Recent Synthesis Research on the Permafrost Carbon Feedback

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ABSTRACT
Permafrost thaw, and carbon released via the microbial decomposition of previously frozen soil organic matter, is considered one of the most likely positive feedbacks from terrestrial ecosystems to the atmosphere in a warmer world. The rate and form of permafrost carbon release is highly uncertain but crucial for predicting the strength and timing of this carbon cycle feedback during this century and beyond. The main objective of the Permafrost Carbon Network is to use data synthesis and modeling to link biological carbon cycle research with well-developed networks in the physical sciences focused on the thermal state of permafrost.

RÉSUMÉ
Le dégel du pergélisol et l'émission de carbone résultant de la décomposition microbienne de la matière organique des sols gelés sont considérés comme étant des rétroactions positives des écosystèmes terrestres vers l'atmosphère dans un contexte de réchauffement climatique. Le taux d'émission de carbone et le type d'émission sont très incertains, mais aussi cruciaux afin de pouvoir prédire la force et le moment de cette rétroaction climatique pendant ce siècle et les suivants. L'objectif du "Permafrost Carbon Network" est d'utiliser la synthèse de données et la modélisation afin de relier la recherche sur le cycle biologique du carbone avec la recherche sur l'état thermique du pergélisol déjà réalisée au sein de réseaux en place dans le domaine des sciences physiques.

1 INTRODUCTION

Approximately 1300 to 1580 Pg of carbon is stored in soils of the northern circumpolar permafrost zone, roughly twice as much carbon as currently contained in the atmosphere. As the climate warms, greenhouse gases released by microbes from the breakdown of thawing permafrost organic matter may increase and accelerate climate change. The impact of carbon released from thawing permafrost on climate depends on the timing and magnitude of these emissions. The Permafrost Carbon Network was formed in 2010 as a multi-year synthesis effort to help constrain current understanding of the permafrost carbon feedback to climate.

2 OVERVIEW OF THE PERMAFROST CARBON NETWORK (PCN)

The PCN includes more than 200 scientists from 18 countries. Over the past five years, activities of several working groups have focused on improving our understanding of 1) the size of permafrost carbon pools, 2) the decomposability of thawed permafrost soil organic matter, 3) the vulnerability of permafrost carbon due to thermokarst and thermal erosion, 4) anaerobic and aerobic processes affecting carbon mineralization, and 5) the capability to upscale and model the fate of permafrost carbon to develop more reliable projections of the role of permafrost carbon dynamics in the climate system. The working groups produce new knowledge by synthesizing existing data that can be assimilated by biospheric and climate models and that will contribute to future global environmental assessments, including the Intergovernmental Panel on Climate Change (IPCC).

The PCN was funded with support from the National Science Foundation's Research Coordination Network from 2010-2015. Additional funding to support PCN meetings and workshops was provided by Climate and Cryosphere, the International Permafrost Association, the International Arctic Science Committee, the United States Geological Survey, and the United States Department of Energy.

3 KEY RESEARCH ACTIVITIES

3.1 Research Findings To Date

Activities associated with the PCN led to a revised northern permafrost zone carbon inventory, with the surface permafrost carbon pool (0-3 m) estimated at 1030

± 180 Pg carbon (± 95% confidence interval) (Hugelius et al. 2014). This revised inventory includes a 10-fold increase in the number of sampling locations deeper than 1 m. New research also has led to improved estimates of the permafrost carbon stock deeper than 3 m, particularly in carbon-rich regions such as yedoma and deltaic sediments. Together, the known pool of permafrost carbon, accounting for surface as well as deep carbon, is 1330-1580 Pg carbon (Hugelius et al. 2014, Strauss et al. 2013, Walter Anthony et al. 2014, Schuur et al. 2015). In comparison, the rest of Earth's biomes, excluding arctic and boreal, occupies 85% of the global soil area and contains an estimated 2050 Pg carbon in the surface 3 m of soil (Jobbágy and Jackson 2000).

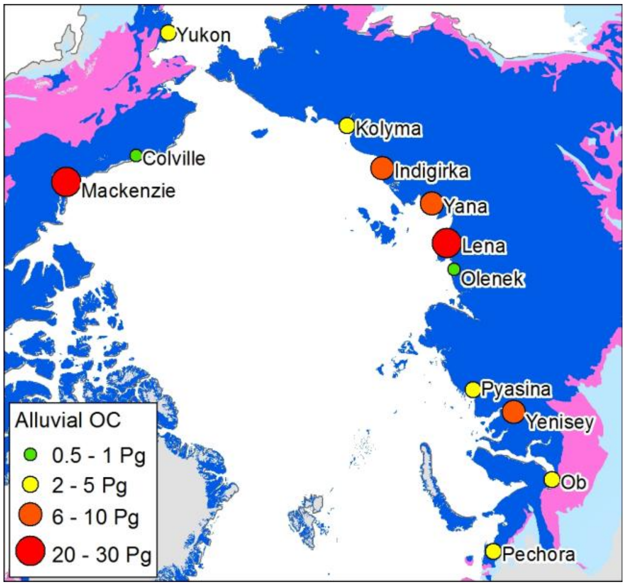

Figure 1. Distribution of estimated alluvium organic carbon (OC) stocks for the major Arctic river deltas (reported to one significant digit). The combined revised estimate of carbon inventory for these major river deltas is 91 ± 39 Pg carbon (± 95% confidence interval). The estimate is based on a combination of deltaic extent, alluvium depth, massive ice content and alluvium carbon content. The access to field data from these regions is very limited and there is a clear need for refined estimates. Delta carbon data are from Hugelius et al. (2014). Permafrost zonation from Brown et al. 2014 (dark blue - continuous; pink - discontinuous; light blue - sporadic/isolated permafrost zones).

Synthesis and analysis of soil incubation data under both aerobic and anaerobic conditions has led to improved understanding of the inherent decomposability of soil organic matter from the permafrost zone (Schädel et al. 2014, Treat et al. 2015). These studies showed that organic soils are more decomposable than mineral soils across depths, leading to greater carbon dioxide and methane production rates. These data, plus a synthesis of field methane emissions across more than 300 sites located in the permafrost region (Olefeldt et al. 2012), demonstrate that anaerobic mineralization of permafrost organic matter will increase as a result of warming as well as shifts in vegetation and ground saturation accompanying permafrost thaw in some settings.

A number of models have incorporated a first approximation of global permafrost carbon dynamics. Key improvements include the physical representation of permafrost soil thermodynamics and the role of environmental controls, in particular soil freeze/thaw state, over decomposition of organic carbon (Lawrence et al. 2008, Koven et al. 2013). Model scenarios show potential carbon release from the permafrost zone ranging from 37-174 Pg carbon by 2100 under a range of climate warming scenarios. Across models, carbon release averaged 92 ± 17 Pg carbon (mean ± SE) (Schaefer et al. 2014). Normalizing the emissions estimates from the dynamic models by their initial permafrost carbon pool size, 15 ± 3% (mean ± SE) of the initial pool was expected to be lost as greenhouse gas emissions by 2100. This decrease in the permafrost carbon pool is similar to the 7-11% loss predicted through an expert opinion survey (Schuur et al. 2011, 2013).

Both modeling studies and an expert opinion survey assessed whether plant carbon uptake may in part offset permafrost carbon release. Plant growth can increase with warmer temperatures, longer growing seasons, elevated CO_2, and increased nutrient availability. Models generally indicate that increased plant carbon uptake will more than offset soil carbon emissions from the permafrost region for several decades as climate becomes warmer (cf. Schaefer et al. 2014). However, over more time and with continued warming, microbial release of carbon is projected to overwhelm the capacity for plant carbon uptake, leading to net carbon emissions from permafrost ecosystems to the atmosphere.

3.2 Circumpolar Assessments of Permafrost Carbon Release due to Thermokarst and Thermal Erosion

Most studies quantifying the effects of permafrost thaw on carbon cycling focus on gradual top-down thawing of permafrost. However, more abrupt permafrost thaw through thermokarst and thermal erosion may affect large portions of the soil carbon stored in the permafrost domain. While the slow gradual deepening of the seasonally thawed layer affects permafrost carbon at regional scales, thermokarst and thermal erosion can potentially affect large volumes of soil at local scales. These processes expose previously-frozen carbon to microbial processes but also alter hydrology and thus the balance of carbon dioxide and methane emissions.

We are using mapping, data synthesis, and simple land cover change modeling to better understand the relevance of abrupt thaw to the overall permafrost carbon feedback. We developed a spatial modelling framework that assesses whether areas are predisposed to thermokarst or thermal erosion. The framework weighs the perceived relative importance of ground ice content, overburden thickness, permafrost zonation (Brown et al. 2014), terrestrial ecoregion (Olson et al. 2001), topographical roughness (Gruber 2012), and regional histel cover (Hugelius et al. 2013) to the formation of wetland thermokarst features, thaw lakes, and hillslope features (retrogressive thaw slumps, active layer detachments, erosional gullies). We estimate that land predisposed to these processes cover less than a quarter of boreal and tundra regions within the permafrost domain. However, given disproportionally high soil organic carbon content, areas predisposed to thermokarst and thermal erosion store nearly half of the organic carbon stored in the upper 3 meters of soil.

Empirical studies show that thermokarst influences carbon emissions by stimulating the mineralization of previously thawed permafrost carbon at depth, but also influences emissions of more recently fixed carbon through land cover and aquatic vegetation change. We are currently synthesizing process-level studies to parameterize a book-keeping model to track the effects of thermokarst disturbance on carbon dioxide and methane emissions at pan-arctic scales. The goal is to enable a comparison of the greenhouse gas emissions resulting from deepened active layer and due to abrupt thaw processes.

3.3 Future Synthesis Research Activities

Over the next several years, other activities led by PCN members will focus on i) revised estimates of carbon inventories in permafrost peatlands, ii) synthesis of existing data on Yedoma coverage, thickness, and ground ice content, iii) improved understanding of how permafrost thaw contributes to wetting or drying of high latitude ecosystems, iv) how changing vegetation structure and productivity in the arctic might affect the decomposability of soil carbon, and v) development of benchmarking tools for evaluating dynamic models approximating global permafrost carbon dynamics.

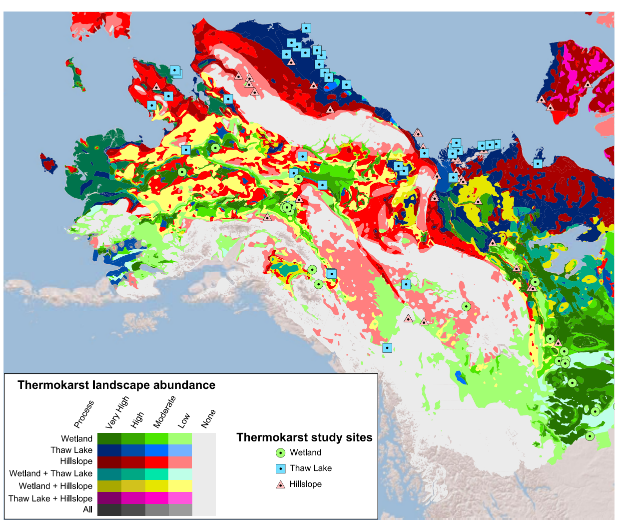

Figure 2. Map of the dominant type of thermokarst landscapes in western Canada and Alaska, distinguishing between regions predisposed to wetland thermokarst (collapse scar wetlands), thaw lakes and hillslope thermokarst (retrogressive thaw slumps, active layer detachment slides, erosional gullies).

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