Title: Topographic controls on scaling of hydrologic and thermal processes in polygonal ground features of an Arctic ecosystem

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Abstract

Arctic and sub-Arctic soils currently contain approximately 1700 billion metric tones of frozen organic carbon, approximately 200 times current annual anthropogenic emissions. This carbon is vulnerable to release to the atmosphere as CO_2 and CH_4 as high-latitude temperatures increase due to climate change. Microtopographic features, such as polygonal ground, are characteristic sources of landscape heterogeneity in the Alaskan Arctic costal plain. Polygonal ground structures, with high or low centers, influences the distribution of snow depth, thereby impacting the energy balance, biogeochemical dynamics, vegetation communities, and carbon releases from the subsurface. In spite of the importance of heterogeneous snowpack on local hydrologic and thermal processes, they are not explicitly accounted for in land surface models.

In this study, we develop a snow redistribution algorithm, which accounts for microtopography, in the Community Land Model (CLM4.5). We perform simulations for four sites in Barrow, AK at multiple horizontal resolutions across several years. Results indicate that heterogeneous distribution of snow, accumulated during winter months, has a strong influence on spatial distribution of active layer depth and surface energy fluxes during summer season. In winter, soil temperature variance (σ_T^2) exhibits a non-linear relationship with spatial scale. Coarse resolution simulations under predict σ_T^2 when compared to average of fine resolution simulation to an equivalent coarse resolution. Lastly, we investigate the role 3D vs 1D representation of subsurface thermal processes by using CLM4.5 simulated top soil temperature as boundary condition for simulations performed by PFLOTRAN, a three-dimensional subsurface non-isothermal flow and reactive transport model. Preliminary PFLOTRAN simulations indicate that the 3D process representation leads to increase in soil temperature variability at depth when compared to 1D simulations.

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Rapid warming at high northern latitudes is resulting in permafrost degradation. When permafrost thaws in wetlands, the peat plateaus tend to collapse, bringing the water table closer to the surface. Methane (CH_4) fluxes increase post-thaw, but it is unclear the extent to which this is caused by CH_4 release from the decomposition of previously-frozen, old carbon, deep within the soil profile, versus waterlogging near the soil surface resulting in anaerobic decomposition of more recent inputs. Quantifying the relative contributions of these contrasting CH_4 sources is essential for predicting future rates of CH_4 release from thawing permafrost wetlands.

The most definitive test of whether old permafrost-derived C contributes substantially to CH_4 release post thaw, would be to measure the radiocarbon (^{14}C) content of the CH_4. However, until recently this was very challenging in remote locations. Using new techniques that overcome previous limitations, we were able to measure the ^{14}C content of CH_4 being released from thawing wetlands in northern Canada. We hypothesised that time since plateau collapse would affect the amount of old CH_4 being released, and so sampled in locations were collapse had occurred at different times. Samples were collected from collars that either included or excluded CH_4 from deep within the peat profile, and CH_4 from a depth of 100 cm was collected by sampling soil water.

Results demonstrate that millennium-old CH_4 was being produced at 100 cm. However, CH_4 being released from the surface had contemporary ^{14}C signatures. Using our collar treatments, we were able to calculate that deep CH_4 contributed less than 10% of the surface flux, and that this contribution did not vary with time since collapse. The effect of permafrost thaw on CH_4 fluxes in these peatlands appears to be related more to changes in near surface conditions than the anaerobic decomposition of previously frozen C. This is not generally reflected in Earth system models.

Methane Emissions are Predominantly Derived from Contemporary Carbon from a Thawing Permafrost Peatland in Canada

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Introduction

- Rapid warming in northern latitudes is resulting in the degradation of permafrost
- Permafrost thaw leads to the collapse of peat plateaus
- Subsequent waterlogging following the collapse creates substantial a source of CH_4
- The extent of the contribution to CH_4 flux from previously frozen 'old' carbon vs more recent carbon inputs are unclear.

Methods

Study site: Whitehorse wetland (60°05'27.5''N, 132°22'06.4''W) is located approximately 20 km south of Teslin in the Yukon Territory within the sporadic permafrost zone.

Sampling Locations: Sampling points were established at 3 locations within the unfrozen wetland; TWMargin, TW5m and Twmid to reflect a spectrum of times since plateau collapse (figure 1).

Methane fluxes: CH_4 fluxes at each sampling location were carried out using static chambers 8 times throughout the growing season until autumn freeze-up between July 14th and Oct 18th 2013.

Methane Radiocarbon: At each sampling location CH_4 was collected from full profile collars, near surface collars (which excluded CH_4 from depth) and CH_4 was collected from degased pore water extracted from 100cm using a metal probe (figure 3).

CH_4 collected was processed for radiocarbon analysis using a novel technique developed by Garnett *et al.* (2012). The contribution of deep C to the CH_4 flux could then be calculated by a simple mass balance equation (Equation 1).

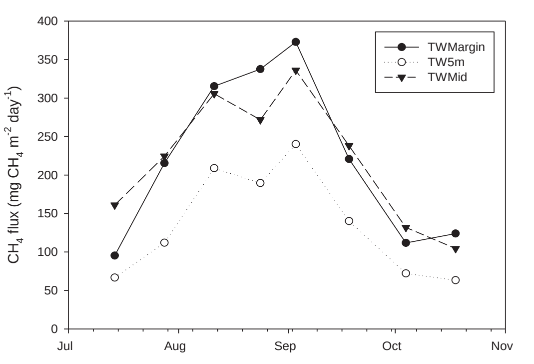

Figure 2 Time series of CH_4 fluxes for each sampling location. Error bars are excluded to improve clarity of the graph

How much of CH_4 efflux is derived from previously frozen organic material?

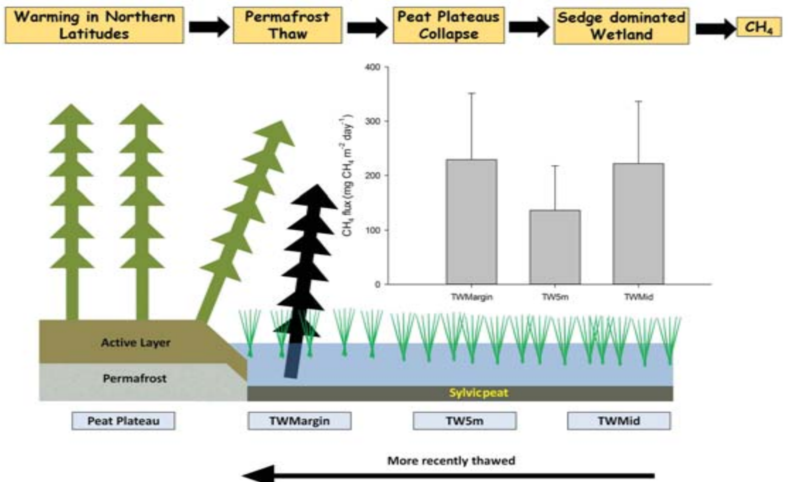

Figure 1 schematic of the intact permafrost peat plateau and unfrozen wetland with sampling locations. The bar chart shows the mean CH_4 flux for each sampling location, error bars indicate standard error.

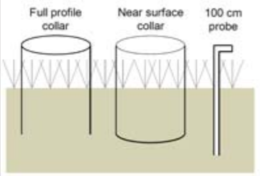

Figure 3 schematic of experimental set up for sampling CH_4 for radiocarbon analysis

The contribution of deep carbon was calculated based on the difference in the radiocarbon (^{14}C) content of the CH_4 respired from the two collar types (Full profile versus Near surface) and the ^{14}C content of the CH_4 collected by the 100 cm probe (Equation 1).

$$\text{Deep } CH_4\,(\%) = \left(\frac{FP^{14}CH_4 - NS^{14}CH_4}{Probe^{14}CH_4 - NS^{14}CH_4} \right) * 100 \qquad \text{Equation (1)}$$

Where Deep CH_4 (%) is the % contribution of deep CH_4 to total CH_4 efflux, $FP^{14}CH_4$ is the ^{14}C content of the CH_4 collected from the Full profile collars, $NS^{14}CH_4$ is the ^{14}C content of the CH_4 collected from the Near surface collars, and $Probe^{14}CH_4$ is the ^{14}C content of the CH_4 collected from the 100 cm probes.

Discussion

- It is clear that 'old' CH_4 is being produced at 100 cm, however, this does not contribute to surface CH_4 fluxes.
- It is likely that more recently fixed 'C' from sedges post collapse provides majority of the substrate for methanogenisis near the surface.
- Previously frozen organic material is more recalcitrant to decomposition therefore methane production at depth is ;likely to be much lower than near the surface.
- Alternatively 'old' CH_4 produced at 100cm is oxidised before reaching the atmosphere.
- Near surface processes are important in the release of CH4 to the atmosphere rather than anaerobic decay of previously frozen organic material.
- Remote sensing techniques i.e. detecting surface moisture from space will allow the assessment of changes in CH_4 from thawing peatlands in these areas of Canada.

Results

- Thawed wetland was a substantial source if CH_4 (figures 1,2).
- CH_4 produced at 100 cm depth varied between 900 and 1600 BP
- CH_4 from the surface collars was enriched in 'post bomb'14C and considered to have a contemporary signature.
- However, the full profile collars contained a slightly lower 14C suggesting contribution from older CH_4 deeper from within the profile.
- The mass calculation (equation 1) suggests ~8.5% of CH_4 at surface could contain a similar age of the CH_4 collected at 100 cm.
- Mass balance output relative to CH_4 flux would suggest that 4.5 g CH_4 m^{-2} $year^{-1}$ of the annual CH_4 released from the unfrozen wetland could be derived from millennia old CH_4 produced at 100cm depth
- However, sensitivity analysis (figure 4) using differences in 14C content between full profile and near surface collars suggests that a greater proportion of the surface flux could contain of CH_4 with a radiocarbon age of < 1000 BP.
- The sensitivity analysis also suggests a greater contribution CH_4 < 1000 BP for more recently thawed sampling locations within the unfrozen wetland.

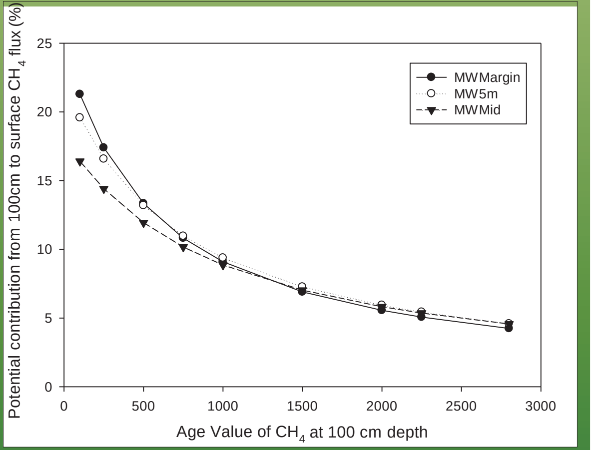

Figure 4 Sensitivity analysis using measured differences between full profile and near surface collars. Age values of CH4 at 100 cm were manipulated between 100 and 2800 BP to create a sensitivity analysis curve.

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What is driving the change in vegetation productivity in northern Eurasia?

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High latitude terrestrial vegetation, by influencing and being influenced by the hydrological and carbon cycles, play a critical role in the global climate. Under a warming climate vegetation productivity is expected to increase. While agreement among remote sensing data point to an increase in vegetation greenness, there is considerable uncertainty about the magnitude and extent of this change. The uncertainty is still greater for northern Eurasia due largely to a scarcity of ground based observational data. IPCC projections suggest that northern Eurasia will become warmer and wetter. Improved characterization of terrestrial vegetation of northern Eurasia are dependent on the identification of the main drivers of change over the recent past.

In this study trends in vegetation productivity over northern Eurasia is analyzed using products derived from several remote sensing based algorithms as well as process-based models. A temporal and spatial analysis is conducted to determine the sensitivity of photosynthesis to abiotic variables like temperature, moisture availability and atmospheric CO_2 concentration. We note reasonable agreement of an increasing trend of gross primary productivity but a disagreement about the rate of increase. Although gross primary productivity is highest in summer, the greatest percentage increase is seen in spring. Productivity increases are however not spatially homogeneous. Preliminary analysis of the abiotic variables also indicate a stronger relative change for the spring months compared to summer and autumn. This would suggest that abiotic factors are driving the phenological changes in vegetation.

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1. What do we already know?

- ❑ Physiological response of plants to *[Morison & Morecroft, 2008]:*
  - ➢ Temperature – optimum effect (bell shaped curve)
  - ➢ Water – affects hydraulics & chemistry
  - ➢ CO_2 – fertilization effect
  - ➢ Sunlight (cloudiness) – direct effect on photosynthesis
  - ➢ Fire – remove old growth / facilitate new growth.
- ❑ Increasing seasonal cycle amplitude of atmospheric CO_2 concentration *[Myneni et al., 1997; Graven et al., 2013].*
- ❑ Most existing studies compare role of temperature and moisture in controlling vegetation productivity. Lack of consensus about dominant factor shows the uncertainty *[Nemani et al., 2003; Yi et al., 2013; Parida & Buermann, 2014]:*
  - ➢ Increasing temperature – dominant stimulatory role
  - ➢ Decreasing or lack of sustained increase in moisture – inhibitory role
- ❑ Abundant soil moisture in permafrost –> bog formation –> increased precipitation decreases productivity *[Kabat et al., 2004].*

2. Questions -> Hypothesis

- ❑ What are the main environmental factors driving vegetation changes in northern Eurasia?
  - ➢ Based on existing studies our hypothesis is that Temperature would be dominant in the colder north while Precipitation in the warmer and dryer south.
- ❑ How are the drivers affecting vegetation productivity?
  - ➢ Since the changes in the environmental factors are maximum in spring the maximum effects should also be observed in spring.
  - ➢ Our hypotheses is that Temperature would have +ve correlation in the colder and wetter north and –ve correlation in the dryer and warmer south.
  - ➢ Precipitation should have mostly a +ve correlation.

3. Data used

- ❑ GPP: GIMMS & VIP
- ❑ Temperature & Precipitation: Univ. of Delaware
- ❑ CO_2: NOAA ESRL
- ❑ Cloudiness: CRU climatology
- ❑ Fire: GFED

4. Land Cover – what grows where?

AVHRR based Land Cover

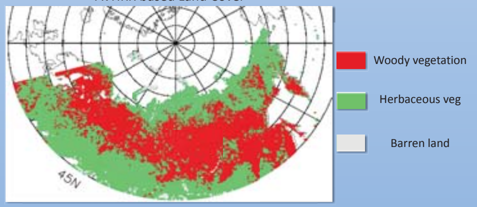


Fig 1. The land cover of northern Eurasia partitioned into woody (Boreal forests) and herbaceous (mosses in north and grasslands in south) to understand different feedbacks and hydrology regimes.

5. Changing above ground productivity (GPP)

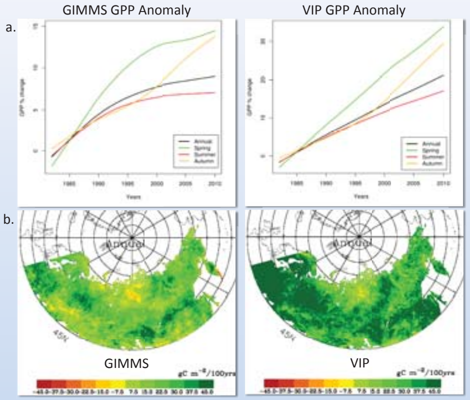


Fig 2. (a.) Seasonal anomaly plot (yearly) for 1982 – 2010 (regional average) showing Spring GPP increasing at a rate higher than other seasons. The increasing productivity for all seasons interestingly asymptotes for GIMMS but not for VIP. (b.) Plot showing the spatially varying Annual GPP trend (for the entire study period) with almost the entire area demonstrating an increase in productivity with the VIP data having a much steeper increase.

6. How are external environmental conditions changing?

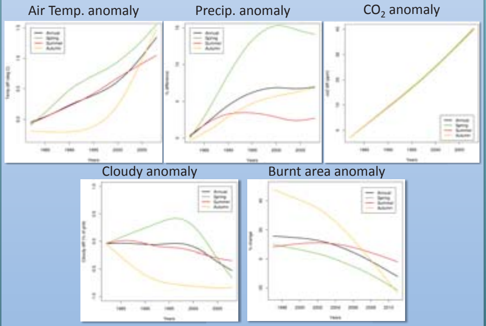


Fig 3. Anomaly plots showing different rates of change for environmental factors (regional evg.) for different seasons.

- Although CO_2 of summer is lowest, rates of increase for all seasons is similar.
- Burnt area has a smaller time window due to unavailability of data and seems to have a decreasing trend.
- Spring appears to have maximum rate of change for Temperature, Precipitation and Cloudiness.

7. What is the main cause for the increasing GPP?

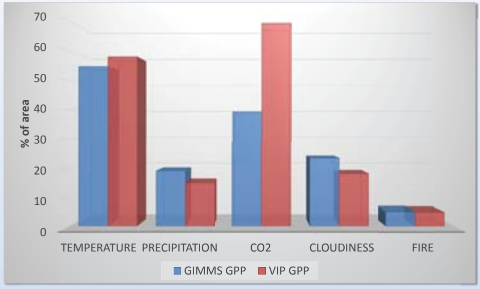


Fig 4. Percentage of area where the annual GPP has statistically significant **ATTRIBUTION (R^2 value or explanation of interannual GPP variability)** to the annual values of the environmental factors. Note: High value for CO_2 is an artifact of statistics. Since more than 50% of northern Eurasia has statistically significant attribution of GPP variability to temperature, it can be considered to be the leading driver of productivity change.

8. When do the factors affect GPP most?

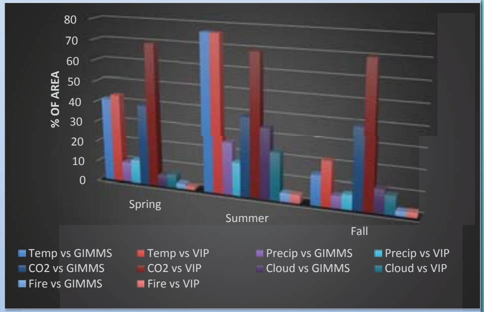
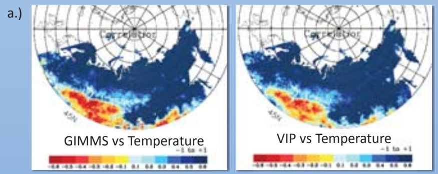


Fig 5. Percentage of area where the annual GPP has statistically significant **CORRELATION** to the seasonal values of the environmental factors. Other than CO_2, correlations of other factors with GPP appear to be highest for summer.

9. How do the environmental factors affect GPP?

(Annual GPP vs Summer Env. factor)



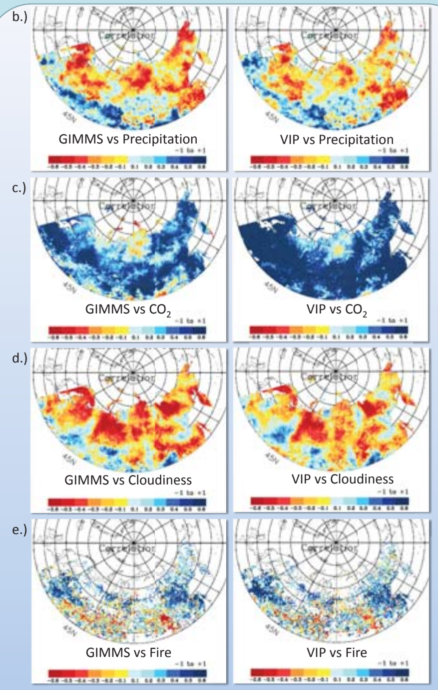


Fig 6. Correlation between summer values of the environmental factors and annual GPP.

10. Conclusions

- ❑ **Summer** being the peak growing season is the best season to study the effect of environmental drivers (Fig 5), though **Spring** has the highest temporal rate of change (Figs 2 & 3). This is because of the higher signal to noise ratio.
- ❑ A spatial distinction can be seen (Figs 9 a,b,d) in the response of the GPP to environmental factors between the **grasslands of the south** and **boreal forest in center-north.**
- ❑ **Temperature** is the strongest driver –> boosts productivity except in southern grasslands (Figs 4 & 9a).
- ❑ **Precipitation** shows negative correlation in the north –> evidence of high soil moisture (maybe saturation or bog) due to permafrost (Fig 9b).
- ❑ **Fire** affects only small percentage of total area –> negligible influence as a driver (Fig 9e).

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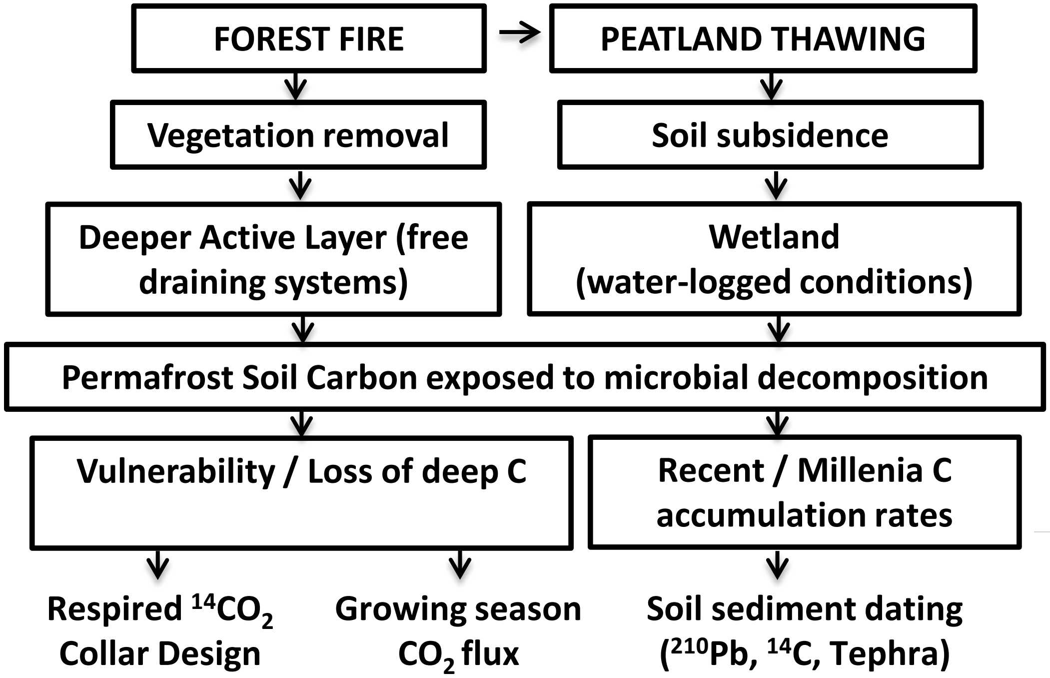
Current project: CYCLOPS project (Carbon Cycling Linkages to Permafrost Systems)

Abstract for AGU 2014:

Permafrost degradation is associated with an aggradation of the active layer thus exposing previously frozen soil carbon (C) to microbial activity. This may increase the generation of greenhouse gases and potentially increase rates of climate change. However, the rate of C release remains highly uncertain, not least because few *in situ* studies have measured the rate at which previously frozen C is released from the soil surface, post thaw. We quantified the contribution of this “old” C being released as CO_2 from permafrost degraded soils in sporadic and discontinuous permafrost in Yukon and Northwest Territories, Canada. Firstly, we studied on the effect of fire on black spruce forests as the removal of vegetation, especially mosses, may play a key role on thaw depth. Secondly, we investigated the collapse of peatland plateau after permafrost thaw which resulted in the formation of wetlands. We combined radiocarbon measurements of respired CO_2 with a novel collar-design that either included or excluded CO_2 released from deeper soil horizons. Our results show that, while excluding deeper layers did reduce the average age of the C being released from the soil surface, more than 90% of the CO_2 came from contemporary sources, even after burn and permafrost plateau collapse. Furthermore, soil cores dated using ^{210}Pb show that the rapid accumulation of sedge peat after plateau collapse may more than compensate for any C losses from depth. Our results from the Canadian boreal contrast strongly with findings from other geographical areas emphasising the complexities of predicting the impact of permafrost thaw on the carbon balance of northern ecosystems.

In Situ Contribution of Old Respired CO_2 from Soils in Burnt and Collapsed Permafrost in Canada

Cristian Estop-Aragones, James P. Fisher, Mark Cooper, Aaron Thierry, Mathew Williams, Gareth K. Phoenix, Julian Murton, Dan Charman and Iain P. Hartley (**CYCLOPS project team)**



FOREST FIRE → **PEATLAND THAWING**

Vegetation removal

Deeper Active Layer (free draining systems)

Soil subsidence

Wetland (water-logged conditions)

Permafrost Soil Carbon exposed to microbial decomposition

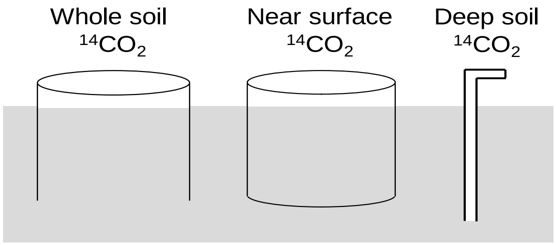
Vulnerability / Loss of deep C

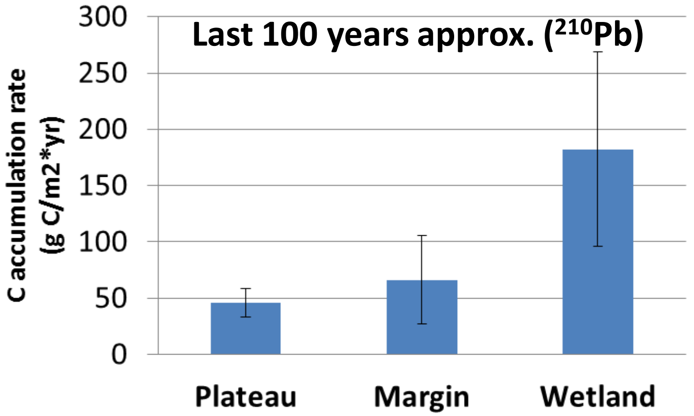
Recent / Millenia C accumulation rates

Respired $^{14}CO_2$ Collar Design

Growing season CO_2 flux

Soil sediment dating (^{210}Pb, ^{14}C, Tephra)





Paul Grogan, Queen’s University, Kingston, Ontario, Canada. Part of Arctic Development and Adaption to Permafrost in Transition (ADAPT) that includes Christiansen C.T., D. Lamhonwah, K. Moniz, S. Montross, P. Das, V. Walker, M. Lafreniere, S. Lamoureux, and W. Vincent, among others.

Is everything everywhere? Investigating the importance of scale in spatial variability of permafrost microbial community composition and biogeochemistry.

One of the key initiatives in our ADAPT programme is to characterize permafrost from multiple Canadian low and high arctic sites, including regions underlain by continuous and discontinuous permafrost, to investigate whether spatial variation in near-surface permafrost biogeochemical properties contains predictable spatial structures at short (<10 m), medium (100s of meters to few kilometers), and long (1000s of kilometers) distances. We have collected biogeochemical data from 13 soil cores obtained from Cape Bounty (Nunavut), Daring Lake (Northwest Territories), and Umiujaq, (Quebec) that ranged in length from 1.5 to 3 meters, including active layer and near-surface permafrost soil horizons. We determined total and dissolved pools of organic carbon, essential plant nutrients (such as inorganic and organic forms of nitrogen and phosphorous), microbial biomass pools of carbon, nitrogen and phosphorous, as well as soil water content and pH. Furthermore, we characterized bacterial, archaeal, and fungal community composition using denaturing gradient gel electrophoresis and pyrosequencing of genomic soil DNA to relate microbial community composition with biogeochemical soil properties, aboveground vegetation cover, and geographical location.

Preliminary data show large variation in soil organic matter and ice lens content with depth and across sites – both close and far apart. To our surprise, organic matter content and microbial biomass increased with depth in some cores, where the permafrost horizon contained greater total and dissolved organic carbon and nitrogen pools than the seasonally thawed active layer above. By contrast, microbial community composition was consistently more diverse closer to the soil surface than deeper in the active layer or permafrost. The implications of these results will be discussed in terms of our capacity to predict the biogeochemical impact of permafrost thaw in a changing climate.

WHAT DOES THE PERMAFROST CONTAIN?

A SOIL DEPTH-SPECIFIC CHARACTERIZATION OF MICROBIAL COMMUNITY COMPOSITION AND BIOGEOCHEMISTRY IN THREE SOIL CORES FROM CAPE BOUNTY, MELVILLE ISLAND, NU

Christiansen, Casper [1], D. Lamhonwah [2], S. Montross [2], C. Inglese [1], K. Moniz [1], V.K. Walker [1,3], M. Lafrenière [2], S. Lamoureux [2] and P. Grogan [1]

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INTRODUCTION

Thawing permafrost soils may have severe consequences for tundra ecosystem carbon and nutrient transport and cycling, with far-reaching feedbacks to global climate change. Yet, our knowledge of the microbial community composition and biogeochemical contents of permafrost soils is still limited. A key initiative in the Arctic Development and Adaptation to Permafrost in Transition (ADAPT) program is to obtain and characterize permafrost cores from 16 sites spread out across the Canadian Arctic (see Figure 1 below). Here, we present the first preliminary biogeochemical and microbial community composition data from three soil cores obtained from Cape Bounty, Melville Island, NU in 2012 and 2013.

Figure 1. Map showing permafrost distribution and ADAPT research sites across the Canadian Arctic.

STUDY SITE

The Cape Bounty Arctic Watershed Observatory (CBAWO) is located in the Canadian High Arctic on the south-central coast of Melville Island, NU (74°55'N, 109°35'W) (Figure 2). The area is overlain by late Quaternary glacial and early Holocene marine sediments. Generally, soil thaw depths are between 50 and 70 cm at their fullest extent in late-summer.

One 160 cm core was obtained in June 2012. Two shallower cores were obtained in May 2013 – one from an area classified as mesic tundra, and one from within an adjacent active layer detachment, a permafrost thaw disturbance.

Figure 2. The West River Watershed, CBAWO, and subcatchment boundaries. Shaded areas represent permafrost thaw disturbances. Sampling locations are marked with a star.

METHODOLOGY

A motorized auger was used to extract the frozen soil cores. Cores were kept frozen while transported to Queen's University and sub-sampled in a walk-in freezer room. For soluble ion extraction, we followed the procedure of Kokelj and Burn (2003). Anion and cation concentrations (ppm) were quantified using a Dionex 3000 IC system.

Dissolved organic carbon (DOC), total dissolved nitrogen (TDN), phosphate and microbial biomass pools of carbon (MBC), nitrogen (MBN), and phosphorous (MBP) were extracted using 0.5M K_2SO_4 and $CHCl_3$ fumigation and quantified using Bran-Leubbe AA3 and Shimadzu TOC-TN auto-analyser systems, following modified procedures of Buckeridge et al. (2009) and Witt et al. (2000). Total carbon and nitrogen content were determined using an Elementar elemental analyser. Phosphate and MBP values were below detection limits and are not shown.

Genomic DNA was extracted using a NucleoSpin Soil DNA isolation kit, following the manufacturer's instructions. The 16S region (bacteria) was PCR amplified following primers and procedures of Liu et al. (1997) and Muyzer et al. (1993), while the 18S region (fungi) was PCR amplified using Sigma-Aldrich primers SSUF, SSUR, FF390, and FRI-GC. Pyrosequencing of genomic DNA was performed at the Research and Testing Laboratory (RTL: Lubbock, TX).

PERMAFROST AND SEASONALLY THAWED SOILS DIFFER GREATLY IN BIOGEOCHEMISTRY

Soluble anion (Figure 3a) and cation (Figure 3b) concentrations; microbial carbon (MBC) and nitrogen (MBN), dissolved organic carbon (DOC) and total dissolved inorganic and organic nitrogen (TDN) (Figure 4a); total nitrogen and carbon (Figure 4b); and soil water content and pH (Figure 5). The largest ion, carbon and nutrient concentrations are seen below 70 cm depth – with peak concentrations around 140-160 cm of depth. Seasonal soil thaw depth for this area is between 50 and 70 cm (orange box in each figure).

Figure 3a. Soluble anions

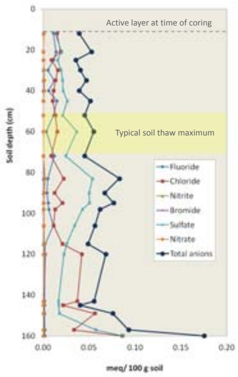


Figure 3b. Soluble cations

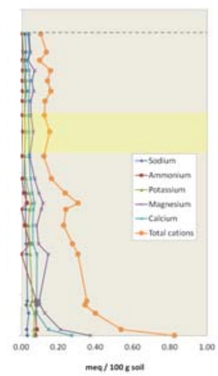


Figure 4a. Microbial C and N, DOC and TDN

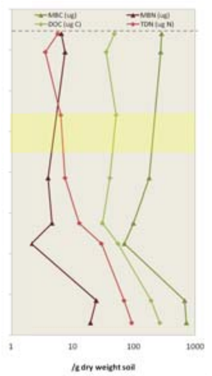


Figure 4b. Total C and N

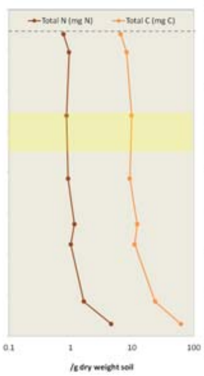
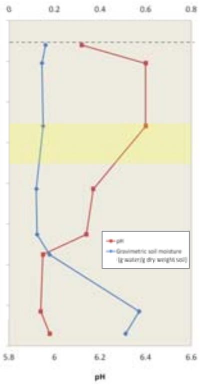


Figure 5. pH and soil moisture



ACTIVE LAYER THAW SLUMP DISTURBANCE LEADS TO ALTERED SOIL MICROBIAL COMMUNITIES

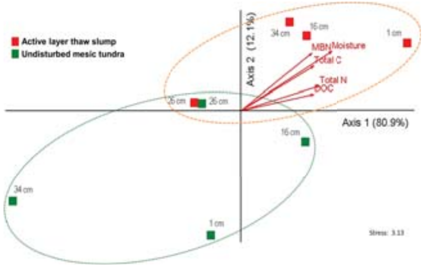
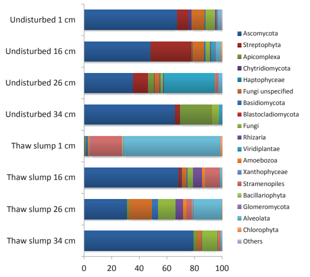


Figure 6 (left). Non-Metric multidimensional scaling (NMS) ordination of soil bacterial communities based on 16S rRNA (taxonomic level: Order). Arrows are biogeochemical variables correlating with the ordination axes (r2>0.3). Parentheses show percentage of variation represented by each ordination axis. Ovals mark soil samples more similar to each other than with the other group (MRPP analysis, P=0.06).

Note: Greater dissimilarity between soil core data points at top (1 cm) and bottom (34 cm) soil horizons.

Figure 7 (right). Stacked bar charts based on 18S rRNA fungal community compositions from the same soil cores as above (taxonomic level: Phylum).

Note: Relatively smooth transition between undisturbed communities, and greater dissimilarity between soil core communities at the top (1 cm) soil horizon.



KEY FINDINGS

1. Soluble anion and cation content was highest in the deepest sampled permafrost, with the highest concentrations seen below 70 cm. **Implication:** In years where active layers depths are relatively deep, ion concentrations in hillslope runoff water may increase due to the high soluble ion concentrations at depth. Moreover, permafrost disturbances that remove and displace the uppermost sections of the soil profile may create new pathways to channel flow and release stored solute-rich water in the transition layer of permafrost.

2. Most C and N pools were greatest in the upper soil horizons and declined with increasing soil depth until ~100 cm below the soil surface. Below this point – and thus, well within the permafrost – **all** carbon and nitrogen pools (total, dissolved, and microbial pools) increased significantly, coinciding with observations of small root fragments and plant litter debris. **Implication:** Thawing permafrost may release significant amounts of organic material into the soil solution, hereby increasing dissolved organic matter (DOM) runoff into streams and lakes, and enhance soil microbial activity, increasing greenhouse gas emissions to the atmosphere.

3. Microbial communities are present even at great depths currently frozen. When exposed to thaw, these communities undergo changes in composition as shown here for bacterial and fungal soil communities after an active layer thaw slump disturbance. **Implication:** Changes in microbial community composition often relate to changes in functionality, and thus activity. Thawing permafrost will release stored organic matter which in-turn will be broken down by a changing microbial community - as it is adapting to its new surroundings.

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ADAPT ArcticNet NSERC CRSNG NSTP PFSN Ontario

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The Land-Atmosphere Interaction Research Group is led by Yongjiu Dai, Professor of the College of Global Change and Earth System Science of Beijing Normal University. The mission is to develop a scientific understanding of land-atmosphere interactions as part of the atmosphere system on the local, mesoscale, regional, and global scales, but also touches on related questions. These interactions include biophysical, biogeochemical, and biogeographic effects. Our approaches include land-surface processes modeling, global and regional atmospheric modeling, and their related in-situ measurement campaigns and satellite data retrievals. The Common Land Model (CoLM), the Global and Regional Multi-scale Advanced Prediction Model System (GRAPES), the Climate version of Weather Research and Forecasting Model (CWRF) and the Beijing Normal University Earth System Model (BNU-ESM) are major tools used in the research. The group consists of graduate research assistants, postdoctoral fellows, research faculties, and visiting scientists, who are working on a wide variety of research questions. The group enjoys productive collaborative relationships with many scientists at centers or institutes under China Meteorological Administration (CMA) and Chinese Academy of Science (CAS), as well as international weather and climate modeling groups.

Basic evaluation of Beijing Normal University Earth System Model (BNU-ESM) version 1

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Introduction

The BNU-ESM (Beijing Normal University Earth System Model) is an earth system model been developed at Beijing Normal University; the model is based on several widely evaluated climate model components and is used to study mechanisms of ocean-atmosphere interactions, natural climate variability and carbon-climate feedbacks at interannual to interdecadal time scales. The coupling framework of BNU-ESM is based on an interim version of the Community Climate System Model version 4 (CCSM4) (Gent et al., 2011) developed at the National Center for Atmospheric Research (NCAR). Notably, BNU-ESM differs from CCSM4 in the following major aspects: (i) BNU-ESM utilizes the Modular Ocean Model version 4p1 (MOM4p1) (Griffies, 2010) developed at Geophysical Fluid Dynamics Laboratory (GFDL). (ii) The land surface component of BNU-ESM is the Common Land Model (CoLM) (Dai et al., 2003, 2004) initially developed by a community and further improved at Beijing Normal University. (iii) The CoLM has a global dynamic vegetation submodel and terrestrial carbon and nitrogen cycles based on Lund-Potsdam-Jena (LPJ) (Sitch et al., 2003) and LPJ-DyN (Xu and Prentice, 2008). (iv) The atmospheric component is an interim version of the Community Atmospheric Model version 4 (CAM4) (Neale et al., 2013) modified with a revised Zhang-McFarlance deep convection scheme (Zhang, 2002). (v) The sea ice component is CICE version 4.1 (Hunke and Lipscomb, 2010) developed at Los Alamos National Lab (LANL), while the sea ice component of CCSM4 is based on Version 4 of CICE. These variations illustrate how the BNU-ESM adds to the much desired climate model diversity, and thus to the hierarchy of models participating in the Climate Model Intercomparison Projects phase 5 (CMIP5) (Taylor et al., 2012).

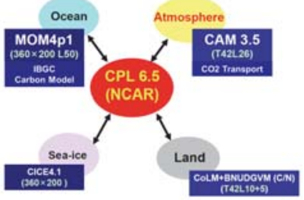

Fig.1 Framework and spatial resolution of BNU-ESM version 1

Climatology in the late 20th century

1. Surface Temperature and Precipitation

The most prominent differences from observations in modeled surface air temperature are a positive bias in Europe of up to 4°C and negative bias in Eastern Siberia up to nearly 7°C. In Central Canada, China, India, the biases are relatively small. Compared with two observational precipitation data sets, BNU-ESM has a wet bias at high latitudes. In Southeastern Asia, the monsoon rainfall in India is more realistic.

The globally averaged surface temperature bias is -0.17 °C with a RMSE of 1.83°C. Positive SST biases are seen in the major eastern coastal upwelling regions; probably due to coast winds that are not favorable for upwelling. The bias in precipitation over ocean is characterized by a double Intertropical Convergence Zone (ITCZ) structure over the central Pacific, as well as over the tropical Atlantic.

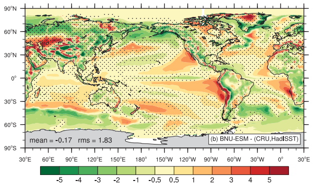

Fig. 4 Annual mean surface temperature bias (°C) of BNU-ESM relative to the CRU TS3.1 and HadISST data set for the period 1976-2005. Dotted area indicates non-significant regions at the 95 % confidence level.

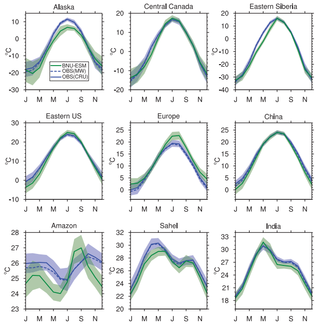

Fig. 2 Climatological annual cycle of 2 meter air temperature for selected regions for BNU-ESM and two observational estimates for the period 1976-2005. Color shading indicates interannual variability.

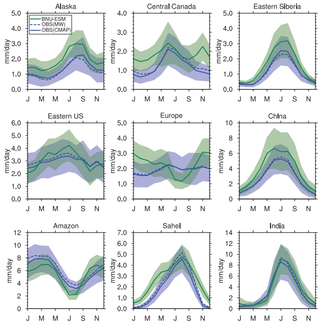

Fig. 3 Climatological annual cycle of precipitation for selected regions for BNU-ESM and two observational estimates for the period 1979-2005. Color shading indicates interannual variability.

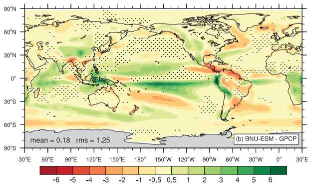

Fig. 5 Annual mean precipitation bias (mm/day) of BNU-ESM relative to the GPCP climatology for the period 1979-2005. Dotted area indicates non-significant regions at the 95 % confidence level.

2. Tropical Pacific SST

BNU-ESM reasonably reproduces features of the annual cycle structure in the eastern Pacific, such as its transition phases and the amplitude and the position of the cold tongue, but the warm season peak is one month later in the model than in observations.

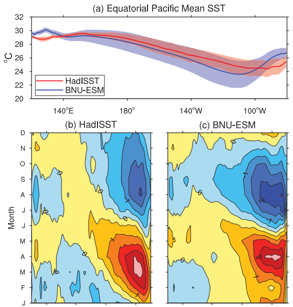

Fig. 6 Mean SST (°C) along the equator (2°S-2°N) in the Pacific Ocean **(a)**, color shading indicates interannual variability. Annual cycle of the tropical Pacific SST anomalies for the period 1976-2005 from HadISST **(b)** and BNU-ESM **(c)**.

3. Sea Ice Extent

The sea ice extent of both polar regions agrees better with the observations in summer seasons than in winter seasons, and the model has a tendency to have excessive ice extent during winter seasons.

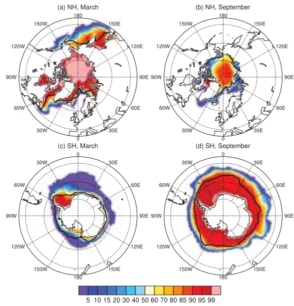

Fig. 7 Mean sea ice concentration (%) over years 1976-2005 of the BNU-ESM for March **(a, c)** and September **(b, d)**. The solid black lines show the observational 15 % mean sea ice concentration.

Climate Variability

1. Tropical Intraseasonal Oscillation

The zonal wave number power distribution of MJO is well captured during boreal winter, but the eastward propagating power tends to be concentrated at lower than observed frequencies. The simulation shows a northward propagating mode of precipitation during boreal summer at wavenumber 1 with a maximum variance between 30 and 50 days, but the northward propagating band is weaker than observed.

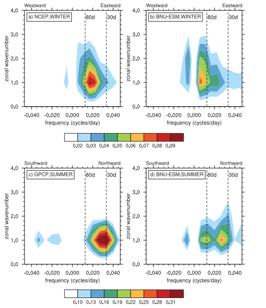

Fig. 8 November-April wavenumber-frequency spectra of 10°S-10°N averaged daily zonal 850hPa winds NCEP **(a)** and BNU-ESM **(b)**. May-September wavenumber-frequency spectra of 15°S-30°N, 65-95°E averaged daily precipitation for GPCP observation **(c)** and BNU-ESM **(d)**

2. El Niño-Southern Oscillation

The observation based Niño-3.4 index has most power between 3 and 7 years, BNU-ESM shows the most prominent variability between 2 and 5 years with a narrow peak at 3.5 years. The seasonal phase locking feature of ENSO is well captured in the model, although the standard deviation of Niño-3.4 SST anomalies from the *historical* simulation is significantly large than in the observations.

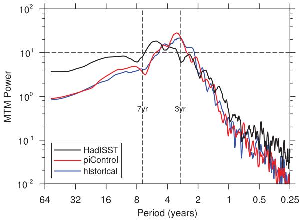

Fig. 9 Power spectra of the Niño-3.4 index using the multitaper method.

Terrestrial carbon cycle

The BNU-ESM model can capture the large store of soil organic carbon in the boreal and tundra regions of Eurasia and North America, and the small storage in tropical and extra-tropical regions. The model simulates substantially less soil carbon than those from the HWSD and IGBP-DIS for the upper 1.0 m of soil, but agrees much better with upper 0.3 m soil-carbon density estimates on magnitude and latitudinal gradients, due to the environmental controls of moisture and temperature for soil-carbon decomposition are diagnosed at 0.25 m depth.

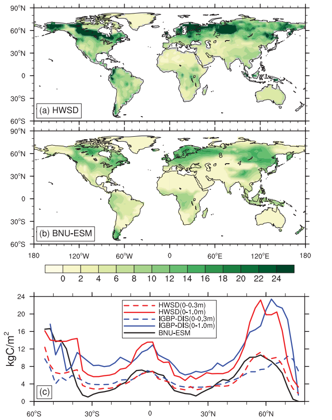

Fig. 10 Soil-carbon density in the top 1 m depth from the HWSD **(a)** and BNU-ESM **(b)**, and zonal average soil-carbon density of BNU-ESM compared with that of upper 0.3 m and upper 1 m soil from HWSD, IGBP-DIS data sets.

Reference:

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Description and basic evaluation of Beijing Normal University Earth System Model (BNU-ESM) version 1, Geosci. Model Dev., 7, 2039–2064, 2014, doi:10.5194/gmd-7-2039-2014

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Dr. Kumar's research group is working on the multi-scale modeling of hydrological and biogeochemical processes from sub-meter resolution in massively-parallel flow and reactive transport model (PFLOTRAN) to global scale terrestrial biosphere model (CLM) utilizing state-of-art high performance computing and computational science. His group also works on development of large scale data analytics using remote sensing, observational and model data with applications in the broad areas of earth and climate sciences, hydrology and landscape ecology. As a part of Department of Energy funded Next Generation Ecosystem Experiments (NGEE-Arctic) project, group is involved in modeling and characterization of Arctic ecosystem processes.

Mapping plant functional type distributions in Arctic ecosystems using WorldView-2 satellite imagery and unsupervised clustering

B41I-0166 December 18, 08:00 AM - 12:20 PM

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Introduction. The Next-Generation Ecosystem Experiments (NGEE–Arctic) seeks to address the challenge in climate projections for high-latitude regions by quantifying the physical, chemical, and biological behavior of terrestrial ecosystems in Alaska. Arctic vegetation is particularly sensitive to warming conditions and likely to exhibit shifts in species composition, phenology and productivity under changing climate.

Objectives. Objective of the this study was to characterize the landscape properties and develop high resolution maps of Plant Functional Type (*PFT*) distributions for better representation of vegetation in Community Land Model (*CLM*).

Study Area. A field campaign was conducted in Barrow, AK during peak growing season in 2012 to collect vegetation harvests from 48 1m x 1m plots (Figure 1), which were then analyzed for distribution of *PFT*: Wet tundra graminoid, dry tundra sedge, bryophytes, forb, lichen, and shrubs.

Approach. Statistical relationships were developed between spectral (WorldView–2 multispectral data) and topographic characteristics (LiDAR) `[Predictor]` and *PFT* distributions `[Predictand]` at the vegetation plots. These derived relationships were employed to statistically upscale the *PFT* distributions for the larger landscape. Growing season phenology was used as a key property to distinguish among the *PFTs*.

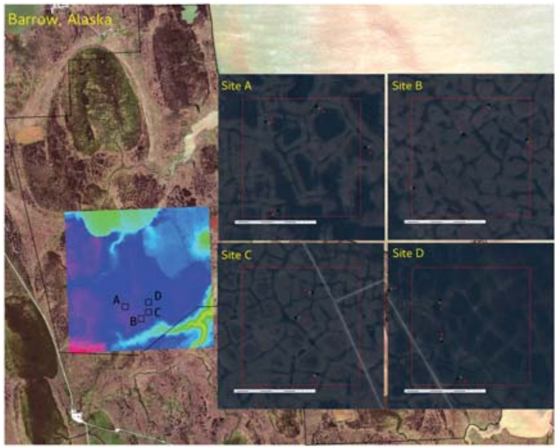

Figure 1: NGEE-Arctic sites at Barrow Environmental Observatory (BEO) spans low, transitional, high centered polyon dominated tundra.

Multivariate Spatiotemporal Statistics

***K*–means Clustering.** *K*–means algorithm was used to identify regions of similar characteristics based on times series (6 snapshots during the 2010 growing season) of WorldView–2 (*WV2*) multispectral imagery (Red, Green, Blue, Near Infrared bands), *WV2*-derived *NDVI* and LiDAR at 2 m resolution. Operating in a 31-dimensional data space, it yields classification of cells in *K* classes based on their spectral and topographic properties.

Vegetation Representativeness. The representativeness metric described by Hargrove et al. (2003) and Hoffman et al. (2013) provides a unit-less, relative measure of the dissimilarity between the pixels of interest (Figure 3). The 31–dimensional observational dataset were analyzed using this metric. This analysis provided a framework to quantify representativeness of field datasets collected during 2012 field campaign. For ground-truthing of the *PFT* distribution products from our work, 3 poorly and 3 well represented areas were selected at A,B,C,D sites (total of 24 sites) and a second field campaign was conducted on July 29, 2014.

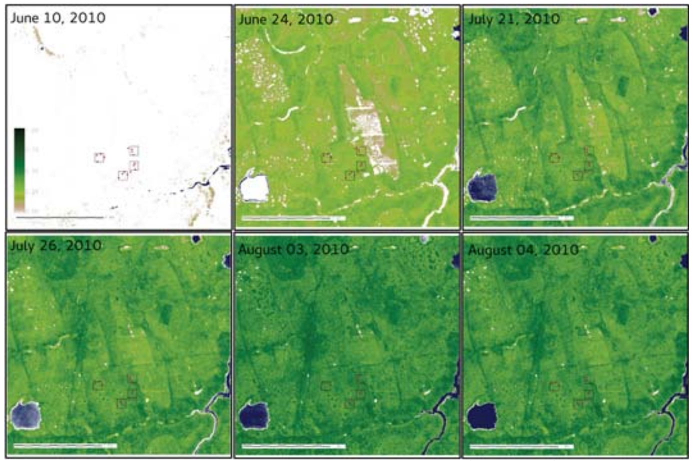

Figure 2: *WV2*-derived *NDVI* based phenology during the 2010 growing season (June – August) allows to understand the timing of green-up and brown-down for different *PFTs*

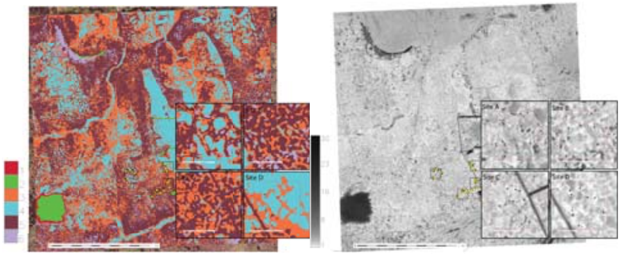

Figure 3: (Left) Six distinct classes identified for the 2010 growing season. (Right) Representativeness of field samples (darker colors indicating poorly represented areas and lighter colors indicating well represented areas).

Plant Functional Type Estimations

Upscaling Algorithm. We were interested in a interpolation algorithm that uses sparse, irregularly scattered data over a multidimensional domain, such as the Inverse Distance Weighting (*IDW*). In *IDW*, the interpolating function is expressed as a weighted average of the data values, where the weights are inverse functions of the distances from the data sites in multi-dimensional data space. Figure 4 shows the estimated distribution of Wet Tundra Graminoid.

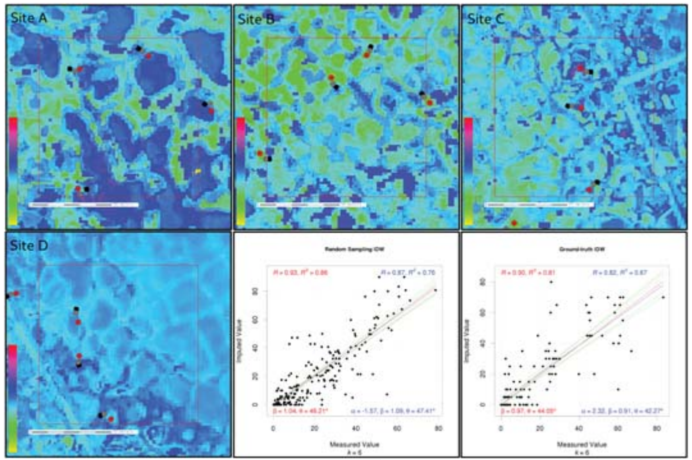

Figure 4: Wet tundra graminoid estimates from *IDW* algorithm. (Bottom Center) Validation again randomly sampled points for all *PFTs*. (Bottom Right) Validation against field campaign conducted on July 29, 2014 for all *PFTs*.

Improving Representativeness. An additional field campaign was performed on August 29, 2014 which included the same poor and well represented sites from July 29, 2014. The *IDW* algorithm was updated using the data collected on July 29, 2014 (Figure 5 Bottom) and compared against the original algorithm (Figure 5 Top).

Conclusions.

- The high resolution *PFT* distribution maps were developed (are being used to parameterize *CLM* for Arctic ecosystems).
- The representativeness analysis allow identification of sampling gaps and optimally guide new observations.
- Growing season phenological significantly improved the accuracy of *PFT* distribution estimates.

References:

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- Forrest M. Hoffman, Jitendra Kumar, Richard T. Mills, and William W. Hargrove (2013) Representativeness-based sampling network design for the State of Alaska. *Landscape Ecology, 28(8):1567-1586.*

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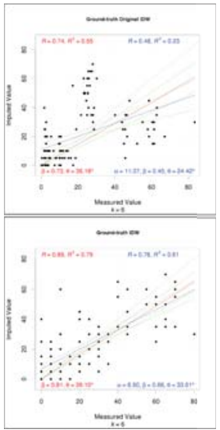

Figure 5: (Top) Original *IDW* based on 2012 field campaign. (Bottom) Improved *IDW* using July 29, 2014 field campaign.

Impacts of hydrology on CO_2 and CH_4 flux patterns in a floodplain in Northeast Siberia

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A large fraction of organic carbon stored in Arctic permafrost soil is to be decomposed and released to the atmosphere under climate change. Among many drivers that influence decomposition, changes in hydrology play a pivotal role: Shifts in water table depth (WTD) often trigger modifications on ecosystem (e.g. soil temperature and vegetation/microbial community structure), which in turn alter CO_2 and CH_4 fluxes.

My PhD research is to investigate effects of drainage on CO_2 and CH_4 fluxes (chamber-based) in a floodplain of the Kolyma River near Cherskii, Northeast Siberia. The study site is separated into two areas, one that has been drained since 2004, and a nearby reference/undrained site. Drainage lowered the WTD by *ca*. 20 cm over growing season in drained site. NEE, ER, and methane flux was measured for ~16 weeks during summer and early winter of 2013, and summer of 2014. Continuous CO_2 flux (ER, GPP) was calculated with polarVPRM based on chamber observations – air temperature as a driver for ER and air temperature, PAR, EVI, and WTD for GPP. Vegetation community structure was investigated with harvest and point-intercept method and microbial community structures and abundance of groups related to methane production and oxidation of two areas were compared with pyrosequencing.

After a decade of drainage history *Eriophorum Angustifolium* (cotton grass) that previously dominated have been decreased and replaced by *Carex Appendiculata* (tussock-forming sedge) and shrub species (*Betula* and *Salix*). These changes in WTD and vegetation influenced NEE, ER, and methane flux rates significantly in both sites, and overall drained site took up slightly less CO_2 in the growing season and emitted more in fall compared to undrained site. Methane flux was primarily determined by WTD: high WTD sites emitted significantly large amount of methane and drained site emitted *ca*. 20 times less methane in the growing season but emitted slightly more in fall than undrained site. Among high WTD sites, sites with *Eriophorum* had higher methane emission than those without, implying that aerenchyma is substantial transport pathway. Methane flux was positively correlated with methanogen abundance as well as with the ratio of methanotrophs to methanogens. Summarizing all effects of vegetation and WTD, the drainage results in a stronger net sink (CO_2 and CH_4 fluxes combined) in the growing season, but a stronger source in fall.

Impacts of water regime on CO_2 & CH_4 fluxes in a floodplain of Kolyma, Northeastern Siberia

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Introduction

This study addresses the impact of **changes in hydrology** on **carbon fluxes** in permafrost-affected floodplain based on a **drainage experiment**.

- **Water table depth (WTD)** influences
  - type of gas (CH_4 vs. CO_2) that dominates the carbon fluxes
  - rate of organic carbon decomposition
- **Future hydrological conditions** are likely to change
  - precipitation patterns: more floods and droughts expected
  - thawing of ice-rich permafrost & micro-topography will form patches of inundated and drained area
- ➢ >9 years of **drainage** → shifts in CO_2 and CH_4 fluxes?
  - biotic factors (e.g. vegetation, microbial community)
  - abiotic factors (e.g. thaw depth, water table depth)

Summary

- WTD variability (& drainage) altered vegetation & microbial comm. str.
- Subsequently CO_2 and CH_4 fluxes are influenced
  - Drier (more *Carex*, shrubs, methanotrophs) → less CO_2 uptake, less CH_4 emission
  - Wetter (more *Eriophorum*, methanogens) → more CO_2 uptake, more CH_4 emission
  - Net effect of drainage: slightly less CO_2 uptake, significantly less CH_4 emission

Method

- **Site:** wet tussock tundra (floodplain) on the Kolyma river near Cherskii
- **Flux with chambers:** CH_4 and CO_2 (NEE, ER), 2013 summer & fall, 2014 summer
- **Abiotic drivers:** air and soil temperatures, water table depth
- **Biotic factors:** vegetation/microbial community structures
- **Gap-filling** model (CO_2): polarVPRM ($ER = f(T_{air})$, $GPP = f(PAR, T_{air}, WTD)$)

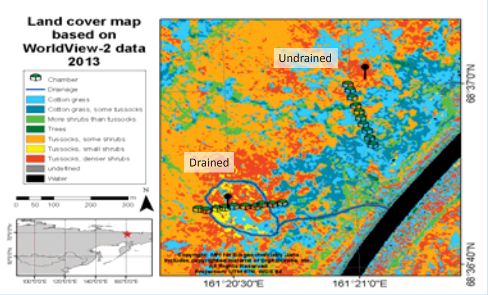


Figure 1 Location and setup of study site. Courtesy of Ina Burjack

Results (2013 summer)

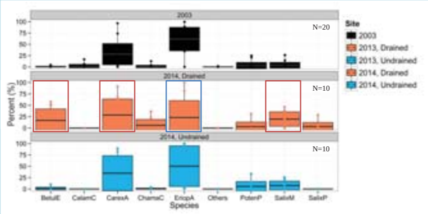


Figure 2 Vegetation community structure, relative abundance of plant species. Method: harvest (2003), point-intercept (2014).

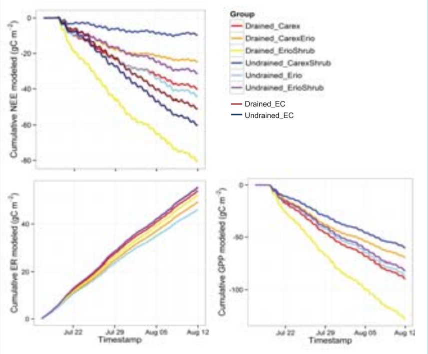
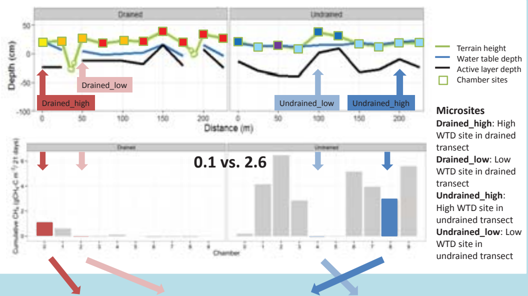


Figure 3 Modeled CO_2 fluxes (polarVPRM) by vegetation group. Vegetation species of which relative abundance was >10% and prevalent in the whole study site were included.

- Drainage → veg. comm. str. changed
  → CO_2 differs
- Drainage & WTD variability
  → composition of microbes
  (esp. methanogen & methanotrophs) differs
  → CH_4 differs

Figure 4 Description of two transects and cumulative methane flux. Chamber sites are categorized into 5 vegetation groups and color-coded (refer to Figure 3). Methane flux of 21 days (3 weeks in 2013) was calculated by linear-interpolation. Averaged cumulative methane over 21 days in 2013 is 0.1 and 2.6 gC m⁻² in drained and undrained site, respectively.



Microsites
Drained_high: High WTD site in drained transect
Drained_low: Low WTD site in drained transect
Undrained_high: High WTD site in undrained transect
Undrained_low: Low WTD site in undrained transect

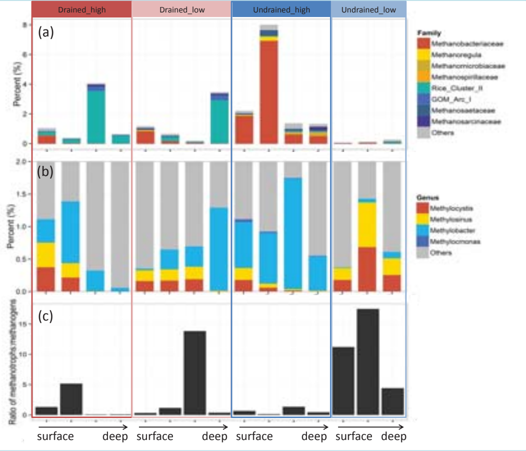
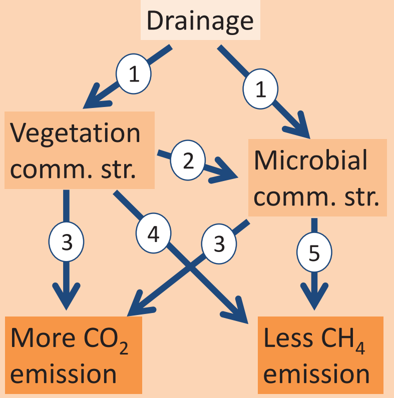


Figure 5 Methanogens and methanotrophs. (a) Abundance of methanogen family, (b) abundance of methanotroph genus, (c) ratio of methanotroph to methanogen.

Discussion



Drainage

Vegetation comm. str.

Microbial comm. str.

More CO_2 emission

Less CH_4 emission

1. less available water, higher temp fluctuation at soil surface
2. root exudates
3. aerobic respiration, less photosynthesis (less productive)
4. less *Eriophorum* (less plant-mediated methane transport)
5. less methanogens, more methanotrophs

Remaining question:

- Similar trend over longer term?
- 10-year drainage vs. natural variability?

Yoo Kyung Lee (Korea Polar Research Institute)

CAPEC Project

We're currently working on a project of CAPEC (Circum Arctic Permafrost Environment Change Monitoring) since 2011. Through this project, we have a plan to establish Arctic monitoring nodes to study environmental changes and develop the state-of-the-art observation techniques for terrestrial permafrost region. This monitoring project includes atmosphere-pedosphere-biosphere monitoring system with Ubiquitous Sensor Network (USN) and GPS monitoring. The research aim of this project is (1) Understanding the correlation between carbon dioxide (CO2) fluxes with soil properties, (2) Estimating the contribution of microbial respiration, and plant photosynthesis and respiration to the CO2 production from soil (3) Understanding geophysical and mechanical behavior of frozen ground correlated with environmental change. In the CAPEC project, we have established three permanent research sites (Ny-Ålesund, Svalbard Archipelago; Council, Alaska; and Cambridge Bay, Canada) and try to expand the sites to Russia and Greenland.

Our group in the CAPEC project is specialized in microbial and soil analysis. Our goal is to understand microbial community structure, soil properties, vegetation, and their relationship in permafrost-affected soil. The microbial team is using high-throughput sequencing (GS-FLX 454 pyrosequencing) to know the bacterial community structure from Arctic soil. The soil team is using density fractionation, pyrolysis GC/MS, and ^{13}C NMR to characterize soil organic carbon.

Glacier Foreland Project

From the project "Environmental Change Studies based on the Arctic Dasan Station: in terms of Geology, Atmospheric Science, and Ecology", we're working on "estimation of soil organic carbon stock and understanding of microbial community structure in the Midtre Lovénbreen Moraine, Svalbard." This project was initiated in 2014, and we will present this topic in this AGU fall meeting. Here is an abstract for the project.

As a glacier retreats, land surface beneath the glacier is newly exposed, and changes in soil have initiated as well as microbial and plants species. Numerous studies have been done on soil development along the chronosequence in the glacier moraine, and mostly undisturbed areas were selected as sampling sites to represent soil age well. However, the surface of glacier moraine is remodeled by active flows, and terrain attributes are very diverse, thus soil organic carbon (SOC) accumulation is not always a linear function of soil age in the glacier moraine. Therefore, we examined the distribution of SOC in the Midtre Lovénbreen morain with a consideration of soil age, microtopography, and runoff activity in this study. Forty two soil sampling sites were selected among previously observed 300 points of plant species via the systematic random sampling method with a consideration of soil age, runoff activities, slope, aspect, and X, Y coordinates. Three close to the glacier terminus and nine sites outside of moraine were additionally sampled. Four different depths (0-5, 5-10, 10-20, and 20-30 cm) of soil were collected, and soil volume was measured by the excavation method in summer 2014. Currently, we are in a status of acquiring microtopographic information from digital elevation model, calculating bulk density, and preparing soil samples for SOC analysis. Once we gather all data, corresponding analysis and classification will be conducted to characterize sampling sites. Then, SOC distribution over the glacier moraine using microtopographic information will be estimated through modelling.

CAPEC (Circum Arctic Permafrost Environmental Changes): Korean Permafrost Research Project

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Arctic Research Center, Korea Polar Research Institute
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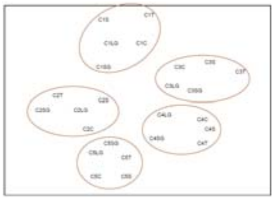
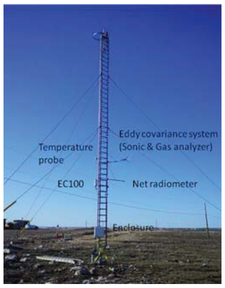
Completely randomized block design
Five blocks and five treatments



Climate manipulation plots since 2004

- **Objective**
  To understand the characteristics of SOC and the effects of climate manipulation on SOC under high arctic heaths.
- **Hypothesis**
  Change in temperature and in growing season length would affect microbial activities and thus the amount and chemical composition of SOC.
- **Results**
  - Most physical and chemical properties in soil were not significantly different among treatments despite a fairly long period of climate manipulation.
  - The amount of LF was lower in T and SG treatments than that in control.
  - 13C NMR showed that in the T treatment, the ratios of the O/N-alkyl C (labile) and that of the alkyl C (recalcitrant) groups were relatively lower and higher than the others, respectively.
  - Warming did not alter the amount of SOC, however, it could cause the change in SOC quality by decreasing a labile portion of SOC.

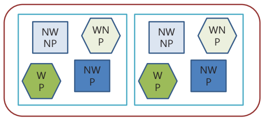
- **Monitoring of CO_2 and energy exchange between the atmosphere and the ecosystem**
- **Study on the effects increasing temperature and precipitation on abiotic and biotic factors**



Eddy covariance flux system together with a net radiometer

Climate manipulation experiment since 2012

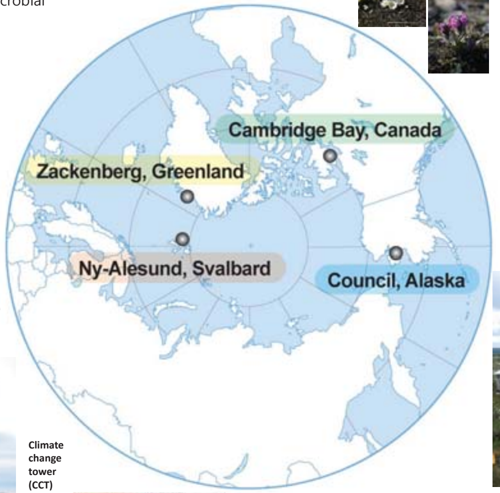
Composition for one block



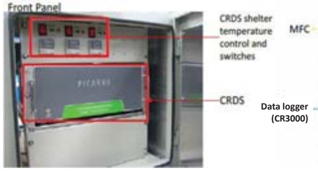
W: warming
NW: non-warming (ambient)
P: increased precipitation
NP: no increase in precipitation

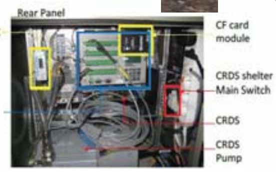
Destructive sampling Monitoring

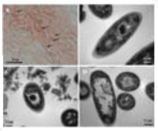
- **Air and soil environments monitoring** : Air temperature and relative humidity (25 cm), soil temperature and moisture content (5 cm depth)
- **Plant** parameters: Plant species, vegetation coverage
- **Soil** properties: Quantity and quality of soil organic carbon, moisture content, bulk density, texture, pH, electronic conductivity, inorganic nitrogen, C, N, P, cations, etc.
- **Soil microbial community** structure through pyrosequencing
- **Gas** fluxes (CO_2, CH_4, N_2O)
- **Microbial activity**: extracelluar enzyme activity
- **Volatile organic compounds** (VOCs)
- **Sterol** in soil, metabolites in plant leaves and roots
- **Nitrogen availability** by using ^{15}N



- **Methane flux measurement in Ny-Ålesund**
- **Soil properties and microbial community structure changes along the chronosequence of Midtre Lovénbreen retreat**
- **Isolation of facultative anaerobic soil bacteria**

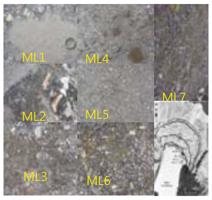




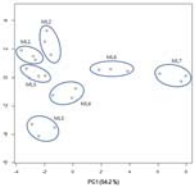


Images of endosphores of the isolates by microscopy after staining (a) and by TEM (b,c, and d).
a. *Bacillus circulans* KOPRI 80146
b. *Paenibacillus borealis* KOPRI 80157
c. *P. donghaensis* KOPRI 80163
d. *P. macquariensis* subsp. *macquariensis* KOPRI 80167.

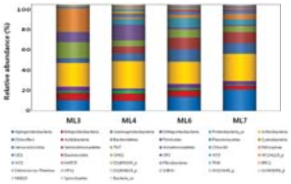
(Kim et al., 2013 Polar Biol. 36:787-796. Isolation of facultatively anaerobic soil bacteria from Ny-Ålesund, Svalbard)



Vegetation cover and soil conditions for each sampling sites along the glacier retreat period

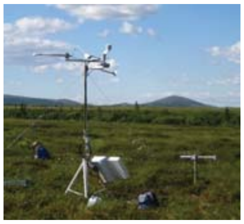


Relative positions of sampling sites in the score plot of the principal component analysis (PCA). All measured physical and chemical properties of soil were used in PCA.



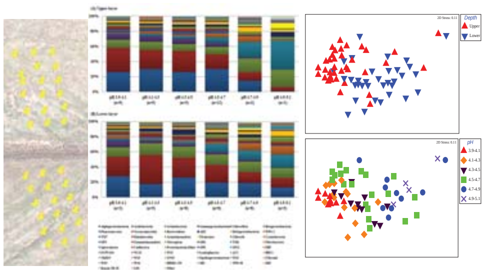
Relative abundance of bacterial phyla from each soil sample at the chronosequence of glacier retreat.

(Kwon et al., *under review* Polar Biol. Soil development and bacterial community shifts along the chronosequence of the Midtre Lovénbreen glacier foreland in Svalbard)



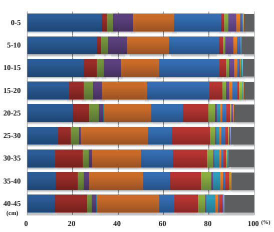
- **To understand the mechanisms of the carbon cycle in tussock tundra**
- **To understand microbial community structure, soil properties, vegetation, and their relationship**
- **To compare simulated variables by CLM4.5 with site observations**

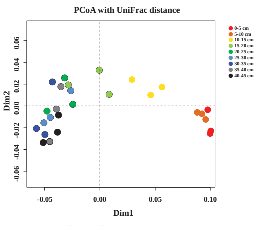
Horizontal distribution of bacteria



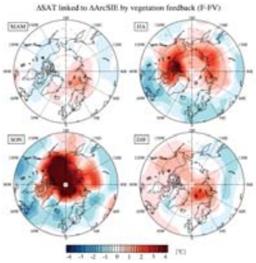
(Kim et al., 2014 FEMS Microbiol. Ecol. 89:465-475 Bacterial community structure and soil properties of a subarctic tundra soil in Council, Alaska)

Vertical distribution of bacteria





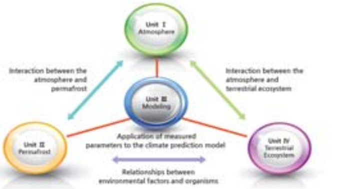
(Kim et al., *under review.* Frontiers in Microbiology Vertical distribution of soil bacterial communities of the active layer in moist acidic tundra, Alaska)



Statistically projected surface air temperature change associated with the Arctic sea ice extent (SIE) change by vegetation feedback effect based on a regression analysis. The SIE is the summation of the areal extent where the sea ice concentration is greater than 15 % over the Arctic sea (North of 70° N), and SAT is the surface air temperature.

(Jeong et al., 2014 Environ. Res. Lett. 9:094007 Intensified Arctic warming by vegetation-atmosphere-sea ice interaction, Highlighted in Nature)

CAPEC structure



Unit I.	**Establishment of Multidisciplinary Environmental Change Observation Network:** The interactions between the atmosphere and permafrost on ecosystem scale
Unit II.	**Understanding Environmental Changes in Arctic Permafrost Region:** Biotic and abiotic factors in permafrost affected soils
Unit III.	**Numerical Simulation and Future Prediction for the Permafrost Environmental Change:** Improving the permafrost modeling system and producing more reliable future climate change scenario
Unit IV.	**Monitoring of Ecosystem Characteristics under the Permafrost Environmental Changes:** Understanding Arctic terrestrial ecosystem structure and monitoring the changes in Arctic plants under climate change

ACKNOWLEDGEMENTS

This study was supported by the National Research Foundation of Korea Grant funded by the Korean Government (MSIP) (NRF-2011-0021063 (PN13081), -0021067 (PN13082), -0021069 (PN13083)).

Estimation of soil organic carbon stock in the Midtre Lovénbreen moraine, Svalbard

Ji Young Jung[1], Dominique Laffly[2], Se-eun Kim[1], Hyeyoung Kwon[1], Myrtill Moreau[3], Yannick Le Nir[4], Lennart Nilsen[5], Yoo Kyung Lee[1]*

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Introduction

The impact of contemporary climate change is a major issue of modern science engagement with humanity. It is predicted that global warming will be the greatest and most rapid in the Arctic region. Global warming is currently accelerating the processes of thawing permafrost, activating dormant microbes, and releasing greenhouse gases (CO_2 and CH_4) into the atmosphere. Furthermore, global warming has resulted in rapid melting of ice and retreating glacier, and the Svalbard glaciers are following the same pattern. The newly exposed glacier forefield gives chances for plants and microorganisms to be established but causes decomposition of old organic carbon stored under the frozen state in the past. Moraines are also continuously revised by increased runoff itself accelerated by increased melting in recent years. Finally, moraines are also areas where surfaces or gas exchanges with the atmosphere appear and intensify. Moraines of the Little Ice Age are therefore privileged areas to study. The quantity of soil organic carbon (SOC) beneath glacier and/or glacier forefield has not been exactly quantified, and we do not clearly understand how much carbon dioxide (CO_2) will be produced in that area either. Since CO_2 production is closely related to the quantity and quality of SOC, it is very important to know the distribution of the SOC stock.

Previous Studies in Midtre Lovénbreen

Supraglacial ecosystem

- Cryoconite
  - Microbes (Anesio *et al.*, 2010)
  - CO_2 fluxes (Hodson *et al.*, 2007)
- Retreat of glacier
- Mass balance of glacier (NPI measurement since 1967)
- Energy balance of the surface of glacier (Arnold *et al.*, 2006)

Midtre Lovenbreen

Proglacial ecosystem (glacier foreland)

- Glacier river system-nitrogen (Hodson *et al.*, 2010)
- Plant succession (Nilsen *et al.*, 1999; Moreau *et al.* 2005)
- Plant and soil succession (Hodkinson *et al.*, 2003)
- Characteristics of SOC by pyrolysis GC-MS (White *et al.*, 2007)
- Microbial community structure (Schuette *et al.*, 2009, 2010)
- Weathering of rocks by pioneer microbes (Borin *et al.*, 2010)

Subglacial ecosystem (ice-bed interface)

- Glacier-bed characteristics by radar (King *et al.*, 2008)

Research gaps on successional studies:

- Most influencing factors: glacier retreat periods, ignored disturbances by melting water runoff
- Linear transect studies: all areas containing have not been covered

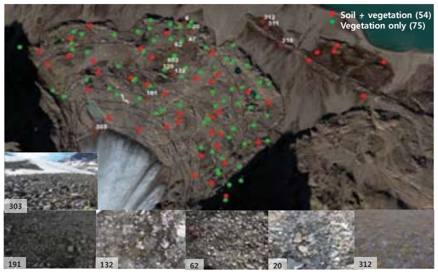
Objectives

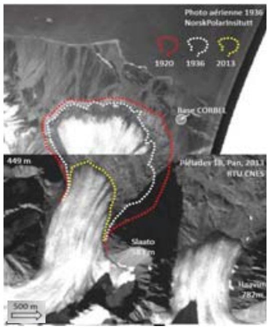
- To understand soil chronosequences in the Midtre Lovénbreen glacier foreland
- To determine stocks and the accumulation rate of SOC in the glacier foreland
- To produce a map of SOC distribution in the glacier foreland with a consideration of several environmental factors especially microtopography and runoff

Study Area & Methods

- **Study area:** Glacier foreland of Midtre Lovénbreen, Brøgger Peninsula, Svalbard (79°N, 12°W)

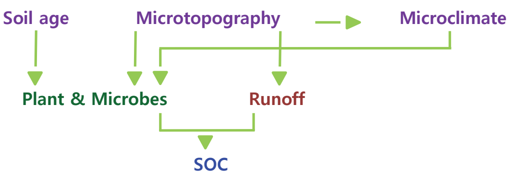
- **Sampling sites selection**: Stratified sampling with a consideration of X, Y coordinates, runoff, age, slope, and wind from 300 sites of Moreau (2005)





Research Approaches

- Factors affecting SOC distribution in the glacier foreland



Soil age

Microtopography

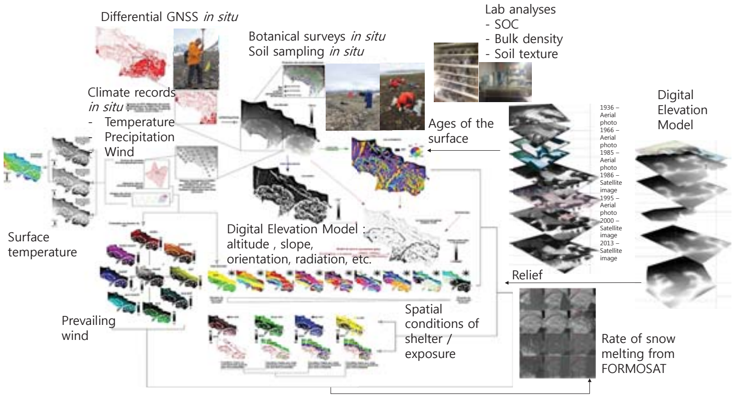
Microclimate

Plant & Microbes

Runoff

SOC

- Field measurement and environmental data acquisition from DEM



Differential GNSS *in situ*

Botanical surveys *in situ*
Soil sampling *in situ*

Lab analyses
- SOC
- Bulk density
- Soil texture

Climate records *in situ* :
- Temperature
- Precipitation
- Wind

Ages of the surface

Digital Elevation Model

1936 – Aerial photo
1966 – Aerial photo
1985 – Aerial photo
1986 – Satellite image
1995 – Aerial photo
2000 – Satellite image
2013 – Satellite image

Surface temperature

Digital Elevation Model : altitude , slope, orientation, radiation, etc.

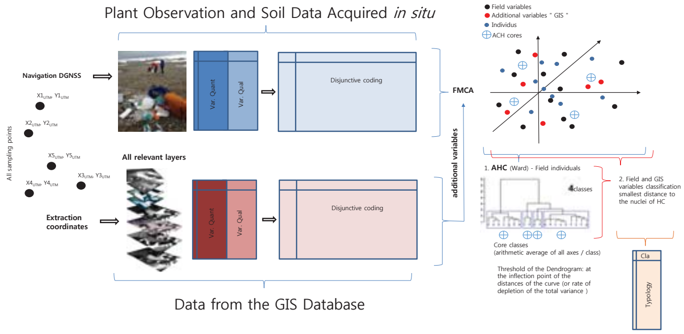
Relief

Prevailing wind

Spatial conditions of shelter / exposure

Rate of snow melting from FORMOSAT

- Factorial Multiple Correspondence Analysis (FMCA) & Hierarchical classification (AHC)



Plant Observation and Soil Data Acquired *in situ*

Navigation DGNSS

$X1_{UTM}$, $Y1_{UTM}$
$X2_{UTM}$, $Y2_{UTM}$
$X5_{UTM}$, $Y5_{UTM}$
$X4_{UTM}$, $Y4_{UTM}$
$X3_{UTM}$, $Y3_{UTM}$

All sampling points

All relevant layers

Extraction coordinates

Var. Quant
Var. Qual

Disjunctive coding

FMCA

additional variables

Field variables
Additional variables " GIS "
Individus
ACH cores

1. **AHC** (Ward) - Field individuals

classes

Core classes
(arithmetic average of all axes / class)

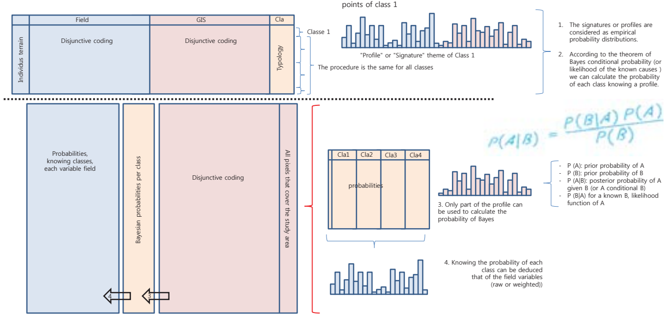
Threshold of the Dendrogram: at the inflection point of the distances of the curve (or rate of depletion of the total variance)

2. Field and GIS variables classification smallest distance to the nuclei of HC

Cla
Typology

Data from the GIS Database

- Bayesian Conditional Probabilities



Field
GIS
Cla
Individus terrain
Disjunctive coding
Typology
Classe 1

Occurrences of each category of each variable for all points of class 1

"Profile" or "Signature" theme of Class 1

The procedure is the same for all classes

1. The signatures or profiles are considered as empirical probability distributions.
2. According to the theorem of Bayes conditional probability (or likelihood of the known causes) we can calculate the probability of each class knowing a profile.

$$P(A|B) = \frac{P(B|A)\,P(A)}{P(B)}$$

Probabilities, knowing classes, each variable field

Bayesian probabilities per class

Disjunctive coding

All pixels that cover the study area

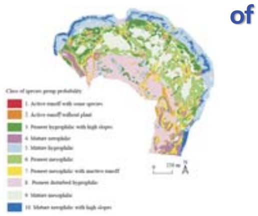
Cla1
Cla2
Cla3
Cla4
probabilities

3. Only part of the profile can be used to calculate the probability of Bayes

- P (A): prior probability of A
- P (B): prior probability of B
- P (A|B): posterior probability of A given B (or A conditional B)
- P (B|A) for a known B, likelihood function of A

4. Knowing the probability of each class can be deduced that of the field variables (raw or weighted))

Expected Result : A SOC stock map in the glacier foreland of Midtre Lovénbreen



An Example of Vegetation Map (Moreau *et al.*, 2005)

Acknowledgements

This study was supported by the "Environmental Change Studies based on the Arctic Dasan Station: in terms of Geology, Atmospheric Science, and Ecology (PE14030)" and by the "Development of Research Program on the Polar Space Environment and Upper Atmosphere (PE14280)" funded by the Korea Polar Research Institute.

BG31G - 0140

Ecosystem carbon dynamics in response to experimental soil warming and permafrost degradation

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[1]University of Florida, Gainesville FL; [2]Northern Arizona University, Flagstaff AZ; [3]Woods Hole Science Center, Falmouth MA

Questions:

- ✧ What are the inter-annual and seasonal patterns of growing season C flux in response to permafrost thaw?
- ✧ How do patterns of ecosystem respiration (Reco) change when increased thaw depth is accounted for?
- ✧ What is the relationship between permafrost thaw, plant biomass and C flux?

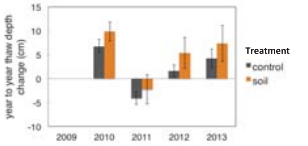
Background

- ✧ Permafrost soils store vast quantities of globally important carbon (C) (Hugelius et al 2014)
- ✧ While we expect C loss to increase with warmer soil temperatures and greater soil volume, we also expect higher nutrient availability to increase plant growth.
- ✧ However, the impacts of permafrost thaw on C balance remain largely uncertain (Schuur et al 2009)

The Experiment:

- ✧ The Carbon in Permafrost Experimental Heating Research (CiPEHR) uses snow fences to passively insulate the soil in the winter and promote permafrost thaw (Natali et al 2011, 2014)
- ✧ Open top chambers simulate warmer temperatures during the growing season
- ✧ Together these manipulations produce a Control, Air, Soil, and Air & Soil warming treatments with significantly deeper active layer depths in the soil warmed treatments.
- ✧ We analysed 5 years of C flux, thaw depth and plant biomass data to understand ecosystem responses to thaw

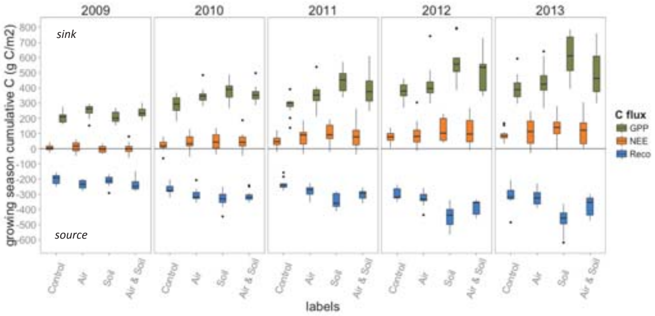
Yearly advance of active layer into previously frozen soil at CiPEHR, as a result of soil warming



Permafrost thaw enhanced C loss and C uptake during the growing season:

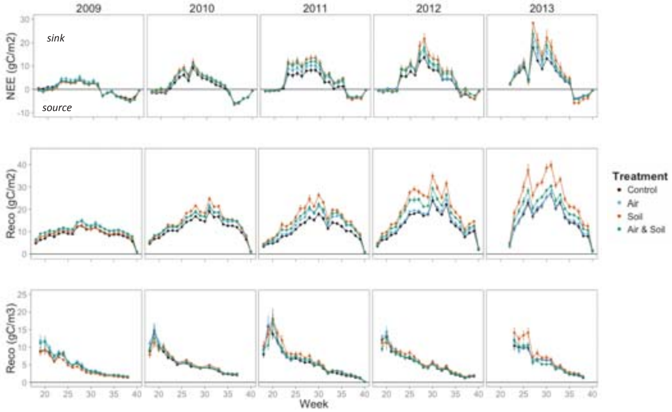
Permafrost thaw enhanced C loss and C uptake during the growing season:

- spatially due to increasingly heterogeneous thaw patterns
- inter-annually due to thawing of previously frozen soil layers



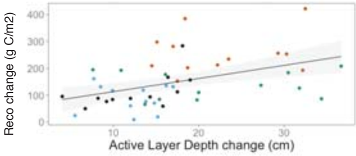
Carbon loss and uptake peaked at mid-growing season:

- Amplified seasonality of NEE in response to thaw indicates a strong plant response
- Similarities in seasonal NEE and Reco patterns indicate a tight link to plant dynamics
- Thaw slightly increased end of season Reco but did not extend the respiration season
- Normalised by soil volume, similarities in Reco regardless of warming treatment, suggest that respiration increased in proportion to thaw
- The early-season peak further highlights plant contributions

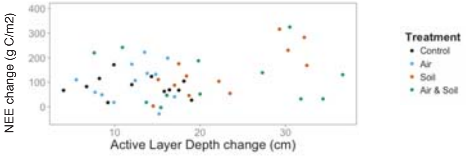


5 years of permafrost thaw promoted ecosystem respiration but C loss was offset by increased plant productivity

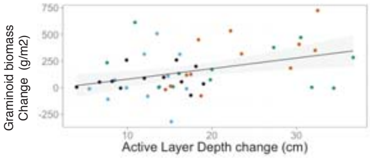
i. Reco increased with active layer depth



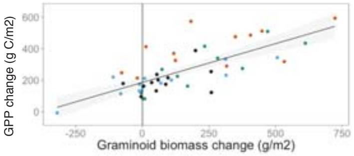
ii. however, NEE did not change with active layer depth



iii. because deeper active layer depth promoted growth



iv. resulting in higher GPP and offset C loss



Conclusions:

- The growing season C sink was surprisingly resilient permafrost thaw
- Plants were largely responsible for the observed patterns in NEE and Reco
- Thaw promoted Reco, but prolific increase in graminoid biomass offset C losses and maintained a growing season C sink
- Inter-annual and spatial differences in C flux were established during the growing season, rather than during shoulder seasons. However, as the active layer deepened so did end of season Reco.
- Reco increased in proportion to the ever-larger thawed soil volume. A previous studies from CiPEHR demonstrated that the relative contribution of heterotrophic respiration is likely to increase as a function of thaw (Hicks-Pries et al, in review) and the tundra is expected to become predominantly a net C source

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Thanks to:
Funding from DOE and NSF grants to EAG Schuur and SM Natali;
Field technicians, too numerous to name, but too valuable to forego acknowledgement

References:
Hugelius et al. 2014 Biogeosciences 11, Schuur et al. 2009 Nature 459; Natali et al. 2011 Global Change Biology 17, Natali et al. 2014 Ecology 95(3)

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As arctic temperatures rise, we expect to see dramatic changes due to thawing permafrost soils. Permafrost stores half the total amount of carbon (C) found in soils globally, and twice as much C as is found in the atmosphere. As permafrost thaws, the stored C becomes vulnerable to loss because low temperatures no longer limit microbial activity. However, thawing soils and warmer temperatures may also allow plants to access more nutrients and grow deeper roots. In the short-term greater plant growth can therefore offset C losses from the soil. Uncertainty about how plants and microbes interact, as the ecosystem continues to change, makes it extremely difficult to predict how warming will affect permafrost C dynamics in both the short, and the long term. Using data from a 5 year field warming experiment in the Tundra, lab soil incubations and ^{13}C&^{14}C signatures from soil respiration, I am interested in improving our understanding of how rising arctic temperatures will affect the C balance of arctic ecosystems.

How does warming impact C balance of arctic ecosystems?
How do changes in the plant community interact to determine the C balance of the ecosystem?
How rapidly is C lost from the soil, once temperature constraints are lifted?
What are the mechanisms responsible for stabilizing C in the soil?
Do greater plant root activity and more extensive soil thawing create a priming effect to stimulate even greater soil C loss?

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Cuicui Mu, Tingjun Zhang, Xiankai Zhang, Bin Cao, Xiaoqing Peng, Qingbai Wu, Guodong Cheng

At present, the research of our lab is mainly about carbon cycling in permafrost regions on the Qinghai-Xizang (Tibetan) Plateau, including permafrost carbon storage, the effects of permafrost warm and thermokarst (thermokarst lakes and thaw slump) on the mechanism of carbon release. The main research contents are as follows:

1. Controls on the fate of soil organic carbon (SOC) stored in permafrost on the Qinghai Tibetan Plateau (QTP) remains largely unclear despite its potential for a significant feedback to climate change. Using a permafrost core from the northeastern QTP, the effect of temperature on SOC decomposition was examined through a 140-day incubation at different temperatures from −5.0 °C to +5.0 °C. In comparison with the soils under thawed conditions, SOC decomposition rates were more sensitive to increasing temperature under frozen conditions. A temperature increase of 4.5° resulted in an average increase in carbon release of 564.8% (±241.8%) at temperature below 0 °C (−5.0 to −0.5 °C), while only 126.9% (±29.9%) at temperatures above 0 °C (0.5 to 5.0 °C). The released CO_2 mostly came from the soils at depths of 10−20 cm and deep permafrost soils (245−255 cm and 285−295 cm), based on the stable carbon isotope analysis of δ^{13}SOC and $\delta^{13}CO_2$. The results suggested a potential, long-lasting feedback of carbon stored in permafrost regions within the alpine meadow on the QTP to the global climate warm.
2. Thermokarst terrains on hill-slopes can lead to the formation of thaw slump that dramatically alter soil properties and carbon emissions, but little is known about the effects of thaw slump on soil carbon biogeochemical processes. We analyzed soil physicochemical properties, CO_2 efflux and carbon decomposition rates at different stages of thaw slump (no slump, slumping and slumped) in the upper reach of Heihe river basin on the northeastern Qinghai Tibetan Plateau (QTP). For the top layer of 0~10 cm, soil organic carbon (SOC) contents in the three types of soils were 10.6%, 8.4% and 9.5%. Total nitrogen (TN) contents were 1.5%, 1.2% and 1.4%. The slumped soils have significant less loss in carbon and nitrogen contents than the slumping soils ($p < 0.05$). CO_2 efflux near to the stage of slumping (2.60 ± 0.23 g CO_2 m^{-2} d^{-1}) was significantly higher than that at stages of no slump (2.20 ± 0.18 g CO_2 m^{-2} d^{-1}) and slumped (1.42 ± 0.21 g CO_2 m^{-2} d^{-1}) from June to September 2014 ($p < 0.05$). The incubation results implied that the slumped soils have significant higher cumulative CO_2 production ($p < 0.05$). In addition, the slumped soils have higher intensity of organic matter compounds than that at stages of no slump and slumping. The study demonstrated that there were abundant carbon and nitrogen loss during processes of thaw slump. The slumped soil can assemble some dissolved and particle matter, and its carbon chemical structure and characteristic were changed greatly. The results showed that thaw slump plays an important role in the impacts of permafrost thaw on soil carbon release and should be paid more attention.
3. Development of thermokarst lakes promotes organic matter biodegradation and potential carbon release to the atmosphere, which has an important role in stimulating global climate change. However, little is known about greenhouse gas emissions from thermokarst lakes in permafrost regions over the Qinghai-Tibetan Plateau (QTP). In this study, we measured the

concentrations of dissolved organic carbon (DOC), dissolved CO_2 and CH_4, and the distribution of stable carbon isotopes of $\delta^{13}C_{DIC}$ (dissolved inorganic carbon), $\delta^{13}C_{CO2}$, $\delta^{13}C_{CH4}$, and $\delta^{13}C_{SOM}$ (soil organic matter) in lake sediments of thermokarst lakes on the QTP. Results showed that concentrations of DOC (1.2–49.6 mg L^{-1}), CO_2 (3.6–45.0 μmol L^{-1}), and CH_4 (0.28–3.0 μmol L^{-1}) were high in the lake water on the QTP. Isotopic evidence suggested that dissolved carbon mainly originated from allochthonous input from the surrounding land, while DIC originated from heterotrophic respiration and carbonate. The $\delta^{13}C_{CH4}$ values ranged from –58.2‰ to –42.9‰ in September, implying that the dissolved CH_4 in lake water was produced by microbial decomposition of organic matter. The results showed that dissolved carbon in thermokarst lakes may play an important role in determining the climate in this arid and semi-arid region on the QTP.

Decomposition of soil organic carbon with increasing incubation temperature in permafrost regions of Northeastern Qinghai Tibetan Plateau

Cuicui Mu, Tingjun Zhang, Xiankai Zhang, Bin Cao, Xiaoqing Peng, Qingfeng Wang, Guodong Cheng
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Abstract

Controls on the fate of soil organic carbon (SOC) stored in permafrost on the Qinghai Tibetan Plateau (QTP) remains largely unclear despite its potential for a significant feedback to climate change. Using a permafrost core from the northeastern QTP, the effect of temperature on SOC decomposition was examined through a 140-day incubation at different temperatures from −5.0° C to +5.0° C. The results showed that permafrost carbon emissions on the QTP increase with soil temperature. In comparison with the soils under thawed conditions, SOC decomposition rates were more sensitive to increasing temperature under frozen conditions. A temperature increase of 4.5° resulted in an average increase in carbon release of 564.8% (±241.8%) at temperature below 0° C (−5.0 to −0.5° C), while only 126.9% (±29.9%) at temperatures above 0° C (0.5 to 5.0° C). The increase in permafrost carbon release in mineral soils was higher than that in organic soils at temperatures from −5.0 to −0.5° C. The released CO_2 mostly came from the soils at depths of 10−20 cm and deep permafrost soils (245−255 cm and 285−295 cm), based on the stable carbon isotope analysis of δ^{13}SOC and $\delta^{13}CO_2$. There is a significant negative correlation between percent SOC and $\delta^{13}CO_2$ ($R^2 = 0.46$, $p = 0.01$), and a positive correlation between $\delta^{13}CO_2$ and δ^{13}SOC ($R^2 = 0.63$, $p < 0.01$). The results suggested a potential, long-lasting feedback of carbon stored in permafrost regions within the alpine meadow on the QTP to the global climate warm.

Methods


Core cutting


Licor-7000 CO_2/H_2O


West system-CO_2 flux analyzer


GC-7890A


A picture of field work


Incubator

Snow and Frozen Ground Laboratory,
College of Earth and Environmental Sciences,
Lanzhou University, China

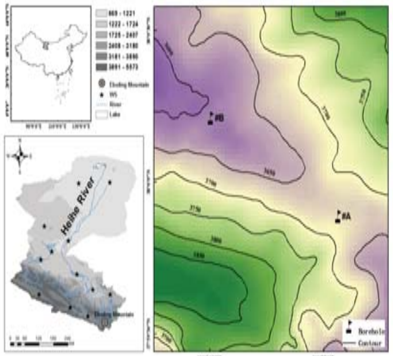

Fig 1. Geographic location of study area and sampling sites


Fig 2. Retrogressive thaw slumps on the Eboling Mountain in the upper reaches of the Heihe River basin, northeastern QTP

Results

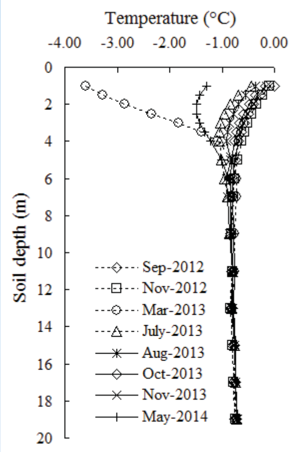

Fig 3. The distribution of measured ground temperature with depth (19 m) during 2012–2014

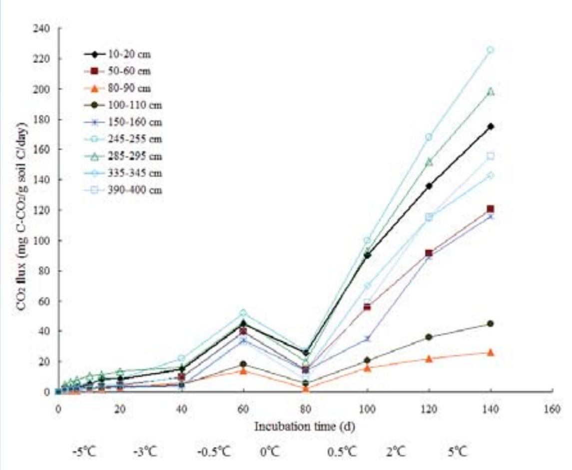

Fig 4. CO_2 emission rates under aerobic conditions for a 140-day incubation with increasing temperature

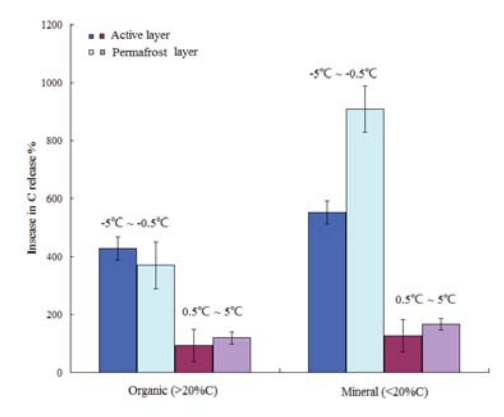

Fig 5. Increase in carbon release (%) for a 4.5° increase in temperature below 0 ° C (the temperature increased from −5.0 to −0.5 ° C) and above 0 ° C (the temperature increased from 0.5 to 5.0 ° C). Data are grouped by soil type (mineral and organic)

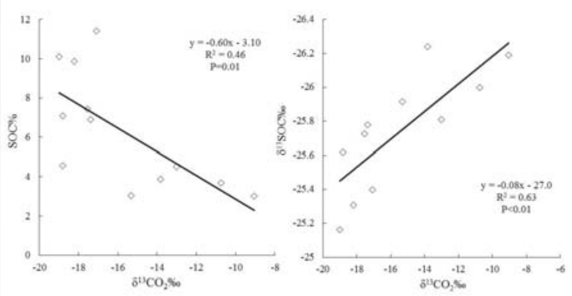

Fig 6. Relationship between SOC contents, δ^{13}SOC (‰) and $\delta^{13}CO_2$ (‰) in permafrost

Table 1 Q_{10} values at depth in permafrost, below 0° C and above 0° C (units of A are µg CO_2-C g^{-1} soil C d^{-1}, units of B are T^{-1})

Depth (cm)	Respiration = A $e^{(BT)}$, T in ° C								
	−5.0 to −0.5 ° C			−0.5 to +0.5 ° C			0.5 to 5.0 ° C		
	A	*B*	Q_{10}	*A'*	*B'*	Q_{10}	*A''*	*B''*	Q_{10}
10−20	53.99	0.37	40.34	54.49	1.56	>1,000	83.58	0.15	4.40
50−60	50.59	0.49	138.39	22.08	1.10	>1,000	35.46	0.24	11.51
80−90	16.88	0.37	42.15	6.61	1.01	>1,000	8.20	0.23	10.06
100−110	21.53	0.36	35.75	11.06	1.23	>1,000	18.71	0.18	5.78
150−160	43.77	0.51	156.42	56.52	1.61	>1,000	30.64	0.27	14.33
245−255	54.01	0.37	38.41	13.42	1.63	>1,000	91.05	0.18	6.14
285−295	82.72	0.36	37.64	12.09	1.21	>1,000	86.45	0.15	4.31
335−345	47.30	0.44	79.63	24.69	1.31	>1,000	64.53	0.16	4.90
390−400	23.80	0.45	90.65	12.80	1.24	>1,000	52.77	0.22	8.69

Reginald Muskett,
Geophysical Institute, University of Alaska, Fairbanks

At the Geophysical Institute Permafrost Laboratory I am applying methods and techniques of Geoinformatics, Mathematics, Space Geodesy, Remote Sensing and Geophysics for detecting and measuring changes of permafrost and associated environment variables across the Northern Hemisphere and at specific site locations with terrestrial ground networks relative to the continuously operating GPS stations of the International Terrestrial Reference Frame. It has been said that the changes of permafrost, the frozen ground beneath the active layer, are undetectable by remote sensing methods. Yet the structure of the Earth is known quite well through geodesy and remote sensing seismology, even though we cannot "see" the structure. Many years ago a "Grand Challenge" presented itself before the geodesy and oceanography communities; to measure the bathymetry, i.e. basin topography of the Earth's oceans at a very fine spatial scale. Geodesy, now Space Geodesy, meet the challenge beginning with the Geosat Mission, and continues with the missions of LAGEOS, CHAMP, GRACE and GOCE. So, even though we cannot "see" the topography of the ocean basins, we know it to great detail nonetheless. There are still "Great Challenges" worth challenging. -- Reginald R. Muskett, Ph.D.

Applying Space Geodesy For Permafrost Research In Alaska And The Northern Hemisphere

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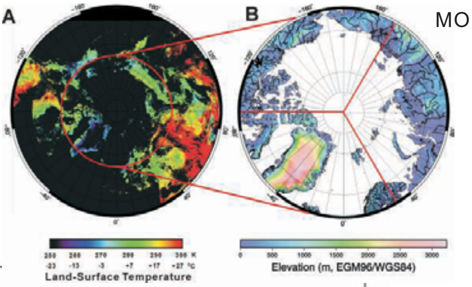
Geophysical Institute, University Of Alaska Fairbanks
http://www2.gi.alaska.edu/~rmuskett/
http://permafrost.gi.alaska.edu/users/rmuskett

Acknowledgements to Prof. Vladimir E. Romanovsky, the USGS Alaska Climate Science Center in coordination with the Arctic and Western Alaska Landscape Conservation Cooperative and the Scenarios Network for Alaska and Arctic Planning and the National Science Foundation Arctic Observing Network. Datasets used in this research are available through the Geophysical Institute Permafrost Laboratory website and server with anonymous ftp available on request. The Generic Mapping Tools and MATLAB are used in computational processing of this research.I thank the Alaska Region Super Computing Center, University of Alaska Fairbanks.

Bringing Space Geodesy & Remote Sensing Down To Earth

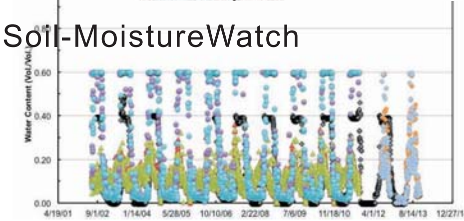
Ground-TemperatureWatch

MODIS



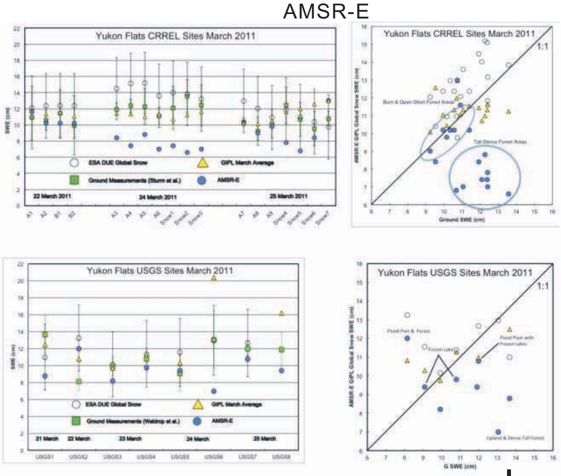
Soil-MoistureWatch

AMSR-E
AMSR2
GIPL



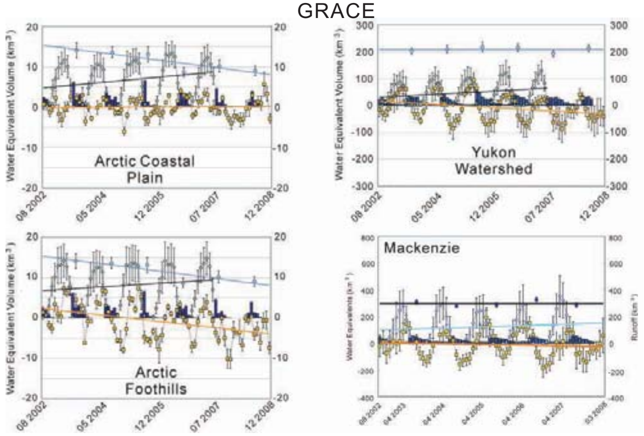
SnowWatch

AMSR-E



WatershedWatch

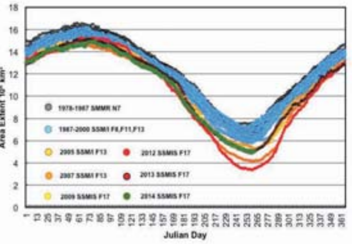
GRACE



SeaWatch

Arctic Ocean Sea-IceWatch

SMMR,SSMI,SSMIS



GMSLWatch

TOPEX,Posidon,
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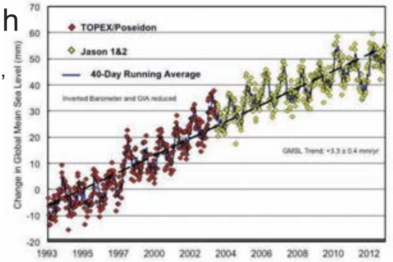
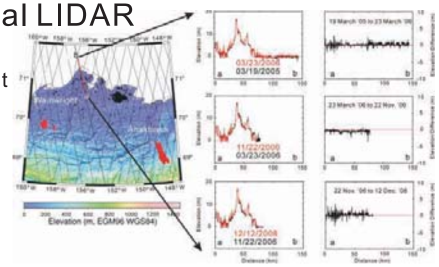


Orbital LIDAR

ICESat



EarthquakeWatch

Noatak

USGS

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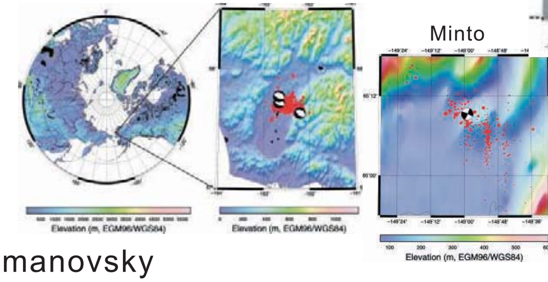
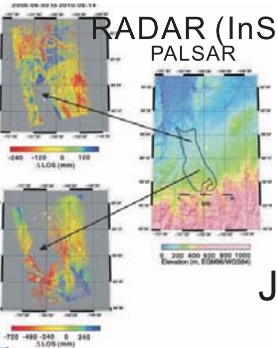


LandWatch

Anaktuvuk Fire Scar

RADAR (InSAR)

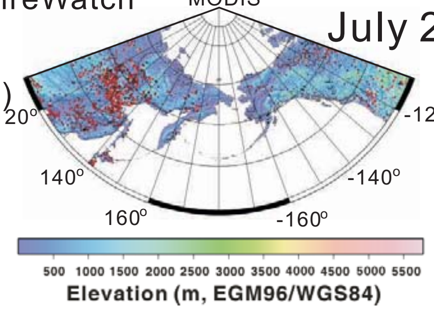
PALSAR



FireWatch

MODIS

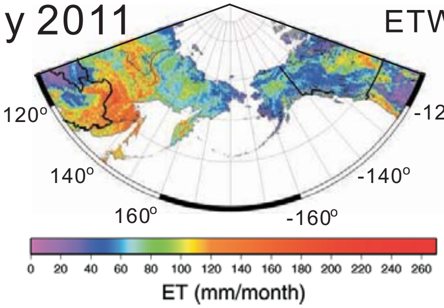
July 2011



MODIS

July 2011

ETWatch



Inspired by PermafrostWatch - Prof. V. E. Romanovsky

AUTHOR: Pegoraro, E.F., E.A.G Schuur
Northern Arizona University, Flagstaff, AZ

TITLE: Priming-induced changes in permafrost soil organic matter decomposition

ABSTRACT: Warmer temperatures attributable to climate change have the potential to warm and thaw permafrost, thereby exposing previously stored soil organic matter (SOM) to microbial decomposition. Because of its large size relative to the fast decomposing carbon (C) pool, slowly decomposing C will likely dominate future permafrost C losses. However, slowly decomposing C that is accumulated over time has low energy content and cannot sustain long-term microbial activity. Nonetheless, warming of tundra ecosystems is predicted to increase plant productivity and litter input to soil. Priming theory suggests that the addition of labile C by plants can accelerate decomposition of old and slowly decomposing C. Therefore, an increase in supply of fast decomposing substrates aboveground from leaf litter and belowground from roots, root exudates, and dissolved organic C leachate could affect the fate of permafrost C. I conducted a short-term (14 day) aerobic incubation to test priming effect on Alaska soil that is seasonally thawed. Soil samples were incubated at 15°C from surface (15-25 cm) and deep (45-55 cm) layers. Soils were amended with U-^{13}C-labeled glucose (66.45 ‰) solution, at a concentration of 3 mg glucose-C g^{-1} dry soil. Glucose addition resulted in higher respiration rates in amended soils; however, priming was only observed in the deep layer, where 30% more soil-derived C was respired compared to control soil samples. I did not observe net priming in the surface layer, indicating that microbes were not energy starved. This preliminary data suggests that microbes in deep layers are limited in energy, and the addition of labile C increases native SOM decomposition in soil with greater fractions of slowly decomposing C. A previous long-term incubation study using soil from the same location found that the fast decomposing C pool in permafrost represents <10% of the total soil C. Therefore, priming in permafrost could enhance mineralization rates of slowly decomposing C accumulated over the long-term in deep layers and increase radiative forcing as the bulk of previously frozen C is released to the atmosphere in the form of CO_2.

Microtopography controls methanogenesis in polygonal tundra as evidenced by *mcrA* gene abundance in anoxic incubation studies

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Abstract

Large reserves of organic carbon (C) in the active layer and permafrost affected soils of the Arctic tundra ecosystems are vulnerable to accelerated microbial degradation and release as greenhouse gases like methane (CH_4) and carbon dioxide (CO_2). In the present microcosm study, we determine dynamics and fluxes of CH_4 and CO_2 from depressed, elevated and subsided areas of Low- and High-Centered polygons from interstitial tundra on the Barrow Environmental Observatory (Barrow, AK). Temperature sensitivities of anaerobic respiration and methanogenesis were determined for organic, mineral and permafrost horizons incubated at -2, +4, or +8 ℃ up to 60 days. Production rates for both CO_2 and CH_4 were substantially higher for organic horizons (20 to 40 % wt. C) than the mineral horizons (< 18 % wt. C). Permafrost soils (~12 % wt. C) produced CO_2 but negligible CH_4. A characteristic lag phase, temperature threshold for methanogenesis, and temporal dynamics indicated that a constant Q_{10} relationship is inadequate to explain temperature responses from a range of -2 to +8 ℃. Temperature response of methanogen *mcrA* genes (encoding the α subunit of methyl coenzyme M reductase) positively correlated with the maximum methanogenic potential in water-saturated active layer soils. qPCR analysis revealed negligible *mcrA* gene copies in the permafrost and oxic active layer soils. Furthermore, time course measurements in this study were used to estimate continuous, differentiable functions for CH_4 and CO_2 production during thaw season in Barrow. These functions enable rate calculations that will help parameterize Arctic terrestrial ecosystem models for anaerobic biogeochemical processes.

Introduction

- Large reserves of organic carbon (C) in the active layer and permafrost (ground that remains frozen for > 2 years) affected soils of the Arctic tundra ecosystems (~ 1700 Pg C) are vulnerable to accelerated microbial degradation and release as greenhouse gases like methane (CH_4) and carbon dioxide (CO_2) (Hugelius *et al.*, 2011).
- Variability in local-scale CH_4 emission observations underscore the challenges of deriving precise regional to global-scale estimates without accurate accounting of environmental parameters.
- Thaw-activation dynamics of methanogen response is an important consideration for understanding CH_4 fluxes in warming permafrost environments. In this study, we address the gaps in our understanding of the magnitude and spatial variability observed in CO_2 and CH_4 production rates from high Arctic interstitial polygonal tundra along a natural chronosequence of low- to high-centered polygons.
- Our objectives are to:
  - (i) understand controls of geochemical parameters on CH_4 production rates;
  - (ii) generate a depth-profile of functional potential for methanogenesis in the active layer and permafrost soils; and
  - (iii) quantify temperature sensitivity of C loss pathways as CO_2 and CH_4.

- The ultimate aim is to develop a conceptual framework to understand the degree of spatial heterogeneity that will inspire new, mechanistic-based modeling exercises.

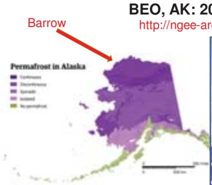
NGEE-ARCTIC, Barrow, Alaska

(a) The first NGEE intensive study at **Barrow Environmental Observatory** (BEO) is being conducted within interstitial polygonal regions, referred to as Site 1.

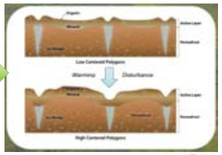
(b) Detailed study plots A, B, C, D, have different polygonal expressions and environmental conditions (FIG 1.).

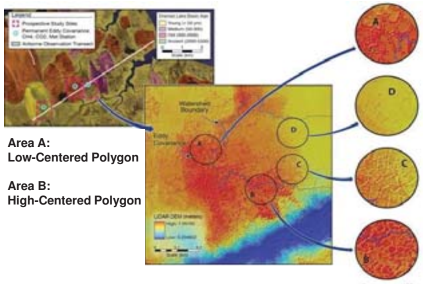
Field sampling campaigns,
BEO, AK: 2012 & 2013

http://ngee-arctic.ornl.gov/



Polygonal Tundra & Permafrost Degradation





Area A:
Low-Centered Polygon

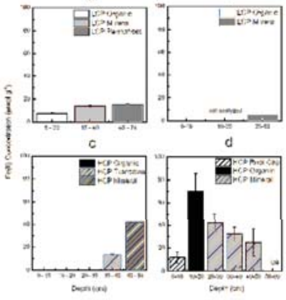
Area B:
High-Centered Polygon

FIG 1. NGEE-Arctic Intensive Study Site 1 showing four major polygonal types

Experimental Design & Laboratory Analyses

Predominantly saturated and reduced geochemistry

FIG 2. Vertical profile of Fe(II) concentrations (μmol g^{-1}dwt.) in soil cores from center (a & c, left column) and trough of (b & d, right column) of low-centered (LCP) and high-centered polygon (HCP)



Microcosm Study

Temperature-Controlled Incubation Experiments: -2, +4, +8 °C

Geochemical Measurements:
- Ion -Chromatography
- HR-Mass Spectrometry

Molecular & process-based Measurements:
- Gas Chromatography
- Microscopy
- DNA extraction
- Functional gene abundance (qPCR)

Model Initiation & Validation

- High concentrations of Fe(II) confirmed anoxic conditions and low redox potentials favorable for methanogenesis (Fig.2)
- Organic acids comprise 5 – 10 % (mineral horizons) to < 1 – 20 % (organic horizons) acetate and propionate

Results I: Dynamics of anaerobic CO_2 production during the Arctic thaw season temperature

FIG 3.

LCP Center

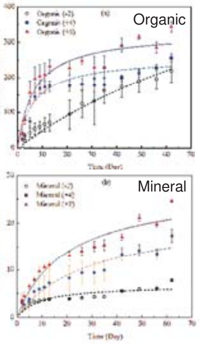


FIG 4.

HCP Center

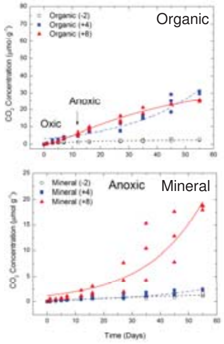
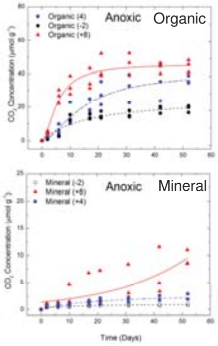


FIG 5.

HCP Trough



Results II: Substrate chemistry driven loss of carbon from Un-amended soils incubated at -2, +4 or +8 ℃

FIG 6.

Total C loss

Specific CH_4-C loss

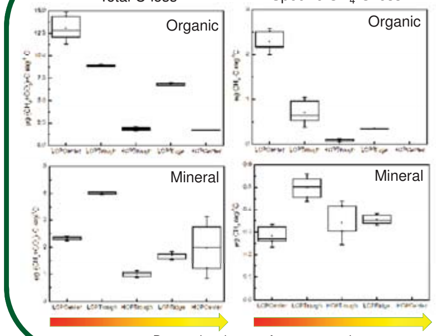
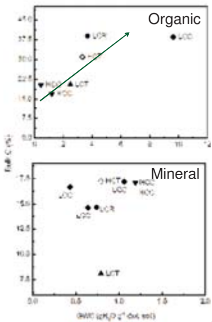


FIG 7.

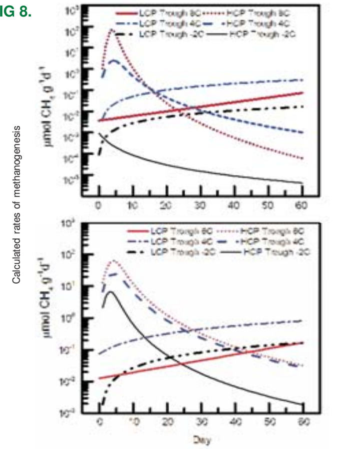
Relationship with θg



Decreasing degree of water saturation

Results III: Relationship between *mcrA* gene abundance & max. CH_4 production

FIG 8.



- CH_4 production increased slowly after an initial lag phase in LCP
- The lag correlated with an increase in biomass and acetate (primary substrate) accumulation and consumption in the Low-Centered Polygons
- Then high initial rate in the HCP trough was followed by a gradual decline

FIG 9.

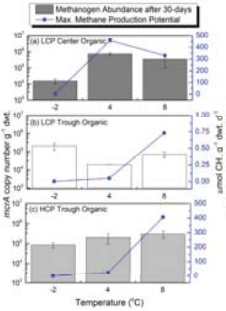
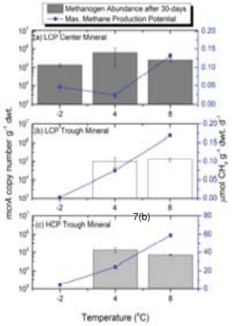


FIG 10.



- Methanogen abundance and CH_4 production was below detection limits in the permafrost and oxic center of the high-centered polygon
- Temperature and time-course response *mcrA* genes positively correlated with activity in the water-saturated active layer soils

Key Findings

- Rates of formation for both CH_4 and CO_2 were substantially higher in microcosms containing active layer O horizon (38 - 43% total carbon) than B horizon (17-18% carbon) samples.
- Traces of CH_4 were released from permafrost during incubations, although CO_2 was continually produced by fermentation and anaerobic respiration. No measurable CH_4 was detected in the HCP center although rates of CH_4 production from the trough were comparable with that of the LCP.
- On average, a minimal 0.3 % of total C loss was recorded as specific CH_4-C (μg CH_4-C mg^{-1}C) from the mineral horizons in both the LCP and HCP soils with no significant difference between the microtopographic features.
- We found that soil depth strongly influenced methanogenesis potential and methanogen abundance; an effect strongly correlated with increase in C:N ratio, and possibly increasing nutrient limitation in the deeper soil layers.
- Best predictor variables for methane production (AIC model selection):

  $$\mu\text{mol-}CH_4\ g^{-1} \sim \text{linear model}(Q_{10}CO_2 + \textit{mcrA} + \text{bulk C} + \text{Water Content})$$
- Temperature threshold for methanogenesis and dynamic time course of CH_4 production indicate that a constant Q_{10} framework do not explain temperature effects from -2 to +8 ℃ in the polygonal tundra C cycle.

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3. Roy Chowdhury, T., E.M. Herndon, T.J. Phelps, D.A. Elias, G. Gu, L. Liang, S.D. Wullschleger and D.E. Graham. In press. Stoichiometry and temperature sensitivity of methanogenesis and CO2 production from saturated polygonal tundra in Barrow, Alaska. Global Change Biology. DOI: 10.1111/gcb.12762

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With interests and expertise in soil biochemistry, isotope geochemistry and microbial ecology, the goal of my research is to generate understanding of soil microbial pathways that can form a basis of sustainable ecosystem management strategies. I have contributed to in-depth studies using stable isotopic probing techniques for tracking ^{13}C into microbial biomarkers during carbon (C) decomposition and methane (CH_4) cycling in temperate wetland and upland soils. A major research interest is to assess and understand the vulnerability of permafrost affected ecosystems in terms of their C loss potential as carbon dioxide and CH_4 in response to warming. Methodologies that I have used extensively are enzyme activities, microbial biomass, direct counts and profiling of microbial communities using phospholipid fatty acids (PLFA) and quantitative PCR based nucleic acid analysis in field and laboratory-based experiments. My holistic approach is to understand microbial ecology and manipulate the soil microbial community to improve soil functions, and optimize ecosystem productivity and sustainability. As such, the research outcomes would inform development of biologically sustainable systems, bioremediation and recycling applications, and mitigating and adapting to climate change (C management and greenhouse gas emission from soils) in sensitive ecosystems.

Total Storage and Landscape Partitioning of Soil Organic Carbon and Phytomass Carbon in Siberia

Matthias Siewert, Jessica Hanisch, Niels Weiss, Peter Kuhry, Gustaf Hugelius

Department of Physical Geography and Quaternary Geology, Stockholm University, Sweden

Key findings

- > 91 % of ecosystem C stored as SOC
- Ecosystem C stored in upper permafrost: 42 % in tundra and 25 % in taiga
- SOC-feedbacks likely more important to C-balance than PC-feedbacks
- Multivariate statistics show distinct SOC storages
- High resolution land cover classifications resolve polygonal tundra SOC storage

I. Introduction

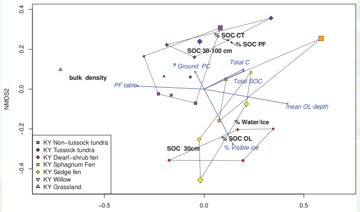
Permafrost affected ecosystems are important components in the global carbon (C) cycle that, despite being vulnerable to disturbances under climate change, remain poorly understood. In permafrost soils alone an estimated 1307 PgC with an uncertainty range of 1140–1476 PgC is stored (Hugelius et al., 2014). Detailed knowledge of total ecosystem C storage including soil organic carbon (SOC) and phytomass carbon (PC) is needed to predict future C-balance trajectories (Schuur et al., 2008). We present results of detailed partitioning of SOC and PC from two study areas in Siberia, reflecting contrasting ecosystems in the continuous permafrost zone.

V. Take home message

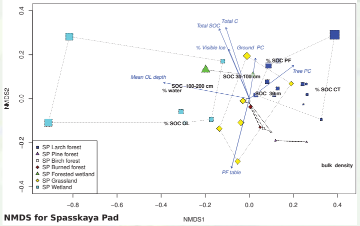
Our study adds new high resolution ecosystem C storage estimates for one tundra and one taiga ecosystem in Siberia. Analogous to Alaska (Johnson et al., 2011), climatic continentality generates a gradient leading to two contrasting ecosystems at high latitudes. Present day C storage in both study areas is controlled by landscape history. Past thermokarst events generated distinct local environments. These are overprinted by ecosystem dynamics, such as ice-wedge polygon formation or forest disturbance resolved by high resolution remote sensing. Considering that >91 % of the ecosystem C is stored in soil, we conclude that potential geomorphic feedbacks to SOC in form of large scale thermokarst are likely more important to the future C-balance than PC-feedbacks.

II. Multivariate statistics

Non-Metric Multidimensional Scaling (NMDS) (Minchin, 1987) was used to explore the relationship of SOC with PC and different soil and permafrost related variables. The chosen land cover classes can be considered distinct storages of SOC. PC is not significantly related to total SOC storage. The largest SOC contribution comes from wetland pedons, but highly cryoturbated individual non-wetland pedons can match these.



NMDS for Kytalyk

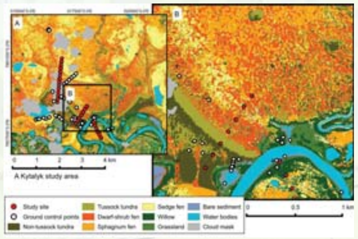


NMDS for Spasskaya Pad

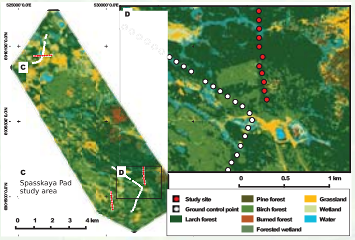
NMDS ordination diagrams: Each dot represents one sampling site. The symbol size reflects the square of total SOC. The dotted line surrounds all sites corresponding to the same class. The black labels show the response variables controlling the ordination diagram. The blue arrows and labels show the environmental variables. The length of the arrow is proportional to the correlation between the environmental variable and the ordination.

III. Upscaling

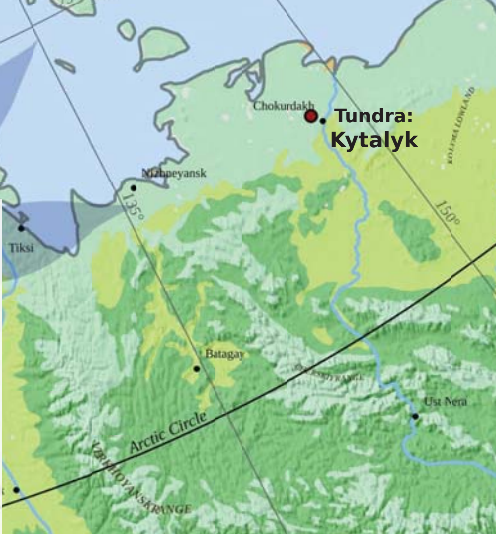
Landscape partitioning was performed by thematic up-scaling. Vegetation based land cover classifications were generated from very high resolution (2x2 m) satellite imagery using a maximum-likelihood classifier and post-processing algorithms (Compare Hugelius et al., 2011).



Land cover classfication for Kytalyk



Land cover classfication for Spasskaya Pad



Ecosystem map

● Study areas

☐ Non Vegetated	☐ Tundra	☐ Middle Taiga
☐ Polar Desert	☐ Forest-tundra & Northern Taiga	☐ Southern Taiga

Made with Natural Earth and Stolbovoi et al,. 1998)

Kytalyk is a low Arctic tundra environment, marked by three geomorphological units: a river floodplain, Yedoma hills and kilometer scale thermokarst features.

IVa. Ecosystem C partitioning

At both study sites > 91% of the ecosystem C is stored as SOC. Tundra has a higher mean SOC storage in the 0-100 cm interval 28 kg C m-² compared to 23 kg C m-² in the taiga. The active layer is 40 cm deep in the tundra and 114 cm in the taiga. Of the ecosystem C 42 % and 25 % respectively is stored in permafrost. Cryoturbated layers contain 31 % and 17 % of the C respectively.

Study area	Mean organic C storage (kg C m-²)				
	Total ecosystem C	Phytomass	SOC 0 - 30 cm	SOC 0 - 100 cm	SOC 100 - 200 cm
Kytalyk	28.6	0.7	11.4	27.9	-
Spasskaya Pad	43.5	3.9	9	23.4	15.1

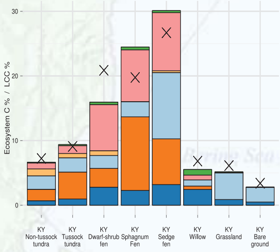
Study area	Percentage of total ecosystem C					Active layer depth
	Phytomass	SOC	Organic layer	Permafrost	Cryoturbated layers	
Kytalyk	2 %	98 %	27 %	41 %	31 %	40 cm
Spasskaya Pad	9 %	91 %	15 %	25 %	17 %	114cm

Spasskaya Pad is located in typical Siberian boreal light taiga. The area is dominated by larch forest. Grassland and peatlands are formed in thermokarst areas.

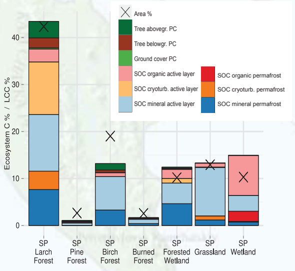
Sampling

In total 57 individual field sites (24 and 33 per study area respectively) have have been sampled for SOC and PC. The SOC storage was calculated separately for several depth intervals, including the permafrost (to 1 m and 2 m depth respectively) (Compare Hugelius et al., 2011).

IVb. Ecosystem C partitioning



In Kytalyk the landscape partitioning of ecosystem C mostly follows large scale geomorphological features. Wetland classes have the highest C estimate and cover the largest areas



In Spasskaya pad the larch forest covers 42 % of the area and stores 43% of the C. Disturbed forest stores considerably less C. Wetland classes have the highest relative C storage.

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Name : Matthias Siewert
Department: Department of Physical Geography and Quaternary Geology, Stockholm University
PhD title: **High-resolution mapping of soil organic matter storage and remobilization potential in periglacial landscapes**

In my PhD I investigate landscape storage and remobilization potential of soil organic matter (SOM) at Nordic and Russian study sites characterized by a gradient in ground conditions, from isolated to continuous permafrost. For this I upscale point measurements of SOM from soil pits to landscape scale using high-resolution satellite imagery and further analyze the spatial patterns.

Process-level controls on greenhouse gas emissions in Arctic coastal tundra

Abstract

According to current estimates, permafrost soils store more than two times the carbon as the carbon in atmospheric CO_2. With climate change causing high latitude soils to warm and dry, this soil carbon will likely become more available to decomposition. The magnitude of these predicted carbon emissions as CO_2 and methane (CH_4) are poorly constrained due to several factors, including fine-scale environmental heterogeneity, unknown and complex controls on microbial processes, and uncertainty in carbon stocks and current emissions rates. This work aims to improve our ability to predict Arctic greenhouse gas fluxes from the cm- to the landscape-scale by investigating the biological and environmental controls on CO_2 and CH_4 production, consumption, and emissions. On the Arctic coastal plain in Barrow, Alaska, we combine a suite of biogeochemical measurements beginning in 2012 and extending through 2013. We measure in situ trace gas fluxes using static chambers and eddy covariance towers across a range of landscape features; greenhouse gas concentrations in soil pore space and stable and radioisotopes throughout the soil depth profile; soil physical data such as temperature and moisture at depth; and vegetation greenness using normalized difference vegetation index (NDVI). In laboratory experiments with soils collected on site and incubated at two temperatures, we measure CH_4 and CO_2 flux and the radiocarbon content of respired CO_2 and bulk soil. Initial results from 2012 indicate that landscape polygon feature, soil water content, soil temperature, and sampling location all influence CO_2 and CH_4 fluxes. Soil CO_2 fluxes measured with static chambers decreased toward the end of the growing season, whereas CH_4 fluxes remained constant or increased. From half-hourly eddy covariance data between September and October 2012, net ecosystem exchange ranged between -0.02 and 0.10 g C m^{-2}, and maximum evapotranspiration and CH_4 flux were 0.03 mm, and 50 mg CH_4 per half hour respectively. NDVI values correlate well with microtopographic polygon features. Stable isotope measurements indicate methane production in deeper and wetter soils, with increasing methane oxidation toward the soil surface, dependent on polygon feature. ^{14}C data show that CO_2 respired from deep soils is very old relative to surface soils. Taken together, along with ancillary microbial, geophysical, hydrological, and vegetation data from collaborative research teams, our results suggest that soil moisture is a major control on carbon cycling processes, with interacting environmental and biological effects. Continued research through 2013 will further investigate the vulnerability to climate change of this region's old carbon stores.

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Authors: Lydia Smith (lydiajsmith@lbl.gov), Margaret Torn, Mark Conrad, Melanie Hahn, Naama Raz Yaseef, Bryan Curtis

PROCESS-LEVEL CONTROLS ON GREENHOUSE GAS EMISSIONS IN ARCTIC COASTAL TUNDRA

Lydia Smith[1] (lydiajsmith@lbl.gov), Margaret Torn[1,2], Mark Conrad[2], Melanie Hahn[3], Naama Raz Yaseef[2], Bryan Curtis[2]

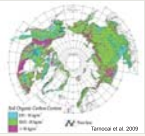
[1] Energy and Resources Group, University of California Berkeley; [2] Earth Sciences Division, Lawrence Berkeley National Laboratory;
[3]Department of Civil and Environmental Engineering, University of California Berkeley

QUESTION

What controls methane and carbon dioxide production, consumption, and emissions in an Arctic coastal plain ecosystem?

BACKGROUND/MOTIVATION

- Permafrost soils store roughly 50% of the world's soil organic carbon (Tarnocai et al. 2009)
- Arctic polygon tundra covers ~ 250,000 km^2 (Minke et al. 2007)
- The Arctic is warming (Allison et al. 2009)
- Permafrost degradation has increased in Arctic Alaska (Jorgenson et al. 2006) with potential biochemical and biophysical feedbacks (Schuur et al. 2009)



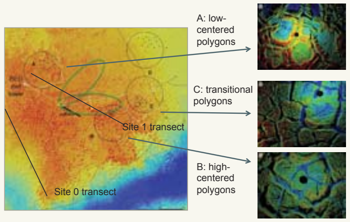
Next Generation Ecosystem Experiment (NGEE-Arctic):

a. quantify the physical, chemical, and biological behavior of Alaskan terrestrial ecosystems
b. improve modeled climate predictions by better representing Arctic tundra

STUDY SITE

BARROW ENVIRONMENTAL OBSERVATORY
BARROW, AK

At 71°N, 157°W , the site is on the northern end of the Alaskan Coastal Plain. Roughly 50% of the area is drained thaw lake basins and 28% is interstitial tundra (Hinkel et al. 2003), with a gradient of low to high-centered polygons.



LiDAR images from Chris Polashenski

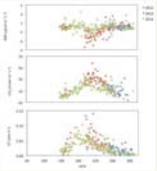
APPROACH AND RESULTS 2012

1. TRACE GAS FLUXES

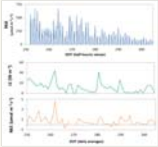
4 m tall tower, measuring CO_2/H_2O (LiCOR 7500) and CH_4 (LiCOR 7700), w/real-time communication.

✧ Static chambers
✧ Eddy covariance

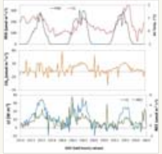
Eddy covariance measurements



Do we see a seasonal pattern?
Do end-of-season values approximate winter fluxes?

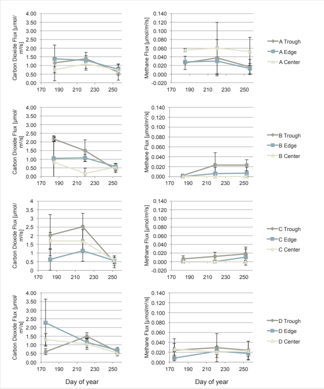


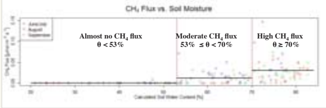
Prominence of the diurnal pattern decreases toward end of season

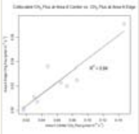


September 14 – 16, 2012

2012 static chamber CO_2 and CH_4 flux measurements



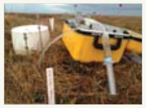




Soil moisture explains only 29% of the variance in CH_4 Fluxes.

Polygons matter!

2. VERTICALLY-RESOLVED CH_4 PRODUCTION AND CONSUMPTION

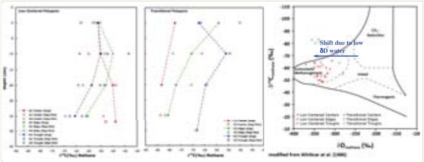


✧ Soil pore water/gas CO2 and methane concentrations
✧ Soil pore water/gas stable isotopes: $\delta^{13}C\text{-}CO_2$, $\delta^{13}C\text{-}CH_4$, $\delta D\text{-}CH_4$

Methane isotope compositions

$\delta^{13}C\text{-}CH_4$ values generally consistent between August and September/October samples (with notable exceptions)

At depth, $\delta^{13}C\text{-}CH_4$ values of center samples much lower in transitional polygon than low-centered polygon



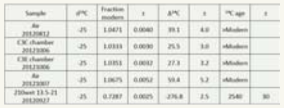
δD analyzed on high concentration samples (generally deeper)

Centers and edges of low-centered polygons distinct from transitional polygons. Trough samples similar across polygon type.

Data suggest acetoclastic methanogenesis dominates low-centered polygons. Transitional polygon centers dominated by CO_2-reduction

3. VERTICALLY-RESOLVED CARBON TURNOVER

✧ Field: $\Delta^{14}C\text{-}CO_2$
✧ Incubations: $\Delta^{14}C\text{-}CO_2$, CO_2 flux, $\Delta^{14}C$-SOC)

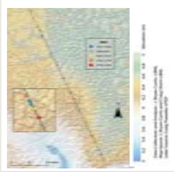


Sample	$\delta^{13}C$	Fraction modern	±	$\Delta^{14}C$	±	^{14}C age	±
Air 20120812	-25	1.0471	0.0040	39.1	4.0	>Modern	
C3C chamber 20121006	-25	1.0333	0.0030	25.5	3.0	>Modern	
C3E chamber 20121006	-25	1.0351	0.0032	27.3	3.2	>Modern	
Air 20121007	-25	1.0675	0.0052	59.4	5.2	>Modern	
210wet 13.5-21 20120927	-25	0.7287	0.0025	-276.8	2.5	2540	30

Warming soil just above permafrost releases CO_2 that is 2,500 y old

4. ANCILLARY ECOLOGICAL PARAMETERS

✧ NDVI
✧ Soil temperature (thermocouple probe)
✧ Soil moisture (TDR and gravimetric moisture content)
✧ Soil pH
✧ Soil C and N content



2013 FIELD SEASON

1. Flux measurements

- Post complete season of eddy covariance data on our website daily – hourly to seasonal cumulative fluxes
- Compare EC fluxes to chamber measurements, other plot scale variables, climate conditions, and from ARM NSA site
- In combination with radiation balance and scaling methods, use these data to test and validate components of CLM.
- Extend static chamber flux sampling to drained thaw lake basin transects

2. Vertically-resolved methane production and consumption

- Monthly measurements June - October: CH_4 and CO_2 concentrations, $\delta^{13}C\text{-}CO_2$, $\delta^{13}C\text{-}CH_4$, and $\delta D\text{-}CH_4$
- Coordinated microbial measurements

3. ^{14}C and carbon turnover times

- Vertically resolved field measurements from 3 time points
- Soil incubation with temperature and substrate input manipulations
- Soil chemical analysis (^{13}C NMR)

4. NDVI and depth-specific soil moisture (TDR) and soil temperature (thermistor probe)

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Spring Hydrology Determines Summer Net Carbon Uptake in Northern Ecosystems

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Increased photosynthetic activity and enhanced seasonal CO_2 exchange of northern ecosystems have been observed from a variety of sources including satellite vegetation indices like NDVI and atmospheric CO_2 measurements. Most of these changes have been attributed to strong warming trends in the northern high latitudes (≥50°N). Here we analyze the interannual variation of summer net carbon uptake (NCU) derived from atmospheric CO_2 measurements and satellite NDVI in relation to surface meteorology from regional observational records. We find that increases in spring precipitation and snow pack promote summer NCU of northern ecosystems independent of air temperature effects. However, satellite NDVI measurements still show an overall benefit of summer photosynthetic activity from regional warming and limited impact of spring precipitation. We hypothesize this strong sensitivity of NCU to spring hydrology may be caused by a strong regulation of spring hydrology on soil respiration in relatively wet boreal and arctic ecosystems, and the reduced sensitivity of NCU to temperature is likely due to similar responses of photosynthesis and respiration to warming. We use a combination of in-situ tower eddy covariance CO_2 flux measurements, satellite soil moisture retrievals, and a process model to test this hypothesis. Our results document the important role of spring hydrology in regulating northern ecosystem carbon uptake, and indicate potentially stronger coupling of boreal/arctic water and carbon cycles with continued regional warming trends.

Spring Hydrology Determines Summer Net Carbon Uptake in Northern Ecosystems

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1. Introduction

Increased photosynthetic activity and enhanced seasonal CO_2 exchange of northern ecosystems have been observed from a variety of sources including satellite vegetation indices (e.g. NDVI) and atmospheric CO_2 measurements. Part of these changes have been attributed to strong warming trends in the northern high latitudes (≥50°N). Here we analyze the interannual variation of summer net carbon uptake (NCU) derived from atmospheric CO_2 measurements and satellite NDVI in relation to surface meteorology from regional observational records. We find that increases in spring precipitation and snow pack promote summer NCU of northern ecosystems independent of air temperature effects. However, satellite NDVI measurements still show an overall benefit of summer photosynthetic activity from regional warming and limited impact of spring precipitation. We hypothesize this strong sensitivity of NCU to spring hydrology may be caused by a strong regulation of spring hydrology on soil respiration in relatively wet boreal and arctic ecosystems, and the reduced sensitivity of NCU to temperature is likely due to similar responses of photosynthesis and respiration to warming. We use a combination of in-situ tower eddy covariance CO_2 flux measurements, satellite soil moisture retrievals, and a process model to test this hypothesis.

2. Questions & Hypotheses

What drives seasonal NCU in the northern high latitudes? We proposed the following hypotheses:

- Warming, esp. in the early growing season, promotes vegetation greening;
- Wetting, esp. in the early growing season, inhibits soil respiration, & enhances net carbon uptake (NCU);
- Warm & dry conditions, esp. in the later growing season, constrains photosynthesis & promotes respiration & C emissions, reducing NCU.

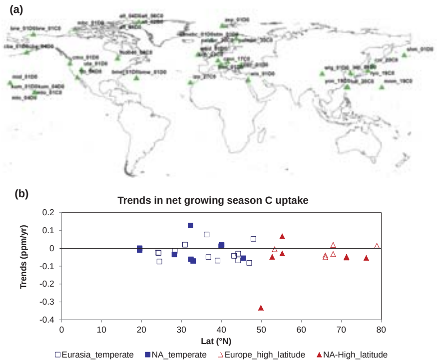


Fig.1 (a) Distribution of long-term (≥ 10 years) Northern Hemisphere (NH) extratropical CO_2 flask monitoring sites[1] (b) Trend of summer CO_2 minimum of CO_2 seasonal cycle extracted from flask sites for varying periods from 1979 to 2010.

[1]*http://www.esrl.noaa.gov/gmd/ccgg/globalview*

3. Data synthesis

Overview: A synthesis of atmospheric CO_2 and satellite & regional climate data reveals the major role of spring hydrology in determining summer net carbon uptake (NCU) for northern (≥50°N) ecosystems, independent of temperature effects.

Datasets: GLOBALVIEW CO_2 measurements (1979-2010), GPCP precipitation (1979-2010) and CMC snow product (1998-2010), GIMMS3g NDVI (1982-2010), GFED Fire emission (1997-2010), Lathuile FLUXNET observations (2000s).

(1) High spring P corresponds with low fire emissions & large summer NCU.

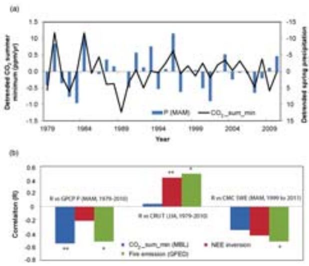


Fig. 2 Co-variation of summer NCU & seasonal climate variables. (a) Time series of detrended summer CO_2 minimum (CO_2_sum_min) from NOAA MBL reference data & GPCP spring (MAM) precipitation (P) averaged over 50 °N to 90 °N, where positive (negative) anomalies denote relative decreases (increases) in terrestrial C uptake. (b) Partial correlation (R) analysis of carbon fluxes including CO_2_sum_min from MBL reference data, global atmospheric inversion model NEE (Chevallier *et al* 2010), and GFED (v.3.1) CO_2 fire emissions vs seasonal climate variables.

(2) Northern ecosystems, esp. tundra, show overall positive productivity response to warming.

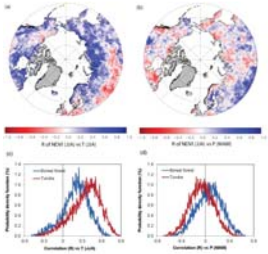
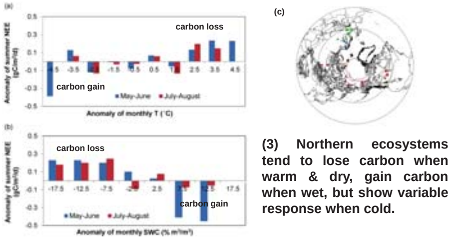


Fig. 3. Summer NDVI sensitivity to northern (≥50°N) climate variation; (a) & (b): partial correlation (R) between summer (JJA) NDVI (GIMMS3g) vs summer air temperature (T, CRU) & spring (MAM) P (GPCP) from 1982 to 2010; (c) & (d): probability density functions of the above correlations for tundra & boreal forest areas; 29.2% & 12.5% of boreal forest pixels, & 61.3% & 2.9% of tundra pixels are positively correlated (p<0.1) with T (JJA) & P (MAM) respectively.



(3) Northern ecosystems tend to lose carbon when warm & dry, gain carbon when wet, but show variable response when cold.

Fig. 4 Tower C flux analysis for boreal sites (c); temporal anomalies summer (JJA) tower NEE fluxes vs (a) monthly T anomalies binned into 1.0 °C intervals, & (b) surface (≤15 cm) soil water content (SWC) anomalies binned into 0.05 m^3/m^3 intervals for early growing-season (May-Jun) and later growing-season (Jul-Aug) periods.

4. Model sensitivity analysis

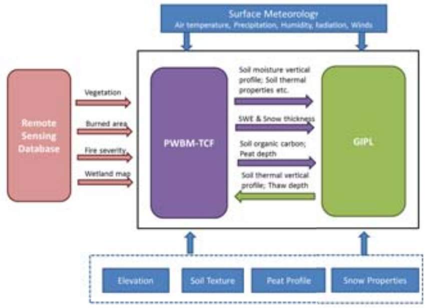


Fig. 5 Coupled hydrology & carbon model (Yi et al. 2013; Rawlins et al. 2013) used for model sensitivity analysis. A detailed soil thermal model (GIPL) was coupled to a large-scale water balance model (PWBM); a terrestrial carbon flux (TCF) model was then coupled to the hydrology model to diagnose C-flux sensitivity to soil active layer conditions.

Model sensitivity analysis conducted to assess ecosystem C flux response to seasonal climate change, for respective T & P increases of 2 °C & 20%.

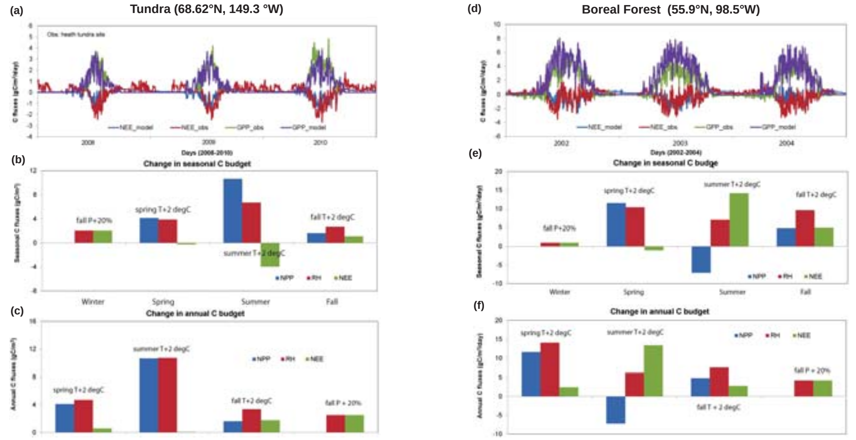


Fig. 6 Model sensitivity for selected tundra (PI: E. Euskirchen) & boreal forest sites (PI: M. Goulden). **Top** (a & d): Simulated vs. observed NPP & NEE; **Middle** (b & e): Impact of climate variability on seasonal C budget; **Bottom** (c & f): Impact of seasonal climate change on annual C budget. Changes in spring, summer & fall T, & fall P show larger C budget impact.

Tundra: Summer T increase promotes NPP & NEE C gain; increasing T in spring & fall has less impact on GPP, promotes respiration (RH), & results in minimal NEE C gain or loss. Early snowfall & larger snowpack promote warmer soil, increasing winter & fall RH.

Boreal forest: Increasing T in spring & fall promote NPP, but increasing summer T reduces productivity due to water stress. Early snowfall & larger snowpack has a smaller impact on winter & fall RH compared with tundra, but significant impact on annual NEE.

5. Conclusions

- Wetter springs promote summer NCU independent of T effects, though warming still promotes widespread greening but with less NCU in warmer, drier years. Evidence of stronger coupling of northern C & water cycles with continued climate warming.
- Similar tundra & boreal model C-flux response to warming, but variable response to P wetting. Fall & winter P has large impact on C fluxes due to snowpack insulating of soil T, while spring & summer P has smaller impact. However, large-scale process models may not adequately capture spatial heterogeneity in surface wetness.

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