Acquisition and Integration of New Knowledge from Arctic Ecosystems into Earth Systems Models (ACME)

Presented to the
BER Advisory Committee

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Environmental Sciences Division
Oak Ridge National Laboratory

Gaithersburg, Maryland
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Deliver a process-rich ecosystem model, extending from bedrock to the top of the vegetative canopy/atmospheric interface, in which the evolution of Arctic ecosystems in a changing climate can be modeled at the scale of a high-resolution Earth System Model grid cell.

Challenges:

…a process-rich ecosystem model

- *Mechanistic studies in the field and laboratory in order to understand not only what happens but why, and integration with models.*

…evolution of Arctic ecosystems

- *Fundamental science, and modeling strategies, that allow us to represent landscape change based on our knowledge of surface and subsurface systems.*

…scale of a high-resolution Earth System Model grid cell

- *Our models must allow us to integrate information obtained in the field and laboratory into Earth System Models (ACME), and do so taking into account landscape complexity and heterogeneity.*

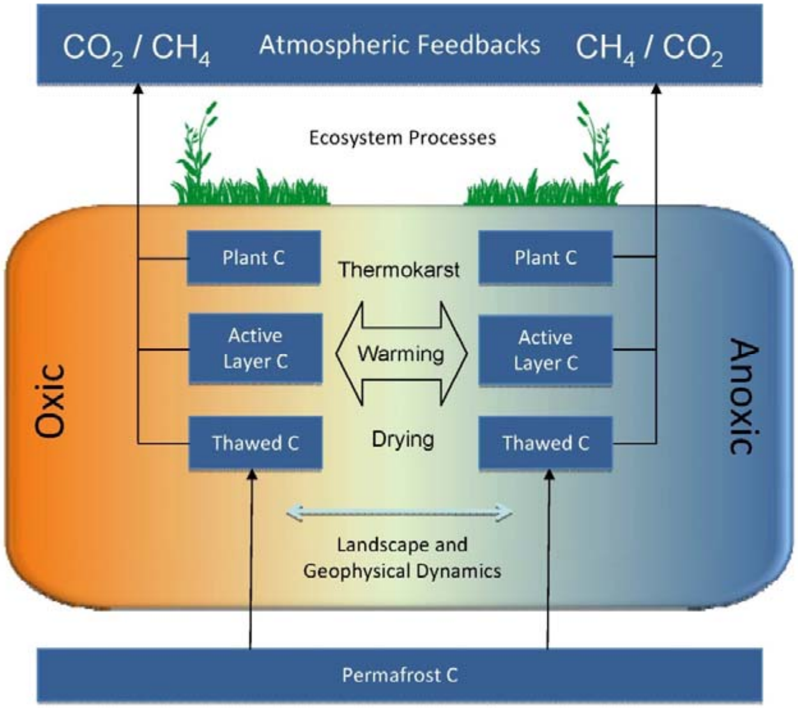
NGEE Arctic Strategy

- **Phase 1 (2012-2014):** Advanced a multi-scale measurement and modeling framework for polygonal landscapes on the North Slope of Alaska.
- **Phase 2 (2015-2018):** Collaborate with ACME effort to drive land surface model development in high-latitude ecosystems through improved process representation from bedrock to the atmospheric boundary layer.
- **Phase 3 (2019-2022):** Conduct pan-Arctic simulations using the ACME Land Model (i.e., ALM) that is parameterized, tested, and benchmarked (e.g., ILAMB) against NGEE Arctic measurements and synthesis products.

NGEE Arctic Approach

Understand the coupling that occurs between biological, geochemical, and landscape processes, taking into account how different components of complex systems are linked and the dynamic interplay that determines system behavior.

Upland Ecosystems



Schuur et al. (2008)

Lowland Ecosystems

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Climate Feedbacks in Arctic Ecosystems

Permafrost Thaw

Permafrost contains 1700 Pg C

A large fraction of that permafrost could thaw by 2100 (*Slater and Lawrence, 2013*)

Microbial decomposition of this C could represent a positive feedback to climate warming

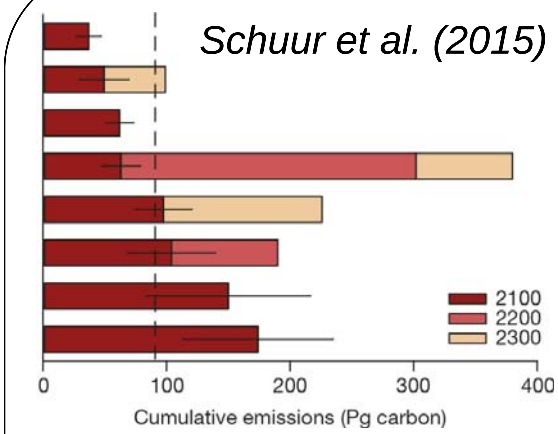
Shrub Expansion

Shrub expansion in Alaska (*Tape et al, 2005*)

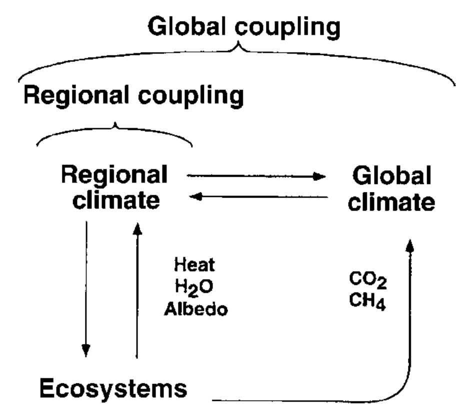
Changes in albedo could mediate feedbacks to climate, but the magnitude is uncertain

Complement carbon cycle with expanded focus on biophysical feedbacks to climate

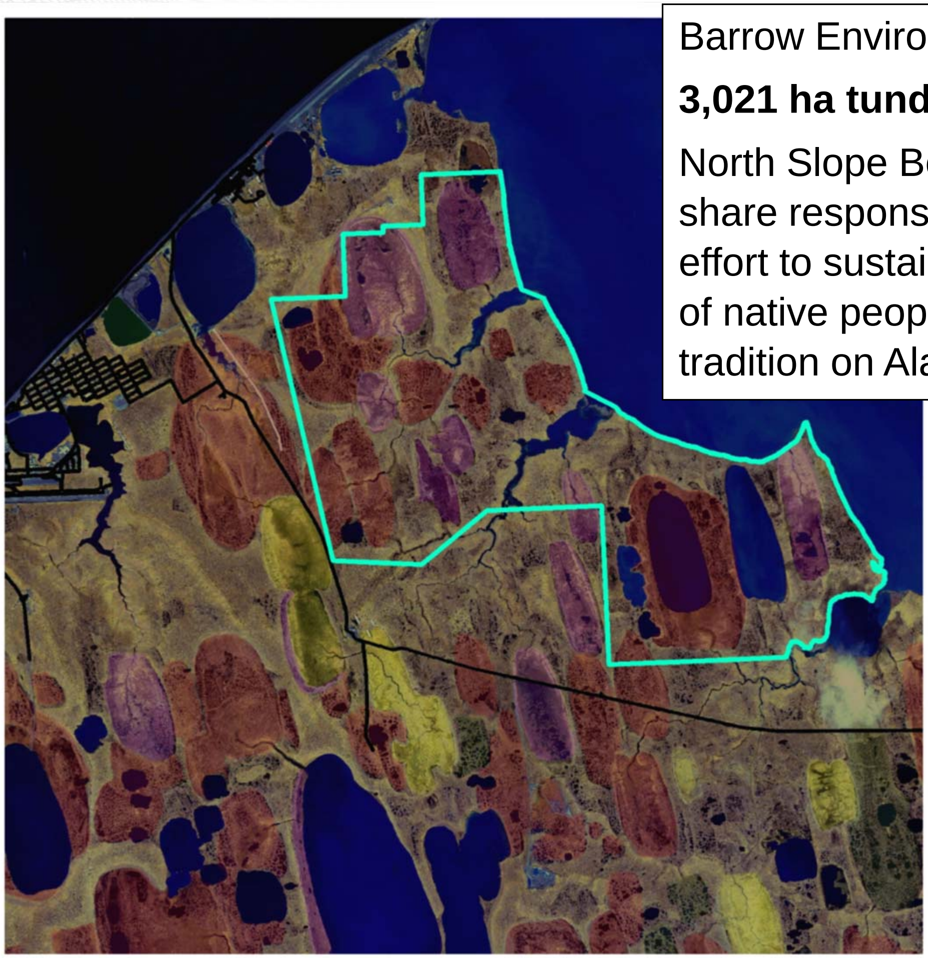
Emphasis on plant traits and dynamics



Schuur et al. (2015)



NGEE Arctic Field Sites (Phase 1)



Barrow Environmental Observatory (BEO)

3,021 ha tundra preserve

North Slope Borough and UIC Science share responsibilities for the BEO in an effort to sustain the long-term commitment of native people to the scientific research tradition on Alaska’s North Slope.

Federal Agency and Program Collaborations

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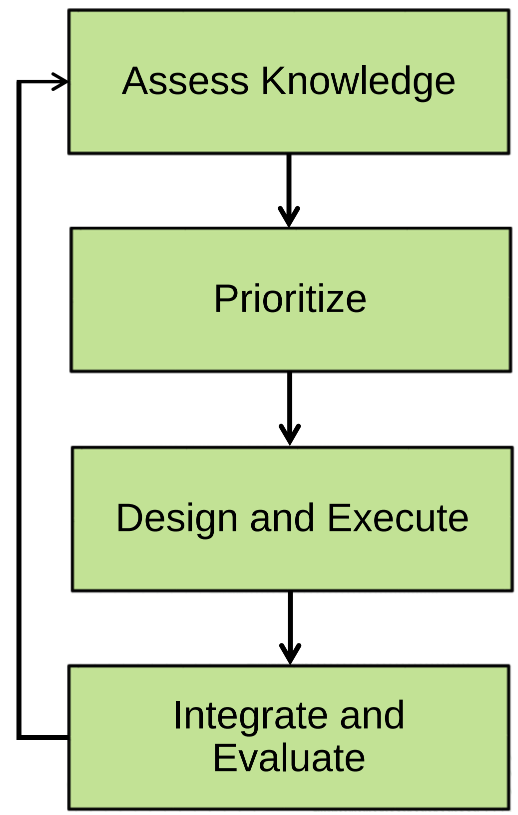
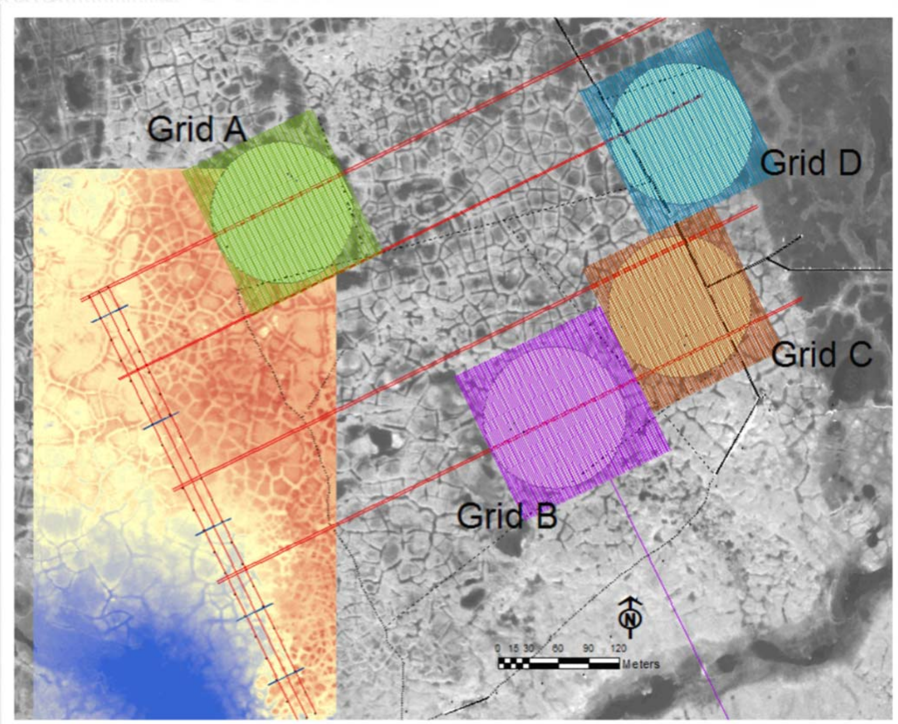
Phase 1 Tasks

1. Scaling Framework Development
   - Scaling strategy and landscape characterization
2. Model Development with Links to Process Studies
   - Fine, intermediate, and climate scales
3. Process Studies with Links to Model Development
   - Site design and characterization
   - Geomorphology
   - Geophysics
   - Hydrology
   - Biogeochemistry
   - Vegetation dynamics

Philosophy

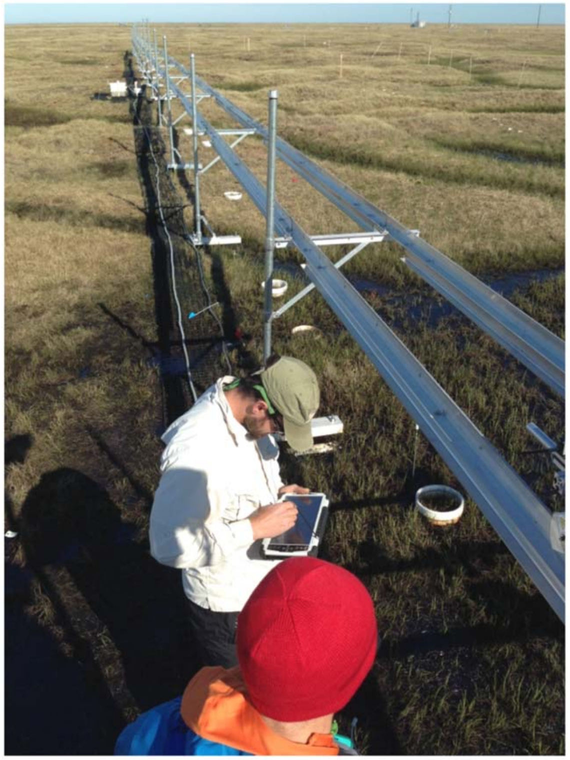


Site Design and Characterization



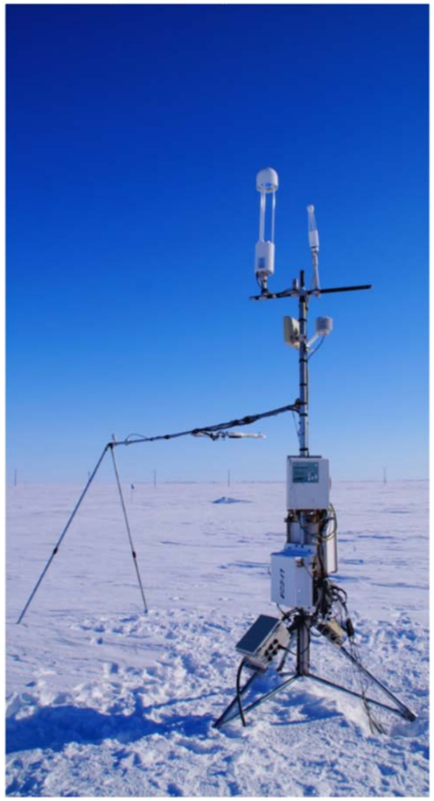
Transects, replicated plots, and synoptic surveys across distinct geomorphological features provided the sampling strategy for Phase 1.

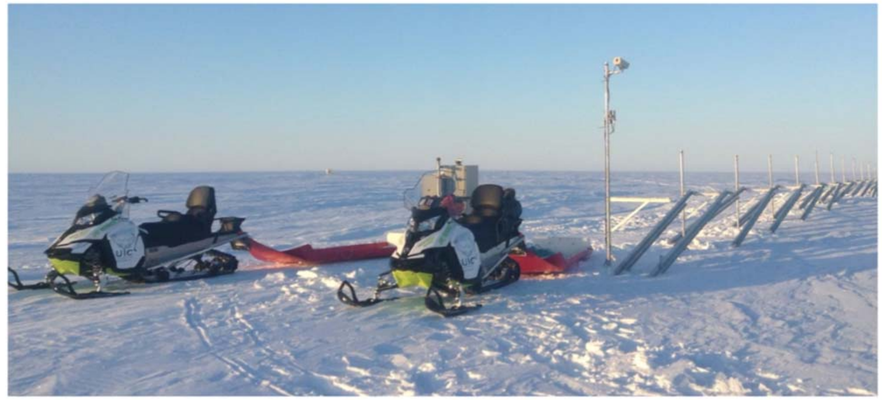
Site Design and Characterization



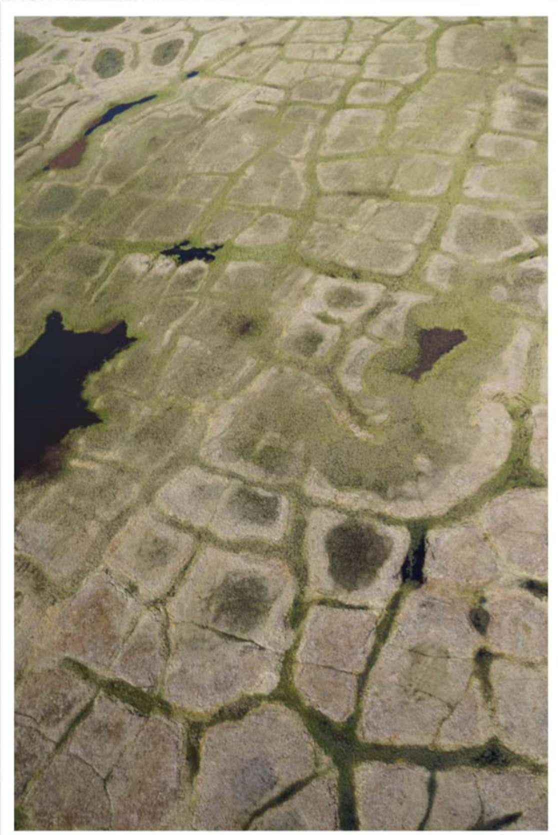
Instruments and infrastructure support the sampling and scientific strategies of the NGEE Arctic project.

Yesterday in Barrow, AK

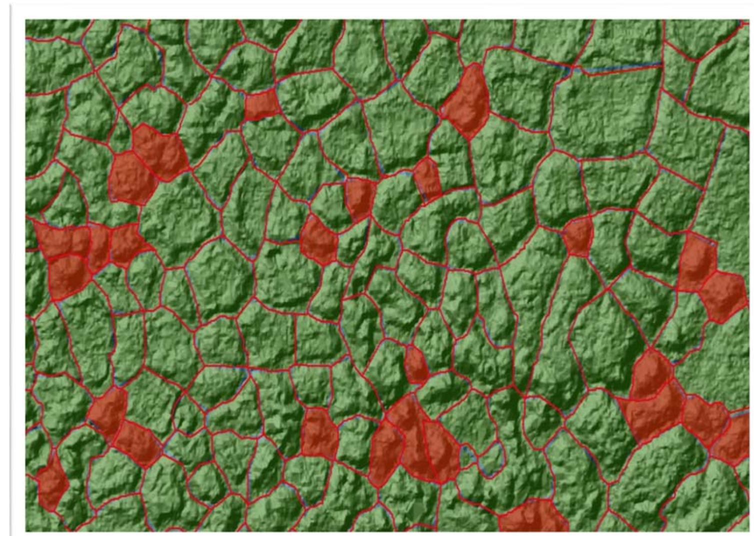




Geomorphology



Subsurface structures are responsible for surface features, and topography drives variation in soil water, inundation, CO_2 and CH_4 flux, and vegetation composition.



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Geomorphology

Urban (1%)

Drainage slope (8%)

High center (11%)

Flat center (16%)

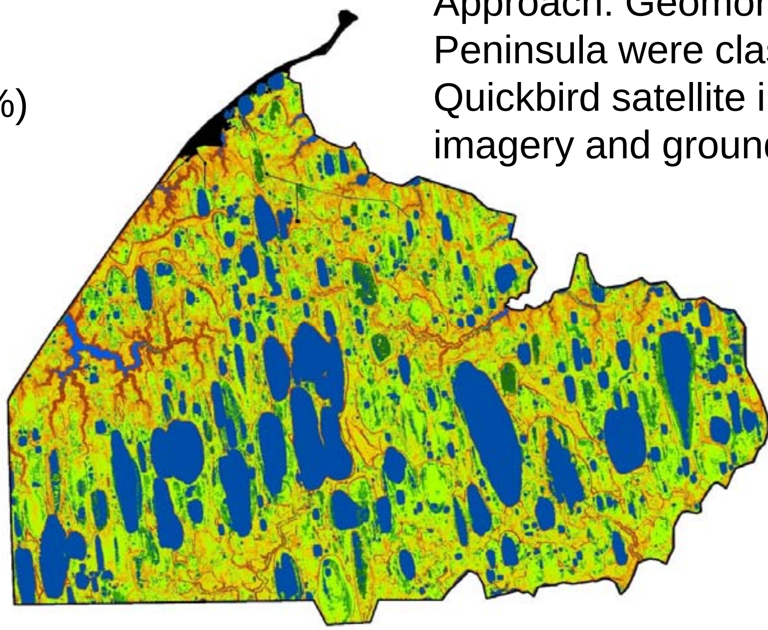
Coalescent (8%)

Low center (24%)

Trough (4%)

Meadow (2%)

Open water (26%)



Approach: Geomorphic types across the 1800 square-km Barrow Peninsula were classified using a combination of Landsat-7 and Quickbird satellite imagery; classifications validated using LIDAR imagery and ground-based observations.

Conclusions: While coalescent polygons and troughs only represent 12% of the total area on the Barrow Peninsula, they account for ~47% of the total CH_4 flux.

Thermokarst formation may have a greater impact on carbon cycle processes than change due to the thaw-lake cycle alone; shrub establishment not considered.

Landscape transition scheme for ACME.

Gangodagamage *et al.* 2014. Extrapolating active layer thickness measurements across Arctic polygonal terrain using LiDAR and NDVI data sets. Water Resources Research 50: 6339-6357.

Lara *et al.* 2015. Polygonal tundra geomorphological change in response to warming alters future CO_2 and CH_4 flux on the Barrow Peninsula. Global Change Biology 21: 1634-1651.

Liljedahl *et al.* 2016. Ice-wedge degradation in warming permafrost and its influence on tundra hydrology. Nature Geoscience 9:312-318.

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Geophysics

Strong interactions exist between surface and subsurface properties, and distribution of cryostructures influence topography as measured using multiple geophysical techniques.

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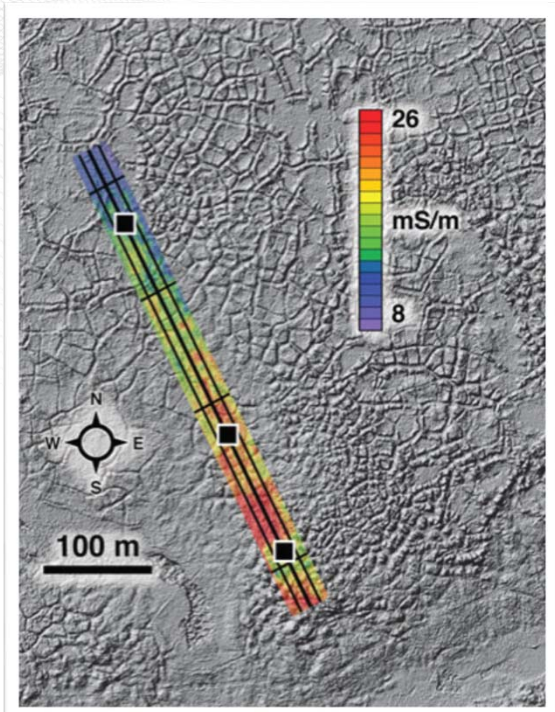
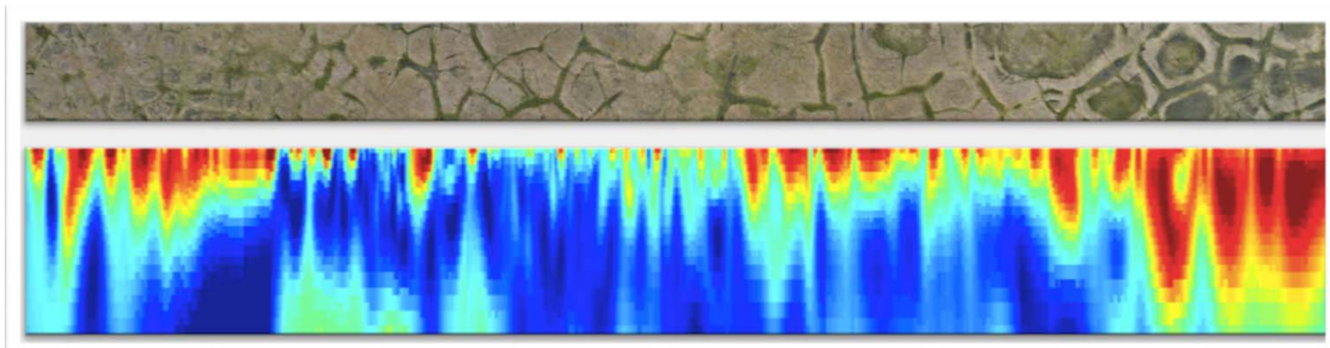
Geophysics



Approach: Use a variety of data sources to develop a zonation method that characterizes the covariation of surface and subsurface properties in ice-rich polygonal landscapes.

Conclusions: Analyses showed that thaw depth, soil water content, soil temperature, and vegetation were closely correlated to each other, and that a two-scale zonation (i.e., polygon types and features) approach can represent the covariability of the properties.



Hubbard *et al.* 2013. Quantifying and relating subsurface and land-surface variability in permafrost environments using surface geophysical and LiDAR datasets. Hydrogeology 21: 149-169.

Wainwright *et al.* 2015. Identifying multiscale zonation and assessing the relative importance of polygon geomorphology on carbon fluxes in an Arctic tundra ecosystem. JGR Biogeosciences 120: 788-808.

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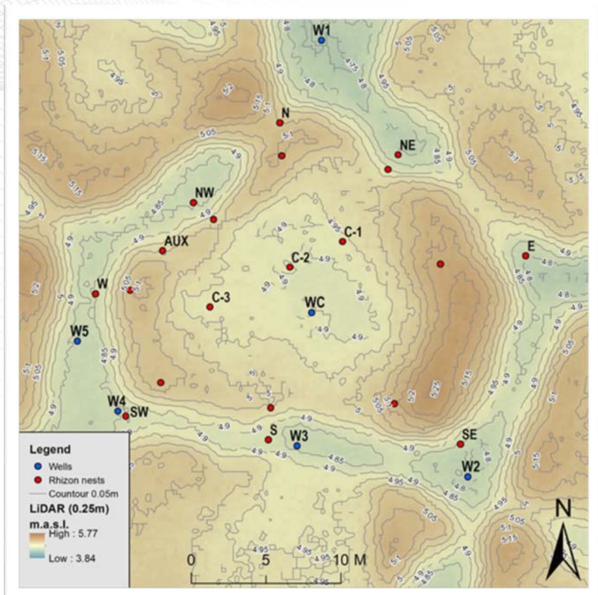
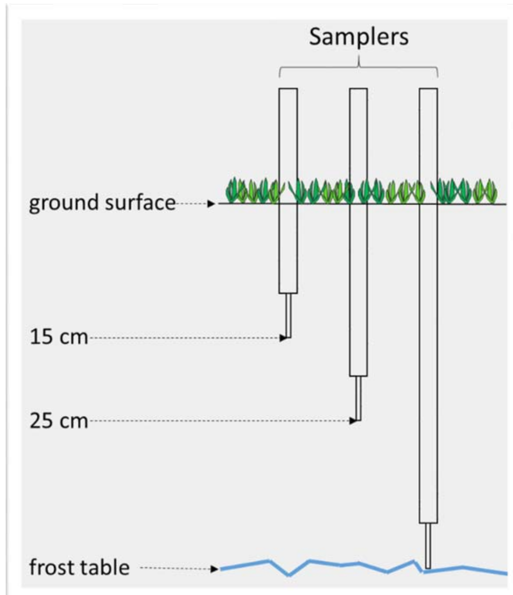
Hydrology

Surface topography of the Arctic Coastal Plain, although subtle, drives distribution of snow, snow depth, timing of snow-melt, and discharge of surface and subsurface water across the landscape. Micro-topography (e.g., rims and troughs) also determine distribution of vegetation and CO_2 and CH_4 production.

Hydrology





Approach: A tracer was applied to the surface of polygons and break-through times followed throughout a two-year period using a dense network of sensors and samplers.

Conclusions: Tracer movement was slow, taking most of the first field season to arrive at rhizons near polygon perimeter.

Preferential flow paths, influenced by topography and frost table, were found to exist between polygon centers and troughs.

Soil hydraulic conductivity was estimated and used in multiscale models.

Frampton *et al.* 2011. Non-isothermal, three-phase simulations of near-surface flows in a model permafrost system under seasonal variability and climate change. Journal of Hydrology 403: 352-359.

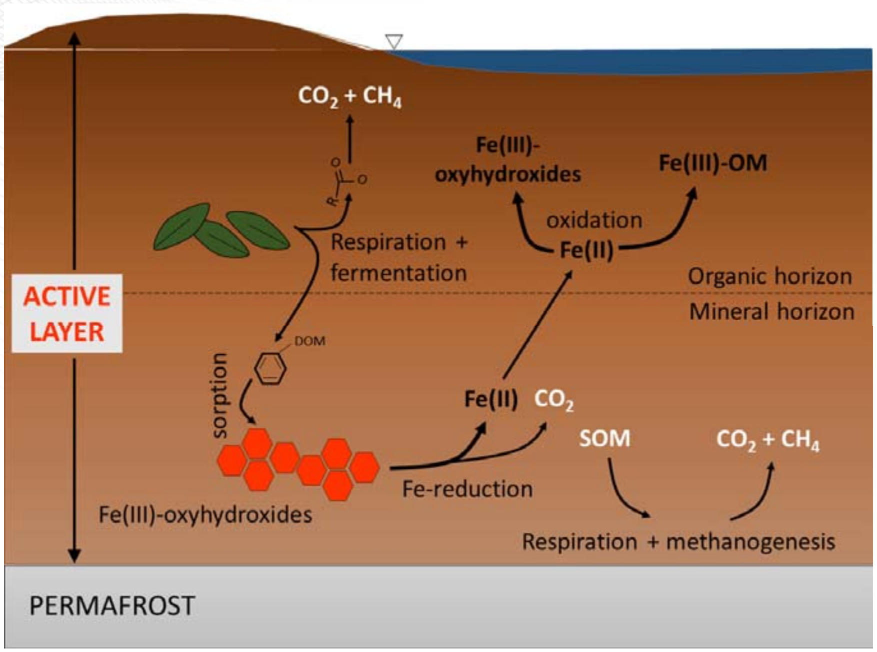
Karra *et al.* 2014. Three-phase numerical model for subsurface hydrology in permafrost-affected regions (PFLOTRAN-ICE v1.0). The Cryosphere 8: 1935-1950.

Wales *et al.* 2017. Understanding the relative importance of vertical and horizontal flow in ice-wedge polygon landscapes using tracers. Water Resources Research (in preparation).

Biogeochemistry

Fluxes of CO_2 and CH_4 are controlled by a complex combination of temperature, soil water, geochemistry, and microbial processes that vary with depth in soil.

Biogeochemistry



Approach: Chamber-based measurements of CO_2 and CH_4 in the field, incubation studies, and synoptic surveys of natural isotopes were used to assess microbial and geochemical controls on carbon cycle processes.

Conclusions: Microbial degradation of SOC proceeds via fermentation pathways that facilitate methanogenesis and Fe reduction in anoxic Arctic tundra soils.

Methane oxidation plays an important role in some but not all landscape positions.

Mechanistic insights gained in NGEE Arctic field and laboratory investigations coupled with multiscale models, are providing a resource for integrating process-rich representations of the carbon cycle into ACME.

Herndon *et al.* 2015. Geochemical drivers of organic matter decomposition in the active layer of arctic tundra. Biogeochemistry 126: 397-414.

Throckmorton *et al.* 2015. Pathways and transformations of dissolved methane and dissolved inorganic carbon in Arctic tundra watersheds: Evidence from analysis of stable isotopes. Global Biogeochemical Cycles 29: 1893-1910.

Vaughn *et al.* 2016. Isotopic insights into methane production, oxidation, and emissions in Arctic polygon tundra. Global Change Biology 22: 3487-3502.

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Vegetation Dynamics

Critical biochemical parameters used in models of photosynthesis to describe uptake of CO_2 for Arctic vegetation do not reflect field measurements.

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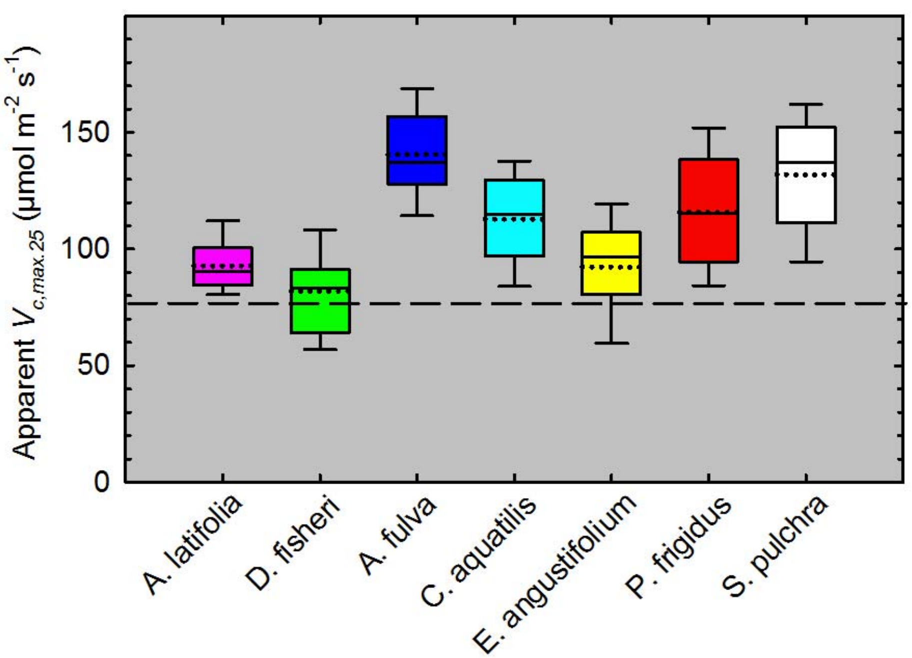
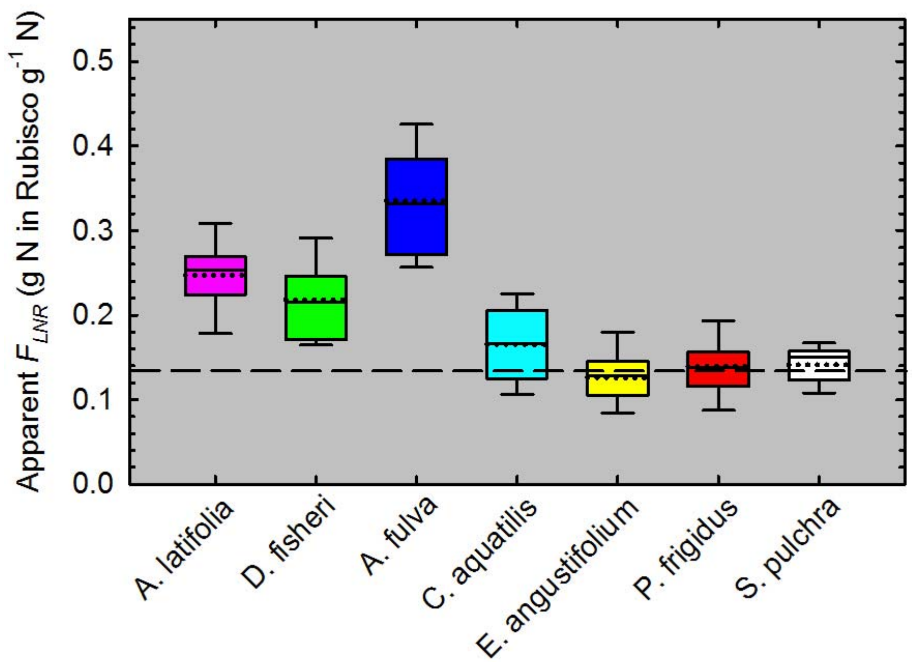
Vegetation Dynamics





Rogers. 2014. The use and misuse of Vcmax in Earth System Models. Photosynthesis Research 119: 15029.

Rogers *et al.* 2014. Improving representation of photosynthesis in Earth System Models. New Phytologist 204: 12-14.

Rogers *et al.* 2017. A roadmap for improving the representation of photosynthesis in Earth System Models. New Phytologist 213: 22-42.

Rogers *et al.* 2017. Earth System Models underestimate photosynthetic capacity in the Arctic. Global Change Biology (in review).

Multi-Scale Modeling

The NGEE Arctic team is working to develop, test, and validate a scaling strategy that includes field, laboratory, and modeling for improved process knowledge in Arctic ecosystems.

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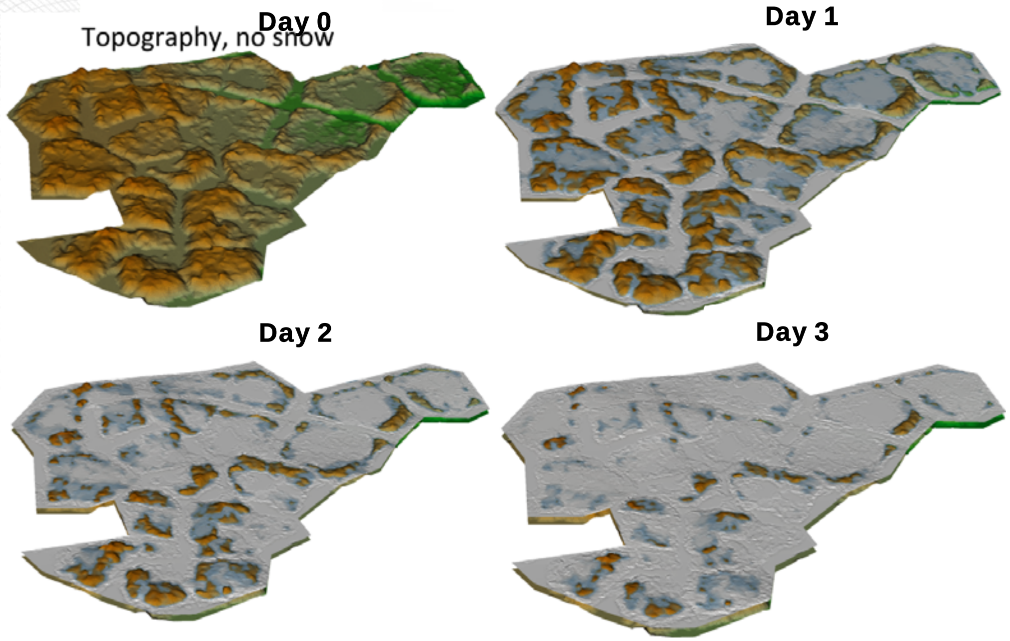
Fine-Scale Modeling



Approach: An ensemble of 3D thermal-hydrology simulations were generated and validated using an iterative observation-model framework; energy transport was evaluated as a function of snow depth and distribution, organic layer thickness, and water inundation.

Conclusions:

- Seasonal active layer was most sensitive to organic layer thickness followed by snow depth but is relatively insensitive to soil saturation or standing water on the landscape.
- Soil temperature profiles provided the most useful integrated dataset for model validation.

Atchley *et al.* 2016. Influences and interactions of inundation, peat, and snow on active layer thickness. Geophysical Research Letters 43: 5116-5123.

Painter *et al.* 2016. Integrated surface/subsurface permafrost thermal hydrology: Model formulation and proof-of-concept simulations. Water Resources Research 52: 6062-6077.

Wainwright *et al.* 2017. Mapping snow depth within a tundra ecosystem using multiscale observations and Bayesian methods. The Cryosphere 11: 857–875.

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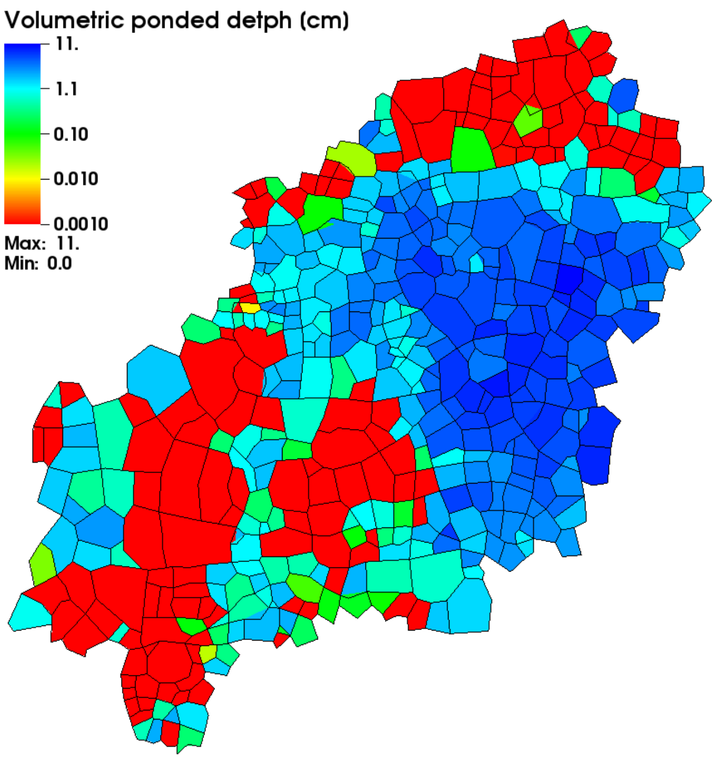
Intermediate-Scale Modeling



Approach: Insights gained from calibrated fine-scale 3D simulations suggested a new multiscale modeling strategy. A mixed-dimensional modeling strategy was developed for process-rich simulations of integrated surface and subsurface thermal hydrology in tundra systems.

Conclusions:

- Thermal-hydrology closely approximates the fully-coupled 3D simulations of the fine-scale model, while maintaining links to native-scale process investigations.
- Highly scalable (e.g., 11 to 468 polygons).
- Allows for dynamic microtopography (e.g., thermokarst) with warming, where subsidence results in substantial changes in hydrology and inundation, and altered drainage networks.
- Model development and NGEE Arctic Use Case was conducted in coordination with IDEAS.

Jan *et al.* 2017. An intermediate-scale model for thermal hydrology in low-relief permafrost-affected landscapes. Computational Geosciences (in review).

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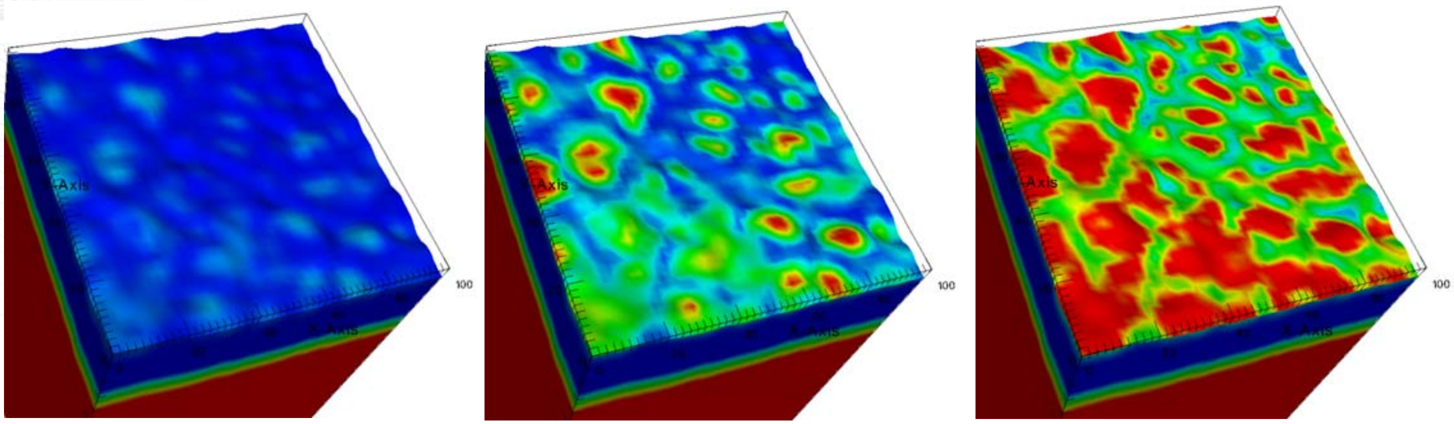
Climate-Scale Modeling (ACME)

Detailed thermal-hydrology-biogeochemistry coupled to land surface component of ACME.



Wet | Moderate | Dry

Approach: ESM connects directly to reactive transport model (PFLOTRAN) and allows dynamics of water, energy, carbon, and nutrients to be simulated.

Detailed 3D process representation was implemented to capture microtopography controls across landscape.

Conclusions: Formulation will facilitate investigation of the role of the redox sensitive microbial reactions for methane production and consumption in response to changing thaw depth, temperature, and water content.

Kumar *et al.* 2016. Modeling the spatiotemporal variability in subsurface thermal regimes across a low-relief polygonal tundra landscape. The Cryosphere 10: 2241-2274.

Tang *et al.* 2016. Addressing numerical challenges in introducing a reactive transport code into a land surface model: a biogeochemical modeling proof-of-concept with PFLOTRAN 1.0. Geoscientific Model Development 9: 927-946.

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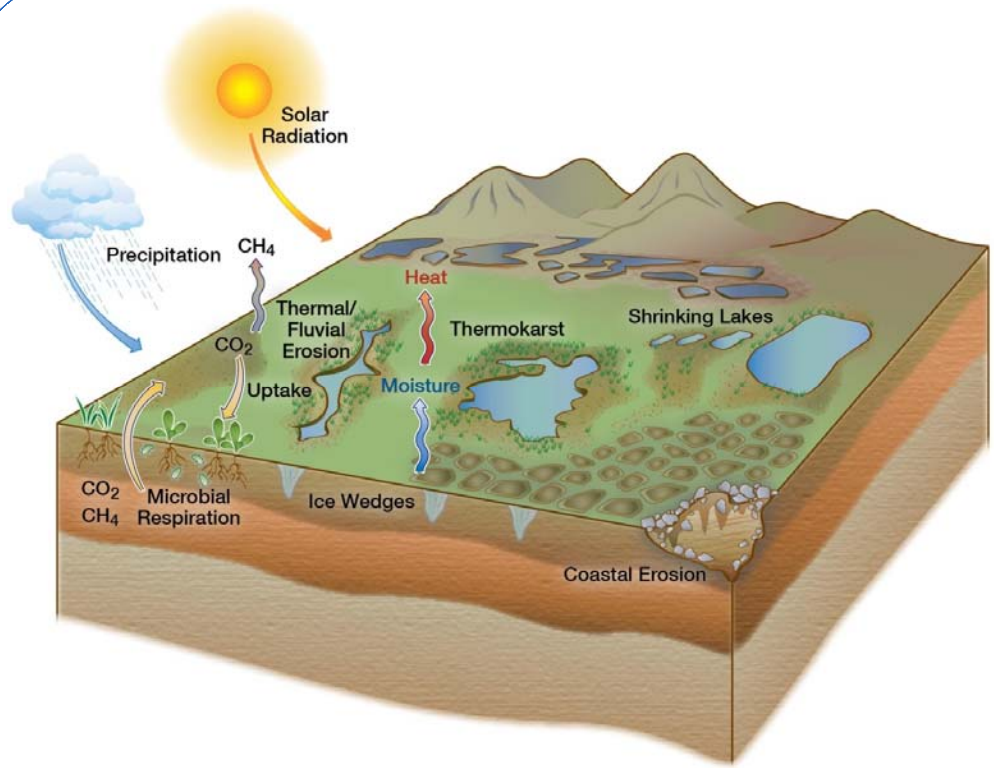
NGEE Arctic Benefits from a Systems Perspective

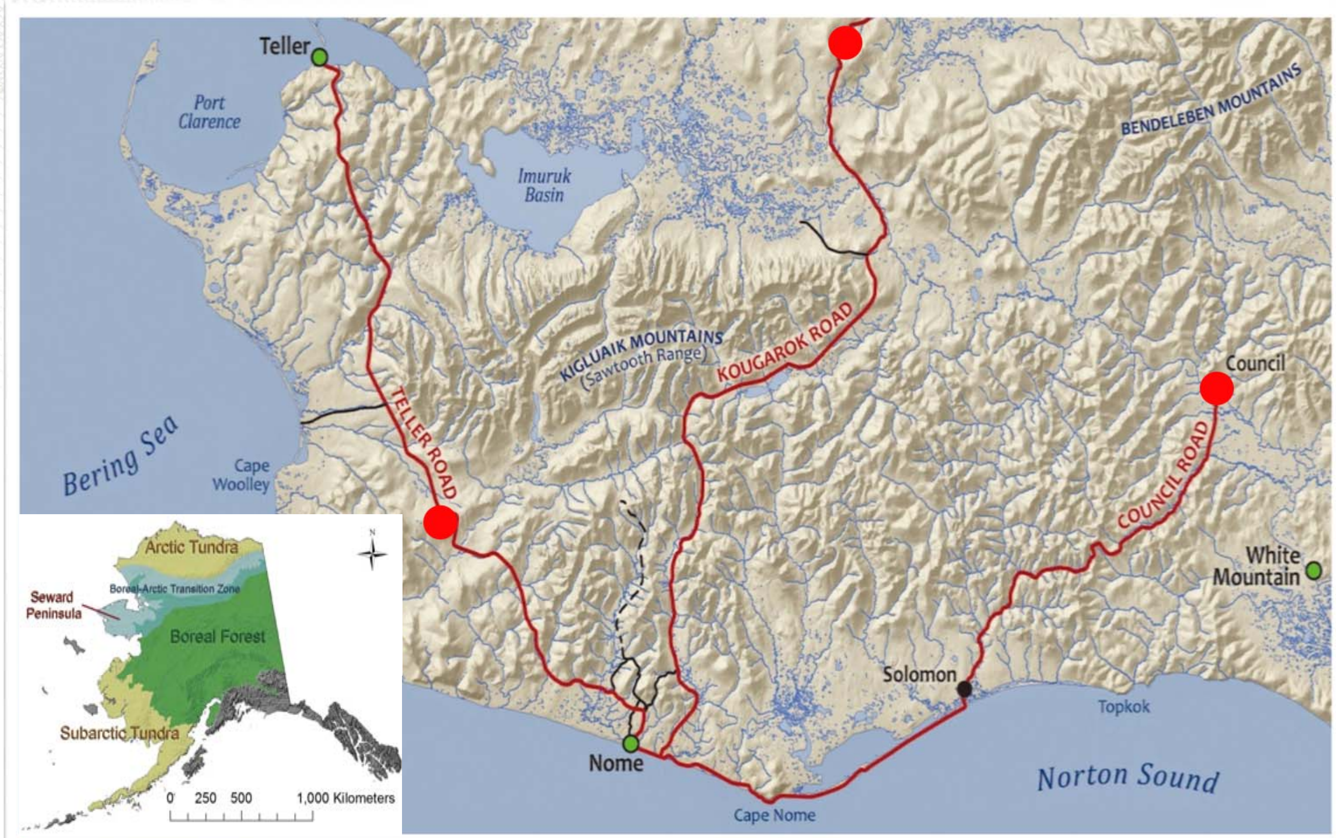
...integrates hydrology, vegetation, soil processes, and energy transfer in the Arctic.



Must understand mechanisms that underlie the processes that control carbon, nutrients, water, and energy transfer in the biosphere.

Must also understand how those processes play out in a heterogeneous and changing landscape.

NGEE Arctic Field Sites (Phase 2)



Overarching Questions (Phase 2)

Q1. How does landscape structure and organization control the storage and flux of carbon and nutrients?

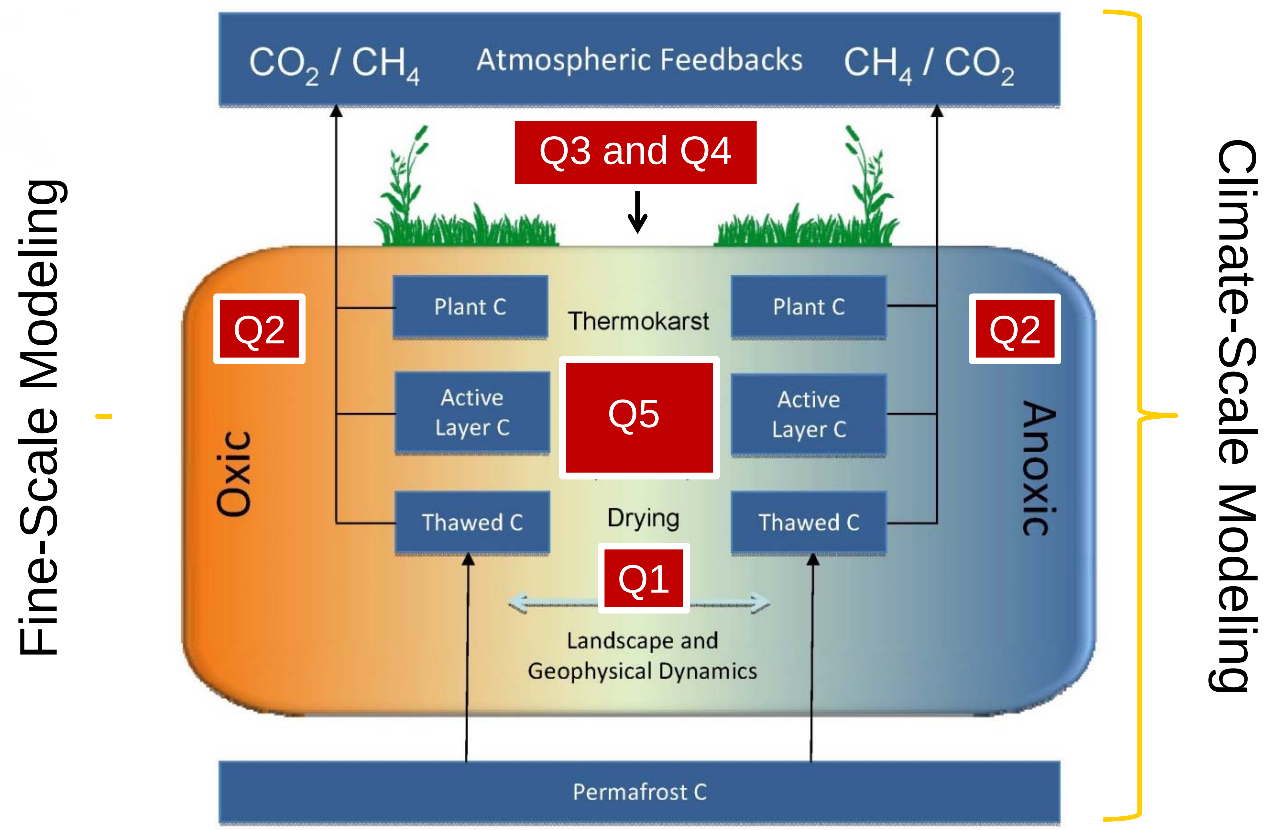
Q2. What will control rates of CO_2 and CH_4 fluxes across a range of permafrost conditions?

Q3. How will warming and permafrost thaw affect above- and belowground plant traits, and what are the consequences for Arctic ecosystem carbon, water, and nutrient fluxes?

Q4. What controls the current distribution of Arctic shrubs, and how will shrub distributions and associated climate feedbacks shift with expected warming in the 21st century?

Q5. Where, when, and why will the Arctic become wetter or drier, and what are the implications for climate forcing?

Mapping Phase 2 Scientific Questions to Conceptual Diagram



Schuur et al. (2008)

Teller Road

(Sitnasuak Native Corporation)

Kougarok Road

(Mary's Igloo Native Corporation)

Council Road

(Council Native Corporation)

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Snow and Geophysics Campaign (March 19 to April 7, 2017)

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NGEE Arctic by the Numbers

>130 NGEE Arctic team members

104 have traveled to Alaska

104 have completed safety training

17 modelers have traveled to Alaska

123 publications since 2012

34 journals

51 different senior authors

78 data sets at NGEE Arctic portal

36 data sets released to the public

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Commitment to Safety

Institutional Requirements
- Research Safety Summaries (RSS)

Project Requirements
- Project Orientation and Safety Videos
- Safety Manuals and Code of Conduct

Logistical Support Requirements
- Land Use and Land Access Permits
- Site Orientation and Certified Staff

Commitment to Data

Institutional Best Practices
- Meet DOE SC and BER Requirements

Project Requirements
- Open Sharing of Data
- Searchable and Accessible by Public

Project Policies
- Data and Code Sharing
- Authorship and Acknowledgement

Field Safety

Data Management

Laboratory Safety

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NGEE Arctic Supports the BER Mission

To advance a robust predictive understanding of Earth's climate and environmental systems ***and to inform*** the development of sustainable solutions to the Nation's energy and environmental challenges.