Final Report for Period: 01/2007 - 01/2007 **Submitted on:** 02/02/2007

Principal Investigator: Kling, George W. **Award ID:** 0408371

Organization: University of Michigan

Title:

Developing Process-Level Understanding of Controls on Belowground Carbon and Nutrient Dynamics in Tundra Ecosystems

Project Participants

Senior Personnel

Name: Kling, George

Worked for more than 160 Hours: Yes

Contribution to Project:

George Kling, University of Michigan, is lead PI on the project and is in charge of coordinating the entire project and specifically the research on dissolved carbon and nitrogen dynamics.

Name: Nadelhoffer, Knute

Worked for more than 160 Hours: Yes

Contribution to Project:

Knute Nadelhoffer, University of Michigan, is a co-PI on the project and is in charge of coordinating the research on root turnover and dynamics.

Post-doc

Graduate Student

Name: Judd, Kristi

Worked for more than 160 Hours: Yes

Contribution to Project:

Kristi Judd worked on the project as part of her dissertation, and graduated with her Ph.D. from the University of Michigan in 2004.

Name: Yelen, Lauren

Worked for more than 160 Hours: Yes

Contribution to Project:

Lauren Yelen started working on the project in late fall of 2004. She received her Masters degree from the University of Michigan in 2006.

Name: Keller, Katy

Worked for more than 160 Hours: Yes

Contribution to Project:

Katy Keller was supported in part by our project, and received her Ph.D. from the University of Michigan in May 2006.

Undergraduate Student

Technician, Programmer

Name: Randazzo, Suzanne

Worked for more than 160 Hours: Yes

Contribution to Project:

Suzanne Randazzo, University of Michigan, was the senior research technician on the project and was responsible for the day-to-day operations of the field and laboratory collections and analyses.

Name: Reichert, Julie

Worked for more than 160 Hours: Yes

Contribution to Project:

Julie Reichert has worked on the project since late fall 2004, and was employed as a technician at the University of Michigan. She has now entered a graduate degree program.

Name: Brosius, Laura

Worked for more than 160 Hours: Yes

Contribution to Project:

Laura Brosius graduated with a Bachelors degree from the University of Michigan in 2006, and worked on our project starting in May 2006. She was instrumental in collecting the final tussock tundra harvest in summer 2006, and is currently applying to graduate schools.

Name: Kostrzewski, Jennifer

Worked for more than 160 Hours: Yes

Contribution to Project:

Jennifer Kostrzewski has worked on our project since August 2006 analyzing root and plant samples for 14C content in the laboratory at the University of Michigan.

Other Participant

Name: Rastetter, Edward

Worked for more than 160 Hours: Yes

Contribution to Project:

Edward Rastetter, Marine Biological Laboratory, Woods Hole, is a co-PI on the project and in charge of the model development on the project.

Name: Johnson, Loretta

Worked for more than 160 Hours: Yes

Contribution to Project:

Loretta Johnson, Kansas State University, is a co-PI on the project and is responsible for the microbial dynamics research.

Name: Sommerkorn, Martin

Worked for more than 160 Hours: Yes

Contribution to Project:

Martin Sommerkorn was a postdoc on the project for 3 years, at which time he assumed a position at the MacCauley Institute, Aberdeen, and was made a co-PI on the project. He is responsible for the above-ground plant dynamics and gas fluxes.

Research Experience for Undergraduates

Organizational Partners

Marine Biological Laboratory

Project co-PI Edward Rastetter is located at the Marine Biological Laboratory

Kansas State University

Project co-PI Loretta Johnson is located at Kansas State University.

University of Copenhagen

Dr. Clemmensen of the Physiological Ecology Group, Botanical Institute, University of Copenhagen, Denmark, is helping us with the analysis of root symbionts.

University of Aberdeen

Project co-PI Martin Sommerkorn is located at the Macauley Institute, University of Aberdeen.

University of Alaska Fairbanks Campus

The Univ of AK-Fairbanks operates the Toolik Lake Research Facility where our field work is centered. Our project benefits from the laboratory space, housing, and communication facilites available at Toolik Lake.

Other Collaborators or Contacts

Dr. Annika Nordin, Forest Genetics and Plant Physiology, Swedish University of Agricultural Sciences, Umea, Sweden, is helping with some detailed analysis of tissue chemistry.

Activities and Findings

Research and Education Activities: (See PDF version submitted by PI at the end of the report)

See attached pdf on Activities and Findings.

Findings:

See attached pdf on Activities and Findings.

Training and Development:

Our training and development of young scientists has been extensive. At the University of Michigan, Dr. Kristi Judd has continued to participate in the project through the publication of her research on the project. She successfully defended her dissertation (November 2004), and moved on to a postdoctoral position working at The Institute for Ecosystem Studies with Dr. Gene Likens. Katy Keller was also supported in part by the project, and she successfully defended her Ph.D. dissertation in May 2006.

Lauren Yelen (Masters student at the Univ. Michigan) joined the project in late fall 2004, and graduated last semester. Her plans are to finish analyzing all her data this winter and prepare a manuscript for publication.

Nadelhoffer, Kling, and Johnson have continued to work with Dr. Jennifer King (Ph.D. 1999, U California Irvine) to complete manuscripts started using previously awarded funds. Dr. King assumed a new position as Assistant Professor in the Department of Soil, Water, and Climate at the University of Minnesota in 2001.

Dr. Wendy Loya successfully completed her Ph.D. thesis from Kansas State University in August 2001, and we have continued to work with her on publishing manuscripts from the project while she is a post-doctoral researcher in the School of Forestry and Wood Products at Michigan Technological University.

Dr. Martin Sommerkorn (MBL), who worked for 3 years as a postdoctoral researcher on our project, accepted a job as a professor at the MacCauley Institute in Aberdeen. His status on the grant was correspondingly upgraded and he was awarded a subcontract to continue working with us on the project.

Suzanne Randazzo worked on the project full time through summer of 2005, and has remained associated with the project by helping with data management and training of new personnel.

Julie Reichert took over the day-to-day operations (from Suzanne Randazzo) in the lab, and worked on processing field samples from 2005. Her experience on the project helped her to decide to go on to graduate school, where she is currently working toward a Masters degree.

Jennifer Kostrzewski (undergraduate at U. Michigan) has been conducting the grinding and 14C analyses of plant and soil samples since August 2006. Jennifer has a Masters in hydrology, and is currently considering her options for continuing on to get a Ph.D.

Laura Brosius was an undergraduate at U. Michigan, and when she graduated she started working as a research assistant on our project in summer 2006. She is currently applying to graduate schools for a Masters degree.

Ms. Karina Clemmensen, is a Ph.D. candidate at the University of Copenhagen, Denmark. She was awarded an independent grant to investigate mycorrhyzal processes. The title of her project is 'Ectomycorrhiza in the Arctic: implication for plant nutrition and carbon cycling'. Ms.

Clemmensen spent the field season of 2002 at Toolik Field Station to work with us in our 14C labeled tundra plots. She took responsibility for identifying and sorting mycorrhiza with the goal to quantify carbon allocation to mycorrhyza. Samples are being analyzed in both Woods Hole and Copenhagen.

Outreach Activities:

The outreach activities from our grant include various efforts, mainly in workshops and presentations, but also in the general category of talking with journalists, the public, and school children about the impacts of climate change on arctic ecosystems. The specific contributions include:

Workshops:

1. K. Nadelhoffer co-organized workshop entitled 'The Fate of Nitrogen Inputs to Terrestrial Ecosystems' at the National Center for Ecological Analysis and Synthesis (NCEAS) held January 10-14, 2005.

This was workshop #2 of a 3-workshop series designed to interpret ecosystem-scale 15N tracer studies. Knute Nadelhoffer is a co-organizer of these workshops (with : Drs. Pamela Templar and Michelle Mack). Nadelhoffer and Martin Sommerkorn participated and presented results and interpretations of 15N- plus 14C-labelling experiments in the arctic, using data from our OPP project.

2. Workshop on Root Turnover, Swedish University of Agricultural Science, Uppsala, Sweden, September 8-10, 2003: Sommerkorn, M., K. Nadelhoffer, L. Johnson, G.W. Kling, and E. Rastetter: 'Belowground production and turnover in wet sedge tundra as assessed by 14C tracer'.

Presentations:

1. Invited keynote address: 'Land-water Interactions in Arctic Tundra', G. Kling. To be presented at the 'Workshop on High latitude terrestrial and freshwater ecosystems: Interactions and response to environmental change', 11 - 14 September 2007, Abisko, Sweden.

2. Invited keynote address: 'A High Latitudes Ecological Observatory: Lessons Learned from Organizing the Great Lakes Regional Observatory'. Open meeting of the High Latitudes Ecological Observatory. Fairbanks, AK. (February 28, 2005) , K. Nadelhoffer.

3. Invited conference seminar, 'Atmospheric Nitrogen Deposition: Implications for Nutrient Cycling, Acidification and Terrestrial Ecosystem Functioning'. Conference titled: Acid in the Environment: Lessons Learned and Future Prospect. Goodwin-Niering Center for Conservation Biology and Environmental Studies, Connecticut College, New London, CT (April 1, 2005), K. Nadelhoffer.

4. Seminar Series, Department of Forest Ecology, Swedish University of Agricultural Sciences, Umea, Sweden. Sommerkorn, M., K. Nadelhoffer, L. Johnson, G.W. Kling, and E. Rastetter: 'Gazing into the peat: what controls the fate of belowground carbon allocation in tundra?'.

5. Seminar Series, Department of Plant and Soil Science, Aberdeen University, Scotland. Sommerkorn, M., K. Nadelhoffer, L. Johnson, G.W. Kling, and E. Rastetter: 'What controls the fate of belowground carbon allocation in tundra? Results from an Ecosystem Scale 14C, 15N Tracer Experiment'.

Education:

1. As part of the Schoolyard Project, funded as a supplement to the LTER project, Suzanne Randazzo helped four local high school students in Barrow, Alaska, designing and setting up warming and fertilization experiments in the local wet sedge tundra. During the summer small greenhouses were built and fertilized. The students collected various data sets which will be presented in their school science projects this winter. Suzanne Randazzo gave a public presentation on the project at Barrow and at the Toolik Field Station.

Journal Publications

Stieglitz, M., J. Shaman, J. McNamara, V. Engel, J. Shanley, G.W. Kling., "An approach to understanding hydrologic connectivity on the hillslope and the implications for nutrient transport.", Global Biogeochemical Cycles, p. art.no.11, vol. 17, (2003). Published

Oswald, W.W., L.B. Brubaker, F.S. Hu, G. W. Kling., "Holocene pollen records from the central Arctic Foothills, northern Alaska: testing the role of substrate in the response of tundra to climate change.", Journal of Ecology, p. 1034, vol. 91, (2003). Published

Loya, W. M., L. C. Johnson, G. W. Kling, J. Y. King, W. S. Reeburgh, K. J. Nadelhoffer., "Pulse-labeling studies of carbon cycling in arctic tundra ecosystems: the contribution of photosynthates to soil organic matter.", Global Biogeochemical Cycles, p. art.no.11, vol. 16, (2002). Published

King, J. Y., W. S. Reeburgh, K. K. Thieler, G. W. Kling, W. M. Loya, L. C. Johnson, and K. J. Nadelhoffer., " Pulse-labeling studies of carbon cycling in Arctic tundra ecosystems: the contribution of photosynthates to methane emission.", Global Biogeochemical Cycles, p. 1062, vol. 16, (2002). Published

Judd, K. E. and G. W. Kling., "Production and export of dissolved C in arctic tundra mesocosms: the roles of vegetation and water flow.", Biogeochemistry, p. 213, vol. 60, (2002). Published

Brown, J., G. W. Kling, K. M. Hinkel, L. D. Hinzman, F. E. Nelson, V. E. Romanovsky, and N. I. Shiklomonov., "Arctic Alaska and Seward Peninsula: The circumpolar active layer monitoring (CALM) program: Research designs and initial results.", Polar Geography, p. 165, vol. 24, (2002). Published

Wendy M. Loya, Loretta C. Johnson, Knute J. Nadelhoffer, "Seasonal dynamics of leaf- and root-derived C in arctic tundra mesocosms.", Soil Biology and Biochemistry, p. 655, vol. 36, (2004). Published

Johnston, C. A., P. Groffman, D. Breshears, Z. Cardon, W. Currie, W. Emanuel, J. Gaudinski, R. Jackson, K. Lajtha, K. Nadelhoffer, D. Nelson Jr., W. Post, G. Retallack, L. Wielopski., "Carbon cycling in soil.", Front. Ecol. Environ., p. 522, vol. 2, (2004). Published

Rastetter, E.B., B.L. Kwiatkowski, and R.B. McKane., "A Stable Isotope Simulator that Can Be Coupled to Existing Mass-Balance Models.", Ecological Applications., p. 1772, vol. 15, (2005). Published

Judd, K.E., B.C. Crump, and G. W. Kling, "Environmental drivers control ecosystem function in bacteria through changes in community composition.", Ecology, p. 2068, vol. 87, (2006). Published

Zak, D. R. and G. W. Kling., "Microbial Community Composition and Function across an Arctic Tundra Landscape", Ecology, p. 1659, vol. 87, (2006). Published

Keller, K., J. Blum, and G. W. Kling, "Geochemistry of soils and streams on surfaces of varying ages in arctic Alaska", Arctic, Antarctic, Alpine Research, p. In Press, vol. 39, (2007). Published

Judd, K. E., B. C. Crump, and G. W. Kling., "Bacterial responses in activity and community composition to photo-oxidation of dissolved organic matter from soil and surface waters.", Aquatic Sciences., p. , vol. , (2007). Accepted

Shaver, G.R., A.E. Giblin, K.J. Nadelhoffer, K.K. Thieler, M.R. Downs, J.A. Laundre, and E.B. Rastetter., "Carbon turnover in Alaskan tundra soils: Effect of organic matter quality, temperature, moisture, and fertilizer.", Journal of Ecology, p. 740, vol. 94, (2006). Published

Booth, M.S., J.M. Stark, and E.B. Rastetter., "Controls on nitrogen cycling in terrestrial ecosystems: a synthetic analysis of literature data.", Ecological Monographs, p. 139, vol. 75, (2005). Published

Rastetter, E.B., S.S. Perakis, G.R. Shaver, and A.I. Goran., " Terrestrial C sequestration at elevated CO2 and temperature: the role of dissolved organic N loss.",   Ecological Applications, p. 71, vol. 15, (2005). Published

Johnston, C. A., P. Groffman, D. Breshears, Z. Cardon, W. Currie, W. Emanuel, J. Gaudinski, R. Jackson, K. Lajtha, K. Nadelhoffer, D. Nelson Jr., W. Post, G. Retallack, L. Wielopski., "Carbon cycling in soil.",   Front. Ecol. Environ., p. 522, vol. 2, (2004). Published

Moore, J.C., E.L. Berlow, D.C. Coleman, P.C. de Ruiter, Q. Dong, A. Hastings, N.C. Johnson, K.S. McCann, K. Melville, P.J. Morin, K.J. Nadelhoffer, A.D. Rosemond, D.M. Post, J.L. Sabo, K.M. Scow, M.J. Vanni, and D.H. Wall., "Detritus, Trophic Dynamics, and Biodiversity.", Ecology Letters, p. 584, vol. 7, (2004). Published

Rastetter, E.B., B.L. Kwiatkowski, S. le Dize, and J.E. Hobbie., "The role of down-slope water and nutrient fluxes in the response of Arctic hill slopes to climate change.", Biogeochemistry, p. 37, vol. 69, (2004). Published

McKane, R., L.C. Johnson, B. Fry, G. Shaver, K. Nadelhoffer, E. Rastetter, B. Fry, A. Giblin, K. Kielland, B. Kwaitkowski, J. Laundre, and G. Murray., "Resource-based niches provide a basis for species diversity and dominance in an arctic plant community.", Nature, p. 68, vol. 415, (2002). Published

Hobbie, S. E., K. J. Nadelhoffer, and P. Högberg., "A synthesis: the role of nutrients as constraints on carbon balances in boreal and arctic regions.", Plant and Soil, p. 163, vol. 242, (2002). Published

Nadelhoffer K. J., L. Johnson, J. Laundre, A. E. Giblin, and G. R. Shaver., "Fine root production and nutrient use in wet and moist arctic tundras as influenced by chronic fertilization.", Plant and Soil, p. 107, vol. 242, (2002). Published

Johnson, L.C., G.R. Shaver, D.H. Cades, E. Rastetter, K. Nadelhoffer, A. Giblin, J. Laundre, and A. Stanley., "Plant carbon-nutrient interactions control CO2 exchange in Alaskan wet sedge tundra ecosystems.", Ecology, p. 453, vol. 81, (2000). Published

Books or Other One-time Publications

Kling, G.W., K. Judd, M. Sommerkorn, K. Nadelhoffer, E. Rastetter, and L. Johnson., "Transfers of carbon across the landscape: the controls on DOC, CO2, and CH4 production in soils.", (2003). ABSTRACT, Published
Bibliography: Ecological Society of America, 88th Annual Meeting, 3-8 August 2003, Savannah, GA. p. 185.

Sommerkorn, M., K. Nadelhoffer, L. Johnson, G.W. Kling, and E. Rastetter., "Carbon and nitrogen allocation of tundra plants assessed through an ecosystem scale dual tracer experiment.", (2003). ABSTRACT, Published
Bibliography: Ecological Society of America, 88th Annual Meeting, 3-8 August 2003, Savannah, GA. p. 315.

Judd, K.E., B.C. Crump, D.R. Zak, R.L. Sinsabaugh, and G. W. Kling., "Dissolved organic carbon in soils, streams, and lakes of an arctic catchment: linking bioavailability, chemistry, and microbial community composition.", (2003). ABSTRACT, Published
Bibliography: Ecological Society of America, 88th Annual Meeting, 3-8 August 2003, Savannah, GA. p. 173.

Judd, K.E., "Dissolved organic matter dynamics in an arctic catchment: Linking DOM chemistry, bioavailability, and microbial community composition.", (2004). Thesis, Published
Bibliography: Ph.D. Dissertation, The University of Michigan, 293pp.

Kling, G.W., D.R. Zak, and K. Judd., "Microbial communities and organic matter processing in heterogeneous environments ? are there patterns or redundancies at landscape scales?", (2004). Symposium Proceedings, Published
Bibliography: International Society of Microbial Ecologists, Society Meeting 22-27 August, Mexico, page 37.

Judd, K., B. Crump, G.W. Kling., "Natural variation of dissolved organic matter controls rates of bacterial production and structures bacterial communities.", (2004). Symposium Proceedings, Published
Bibliography: International Society of Microbial Ecologists, Society Meeting 22-27 August, Mexico, page 144.

Judd, K., B. Crump, and G. Kling, "Upslope dissolved organic matter controls bacterial activity through shifts in community composition", (2005). Proceedings, Published
Bibliography: EOS, Trans. American Geophysical Union, 86(18), Jt. Assem. Suppl., Abstract B24A-04

Judd, K.E., "Dissolved organic matter dynamics in an arctic catchment: Linking DOM chemistry, bioavailability, and microbial community composition", (2004). Thesis, Published
Bibliography: Ph.D. Dissertation, The University of Michigan, 293pp.

Keller, K. A., "Geochemistry of streams, soils, and permafrost and the geochemical effects of climate change in a continuous permafrost region, Arctic Alaska, USA", (2006). Thesis, Published
Collection: Ph.D. dissertation
Bibliography: University of Michigan, 180 pp.

Web/Internet Site

URL(s):
www-personal.umich.edu/~gwk/
Description:
This site describes the project in the context of arctic research done in the PIs laboratory.

Other Specific Products

Contributions

Contributions within Discipline:

Much more is known about above-ground C dynamic (plant growth and surface litter decay) than is known about belowground C dynamics in tundra (and most other) ecosystems, even though most tundra carbon is stored and cycled below ground. Knowledge about belowground C dynamics is required in order to assess the role of tundra ecosystems in the global C cycle and to predict how climate change will alter the C balances of tundra ecosystems. Our project is providing needed information about the magnitude of root growth in tundra ecosystems and about controls on (a) the rates of root growth by tundra plants and (b) the movements of root carbon to tundra soils (or peat), and (c) the transfers of root-derived carbon among particulate and dissolved organic material, microbes and gasses in tundra soils. We are accomplishing this by applying 14C and 15N tracers to replicate 1-m2 areas within long-term research plots and subsequently following the movements of these tracers through below- and aboveground ecosystem pools. Results of this field study will provide needed insights into belowground processes (i.e. rooting dynamics, soil organic matter formation and decay, CO2 and methane release) in tundra ecosystems. Also, results of the field studies will be used to test the predictions of a process-based model now under development about how tundra C cycling will be altered by climate changes.

Contributions to Other Disciplines:

We anticipate that the improved understanding of belowground processes in tundra resulting from our research will be useful for global-scale biogeochemical and climate models that will need to incorporate information on tundra carbon and nitrogen balances to predict how changes in tundra might either increase or decrease atmospheric CO2 accumulation in the future. As part of this effort, K. Nadelhoffer served as a member on the Oversight Board of the North American Nitrogen Center (NANC). The NANC is one of five globally distributed centers of the International Nitrogen Initiative (http://www.initrogen.org/) sponsored by the International Council of Science (ICSU) through the Scientific Committee on Problems of the Environment (SCOPE) and the International Geosphere-Biosphere Program (IGBP).

In addition, this project has contributed to the development of a new, general class of ecological model that can simulate the real-world conditions of multiple element needs and limitations. The two models developed (described in detail in the Activities and Findings section) will be used by plant physiologists, community and population ecologists, other modelers including (in time) regional climate modelers, as well as biogeochemists and ecosystem scientists.

Contributions to Human Resource Development:

Four Ph.D. students (Wendy Loya, Kansas State University, Jennifer King, UC-Irvine, Kristin Judd and Katy Keller, University of Michigan), one Masters student (Lauren Yelen, U. Michigan), and a postdoctoral Researcher (Dr. Martin Sommerkorn, MBL) have been key people in our research team. Their professional development was and still is strongly linked to our project, its objectives, and the ongoing writing of results for publication. They are learning to conduct their own research as part of a larger collaborative effort and are expected to author and co-author publications based on the project and to further develop their research skills during the course of their involvement with the project. Two of these researchers have now moved on to assume faculty positions, and the others have postdoctoral appointments. In addition, we continued to involve students (undergraduate through post-doctoral) as the project matured, and they will be associated with our ongoing efforts. This includes several REU students and undergraduate or recent graduate research assistants that we have supported over the years.

Contributions to Resources for Research and Education:

This project provided course material for use by the Principal Investigators, all of whom teach undergraduate courses at their home institutions (including the MBL at which a semester-long, intensive undergraduate course, the Semester in Environmental Science, is offered each fall). In addition to the contributions described in the 'Training and Development' section, we have contributed directly to the scientific education of others including:

Laura Brosius - Ms. Brosius (undergraduate at U. Michigan) worked as a temporary summer research assistant on our project in summer 2006. She is currently applying to graduate schools for a Masters Degree.

Maria Dzul - Ms. Dzul (undergraduate at U. Michigan) worked as a temporary summer research assistant on our project in summer 2005 and 2006, and she is currently completing her Bachelor's degree at the University of Michigan.

Shane Heath - Mr. Heath (Dartmouth College undergraduate) worked as a temporary summer research assistant for the LTER terrestrial group and on our project. In addition to his overall LTER responsibilities for collecting weather data, he participated in the team efforts of our project during periods of intensive sampling that followed plot labeling.

Varsha Mathrani - Ms. Mathrani (B.S. 2000, Scripps College) was a student in the MBL Semester in Environmental Science during the fall of 1999. She worked with Dr. Johnson at KSU and spent the summer working on our project participating in investigations of soil and microbial carbon cycling. She is currently a graduate student at the University of Michigan.

Vandana Mathrani - She also was a student in the MBL Semester in Environmental Science during the fall of 1999 and finished a B.S. in B.S. 2000 at Scripps College (simultaneously with her twin sister, Varsha). Vandana worked for approximately 1 month period during the summer to assist during a particularly busy sampling period. She gained valuable field research experience, and is currently working as a research technician at the University of Michigan.

Julie Reichert -- Julie was a technician at the University of Michigan who started working on our project in 2005. She has a Bachelor's degree in biology and chemistry, and wished to gain some practical research experience in a lab before moving on to graduate school. Julie was trained and took over the major day-to-day operations in late 2005, and then started a Masters Degree in graduate school in Fall 2006.

Contributions Beyond Science and Engineering:

Our project will provide critical information about how tundra soils, and therefore tundra ecosystems as a whole, may change as climate warms. This information will be of value to people dependent in whole or in part on tundra resources to maintain their livelihoods, managers of wildlife and natural resources in far northern regions, and to public policy makers and others with interests in tundra regions. It is interesting to note that the recent report on climate change impacts in the Arctic that was 4 years in the making (ACIA 2005), and received wide coverage in the national and international press, had very little description of studies or experiments or even models of how climate change will impact belowground ecosystems, especially carbon flow, in the future. We fully expect that the results from our project will help to remedy this lack of knowledge and ability to predict the future state of arctic ecosystems and the implications for people who depend on them.

Categories for which nothing is reported:

Any Product

ACTIVITIES and FINDINGS

This final report summarizes our activities and findings on the grant so far. The final harvest of the tussock tundra plots occurred in summer 2006, and we have almost completed the data analysis of plants and other materials collected. The PIs met this last summer in the field, and a final synthesis meeting will occur in Woods Hole at the end of February. In the summer field meeting we reviewed the results to date, planned the completion of the summer field season, and continued the conceptual development of the model. At the synthesis meeting in Woods Hole we will discuss the most recent data and overall progress of the project; a summary of the activities and findings is presented here.

Activities:

The main *activity* in the field this year was the final harvest of the tussock tundra site which was labeled 4 years ago. This completes the full data set of harvests for both ecosystem types, tussock tundra and wet sedge tundra, 4 years after their initial labeling with 14C. The sampling associated with this harvest included above- and belowground plant tissues, microbial biomass, dissolved carbon and nitrogen (inorganic and organic) and gaseous (CO_2 and CH_4) pools for ^{14}C and ^{15}N labels. We also made estimates of above and below ground biomass, of productivity and respiration rates, and of microbial activity.

Currently our *activities* include analyzing the plant, soil, and some dissolved samples (dissolved organic carbon and nitrogen) that we collected the two last summers in order to synthesize our understanding of belowground carbon flows. This synthesis will include the mass-balance of the two isotope tracers used for C and N. Sample analysis is being carried out at the University of Michigan, at Kansas State University, and at the Macaulay Institute, Scotland. The modeling activities are centered at Woods Hole. As these final data become available our activities will switch back to writing journal articles and making presentations about the results.

Finally, our education *activities* (detailed in another section of the report) have included the training of two Ph.D. students (Kristi Judd and Katy Keller) and a Masters student (Lauren Yelen) at the University of Michigan. Dr. Judd defended her thesis in 2004 and is currently in a postdoctoral position at The Institute for Ecosystem Studies working with Dr. Gene Likens. Dr. Keller completed her Ph.D. thesis in May 2006, and Ms. Yelen completed her Masters thesis in fall of 2006.

Findings:

Our *findings* indicate that the added label was still in sufficient abundance to trace the flow of carbon between different soil pools such as soil organic matter and microbial biomass, as well as in persistent plant tissues, such as wood and evergreen leaves.

The gaseous and soil water samples collected this summer were analyzed in the field. For these samples, we found that the added label has become so dilute in these rapid turnover pools that we cannot detect it in the plots. This was to be expected, and it will help us to parameterize our model of how C moves belowground.

The *major finding* from this work has been that the contribution of roots alone to the dissolved pools of DOC, DIC, CO_2 , and CH_4 in the soils is much larger than previously thought. Results show that the total amount of dissolved carbon produced from the roots per m^2 is ~300 times greater than the total output of dissolved carbon (per m^2) from tundra catchments. This implies not only a rapid root turnover, but also that a tremendous amount of carbon processing occurs somewhere on the landscape before draining from a watershed or flowing into the coastal oceans.

In order to help *synthesis our activities and findings* we have been developing several computer models. The goal is to simulate belowground carbon and nutrient dynamics in these tundra ecosystems. Last year Dr. Sommerkorn applied for and obtained a grant from the Royal Society of Edinburgh paying for a two-week visit of Dr. Rastetter to The Macaulay Institute in Aberdeen, Scotland, during April. Continuing a collaboration stemming from Dr. Sommerkorn's affiliation with The Ecosystem Center, we worked on developing a model of C and N allocation in tundra ecosystems. In collaboration with Dr. B. Foereid, who also visited Dr. Rastetter, we furthermore explored the possibility for its application in a Scottish organic soils. The visit was highly productive and resulted in the development and the first calibration of the proposed model. We plan to apply the model to our datasets as the next step and anticipate starting to write manuscripts on this exercise shortly.

Results from this project also have been used in the restructuring of the Multiple Element Limitation (MEL) model. Rastetter has now generalized the model to include more than just two elements, non-element resources (e.g., light), and substitutable resources (e.g., NH_4, NO_3, DON, and N fixation as substitutable sources of N). The model simulates changes in resource acquisition by redistributing plant assets allocated toward resource uptake. The resource requirement ($\boldsymbol{R_i}$) is calculated as the rate of the resource loss in tissue turnover, plus the rate of consumption in maintenance metabolism, plus the rate of consumption as part of the uptake of other resources. The acclimation is then calculated based on the ratio of requirement to uptake:

$$\frac{d\boldsymbol{V}_i}{d\boldsymbol{t}} = \boldsymbol{a} \ln\left(\Phi \frac{\boldsymbol{R}_i}{\boldsymbol{U}_i} \right) \boldsymbol{V}_i \qquad (1)$$

where $\boldsymbol{V_i}$ is the fraction of uptake assets allocated toward the acquisition of resource $\boldsymbol{i}$, $\boldsymbol{a}$ is a rate parameter, $\boldsymbol{R_i}$ and $\boldsymbol{U_i}$ are the requirement and uptake rates, and Φ is a variable that is selected to ensure that the $\boldsymbol{V_i}$ sum to one:

$$\Phi = \prod_{j=1}^{n} \left(\frac{\boldsymbol{U}_j}{\boldsymbol{R}_j} \right)^{V_j} \qquad (2)$$

For substitutable resources (i.e., resources filling the same requirement), the requirement is partitioned based on the uptake rates per unit allocated effort, which we call the yield. Yield includes not only the effort directly allocated toward uptake to the resource, but also effort allocated toward the uptake of other resources consumed during uptake (e.g., the C cost of N fixation). Allocation of effort will be toward the substitutable resource with the highest yield.

At steady state, all the dV_i/dt equal zero, which can only occur if

$$\frac{U_i}{R_i} = \Phi; \text{for all } i \qquad (3)$$

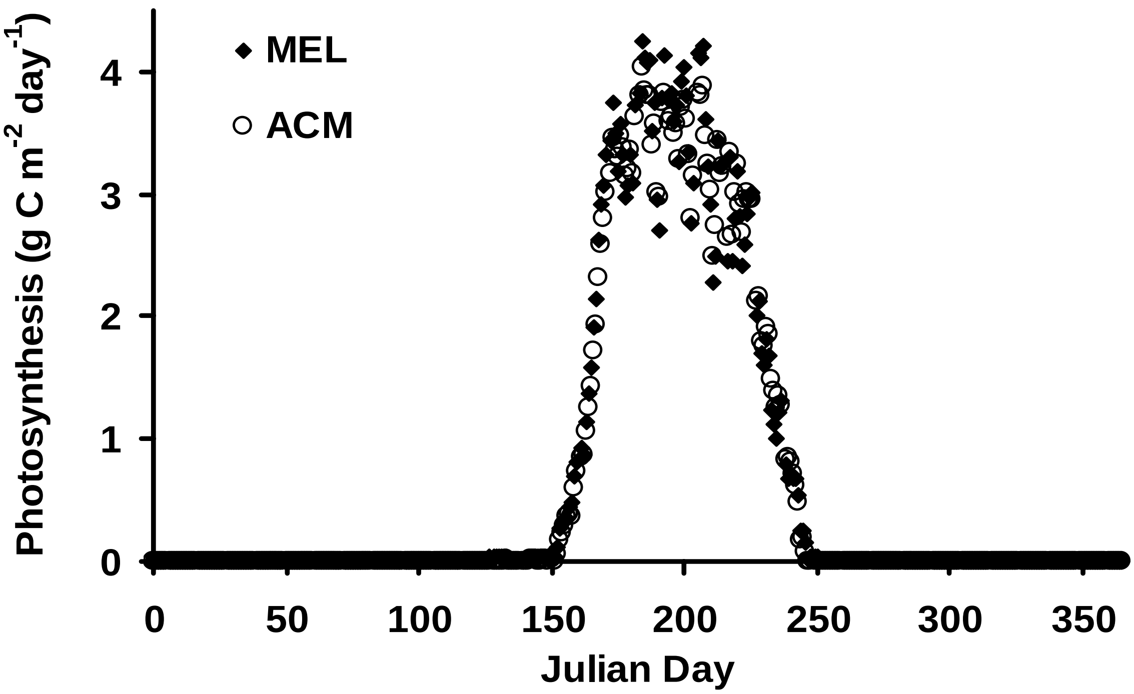

Figure 1: Photosynthesis predictions based on the MEL model for Tussock Tundra. Predictions with the Williams et al. (1997; Ecological Applications 7:882-894) Aggregated Canopy Model (ACM) are shown for comparison.

That is, the ratios of acquisition to requirement for all resources are equal (but not necessarily equal to one). It is in this sense that all resources are equally limiting at steady state. Figure 1 shows that the new model exhibits a close correspondence with older, established models that do not have the ability to incorporate the real world situation of multiple element requirements. The development of this model will aid not only our efforts, but those in various disciplines that consider how plants in general operate under different conditions and in different ecosystems.

A second model we have developed incorporates a soluble (sol) and a structural (str) component for each of three plant tissues (leaves = L, stem = S, and roots = R). The soluble component exchanges between leaves and stem and between stem and roots. The structural components grow from the soluble components of the respective tissues. Respiration losses are from the soluble pools and there is also a turnover loss from the structural pools (Fig. 2).

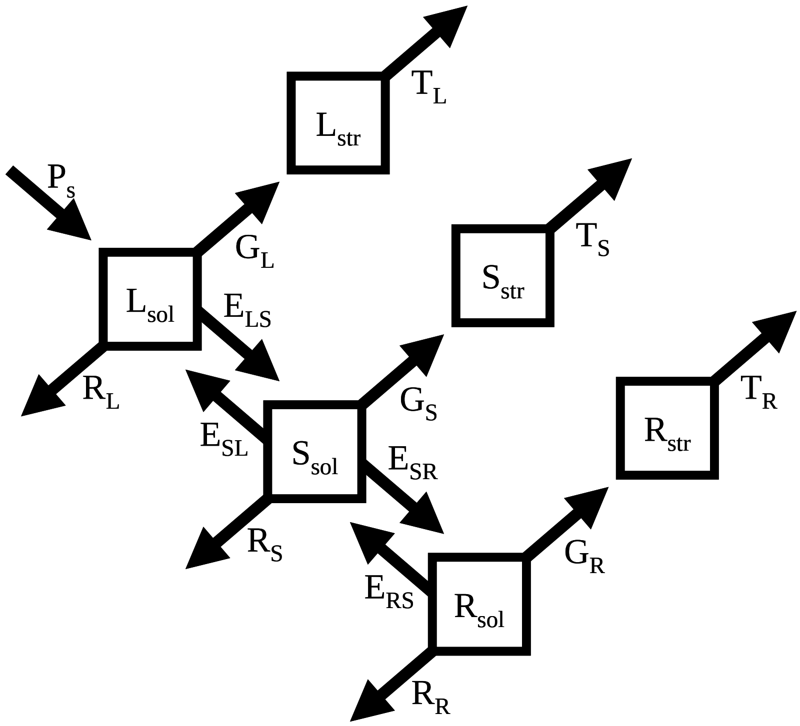

Figure 2: Model structure. L, S, and R indicate leaves, stem, and roots. P_s is photosynthesis, T_x, G_x, and R_x are turnover, growth, and respiration for tissue x, and E_{xy} is the exchange of soluble C from tissue x to tissue y.

The dynamic equations of this model are as follows:

(1) $$\frac{dL_{sol}}{dt} = P_s - G_L - R_L - E_{LS} + E_{SL}$$

(2) $$\frac{dL_{str}}{dt} = G_L - T_L$$

(3) $$\frac{dS_{sol}}{dt} = E_{LS} - G_S - R_S - E_{SL} - E_{SR} + E_{RS}$$

(4) $$\frac{dS_{str}}{dt} = G_S - T_S$$

(5) $$\frac{dR_{sol}}{dt} = E_{SR} - G_R - R_R - E_{RS}$$

(6) $$\frac{dR_{str}}{dt} = G_R - T_R$$

The magnitude of each C flux except photosynthesis is assumed to be proportional to the magnitude of the C pool from which it originates (photosynthesis is assumed constant).

Growth equations:

(7) $G_L = g_L L_{sol}$ (8) $G_S = g_S S_{sol}$ (9) $G_R = g_R R_{sol}$

Respiration equations (with this structure, root exudates are lumped in with root respiration):

(10) $R_L = r_L L_{sol}$ (11) $R_S = r_S S_{sol}$ (12) $R_R = r_R R_{sol}$

Turnover equations:

(13) $T_L = t_L L_{str}$ (14) $T_S = t_S S_{str}$ (15) $T_R = t_R R_{str}$

Exchange equations:

(16) $E_{LS} = \varepsilon_{LS} L_{sol}$ (17) $E_{SL} = \varepsilon_{SL} S_{sol}$

(18) $E_{SR} = \varepsilon_{SR} S_{sol}$ (19) $E_{RS} = \varepsilon_{RS} R_{sol}$

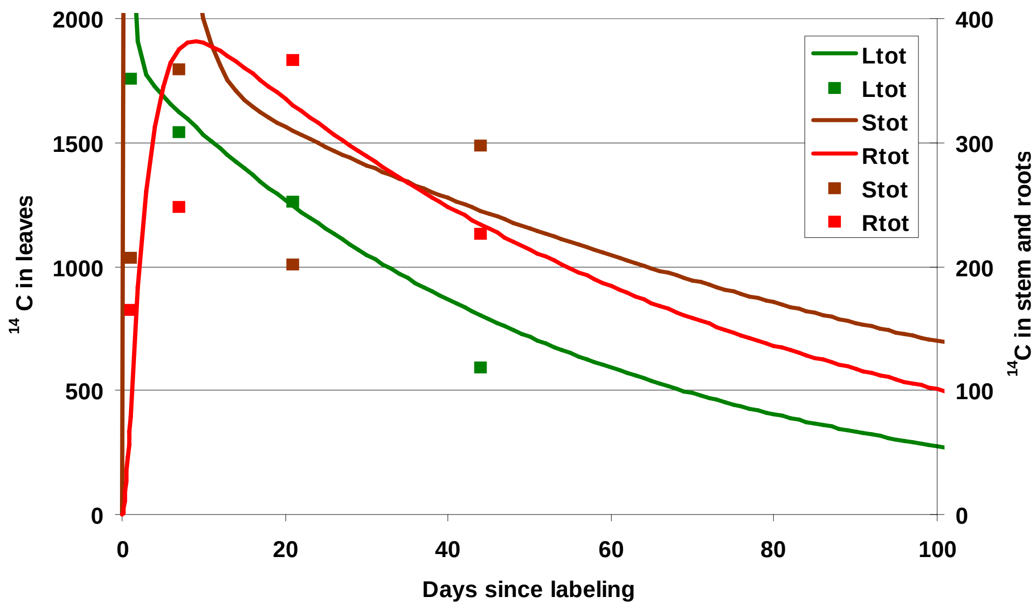

Figure 3: ^{14}C simulations and data

The thirteen parameters can be estimated using an optimization routine to fit the model to data. For the ^{14}C data, we fit the model by assuming all the label was initially in the leaf soluble component (L_{sol}), P_s was zero (i.e., no new ^{14}C entering the system), and used a least-squares approach to minimize the deviations between observed ^{14}C in each tissue and the modeled soluble plus structural components of the tissues (i.e., fit $L_{sol} + L_{str}$, $S_{sol} + S_{str}$, and $R_{sol} + R_{str}$ to observations).

The model fit the data very well assuming only downward flow of carbohydrate (i.e., no ^{14}C flow from stem to leaves or from roots to stem) so $\varepsilon_{SL} = 0$ and $\varepsilon_{RS} = 0$. We also had to assume that respiration losses are derived from the structural pools rather than the labile pools as was initially conceived for the model structure. Thus, the turnover (T_x) includes respiration so that $r_L = 0$, $r_S = 0$, and r_R is assumed to represent root exudates only (Fig. 4). These assumptions allowed us to remove four of the thirteen parameters. The problem with lumping respiration into the turnover is that we don't know how to separate growth from respiration. The results of this parameterization indicate that of the 2.82 gC/m^2/day entering the plant as photosynthesis, 1.05 is allocated to leaves, 0.21 is allocated to stem, 0.25 is allocated to roots, and 1.31 is lost as root exudates.

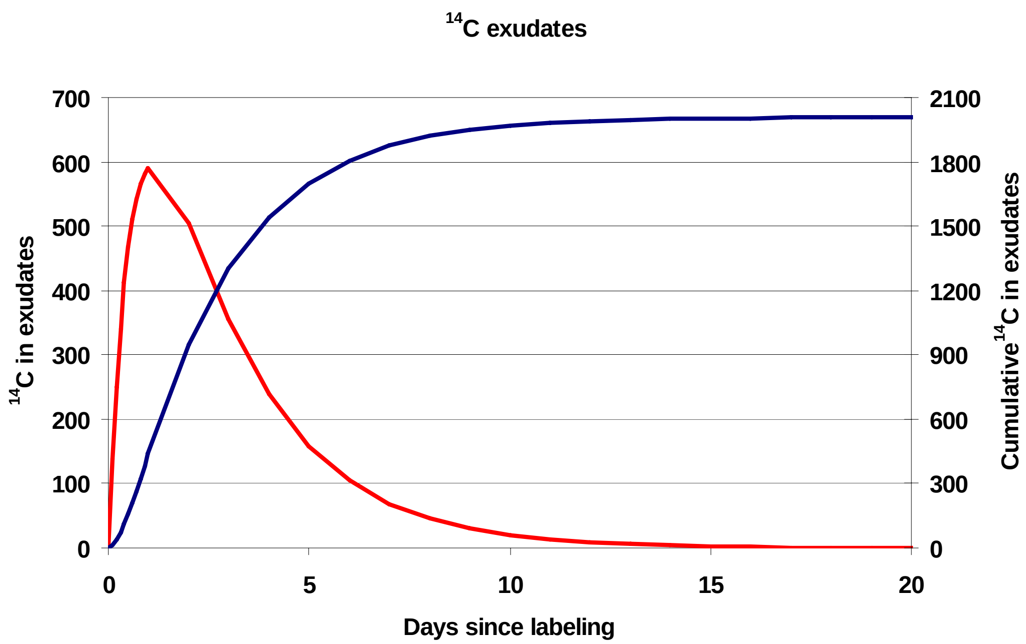

Figure 4: Simulated ^{14}C exudates (red) and cumulative exudates (blue)

Future Activities

The overall **GOAL** of our project is to **increase understanding of processes controlling C and nutrient inputs to arctic soils from belowground sources, and to predict how climate change will alter C storage and nutrient cycling in tundra ecosystems.** We will continue the final laboratory analysis, and then the writing and modeling activities to achieve this goal. As the data manuscripts are published we will finish the modeling work that will allow a synthesis of the large amount of data on the vegetation and biogeochemical dynamics of tundra ecosystems.

The manuscripts will be completed in part by taking advantage of several meetings and conferences that the PIs will attend. Currently this list includes an NCEAS workshop in Santa Barbara (Nadelhoffer and Sommerkorn attending), a meeting in Michigan (Kling, Nadelhoffer, and Sommerkorn attending), and the Arctic LTER meeting in Woods Hole (all PIs attending) in spring 2007.