower, less dense canopies at Abisko, Sweden. Blue data points indicate measurements made in diffuse light; orange indicates measurements in direct light.

In a major synthesis effort (Shaver et al. 2013, accepted) using many of the same data, we showed ~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 5).

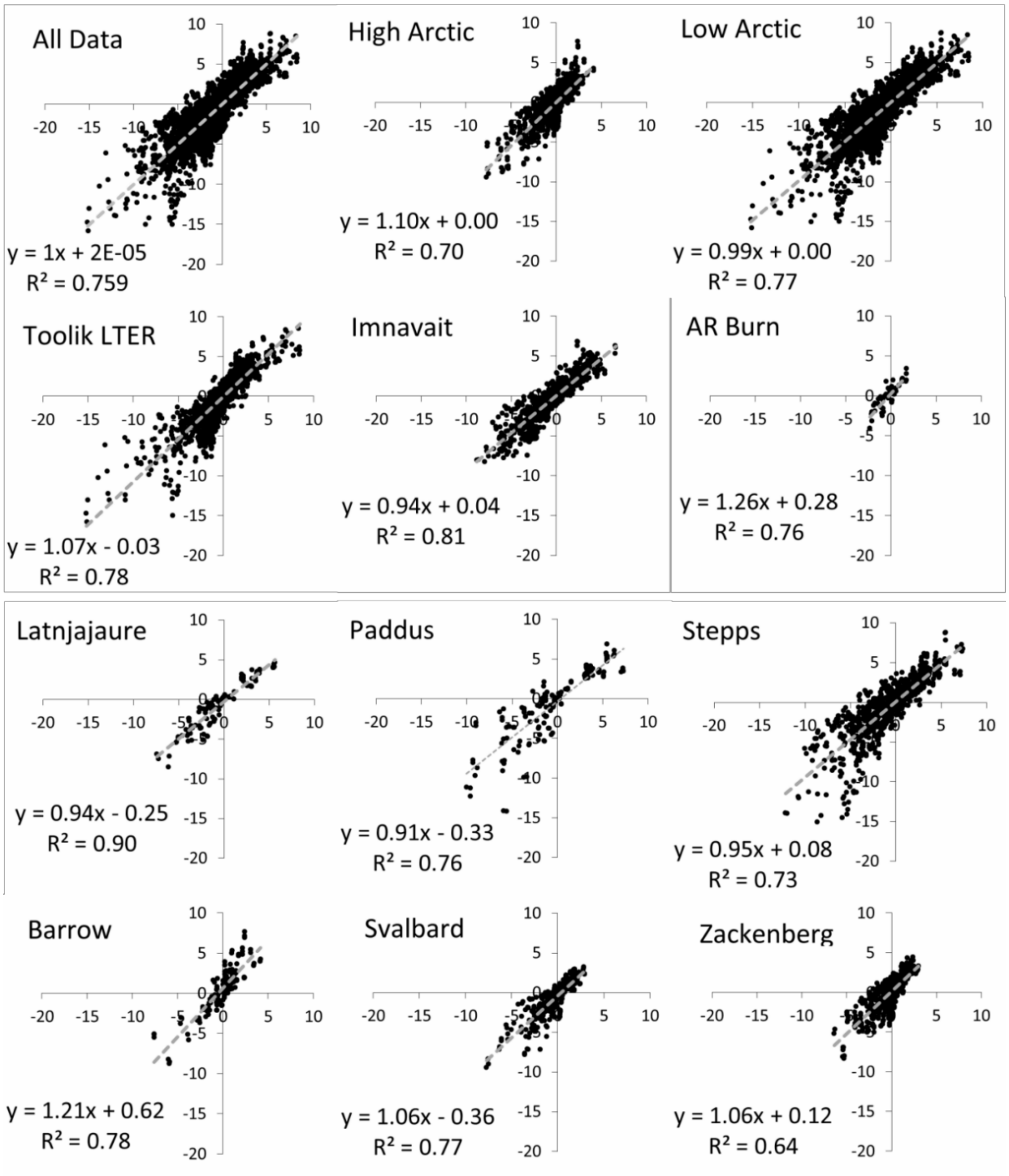


Figure 5. Predicted versus measured NEE using the entire data set ("All Data") in the regression to determine model parameters. Predicted values of NEE using these "All Data" regression parameters are plotted on the horizontal axes, with measured values on the vertical axes. Units of both axes are µmol 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.

Ecotypic variation in arctic plants and their responses to climate change: In 1979-80, before the ARC LTER was established, G Shaver, Ned Fetcher, J. McGraw, and FS Chapin set up a series of reciprocal transplant gardens along the Dalton Highway between Fairbanks and Prudhoe Bay. The species of interest was the tussock-forming sedge, *Eriophorum vaginatum*, a common and often dominant plant throughout this 500 mile N-S transect. Initial results (publications in Ecology in 1986 and American Naturalist in 1990) showed that there was a significant genetic component (i.e., ecotypic variation) to several measures of plant growth and plant size along the transect, suggesting specific adaptations to the local climate along this long climate gradient.

Since 1989, the ARC LTER has maintained these gardens and in 2009-2011, we collaborated with Fetcher and McGraw in a final sampling after 30 years. In one paper (Bennington et al. 2012) we showed significant "home site advantage" to populations transplanted back into the same site from which they had been removed, further supporting our earlier conclusions. We also showed significant ecotypic variation in stomatal density (Peterson et al 2012) and in dark respiration (van de Weg et al. 2013). Most intriguingly, McGraw, Fetcher, and their students have shown that the optimum temperature regimes for growth of the low-latitude populations in this experiment are now about 50 degree days farther north than their present position. McGraw et al. (in prep) are calling this phenomenon "adaptational lag" and suggest that this mismatch between current climate and ecotypic adaptations to former climates may be a significant factor in determining the rate of change in plant production along this transect as climate changes.

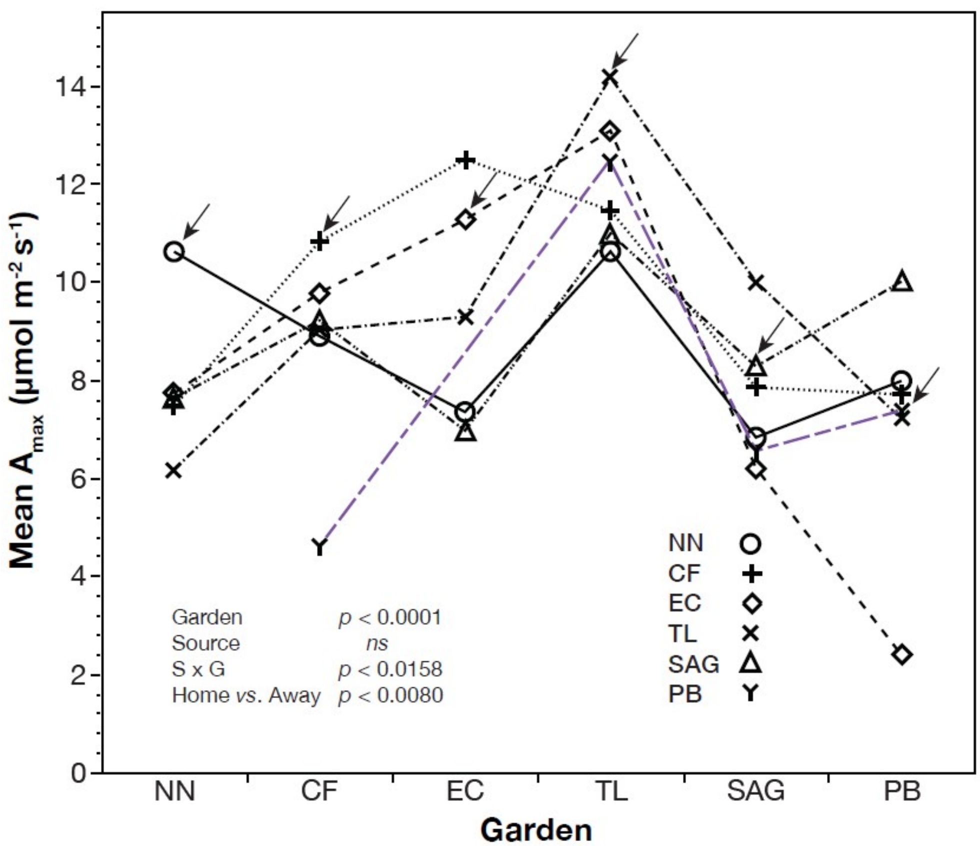


Figure 6. "Home site advantage" in maximum rates of photosynthesis (A_{max}) in the *E. vaginatum* reciprocal transplant gardens in 2011. Gardens are arranged from S to N (left to right) on the horizontal (TL = Toolik Lake). Lines connect points representing populations transplanted into each garden. Arrows indicate A_{max} of the "home" population in each garden.

Long term response to fertilizer: Long term experiments are the heart of the ARC LTER research. In 2012 we continued to monitor these experiments, most of which were established in 1989 In 2012, however, the greatest effort was a harvest of a multilevel N+P fertilizer experiment established in 2006.

Vegetation: Our preliminary analysis of the biomass of the plant communities harvested in 2012 suggests that the vegetation does not change dramatically after 7 years of fertilization with either 2 or 5 g/m2 of N. However, with 10 g/m2 applied each year, we replicated the shift we have documented in other experiments of a change from a community comprised of a mixture of tussock-forming sedges, dwarf evergreen and deciduous shrubs, and mosses towards a less diverse community dominated by one deciduous shrub (*Betula nana*) and one perennial forb (*Rubus chamaemorus*; Fig. 7).

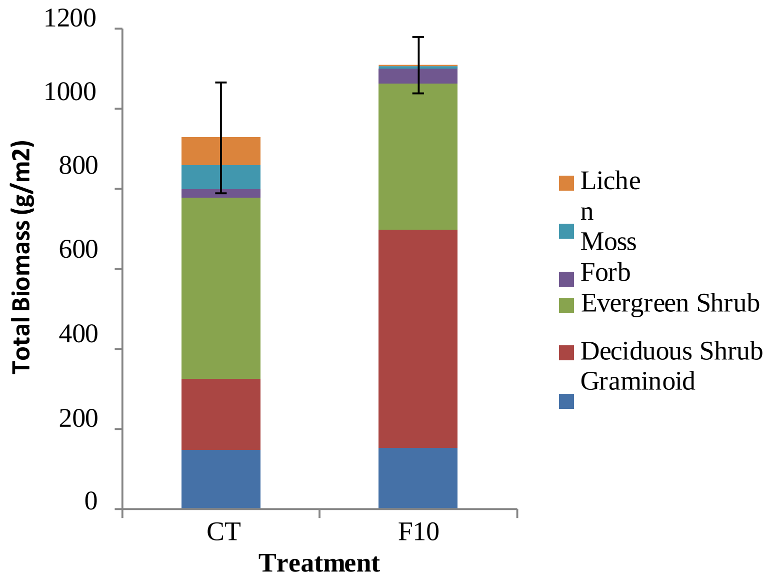


Figure 7. Total plant biomass (excluding roots) from moist acidic tussock tundra harvested in 2012. Experiment began in 2006, with 10 g/m2/year nitrogen and 5 g/m2/yr phosphorus added to the F10 treatment plots annually; CT indicates control plots.

Soils: In 2011, soil samples were collected from plots fertilized since 1989 as well as those fertilized since 2006 and were subsequently analyzed for soil invertebrate and microbial communities. The soil bacterial communities significantly changed with fertilization, although this was only detected in the longer-running experiment (Fig. 8). In addition, bacterial community composition was found to differ significantly between organic and mineral soils across both experiments.

The soil invertebrate communities, including functional groups of protozoa, nematodes, Collembola, and mites, were sampled from the same locations in 2011 as the bacterial communities shown above. Somewhat similarly, the organic and mineral horizons were quite different from each other (Figure 9). The fertilization can be seen as altering the organic horizon invertebrate communities, but not the mineral. Interestingly, the short-term fertilization was associated with a different invertebrate assemblage than the long-term fertilization treatment.

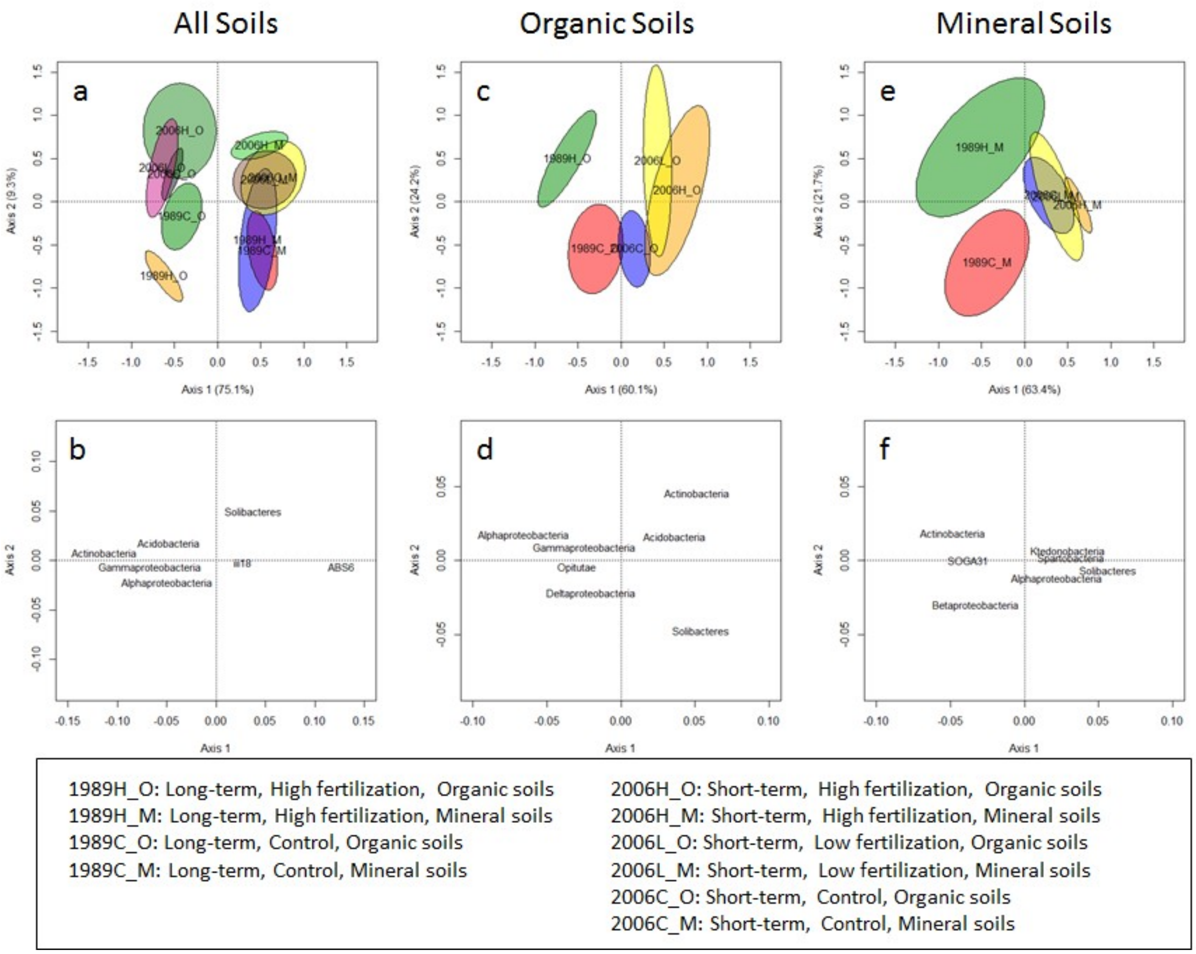


Fig. 8. Results of distance-based redundancy analyses for bacterial community structure. Analyses were performed with all soil types pooled (a and b), only organic soils (c and d) and mineral soils (e and f).

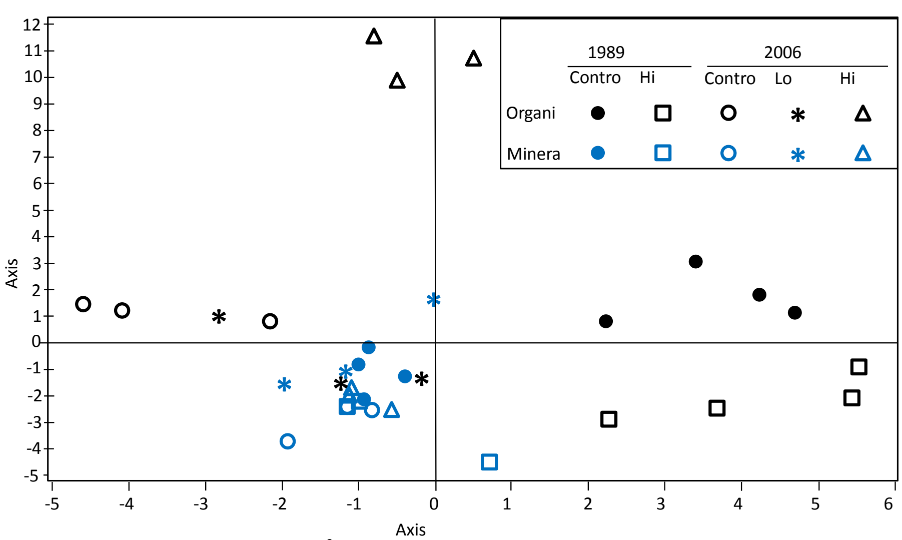


Figure 9

2011 Non-Microbe Foodweb (mg C/m^2) Canonical Discriminant Analysis with Organic/Mineral Layers from 1989 and 2006 plots. Wilks Lambda = .0015

Long term response to warming: High latitudes contain nearly half of the world's soil carbon (C), prompting substantial interest in understanding how Arctic terrestrial C balance will respond to ongoing, rapid, climate warming. Low temperatures suppress the activity of soil biota, retarding decomposition and nitrogen (N) release, further limiting plant and microbial growth. Warming initially accelerates decomposition, increasing plant-available N, productivity, and woody-plant dominance. These responses may be transitory, however, because they are affected by the longer-term development of coupled abiotic-biotic feedbacks that alter soil temperature dynamics and change the structure and activity of soil communities. In a new paper currently in press in Nature (Sistla et al. 2013) we report the effects of two decades of experimental summer warming on an Alaskan tundra ecosystem.

The warming promoted a gain in net ecosystem C storage. Warming increased plant biomass and woody dominance, indirectly increased winter soil temperature, homogenized the soil trophic structure across horizons, and suppressed surface soil decomposer activity but did not change total soil carbon or nitrogen storage. Intriguingly, we consistently found the strongest biogeochemical effects of the warming treatment to be in the mineral horizon, where the majority of permafrost soil C is stored. Warming increased mineral soil decomposer activity and carbon stock, and therefore appears to have stimulated a 'biotic-awakening' at depth. It remains unclear, however, whether our observations reflect a sustained trajectory or a transitory condition whereby a stimulated tundra decomposer system will eventually outpace increased soil C inputs.

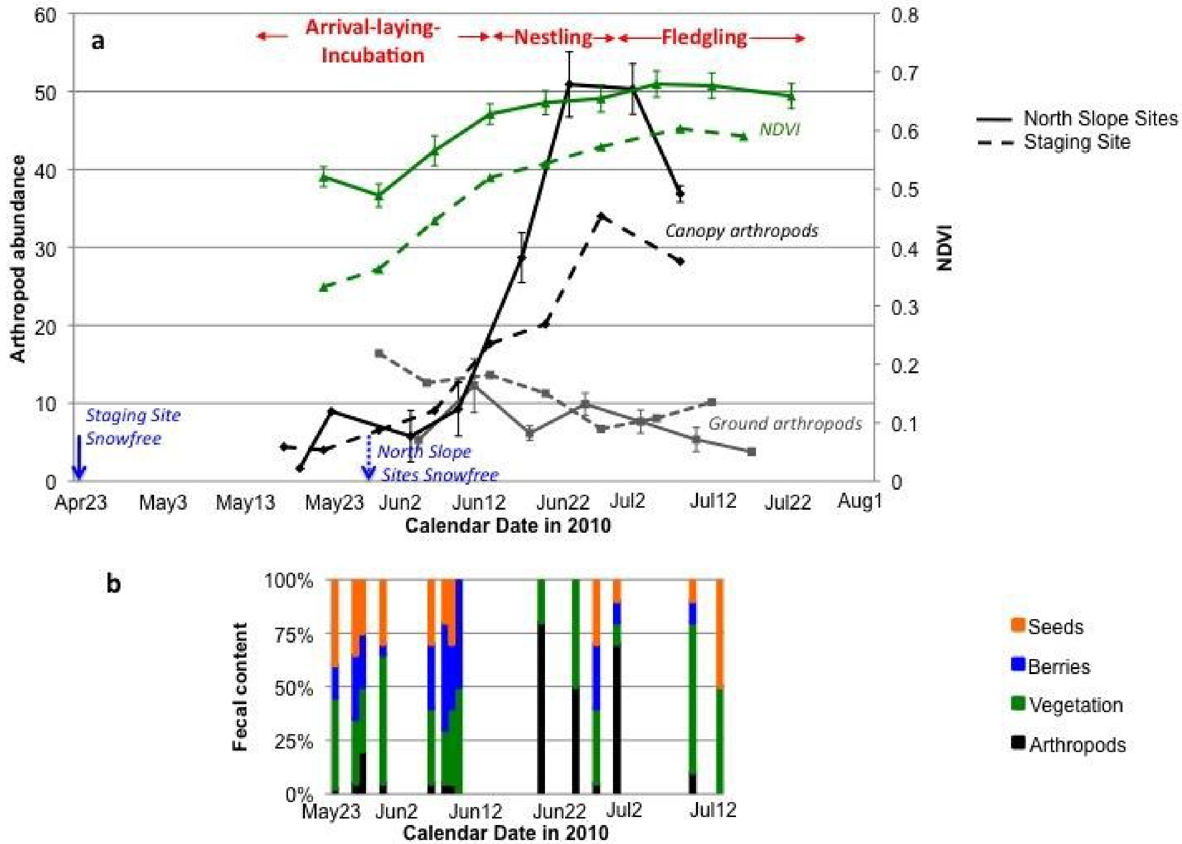
Table 1. Effects of greenhouse warming on tundra carbon and nitrogen pools after 20 years of treatment.

	Surface organic		Deep organic		Mineral	
Soil characteristic	**Control**	**Greenhouse**	**Control**	**Greenhouse**	**Control**	**Greenhouse**
Carbon (g m^{-2})	1026.9 ± 101.2	929.1 ± 101.8	4547.2 ± 1064.4	3906.6 ± 638.0	**6381.7 ± 1411.1**	**8342.3 ± 786.5**
Nitrogen (g m^{-2})	26.5 ± 4.1	27.5 ± 3.1	163.5 ± 47.2	145.5 ± 18.1	318.0 ± 75.5	376.9 ± 29.3
C:N	**42.2 ± 1.7**	**35.8 ± 2.6**	31.5 ± 1.4	28.4 ± 1.3	**20.4 ± 0.4**	**22.4 ± 0.6**
% C	44.6 ± 1.5	38.2 ± 2.9	30.4 ± 2.5	28.3 ± 2.0	7.2 ± 1.5	8.7 ± 1.8
% N	1.1 ± 0.04	1.1 ± 0.08	0.97 ± 0.067	1.1 ± 0.11	0.37 ± 0.083	0.39 ± 0.076
Bulk density (g soil cm^{-3})	0.05 ± 0.006	0.06 ± 0.02	0.14 ± 0.04	0.2 ± 0.04	1.0 ± 0.11	0.8 ± 0.1
Sampling depth (cm)	5 ± 0	5 ± 0	10.1 ± 1.5	11.2 ± 1.2	17.0 ± 1.6	15.7 ± 0.8
Percent soil moisture (g H_2O g^{-1} dry soil)	443.5 ± 40.5	531.6 ± 65.2	391.8 ± 27.4	446.1 ± 82.3	75.5 ± 14.9	107.9 ± 24.1

All values reported as means ± one se

Multitrophic approaches to changing seasonality and phenology in the Arctic: As a result of recent climate change, the Arctic has been warming at a rate almost triple that of other regions. In particular, spring air temperatures are warmer, contributing to earlier spring snow melt on much of the tundra. Several studies have reported a concurrent shift in the timing of plant phenological events, but few have explored the impact that such shifts in seasonality have on trophic interactions or vertebrate communities in general. In this study, we take a first step towards understanding the potential for trophic mismatches to develop in arctic tundra by determining what synchrony currently exists among vegetation phenology, arthropod abundance, and the timing of life history events of two species of migratory songbirds (*Zonotrichia leucophrys gambelii* and *Calcarius lapponicus*) that breed on the North Slope of Alaska. While songbird arrival on the tundra is cued by photoperiod, arthropod and vegetation phenology are closely linked with climate conditions, thus there is strong potential for a trophic mismatch to develop. Data were collected during a growing season characterized by an average spring snowfree date relative to the past thirty years. We found that during the songbird Arrival Period, berries produced the previous summer, green shoots, and leaf buds were available to and consumed by songbirds immediately upon snowmelt, so that most of their diet during that time was comprised of vegetation (Figure 1). Ground-dwelling arthropods were also present during the Arrival Period, but made up only a small portion of bird diet. The abundance and consumption of canopy dwelling arthropods increased with tundra canopy development, and reached a peak during the songbird Nestling Period when songbird nutritional demands are highest (Figure 10). Similar synchrony between arthropod abundance and the Nestling Period has been noted in more southern ecosystems, suggesting adaptations by songbirds to time breeding to maximize high quality food availability. If consistent spring warming in the Arctic causes a mismatch to develop during the Nestling Period, songbird reproductive success is likely to suffer, and this could have ecological consequences not only for the tundra, but also for more southern ecosystems where the birds overwinter and stop-over during spring and fall migration. These findings, based on fieldwork in 2010 and 2011, are now in review at *Arctic, Antarctic, and Alpine Research* in a paper (Boelman et al. 2013). The title is 'Evidence of existing synchrony among vegetation, arthropods and migratory songbirds in Northern Alaska' Additional findings from 2012: include

Figure 1



Part II – Landwater Group

The major research activities of **the Land-Water subgroup** include collection and analysis of 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). We also measure the 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. In addition, we have aided in the measurement of bacterial production in Toolik Lake (weekly) and in the series of lakes draining into Toolik Lake (3 times per summer). Finally, we also conduct a thaw depth survey twice each summer in two catchments, Imnavait Creek, and the Tussock Watershed just south of Toolik Lake.

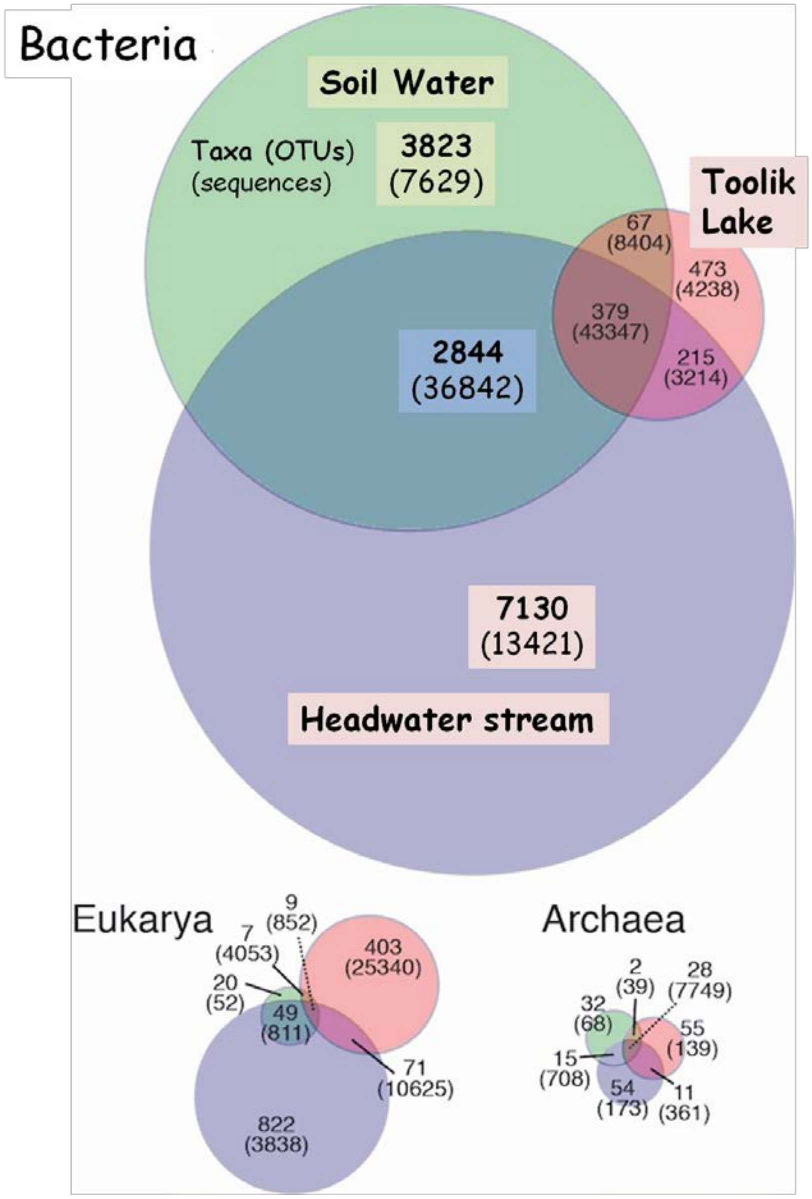
We coordinate our sampling closely with two other NSF projects: (1) the LTREB program (Dr. Byron Crump, lead PI) – these results related to the LTER program are described under the section provided by Byron Crump, and (2) the DOM-Photochemistry project (Dr. Rose Cory lead PI, University of North Carolina). Our activities on this second project included collection of water samples and soil core samples for analysis of chemistry and bacterial activity, and for experiments on the effects of photo-oxidation on water chemistry and biological activity. These photo-oxidation experiments were done at Toolik Lake.

In the summer of 2012 we used LTER support to help investigate the biogeochemical consequences of physical stratification in beaded stream pools, and the nature of riparian zone interactions with uplands and the stream; this work was done with Dr. Beth Neilson at Utah State University. With LTER support we also coordinated with our collaborators to set up and monitor surface waters (lakes, streams) and soil waters of a large tundra fire north of Toolik Lake. Our activities included collection of water samples and soil core samples for analysis of chemistry and bacterial activity, and for experiments on the effects of photo-oxidation on water chemistry and biological activity. These photo-oxidation experiments were done in coordination with Dr. Rose Cory at the University of North Carolina.

Major findings for the Land-water Interactions group include:

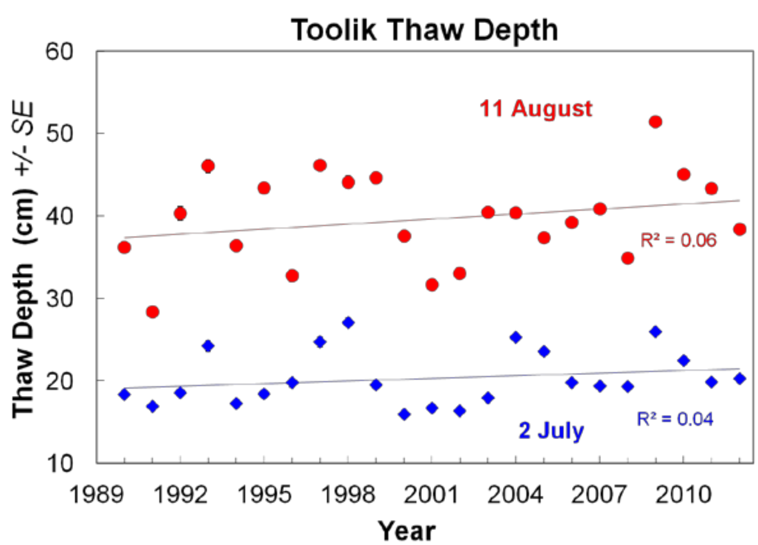
(1) There is a landscape-level connection between lakes and streams which affects the patterns of chemistry and biology among sites, and which produces temporal coherence in the behavior of these sites. This connection is due to the processing of materials (inorganic and organic) in lakes and streams, and the consistent differences between how this processing occurs among all lakes, and among all streams. This last summer (2011) we continued to expand on this research (started in 2008) to show that the 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 2011 and 2012 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 habitats, notably the soils and the small headwater streams (*see Figure below*).

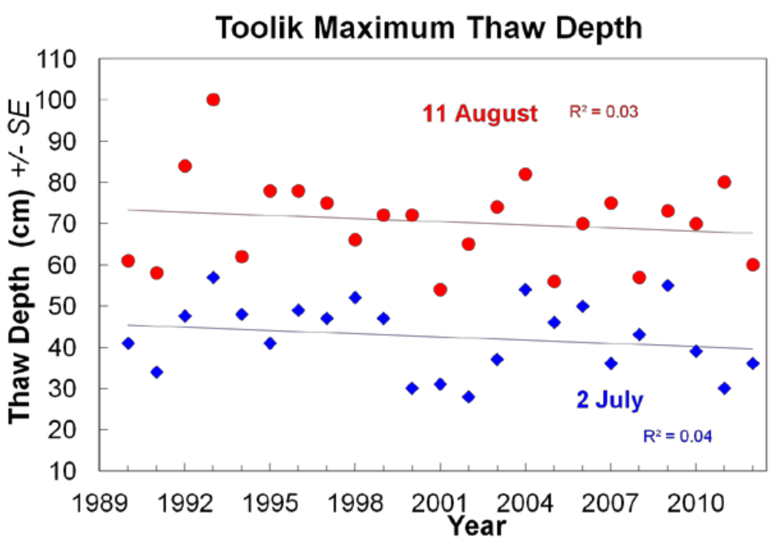
This Venn diagram shows the number of shared bacterial, archaeal and eukaryotic taxa (in bold, defined by 97% sequence similarity) among soil water, headwater stream, and lake samples. The three circles indicating soil, stream, and lake are in the same relative position for each group shown, Bacteria, Archaea, and Eukarya, and the number of sequences associated with taxa is shown in parentheses (from Crump et al. 2012).

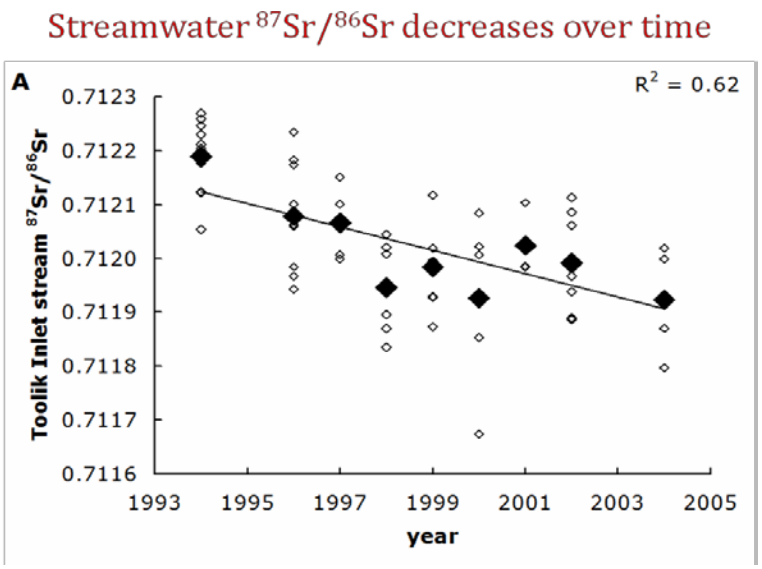


This is the first report of decreasing downslope diversity along a set of hydrologically-connected ecosystems, but what was most surprising was the pattern of overlap in species distributions. For example, in Toolik Lake a substantial fraction of the taxa of Bacteria (58% of taxa) and Archaea (43% of taxa) were first observed in soil water or a headwater stream. In addition, the 39 most common bacterial taxa in Toolik Lake (89% of the bacterial sequences recovered) were also found higher on the landscape in the soils or headwater stream. Because most of these 39 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.

(2) <u>Despite arctic warming, thaw depth measurements using steel probes have not increased at Toolik</u>. The summer of 2012 had the most shallow thaw depth of the last 4 years, and there is still no long term trend in thaw depth at Toolik. Thaw depth is always measured on the same two days in July and August (*first graph below*), and each yearly point on the graph is comprised of an average of 288 measurements from a grid in the Tussock Watershed, immediately south of Toolik. We can verify this finding of no change over time by examining the maximum thaw depth on our grid, where we also see no change over time (*second Figure below*) and if anything the maximum thaw depth is decreasing slightly, although the trend is not statistically significant. 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) (*third Figure below)*. 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) **The extent and variability of water storage and residence times throughout the open water season in beaded arctic streams is much stronger than we thought, and separation of water masses within the stream pools was consistent, and unexpected**. Data collected in 2011 and 2012 from Imnavait Creek, a beaded stream just east of Toolik, were used to better understand the effects of in-pool and riparian storage on heat and mass movement through beaded streams (Merck et al. 2012, Merck and Neilson 2012). Temperature data of high spatial resolution within the pools and surrounding sediments were used with discharge and electrical conductivity to identify storage areas within the pools, banks, and other marshy areas within the riparian zone, including subsurface flow paths that connect the pools. These subsurface flows were found to alter water conductivity and the character of dissolved organic matter (DOM) in short reaches (10s of m) while influencing the chemistry of downstream pools. During low flow periods persistent stratification occurred within the pools due to absorption by dissolved organic matter of strong solar radiation inputs coupled with low wind stress at the pool surface (*see Figure below*). This consistent separation of surface and bottom water masses in each pool will increase the travel times through this and similar arctic watersheds, and therefore will affect the evolution of water chemistry and material export.

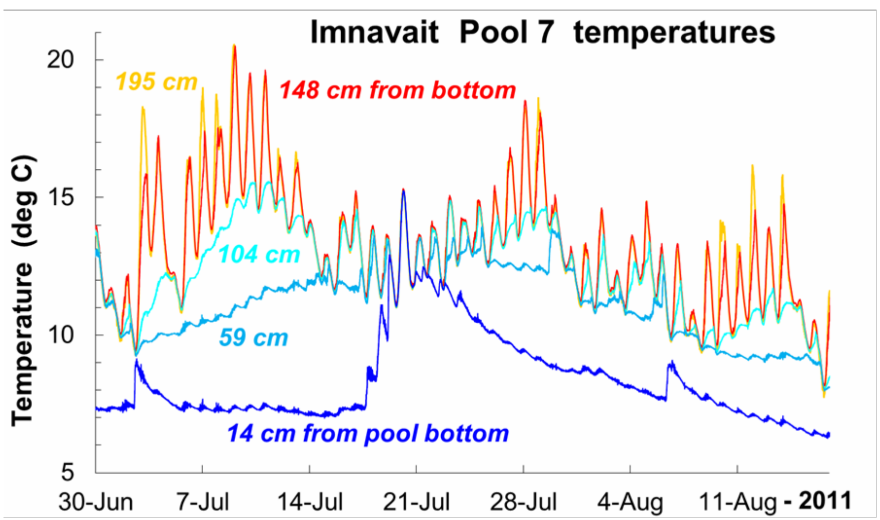
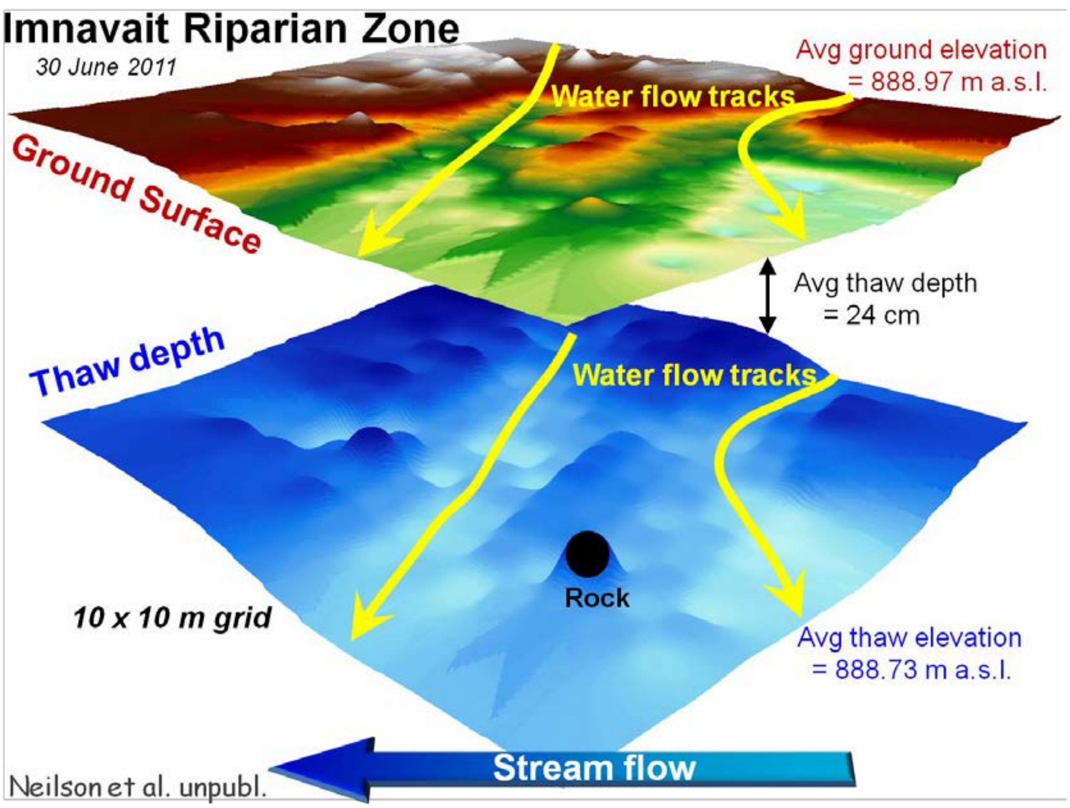
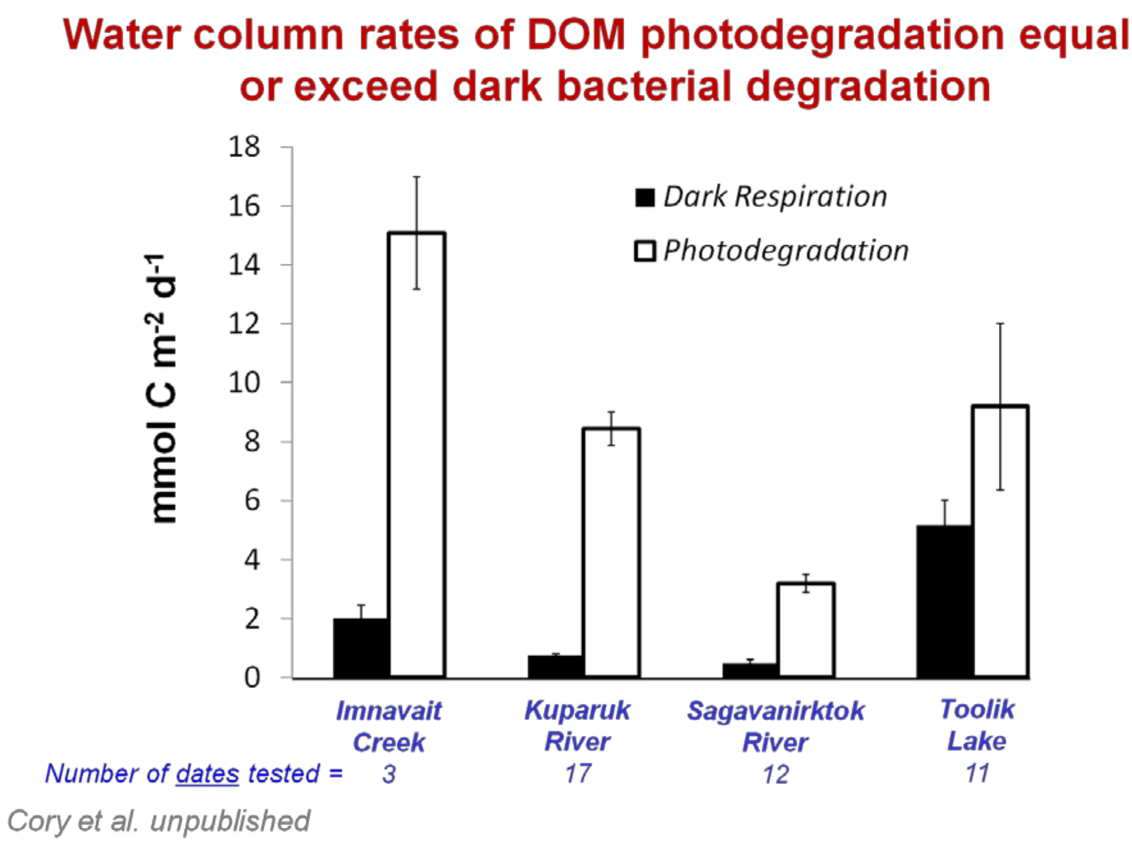


Figure showing thermal stratification (isotherms from thermistors placed at different depths in the pool) in an Imnavait Creek pool. At low discharge in early July the stratification was extremely strong (>10°C difference from top to bottom), effectively isolating the surface and bottom waters. During stratification the bulk of stream discharge acted as an overflow on top of the separated bottom layer. After a substantial rainstorm on ~20 July, this pool mixed as shown by the isotherms collapsing to ~12°C, after which the pool re-stratified.

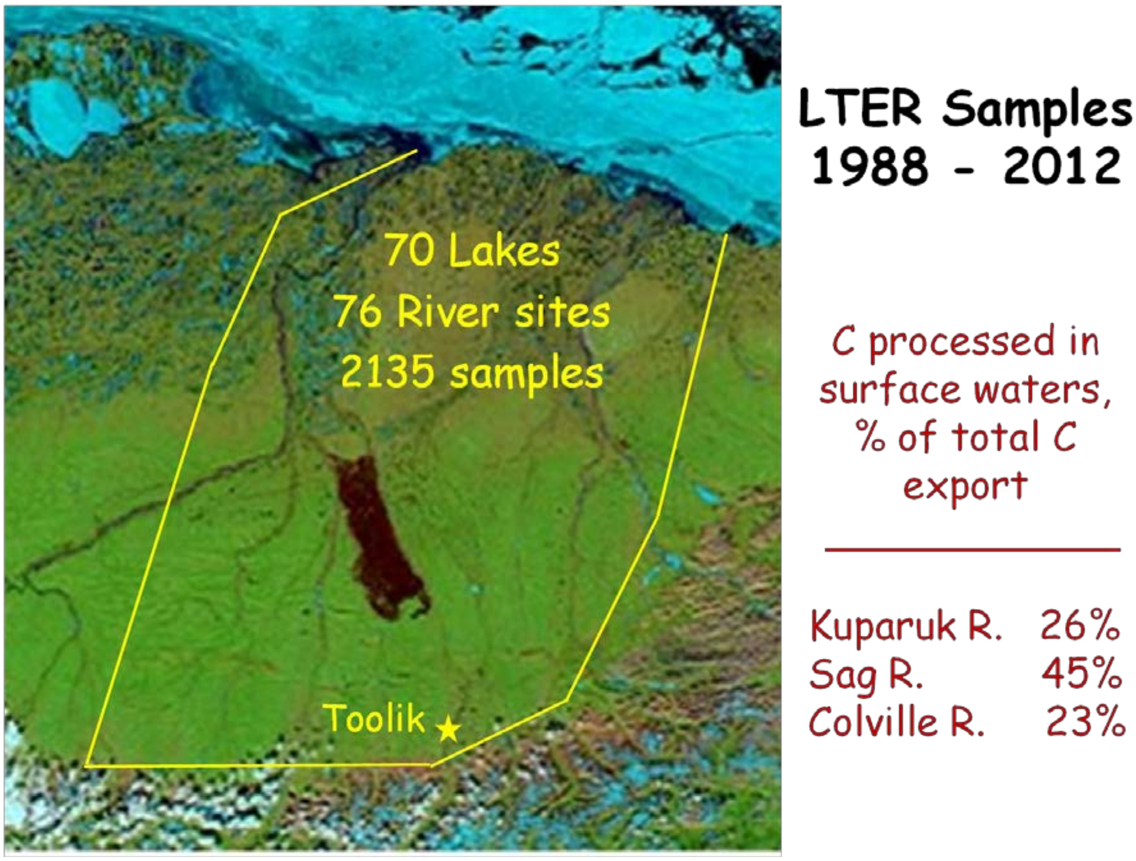
(4) <u>We found that the subsurface topography along the frozen soil strongly mimics the soil surface topography, and thus controls the subsurface water flow paths</u>. One of the most difficult aspects of understanding the dynamics of water flow within a catchment is to define water flow paths in areas of low hydrological gradient. These areas are typically found in valley bottoms and include the riparian zone adjacent to streams. Knowing exactly what flow paths the water takes when it moves from the hillslope into the riparian zone is important for determining how that water is changed chemically on its way to the stream and finally out of the basin. In regions with permafrost this difficulty is compounded by the changing depth of soils as summer progresses and the upper soil layers thaw more deeply. In summer 2011 in coordination with Dr. Beth Neilson we used high-resolution GPS measurements (every 10 cm in a 10x10 m grid) of the soil surface coupled with co-located measurements of thaw depth to determine the relationship between the topography of the soil surface and the subsurface "thaw front". In 2012 we analyzed these data to produce a flowpath diagram (*see Figure below*). We found that the two surfaces are highly correlated, which is important because it means that (1) surface mapping in areas of low relief is possible, and that (2) we can use the surface topography to estimate the below ground topography and thus where the water is flowing in this critical riparian area of the catchment.



(5) **<u>Processing of dissolved organic matter (DOM) by photochemistry in surface waters on the North Slope of Alaska can be substantial.</u>** In coordination with Dr. Rose Cory, we used LTER support to help 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") 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). After these laboratory studies we next examined whether this susceptibility to degradation actually occurred within the water column of streams and lakes where sunlight is rapidly absorbed (mainly by DOC) with depth. In most studies the assumption is that dark bacterial degradation is more important than photochemical degradation of DOM when integrated over the water column. However, most studies have only inferred the importance of photodegradation of DOM based on indirect measures, and 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 (*see first Figure below*). 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.

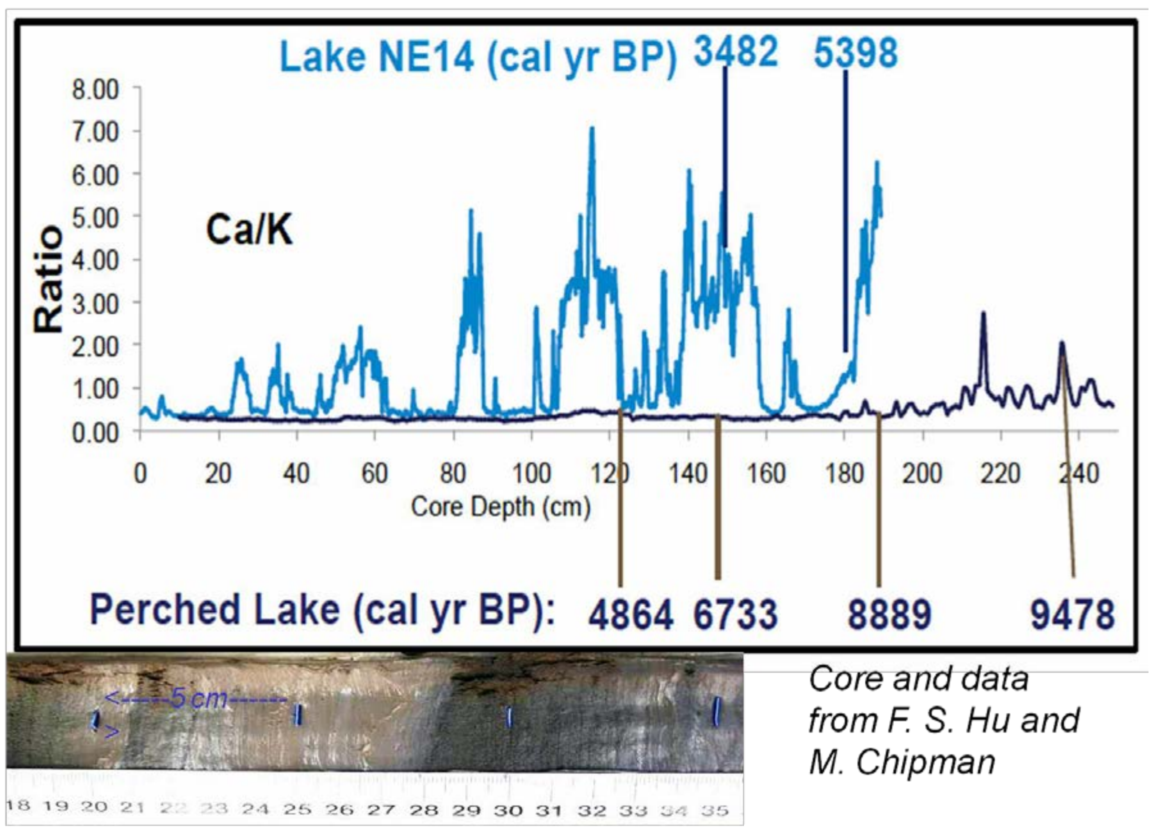


Once we had this finding of the importance of photochemical processing of DOM we used long-term LTER data on 70 lakes and 73 rivers sampled on the North Slope of Alaska from Toolik Lake to the Arctic Ocean to scale up to larger areas (*see second Figure below*). Despite the relatively rapid extinction 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 terrestrial investigations of carbon cycling with those in surface waters in order to more completely understand the fate of soil carbon in the Arctic.



(5) **<u>Thermokarst activity near Toolik appears to be a common feature through time of at least some landscapes</u>.** In coordination with Dr. Feng Sheng Hu a sediment core analyzed from Lake NE14 just 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 (increases in the 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 *(see Figure below)*. This variation indicates that at least in this catchment the thawing of permafrost with ice- rich layers that leads to soil collapse and export of mineral materials into the lake has been a regular feature. 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.

Thermokarst events identified in sediment by Ca/K



Part III -- LTER Streams

Below we give first a description of the *Activities* of this project, making special reference to the "coordinating" projects and personnel working with the LTER, and second we present the major findings of this research.

Long term fertilization of the Kuparuk River with the addition of phosphoric acid continued this year for the 30th season in a row. In 2011, the location of phosphoric acid addition was moved upstream, and remained at the same location in 2012. The movement upstream created a re-fertilized reach that had formerly been the recovery reach for 15 years. A "Big Dripper", dripping at the rate of 2.4ml/min, continued at 0.0k, while a "Small Dripper", dripping at 1.2ml/min, maintained phosphorous concentrations throughout the fertilized reach. Nutrient monitoring of sestonic and benthic samples were done three times during the summer on both the Kuparuk and Oksrukuyik. Young-of-the-year Arctic grayling were also caught on both streams throughout the season. Moss point-transects were done during the early and late summer on the Kuparuk. Sampling of nutrients, Surber samples, discharge, and rock scrubs were done on the headwaters of the Kuparuk near the confluence of watershed 1 (WS1) and watershed 2 (WS2), as well as two of the tributaries of the Itkillik River. HOBO pressure transducers collected continuous data for stage height at each of these locations, as well as the experimental reach of the Kuparuk and Oksrukuyik.

Another task this year focused on the metabolism of the Kuparuk River. Four YSI probes, measuring dissolved oxygen, conductivity, and temperature, were placed at -0.3k, 0k, 1.39k, 2.5k, and 5.5k. The goal of this project is to track oxygen uptake, and aeration within the stream. Three times during the summer conductivity probes recording every few seconds were placed at each of these locations, except for 5.5k. After measuring wetted width and sound on the stream from 2.5k to -0.3k, salt was added as a to the Reference reach. Each of the conductivity probes then recorded conductivity of the water as the salt moved downstream. This data has provided information on stream travel time and discharge, which will help calculate the overall metabolism of the river system.

Fishscape – Deegan and Huryn

The Fishscape project continued activities on the North Slope to determine how shifting seasonality of arctic River hydrology alters ecosystem processes in lakes and streams of arctic tundra watersheds. The focus was monitoring Arctic grayling migration throughout the Kuparuk watershed in response to hydrology as we did in 2010 and 2011 and monitoring on Oksrukuyik Creek was continued for recaptures at the antennas. No adult grayling were captured in the Oksrukuyik watershed in 2012. Another major sampling effort was to describe the dynamics of in-stream residents in both streams by tracking growth and condition throughout the season and collecting detailed information on in- stream conditions. Graduate students Michael Kendrick (University of Alabama, Huryn) and Heidi Golden (University of Connecticut, Deegan) continued field research.

Water Tracks – Harms, Godsey, Jones, Gooseff

The overarching objective of our research program is to determine how climate-induced changes in precipitation and temperature influence the flux of water and materials from hillslope flowpaths in the Arctic. We focus on water tracks, ubiquitous features of arctic catchments that contain surface flow in response to snowmelt and precipitation, and subsurface flow throughout the thaw season. The project requires an intensive field program focused on collection of physical and biogeochemical data. We use seasonal changes in thaw depth and storm responses to test several hypotheses, and thus have deployed a field team continuously at the site from May through August.

We selected 6 focal water track sites, 3 on an E-facing slope, and 3 on a W-facing slope in the upper Kuparuk basin near Toolik Field Station. Installation of equipment began in September 2011 when thaw depth was near the annual maximum. Equipment included weirs to support discharge measurements; thermocouples placed in- and outside of water tracks to provide automated, depth-specific ground temperature; and resin bags to record soil chemistry during snowmelt in- and outside of water tracks. Further deployment of field equipment continued in May 2012. This included installation of logging electrical conductivity probes, automated water samplers, precipitation gauges, and precipitation collectors.

Data collection began in May 2012. We began logging ground temperatures, and manually recorded snow depths at each site. We assessed snow characteristics including snow density in pits dug within and outside of each of the 6 water tracks. Depth-specific snow samples were collected for analysis of snow chemistry. We began gauging surface discharge at the onset of flow using salt dilution gauging, and began collecting surface water samples. Further installation of equipment proceeded as thaw conditions allowed and included custom fiberglass flumes with pressure transducers for measuring surface discharge at each site, and extensive groundwater well networks to measure water table elevation.

The ongoing summer field season has several goals. These include: 1) storm hydrograph separation based on samples collected by automated water samplers triggered by precipitation gauges, 2) determine sources of water to water tracks by end-member mixing analysis, 3) measure retention of N and P in water tracks by mass balance for each study reach, and from surface and subsurface uptake experiments, 3) document soil thaw dynamics within water tracks and in non-track hillslope by manual thaw surveys, 4) measure surface discharge in water tracks continuously via automated methods, calibrated to a rating curve developed for each site, and 5) track the groundwater surface inside and outside of each water track to estimate hillslope flow direction.

Whole-stream metabolism and nutrient uptake

An important part of the LTER research was to measure whole-stream metabolism and conduct experiments to measure nutrient uptake using a new methodology based on pulse or slug additions of nutrients. This work was the core for a Masters student project. Unfortunately the student we selected to do this work decided after two field seasons of work that he no longer wanted to pursue a degree in science. Fortunately, the student completed all of the field work required and left the data in a well-organized database. Even more fortunately, we have been able to contract with Dr. Tim Covino to assist us with the analysis of the nutrient uptake data. Dr. Covino originated the new pulse addition method that we are using (Tracer Additions for Spiraling Curve Characterization or TASCC). In addition, Dr. Kyle Whittinghill, who is already a member of our research team, has agreed to take on the analysis of the whole-stream metabolism data. Thus, while it is unfortunate that we lost a good student, we will be able to complete the work as proposed, within the period of our approved no-cost extension.

During the 2011 season we made an important change in our research plans. In 2010, the first year of this project, we employed a “campaign” experimental plan in which we did intensive experiments in July and in September to address the “seasonality” theme of this proposal. We rapidly found, however, that prevailing short-term weather conditions (e.g., a rainy period or a dry period) could strongly influence the results we obtained. For this reason we found it necessary to change our experiment plan to maintain a continuous presence from as early in the season as we could practically manage to as late as we could manage. To accomplish this we had fewer people in the field at one time but for a longer period overall.

With this new plan we were able to work continuously from early June to early October and were able to pick and choose conditions that would be conducive to the measurements we needed to make. This continuous occupation plan turned out to be much more productive than the 2010 campaign plan.
With respect to stream biogeochemical measurements: we sampled stream water for basic chemical analyses (nitrate, ammonium, phosphate, anions, cations, DOC, DON, pH and conductivity) at least weekly throughout the season at all three of our primary sampling sites and at the Kuparuk River and Oksrukuyik Creek. We measured whole-stream metabolism continuously at all three primary stream reaches over the entire season. We conducted a total of 22 individual solute injection experiments, most of which consisted of individual estimates of nitrate, ammonium, and phosphate uptake. On three dates we also conducted more widely-used constant rate solute injection analyses for comparison to the newer TASCC (pulse) additions. All of the 2011 nutrient data have been analyzed. We are currently analyzing all of the whole-stream metabolism data.

SCALER – Bowden and Flinn

The Scale, Consumers and Lotic Ecosystem Rates (SCALER) project is a continental scale experiment that will be carried out in several North American biomes. Consistent methodology will be employed in each biome to determine how patch- and reach-scale measures can be used to predict stream function (e.g., nutrient processing and system metabolism) at the network scale. Consumers (i.e., fish) will be excluded at experimental sites to evaluate the scaling of trophic interactions. In the Arctic biome, preliminary site reconnaissance and synoptic sampling was conducted during the 2012 field season on the Oksrukuyik Creek. The Oksrukuyik Creek is a clearwater stream that drains a 70 km^2 catchment to the southwest of the Trans-Alaska Pipeline about 8 km to the east of the Toolik Field Station. Elevation in the basin ranges from 750 to 1,100 meters above sea level and the watershed is comprised of a heterogeneous mix of moist acidic and nonacidic tundra. Riparian shrub land and shrub tundra are prevalent near the surface waters, especially in the lake-rich area located in the southeastern portion of the watershed.

Findings:

LTER Streams

Chlorophyll a
Sestonic chlorophyll *a* concentrations were low in the re-fertilized reach of the stream, as shown in Figure 4. These values are much lower than seen last year, when chlorophyll *a* concentration doubled in Re-Fert 1 reach compared to concentrations before the dripper was placed in June. Phosphorus began being added at the 0.0k station in 2011, for the first time since 1984. This year we added the same amount of

phosphorous, but had much higher discharge. With the lower phosphorous concentrations, we noticed slightly lower amounts of chlorophyll *a* in the water than observed last year.
Chlorophyll *a* was analyzed at Toolik Field Station using a Turner 10AU fluorometer.

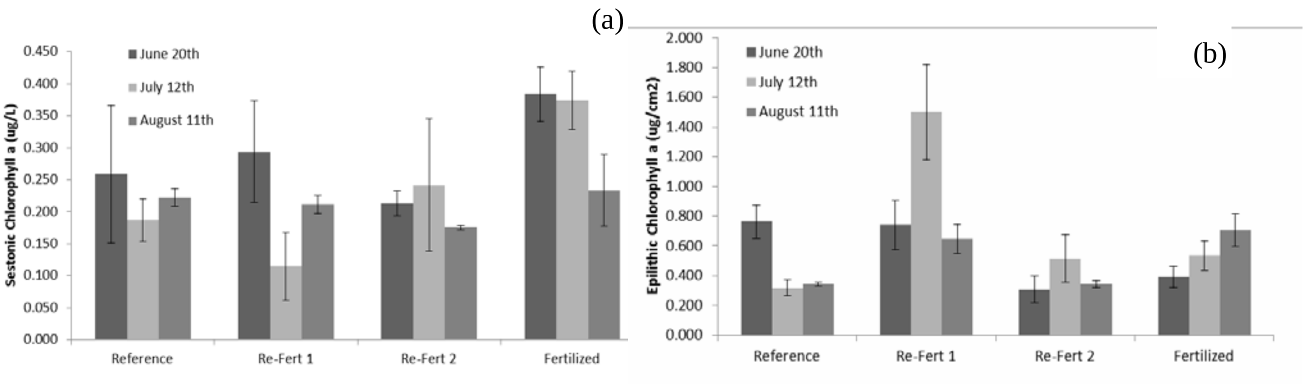


Figure 5: Sestonic (a) and epilithic (b) chlorophyll *a* averaged from each reach in the Kuparuk River on three occasions.

Moss

Moss Point transects were done on 25-26 June and 31 July – 1 Aug 2012; the June sampling dates occurred the day phosphorus addition began, and the day after. Levels of *Hygrohypnum* increased within the Re-Fert 2 reach in the late summer. The amount of *Orthocladius* seen in these reaches dropped substantially by late July, possibly due to fast moving water this field season.

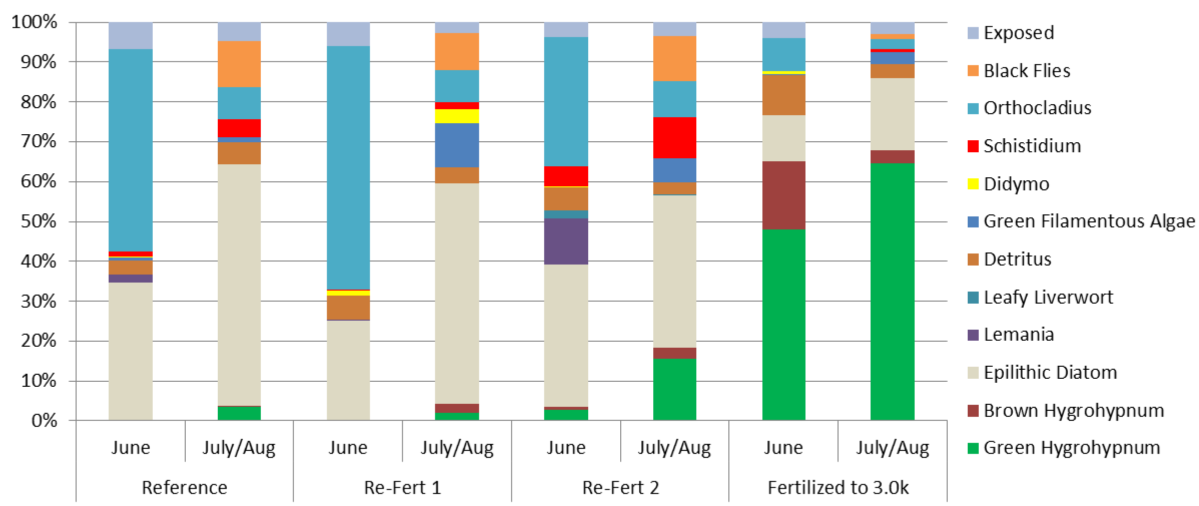


Figure 7: Percent cover of moss and algae in each of the reaches of the Kuparuk River during the sampling events in June, and Late July/Early August.

<u>Fishscape – Deegan and Huryn</u>

The PIT antennas provided more coverage of the Kuparuk than in previous years. The antennas were functional throughout the ice-free season and provided data throughout the spring and fall migrations. The Oksrukuyik antennas were functional throughout the season and provided good information on the movement throughout the system.

Kuparuk grayling movement

On the Kuparuk river, timing of stream channel drying events was similar to 2010 and no major disruptions of connectivity to overwintering lakes (Green Cabin Lake) was experienced during the migration period (Fig.1). After the spring flood, discharge remained relatively high throughout the summer. As in previous years, the Kuparuk developed two dry reaches where the river had no surface expression or flowing water; the upper dry zone was approximately 4 km downstream and the lower dry zone was approximately 45 km downstream of Green Cabin Lake. The upper dry zone went dry Jun 20-30 and ≈Aug 24-28; the lower dry zone was hyporheic prior to Jun16 - Jul01, effectively blocking in-stream grayling from moving to their overwintering habitat. Similarly, dry reaches on Oksrukuyik Creek prevented grayling from moving into Sagavanirktok River ≈Jun 08 - Jul 08.

In contrast to the 2011 season, where a prolonged drought occurred during the fall migration, grayling fall movement during 2012 was similar to previous years (Fig. 1). Grayling were generally able to migrate from summer habitat into the overwintering lake unimpeded, with a mean travel time of 2 days (Fig. 2). Because grayling were able to migrate unobstructed by dry reaches no drop in body condition and mass was observed in the migrants entering Green Cabin Lake (Fig.3).

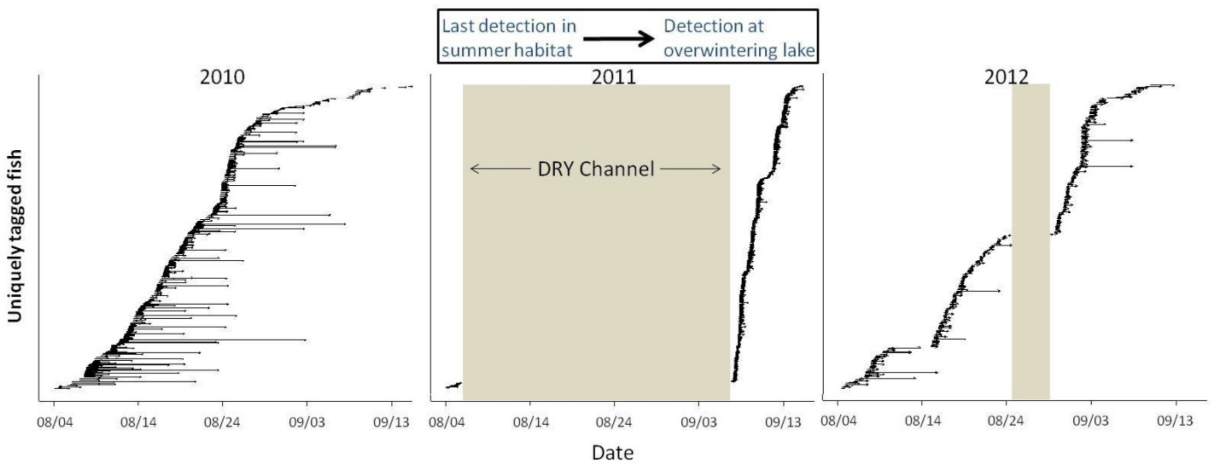


Figure 1 – Arctic grayling movement timing and duration between Kuparuk River summer habitat and overwintering lakes in the fall of 2010 to 2012. Each arrow represents a unique tagged Arctic grayling and symbolizes the last detection at the downstream antenna (Kuparuk River summer habitat) to the first detection at the upstream antenna (outlet to GCL; overwintering lakes). Distance traveled between antennas was approximately 14 km. The timing of the dry channel between the two sites is indicated by brown shading.

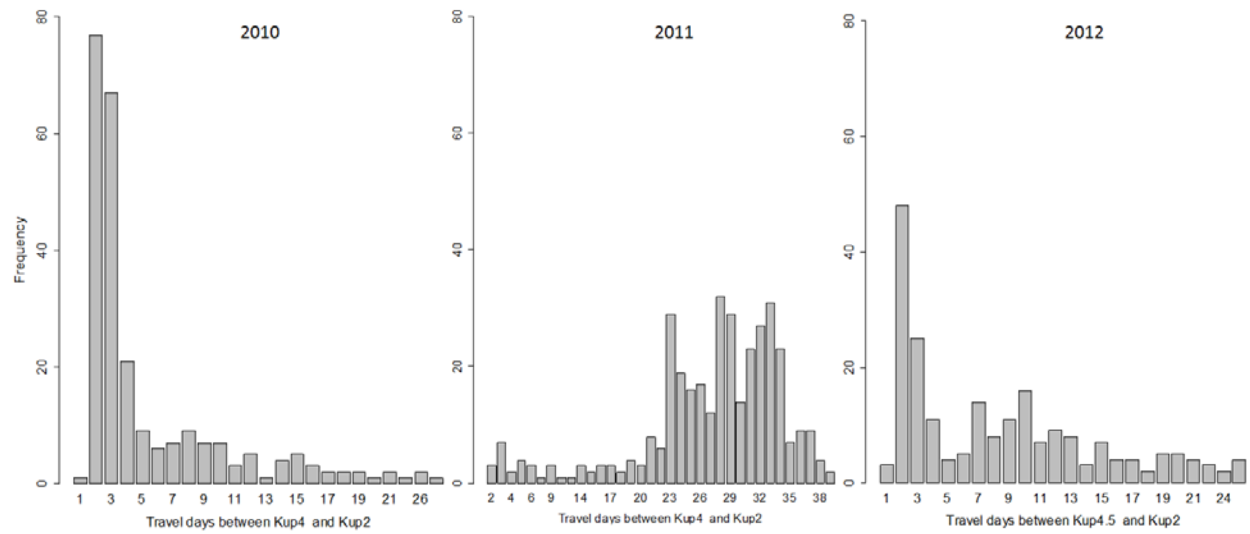


Figure 2 – Duration of Arctic grayling fall migration, 2010 to 2012 in the Kuparuk River watershed.

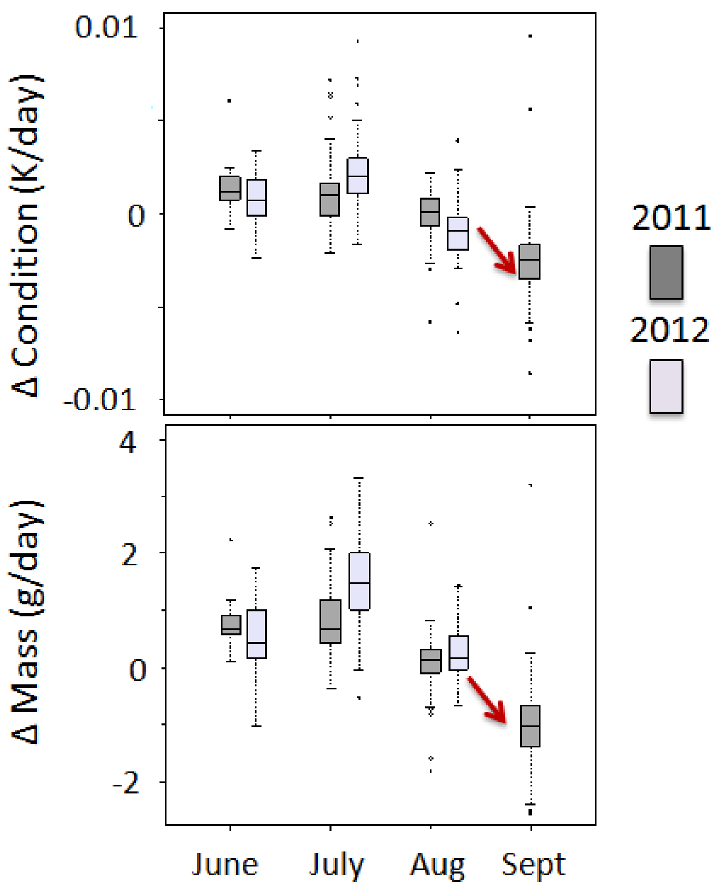


Figure 3 - Changes in condition and mass of Kuparuk River Arctic grayling throughout the summer residency in the stream, 2011 and 2012. The change was calculated as the difference in condition and mass of fish recaptured in the following sampling event, standardized by the number of days between events. The red arrow indicates the cost of being trapped in the stream and increased duration of migration in 2011.

Water Tracks – Harms, Godsey, Jones, Gooseff

As we are in the midst of our first field season, our findings to date are preliminary, and are focused on physical characteristics measured in the field. Biogeochemical data are forthcoming following the conclusion of field collections in the fall. To date, we have completed and analyzed data from repeated snow and soil thaw depth surveys. These surveys have shown that for some sites, snow depth was greater within water tracks as expected, due to collection in topographic lows, and that soil thaw proceeds more rapidly in water tracks than on the surrounding hillslope (Fig. 1). Rate of soil thaw is highly variable among sites, and further geospatial analyses will allow us to determine which site characteristics contribute to these differences.

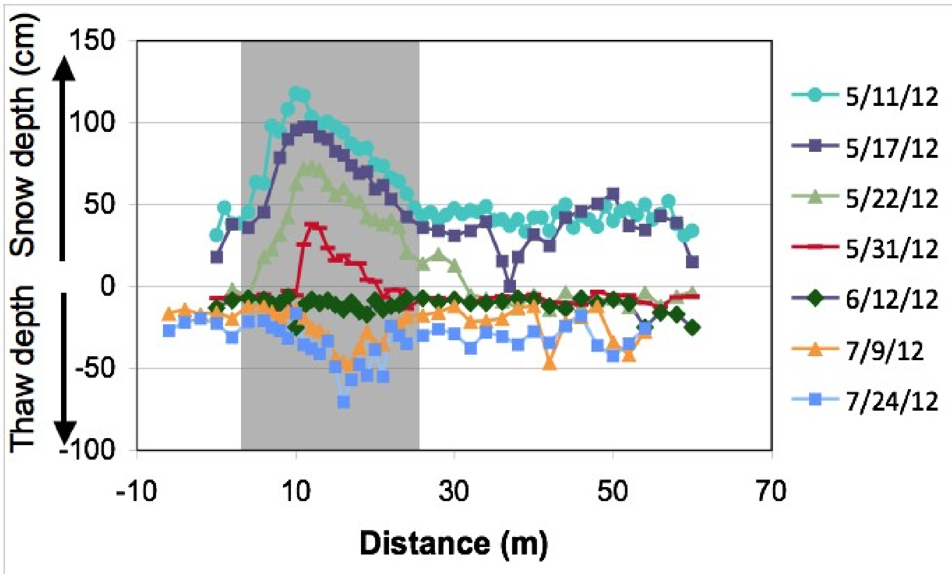


Fig. 1. In several water tracks, snow was deeper and thawing of the soil profile is proceeding more rapidly within the water track (indicated by gray box) than in the non-track hillslope.

ARCSS/Thermokarst – Bowden and Flinn

Impact of thermo-erosional gullies on stream state variables

Ammonium (NH_4) and soluble reactive phosphorus, SRP (PO_4) (Figure 2) were the only dissolved constituents that were significantly different between reference and gully-impacted streams in 2011. In 2011, Iminus-2 and Toolik River references reaches had significantly higher SRP and $NH4^+$ concentrations, respectively. We expected that thermo-erosional gullies would deliver sediment and nutrients to streams, resulting in significantly increased concentrations of dissolved nutrients in impacted streams. Inorganic nutrient concentrations from all three study years indicate that this is not always the case. We found that nutrient concentrations in the downstream "impacted" reaches were often not significantly different from the upstream reference reaches. Contrary to our expectations, the reference reaches sometimes had higher concentrations than impacted reaches. Significantly elevated concentrations of nutrients in impacted reaches were detected in I-minus 2 and Toolik River in 2009 (for ammonium only); in the Toolik River in 2010 (for nitrate and SRP only). Dissolved organic carbon (DOC) concentrations were significantly higher in gully-impacted reaches in 2009 only (Figure 3). We found that epilithic chlorophyll-*a*, a proxy for primary production, was significantly higher in the Toolik River-impacted reach and the I-minus 2 reference reach in 2011 (Figure 4).

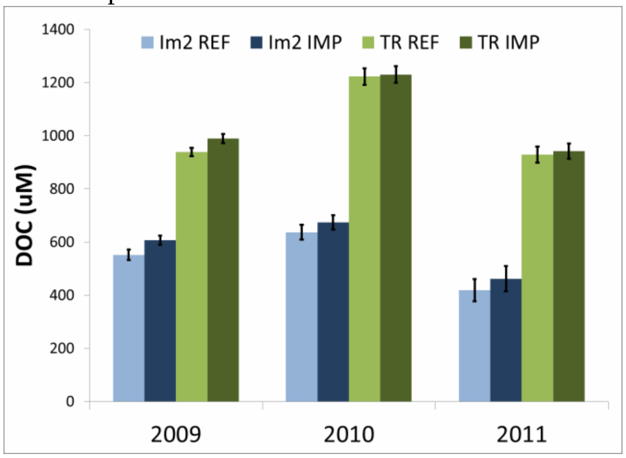


Figure 1. Dissolved organic carbon (DOC) concentrations in the reference and gully-impacted reaches at I-minus 2 and Toolik River for 2009-2011. Standard error bars are shown.

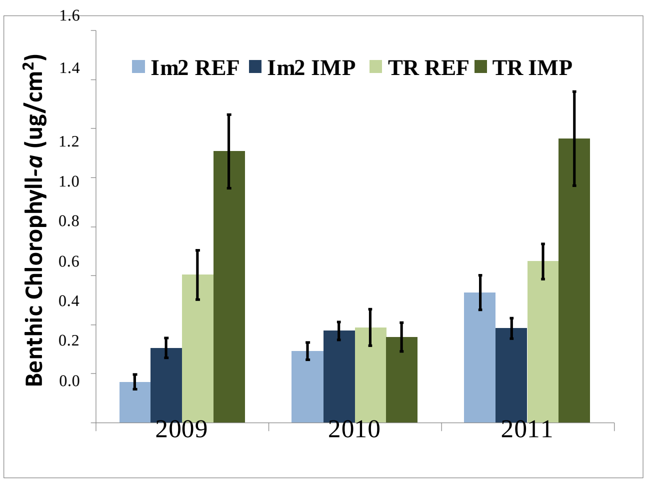


Figure 4. Benthic chlorophyll-*a* concentrations in the reference and gully-impacted reaches at I-minus 2 and Toolik River for 2009-2011. Standard error bars are shown.

<u>Impacts of thermo-erosional gullies on stream sediment dynamics</u>

Sediment Loading

The total suspended sediment (TSS) levels of the impacted reaches were significantly higher than reference reaches in both 2009 and 2010; however, there were no differences found in 2011 (Figure 5). Observations of other types of thermo-erosional features, in particular active layer displacement slides (ALDS) suggest that exposed sediments de-water as these features age. As the exposed sediment dewaters the exposed soil material consolidates and dries forming an extremely compact material that resists infiltration into the subsurface. Based on observations of many different thermo-erosional features we now think that they stabilize more quickly than we thought earlier. In the particular case of the Iminus2 and Toolik River thermokarsts we think they have stabilized, which has reduced the mobilization of soil and sediment downslope to the receiving streams. If thermo-erosional feature stabilize more rapidly that we thought, then there is a lesser risk that thermo-erosional feature will have long-term negative impacts on stream ecosystems.

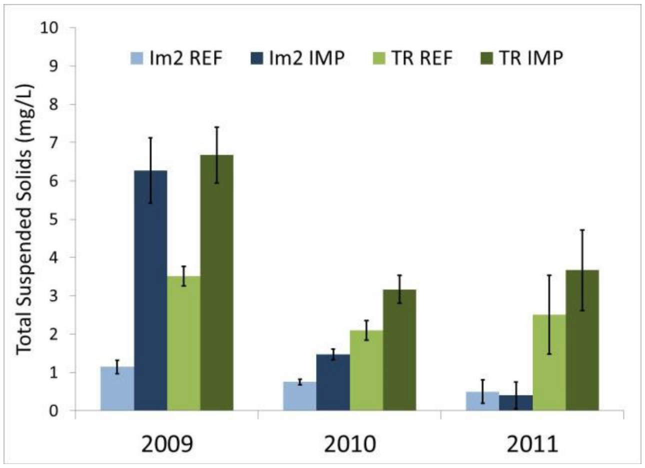


Figure 5. Total suspended sediment (TSS) concentrations in the reference and gully-impacted reaches at I-minus 2 and Toolik River for 2009-2011. Standard error bars are shown.

Impacts of thermo-erosional features on stream benthic macroinvertebrates

We quantified the impact of sediment inputs on benthic macroinvertebrate community characteristics (i.e. diversity, richness, abundance, overall biomass, functional feeding groups) in downstream impacted reaches relative to upstream reference reaches. Benthic macroinvertebrates were sampled at 5 sites within each Reference and Impacted reaches and identified to lowest taxonomic level. Samples were collected once per month over the summer 2011 season to assess seasonal shifts within the community. Species richness, diversity, abundance of organisms and total were calculated during each sample period. Macroinvertebrate data were then compared to sedimentation data to assess correlations between community dynamics and sediment inputs throughout the season.

Macroinvertebrate data collected in Iminus2 revealed similar trends as those observed in 2010. Samples collected in June revealed increased abundance in the impacted reach; however, biomass was noticeably lower compared to the reference reach. Diversity was significantly lower compared to reference reach ($p<0.10$). During July sampling overall abundance was significantly lower ($p<0.07$) in the impacted reach and the trend persisted through 8-August samples ($p<0.002$). Biomass was significantly lower in the impacted reach during August ($p<0.08$; Figure 9). Similar to 2010, no significant shift of dominant taxa occurred in June 2011, though as the season progressed samples taken in July and August revealed a significant decrease in grazers Acentrella sp. and Cinygmula sp.

The impacted reach of Toolik River had a significant decrease in community biomass during June sampling ($p<0.01$), though no immediate trend was observed during July and August. There were no significant differences in diversity and richness between reference and impacted reaches during the 2011 season (Figure 11). June samples showed a significant decrease in the grazer Valvata sp. (Gastropoda); but no other shifts in functional taxa were observed in July or August

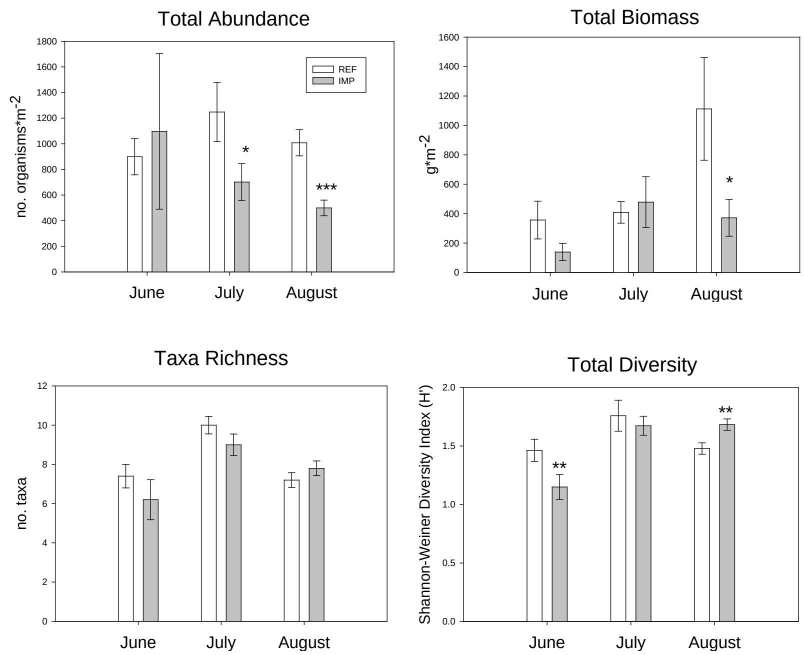


Figure 9. Benthic macroinvertebrate community parameters observed in Iminus2 during summer 2011. Single asterisk denotes ANOVA significance at α=0.10, double at α=0.05, triple at α=0.001. Bars represent means ±1 standard error of five samples collected per reach.

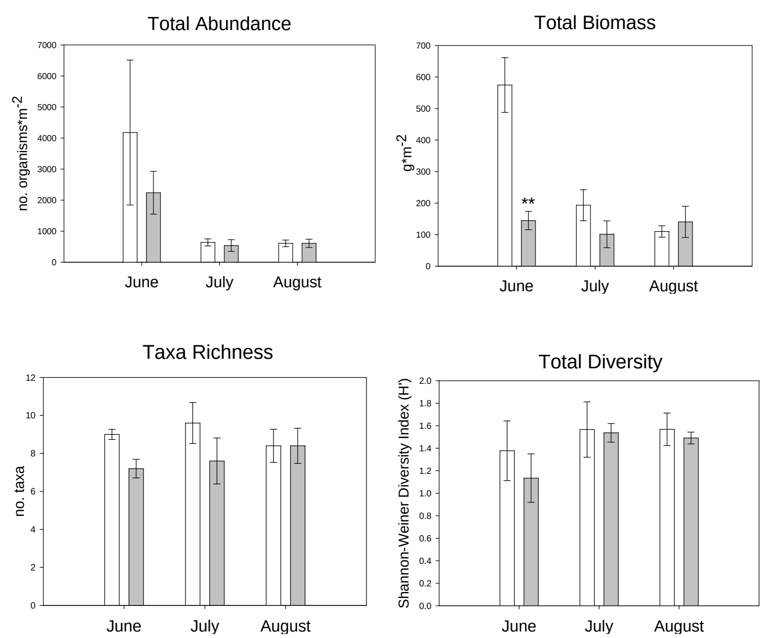


Figure 11. Benthic macroinvertebrate community parameters observed in Toolik during summer 2011. Double asterisk denotes ANOVA significance at α=0.05. Bars represent means ±1 standard error of five samples collected per reach.

Impact of thermo-erosional gullies on stream ecosystem processes

Nutrient Spiraling

Ambient nutrient uptake rates for key inorganic solutes (NO_3^--N; NH_4^+-N; and PO_4^--P) (Figure 13) were elevated in the I-minus 2 impacted reach for the June 2010 and August 2011 suite of experiments. Increased rates of NH_4^+-N and PO_4^--P were estimated in the reference and impacted reaches, respectively. Nutrient uptake rates in the reference and impacted reaches in June 2011 were not significantly different at either site.

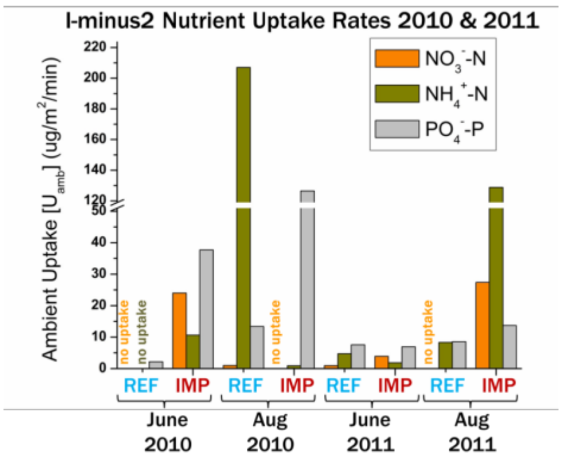


Figure 13. Estimated ambient nutrient uptake (U_{amb}) rates for nitrate (NO_3 -N), ammonium (NH_4 -N), and phosphate (PO_4 -P) in the reference (REF) and gully-impacted (IMP) reaches at I-minus 2 and Toolik River for 2009-2011.

Impact of thermokarsts and fire on dissolved organic carbon lability

The amount and lability of DOC exported from different thermo-erosional feature differs significantly (Figure 14). Yedoma soils and burned thaw slumps contain high fractions of labile DOC (65% and 36%). Gullies export higher amounts of DOC compared to ALDs and unburned thaw slumps, but of relatively low quality, perhaps due to greater interaction with mineral soils. Impacted streams show little variation in DOC quality despite the higher quantity of DOC in burned streams (Figure 15). Both DOC characterization methods (DOC loss over time & SUVA) reveal similar patterns in carbon lability.

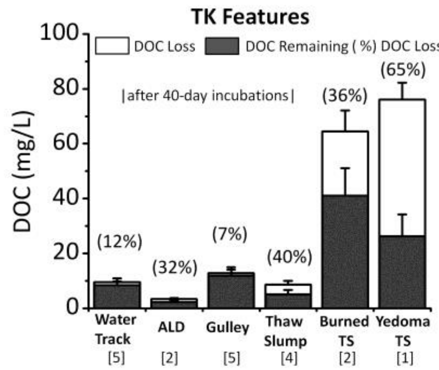


Figure 14. Dissolved organic carbon (DOC) loss from TK features by type (water tracks sampled as a potential reference; ALD = active layer detachment; gulley = thermo-erosional gully; thaw slump = retrogressive thaw slump; burned TS = burned retrogressive thaw slump; Yedoma TS = Yedoma-rich thaw slump). Standard error bars are shown. [ ] = number of sites.

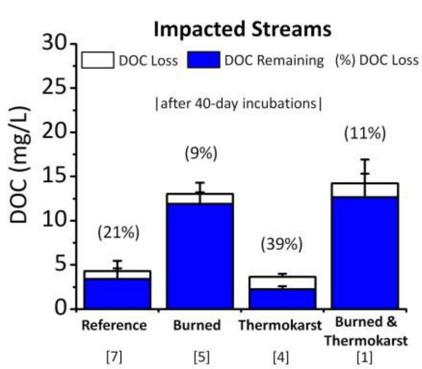
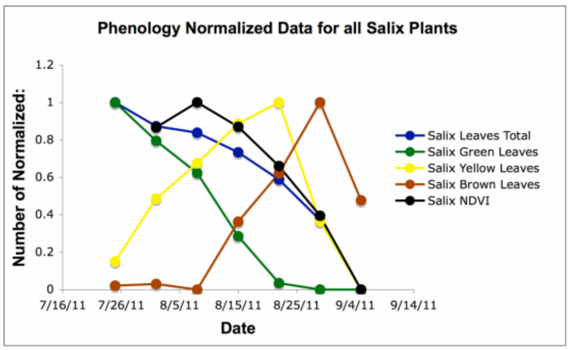


Figure 15. DOC loss from impacted streams by disturbance type (reference streams; burned streams; streams impacted by thermo-erosional features; streams impacted by both fire and thermo- erosional features). Standard error bars are shown. [ ] = number of sites.

Changing Seasonality in Arctic Stream Networks – Bowden, Gooseff, Wolheim

Seasonal asynchrony in nutrient production

Of the seven species studied, two species were singled out for further investigation, *Salix pulchra* and *Betula nana*. These two species were chosen since both are common on the landscape and clear phenological changes could be easily observed. Figs. 2 and 3 show the normalized phenological and NDVI data for *S. pulchra* and *B. nana* over the season. Total leaves and green leaves decrease over time, while yellow and brown leaves increase later in the season and then decrease at the very end of the season. NDVI follows the green and total leave trend, decreasing over time with a minimum at the end of the season. The highest NDVI value was found at the second point, which means that this was the peak "greenness" over the season. B. nana followed a similar trend.



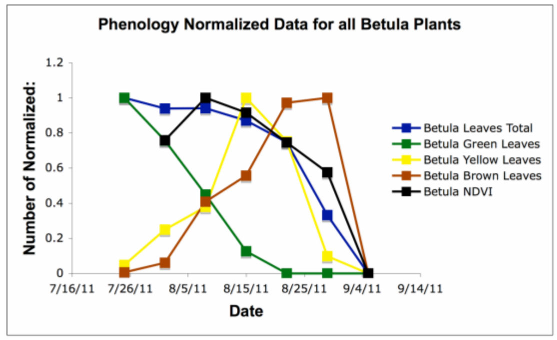


Figure 2. *Salix pulchra* and *Betula nana* phenology data over the 2011 season

Stream samples were collected at the top and bottom of each of the three reaches and all of these samples have been analyzed and summarized. For this report we focus on the I8-Inlet because it is the only reach without any lake effect, so inputs to the stream are solely from the landscape. As hypothesized we observed an increase of nitrate and ammonium concentrations at the end of the season around the middle of September (Fig. 4). The increase in nitrate concentrations was most pronounced followed by an increase in ammonium concentration; phosphate concentrations only increase briefly and slightly. An increasing concentration of dissolved inorganic nitrogen (DIN) might be expected if the discharge is decreasing (i.e., a concentration effect). However, we observed that DIN flux also increased at the end of the season (Fig. 5). A snowfall followed by melt interrupted the progression of nutrient flux. However, nutrient flux increased with the flush of snowmelt water and was not diluted. After this event the flux of DIN continued at a higher level even though discharge returned to low levels.
We observed that normalized nitrate and ammonium concentrations increased and normalized NDVI values decreased (Fig. 6). The relationship between normalized DIN (nitrate plus ammonium) concentration and normalized NDVI is linear (Fig. 7). The relationship between normalized DIN flux and normalized NDVI appears to have a step function that is likely to be driven by the snowmelt event (Fig. 8).

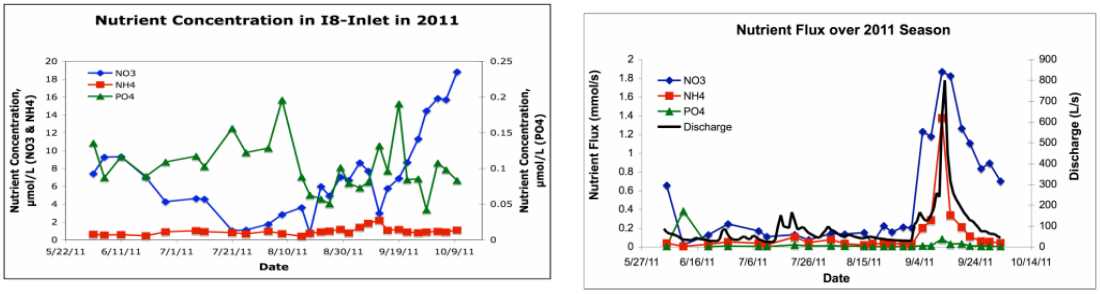


Figure 4. Nutrient concentrations and flux over time.

In summary, the phenology and NDVI data show that individual plants of *S. paluchra* and *B. nana* began to senesce around the 23rd of August and lost most of their leaves by September 11th. As the vegetation began to senesce there was an increase in the concentration of nutrients in I8-Inlet (Fig. 6). The relationship between normalized DIN concentration and NDVI was linear (Fig. 7.) and the relationship between DIN flux and NDVI was similar (Fig. 8). These data provide at least correlative evidence supporting our seasonal asynchrony hypothesis. This correlative evidence is encouraging. There are alternative hypotheses that could explain the trends in increasing nutrients that we observed in the late season. To confirm why this phenomenon occurs will require additional measurements of the processes involved and testing of the alternative hypotheses.

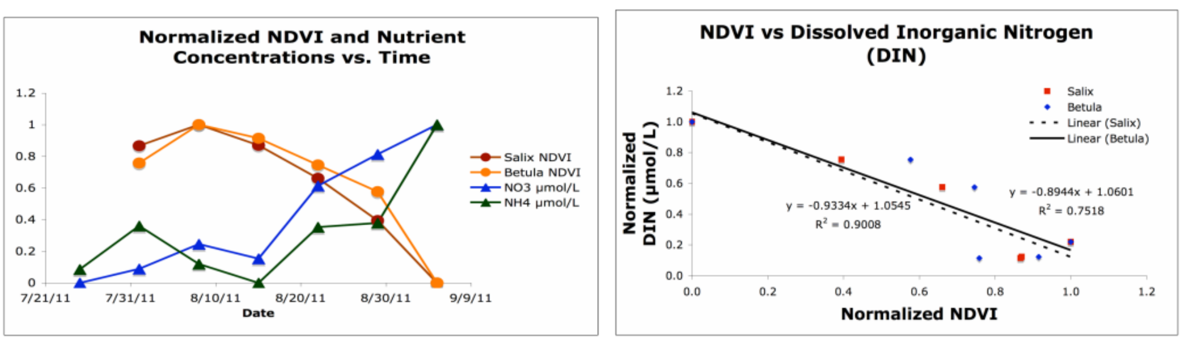


Figure 6. NDVI with nitrogen concentrations over time and dissolved inorganic nitrogen (DIN) concentrations vs. NDVI

<u>Whole-stream metabolism and nutrient uptake</u>

We have completed the analyses for about one third of TASCC solute injection experiments. These results show that hysteresis occurs commonly in our streams (e.g. Fig. 9), which was not observed in the original studies. We do, however, see patterns in uptake that seem consistent with our expectations according to the geomorphology and morphology of the study reaches (Fig. 10). We observed that when we add ammonium it is very rapidly nitrified to nitrate (Fig. 11). This is not a new finding, nor one that is uncommon. However, we are intrigued by the speed and magnitude of nitrification in these streams. Very active nitrification seems to be a characteristic of these streams, but it less clear why this should be the case and how it affects stream function. Finally, our initial assessment is that the TASCC methodology provides estimates of nutrient uptake that are comparable to those that would be obtained using the older and more widely-used constant rate addition method (Fig. 12). This is very encouraging because the TASCC method requires less time and fewer resources than the constant rate method and allows us to do more experiments. We conducted other comparative experiments that we are in the process of analyzing now.

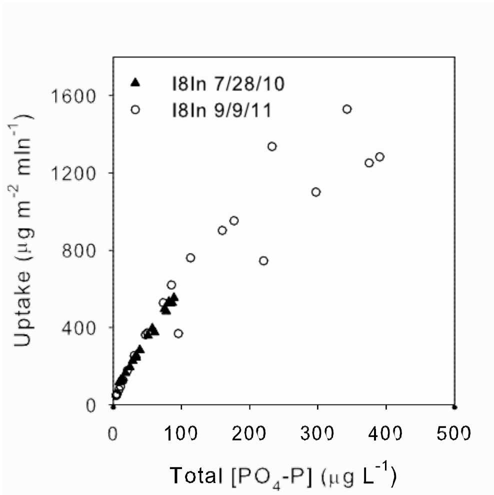


Figure 9. Results from PO4 pulse (TASCC) addition experiments done in July (closed triangles) and September (open cirlces). The September data exhibit hysteresis (different paths on the upward (lower) and downward (upper) paths of the solute pulse. Ambient concentrations on these dates were near zero and so the estimated uptake rates on both dates would be similar.

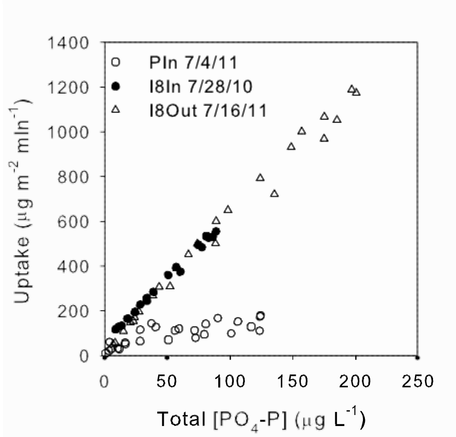


Figure 10. Uptake rates for PO4 at all three of the main research reaches in July. The uptake dynamics in the two high-gradient, alluvial reaches (I8in and I8out) are similar even though the two experiments were done in different years (2010 and 2011). The uptake dynamics in the low- gradient, peat reach are different.

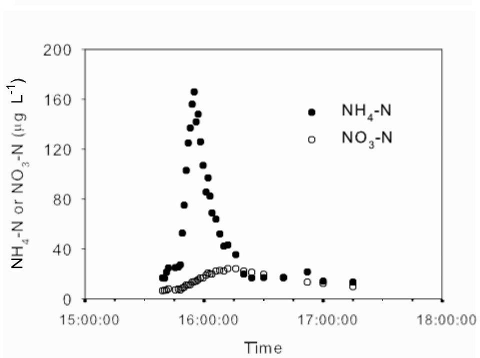


Figure 11. Results from a pulse addition of NH4 conducted on 16 July 2011. No NO3 was added in this experiment.
The appearance of NO3 in stream is due to nitrification of added ammonium. In this experiment approximately 18% of the added ammonium was nitrified.

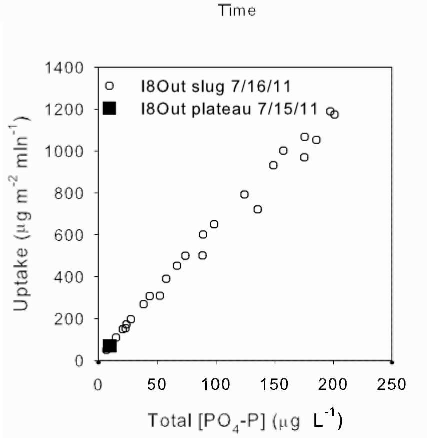
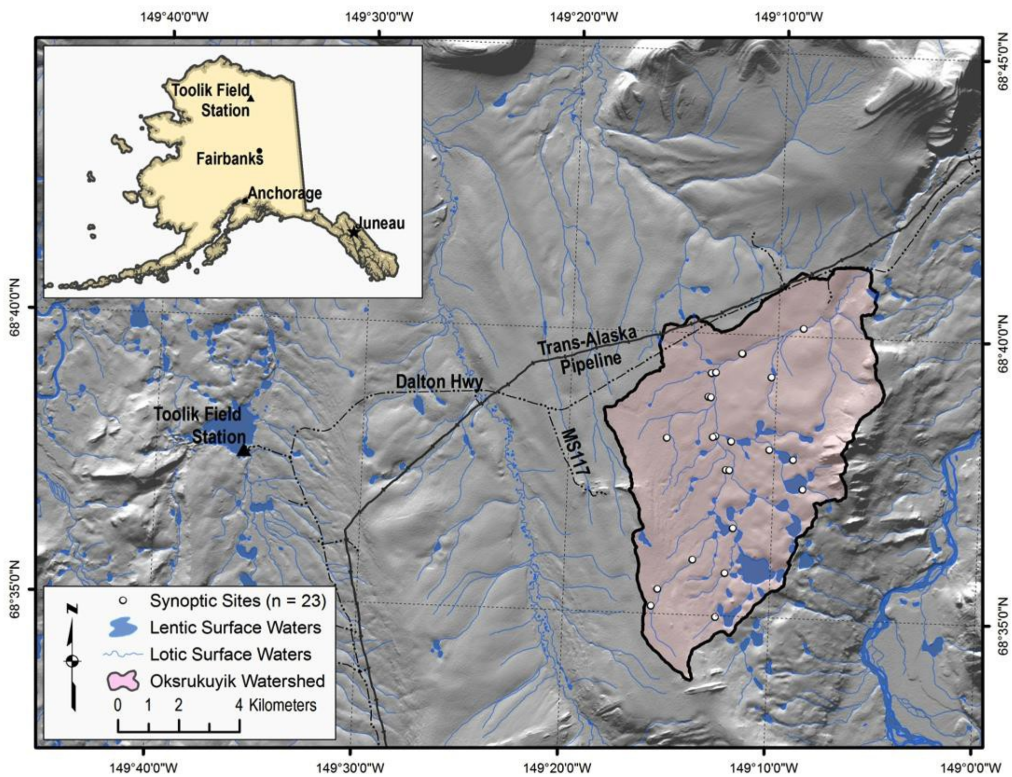


Figure 12. Comparison of PO4 uptake obtained from slug and plateau approaches for the I8Out study reach on 7/15 and 7/16/2011

SCALER – Bowden and Flinn

Twenty-three (*n* = 23) synoptic sampling sites were sampled in early August to determine background surface water nutrient concentrations throughout the basin (Figure below). Mean nitrate and ammonium concentrations for the synoptic surface water samples were 1.38 and 0.40 µmol L^{-1}, respectively. The nitrate concentrations ranged from 0.0 to 10.97 µmol L^{-1}, and 42.9% of the samples were below the detection limit of 0.035 µmol L^{-1}. Ammonium had a similar range of concentrations, from 0.0 to 7.42 µmol L^{-1}, and the majority of the samples were below the detection limit of 0.421 µmol L^{-1} (88.1%). Mean soluble reactive phosphorus (SRP) concentration among synoptic sites was 0.06 µmol L^{-1}. The SRP ranged from 0.0 to 0.15 µmol L^{-1} and 21.4% of the samples were below the detection limit of 0.038 µmol L^{-1}.



Part IV – Lakes

Activities

- Sentinel lake long-term sampling (Lakes group): Continued sampling of 16 sentinel lakes for limnological characteristics in order to understand changes in arctic lakes as a product of direct effects of climate change.
    - Continued to compare limnological characteristics of these lakes during the past two decades.
    - Continued to work on the addition of a new study lake in anticipation of local extinction in one of the long-term study lakes; had bathymetric map data collected for new lake.
- Continued to follow the water chemistry of lakes in the burn region (Lakes group). Some of these lakes are continuing to exhibit significant slumping. The five year data set is currently being analyzed.
- Whole system fertilization experiments (Lakes group): We continued fertilization of two lakes and monitoring the effects of fertilization on zooplankton and fish abundance patterns in the four experimental lakes (2 treatment, 2 control) in order to understand changes in arctic lakes as a product of indirect effects of climate change through a changing disturbance regime.
- Fish population dynamics (Budy & Thiede): To address both of above, we also continued annual fish sampling for population dynamics and community structure in the long-term experimental study lakes including mark-recapture study. As part of this activity, we continued laboratory assessment of fish diet contents and age/size structure of arctic char populations using otolith aging and size-frequency evaluations.
- Whole system fertilization experiments; additional components: (Lakes group)
    - Continued annual food web structure analyses using isotopic composition and dietary analyses. Over this reporting period, we quantified alternative pathways of secondary and tertiary energy flow not previously investigated in depth since 2000, before the fertilization experiment began (the fertilization is slated to be ended).
    - From 2011-2012, we have continued ongoing monitoring of lake benthic metabolism in fertilized and reference lakes (Giblin).
    - We also used sediment cores in the fertilized lakes to analyze changes in diatom species assemblages that accompany changing nutrient regimes (Daniels). This work has implications for food web and paleolimnologic studies.
    - Collected alkenone biomarker samples from the sediments and water column of a variety of lakes in the Toolik region over the course of the summer (Longo & Giblin).

Findings

- Sentinel lake long-term sampling (Figure 1): using the experimental lakes for preliminary analysis, it continues to be difficult to detect a consistent warming trend in lake summer temperatures associated with climate change. However, mid summer temperatures at 2 m were generally warmer on average as compared to the years 2000-2006. The lakes do also appear to experience some degree of synchrony as indicated in particular by the ubiquitous response to the cold summer of 2007.

- Fish population dynamics & food web structure (Figures 2, 3, 4, and 5):
  - We continue to observe dramatic variation in the diets of arctic char in the experimental and reference lakes (Figure 2; 2011 data). While both small and large char eat predominantly diperans in Fog2, small char consume other invertebrates and large char consume exclusively mollusks in Fog1. In E5, the fertilized lake, both large and small char consumed near equal proportions of fish, other invertebrates, and tricopterans with large char also consuming a significant proportion of mollusks.
  - Differences in diet and size structure among lakes is manifested in different trophic niche structure (Figure 3). In the Fog reference lakes, small char hold a higher trophic niche relative to large char, whereas in fertilized lake E5, the trophic niches of small and large char overlap and both appear to be more pelagic relative to the Fog lakes.
  - Fish abundance has remained stable in reference lake Fog2 but has increased dramatically in fertilized lake E5. At the same time char population size structure undergoes a dramatic cycle every 3-5 years (Figure 5).
  - Populations of fish in all study lakes remain particularly sensitive to day of ice-off, an environmental variable that may change significantly with climate change. Over the short term (< 10 years), we predict increased growth rates, increased net reproductive rate, and an in increase in the net biomass of fish. However, over the longer-term (> 10 years), we predict a dramatic increase in amplitude and duration of fish population structure cycles with a concordant increase in the probability of local extinction (e.g., lake level) (*in progress*).

- Whole system fertilization experiments: Zooplankton abundances in lakes receiving low levels of nitrogen and phosphorus have increased to date by 50% since the initiation of increased nutrient additions in 2001. Water clarity is greatly reduced in the fertilized lake, and Hydra has become more a more dominant part of the benthic community. Densities of arctic char have increased several fold, yet the age structure appears to be now temporarily stabilized at near equal proportions of small and large char after a period of dominance of a very high proportion of small char following increased lake productivity. A strong legacy effect of adding enriched nitrogen in 2001 still remains in the fertilized lake, nine years later, a pattern worthy of closer exploration. These data are under analysis and will be synthesized and finalized in 2012 (2011 was the final year of the fertilization)

- We have 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 subsequent there has been a reduction in both. However, since GPP has decreased more than respiration the NEP has decreased over time (Figure 6). Sediment chlorophyll concentrations also increased in the early years of the experiment but have now also decreased. Some of these changes however, are similar to Fog 2, a nearby reference lake where NEP and chlorophyll concentrations were lower in 2010-2011 than in previous years, however, Fog 2 normally showed a positive benthic NEP. The causes of interannual variability and threshold behavior are currently being considered.

- 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 locations (*in progress*). This work has implications for food web and paleolimnologic studies.

- Initial data shows that the degree of un-saturation in the alkenones responds to temperature and the lakes in the Toolik region. The preliminary data fall on a calibration curve developed for Greenland lakes. He has now been able to separate all of the tri-unsaturated alkenones into isomers and found isomers in every sample from Toolik, Fog2 and E5. This should allow for a more robust temperature calibration (*in progress*). The long term goal of this work is to use it to identify changes in temperature in this region of the arctic over the last 10,000 years and to see how changes in temperature correlate with other measures of lake productivity.

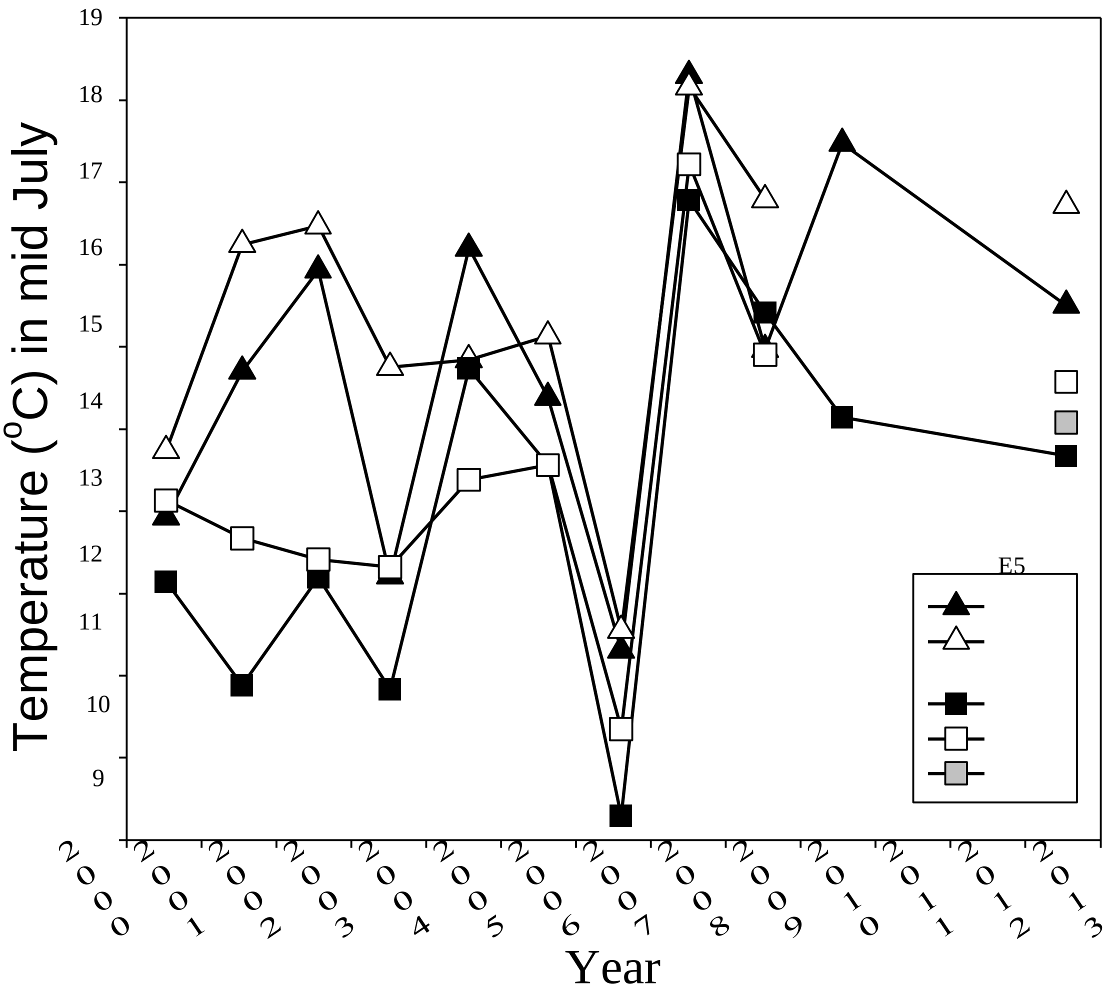


Figure 1. Mid-July temperature at the 2-m depth contour in the four experimental lakes, and newly added Lake Fog1.

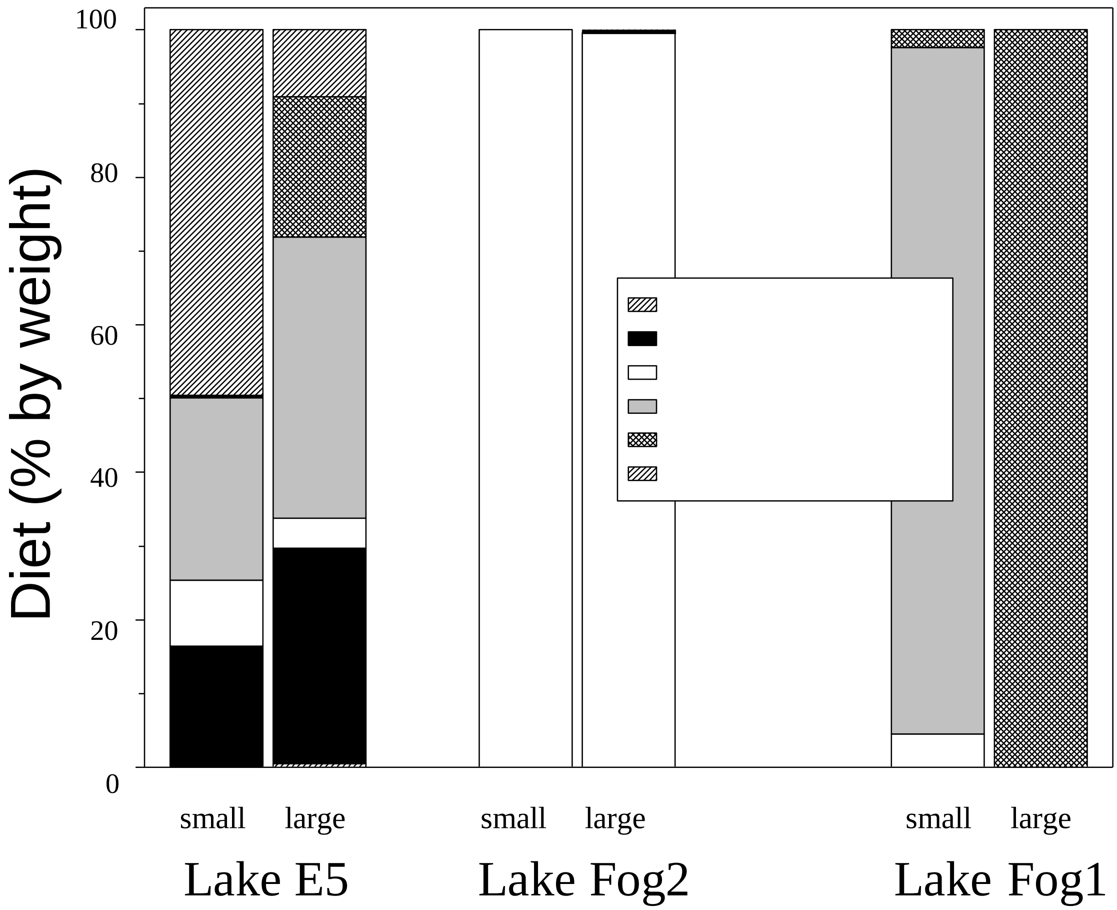


Figure 2. Diet proportion by percent wet weight from Arctic char collected in long-term study lakes E5, Fog2 and Fog1, 2011 - 2012. Data are shown for fish greater (large) and less than (small) 300 mm.

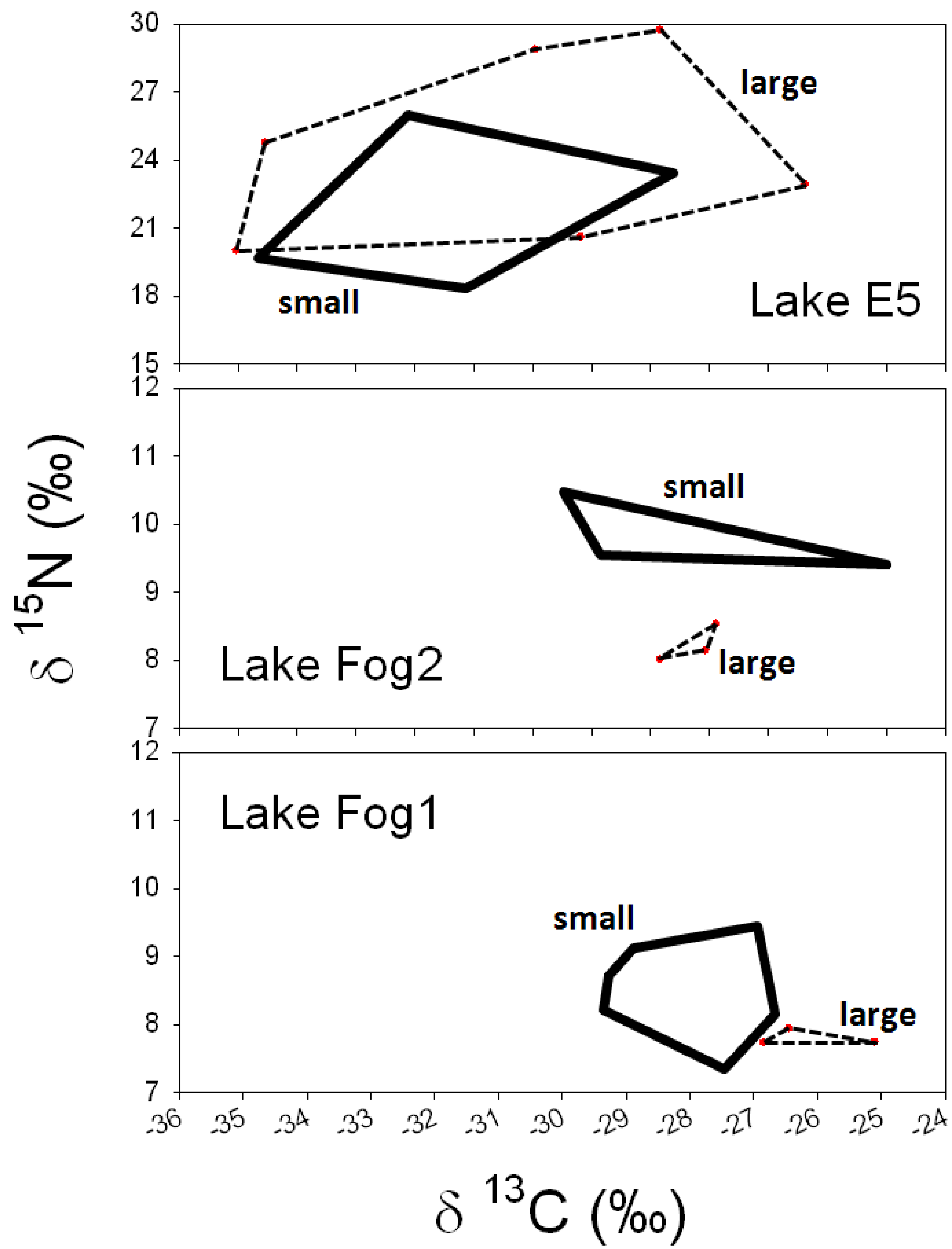


Figure 3. Convex hulls depicting trophic niche spaces (based on stable isotope analysis) occupied by small (< 300 mm TL; solid black hulls) and large (> 300 mm) arctic char (dashed-line hulls) in lakes E5 and Fog 2 (2008 - 2009), and Fog1 (2011). Note large changes in y-axis scales.

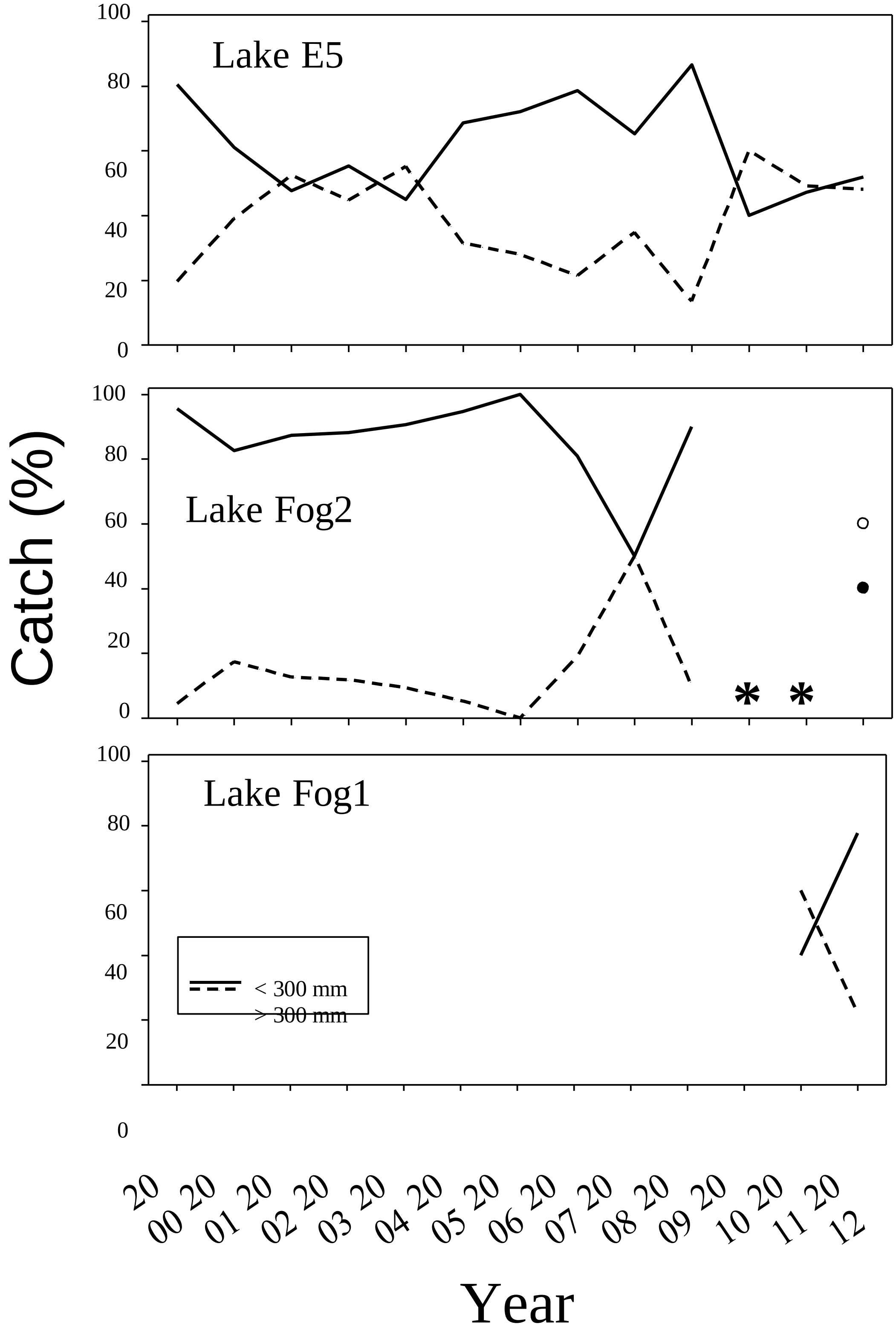


Figure 4. Percentage of catch (both angling and gill net) of small (< 300 mm TL; solid black line, circle) and large (≥ 300 mm TL; dashed line, open circle) arctic char in lakes E5 and Fog2, 2000 to 2012.

Asterisks indicate no char were caught in Lake Fog2 in 2010 and 2011. Lake Fog1 was added in 2011 due to low catch in Lake Fog2.

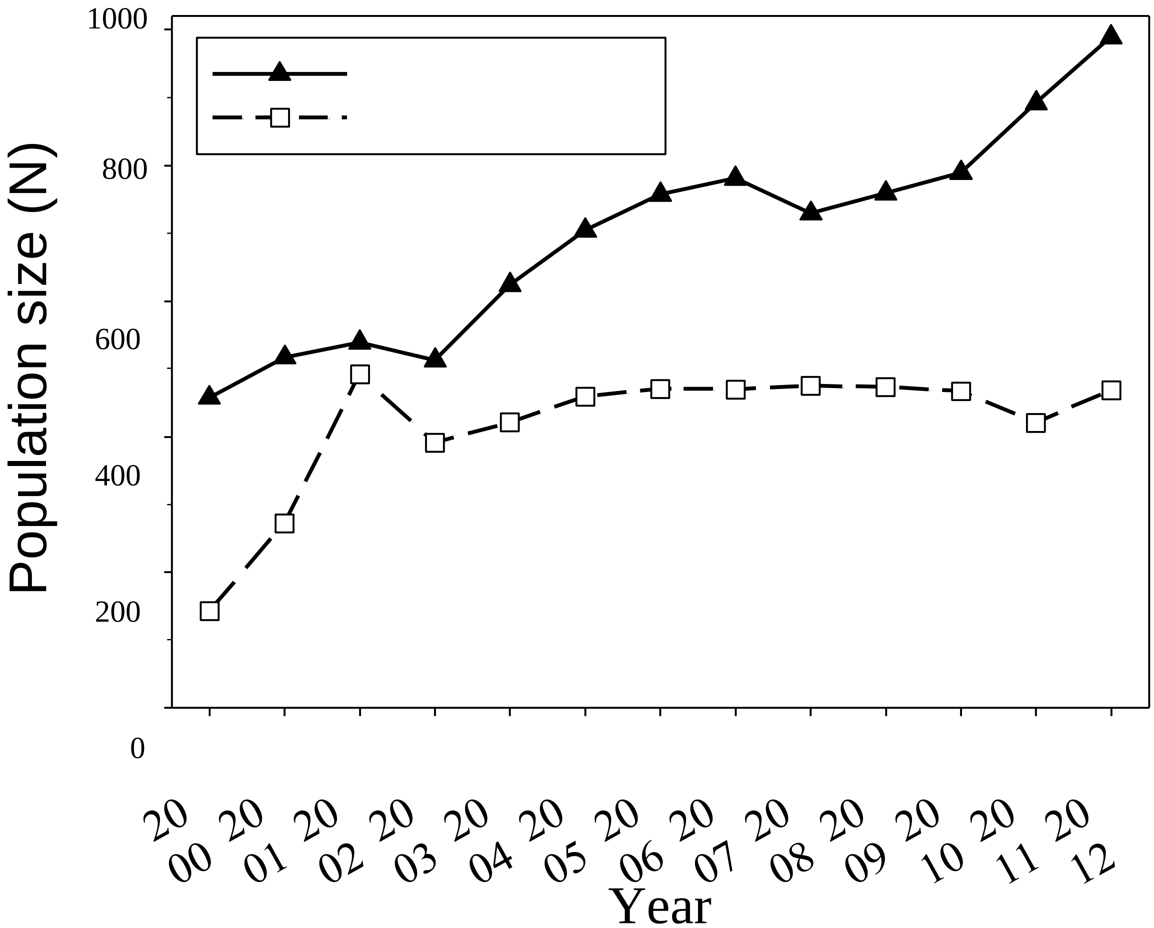


Figure 5. Annual population estimates (N_{hat}, Schnabel estimate based on mark-recapture) of arctic char in two deep experimental lakes: Lake E5 (fertilized, black triangles) and Lake Fog2 (reference, white squares) from 2000 – 2012.

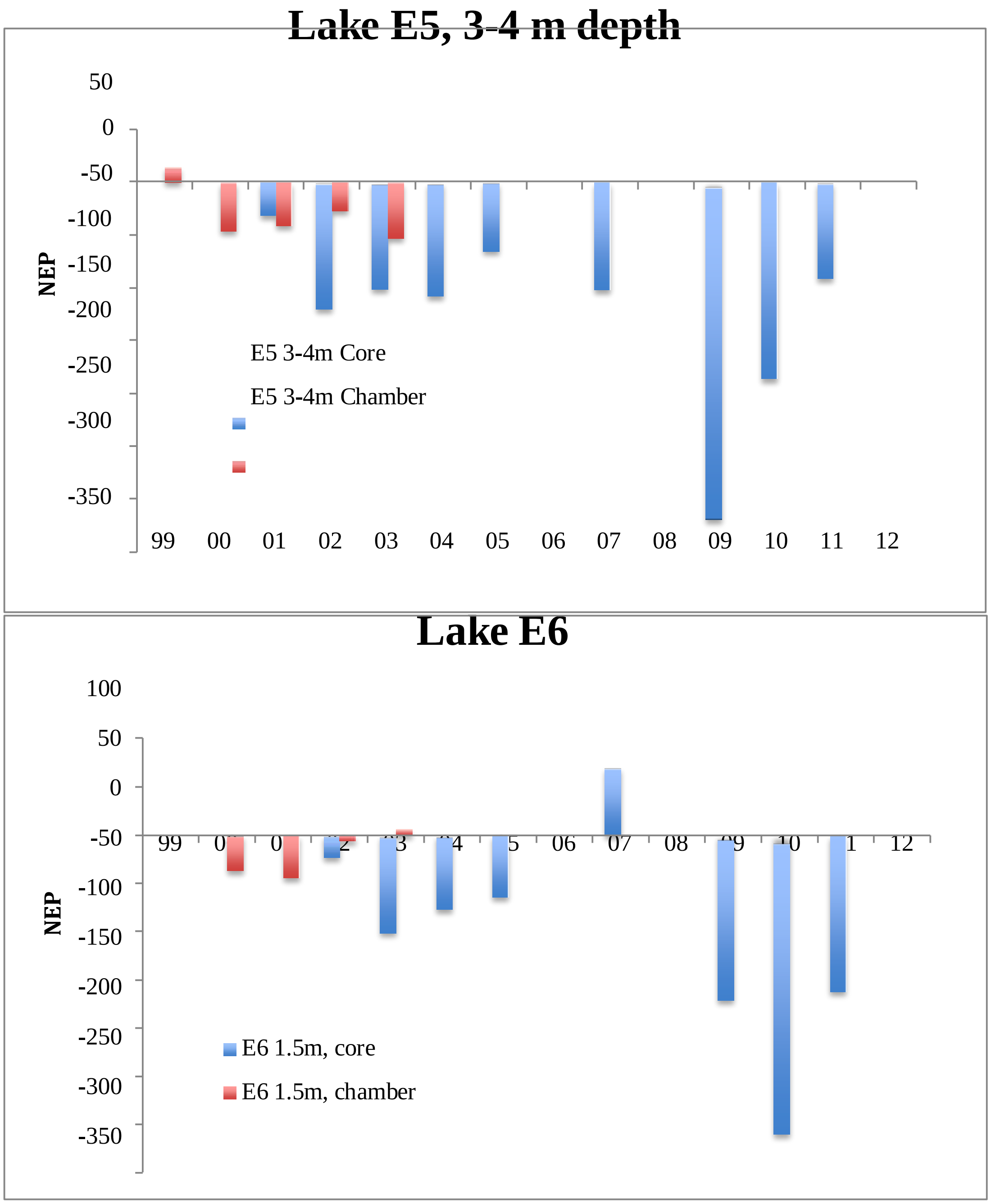


Figure 6. Changes in benthic net ecosystems production (NEP) over time in a deep (E5) and shallow (E6) fertilized lake. Measurements from 1999 to 2003 were made using in- situ benthic chambers. Measurements from 2001-2012 were made using cores brought back to the lab.