2015

PERMAFROST CARBON NETWORK

5-YEAR SYNTHESIS REPORT

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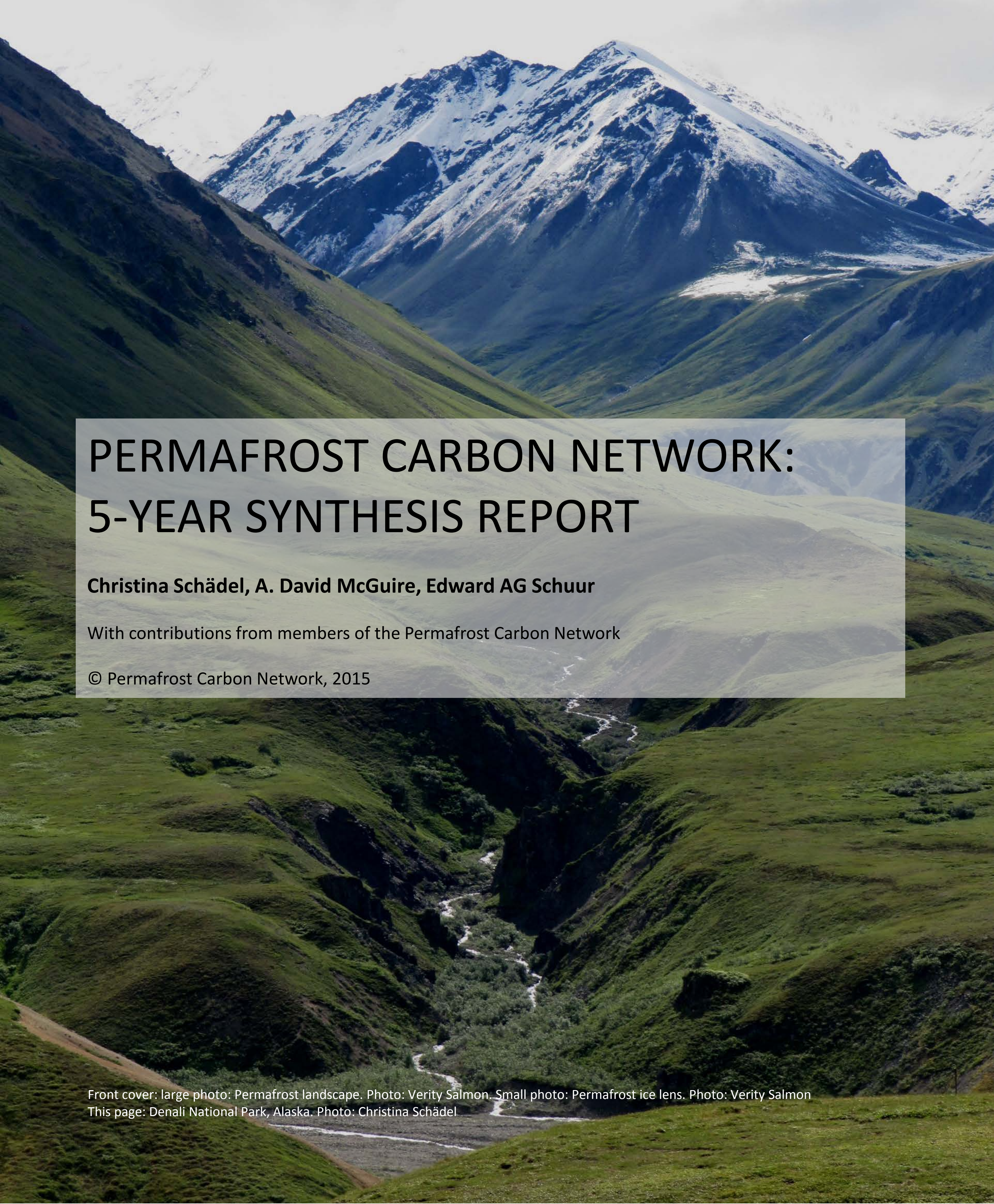


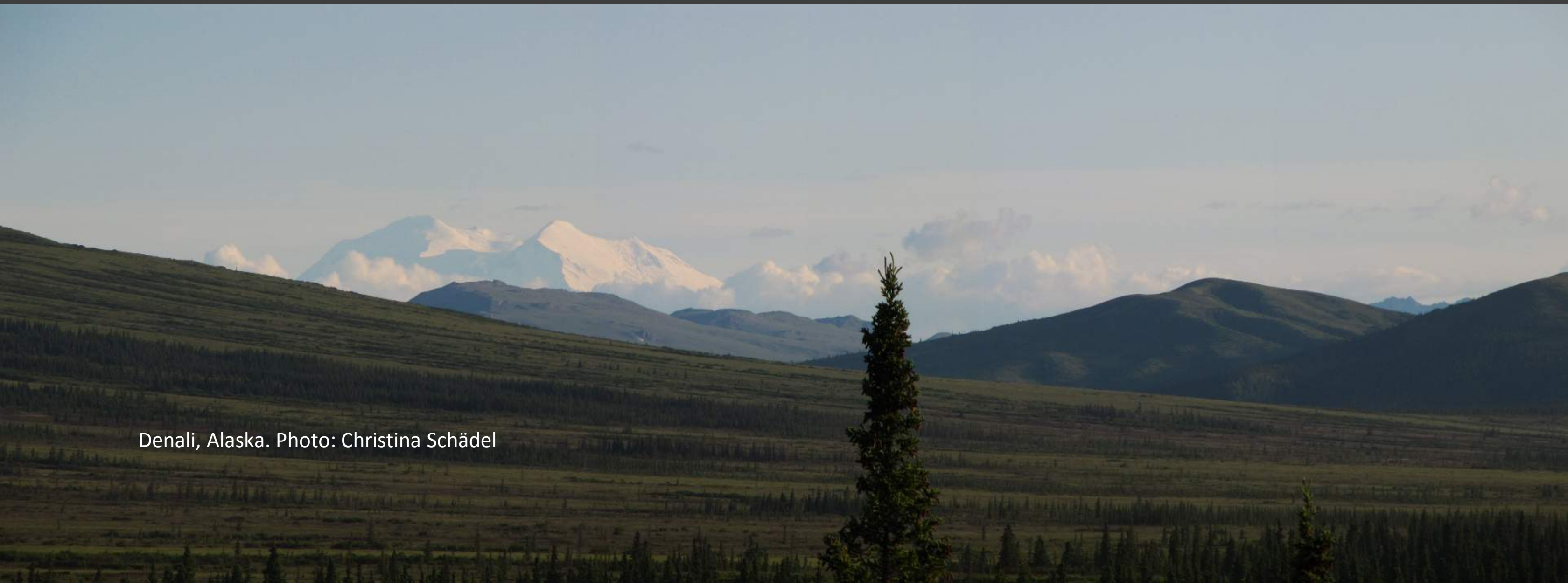
PERMAFROST CARBON NETWORK: 5-YEAR SYNTHESIS REPORT

Christina Schädel, A. David McGuire, Edward AG Schuur

With contributions from members of the Permafrost Carbon Network

Front cover: large photo: Permafrost landscape. Photo: Verity Salmon. Small photo: Permafrost ice lens. Photo: Verity Salmon
This page: Denali National Park, Alaska. Photo: Christina Schädel

CONTENTS



Denali, Alaska. Photo: Christina Schädel

FOREWORD

Sustained and substantial carbon release from the Arctic is a wildcard that could alter the future trajectory of climate change. In the Arctic, temperatures have risen twice as fast as the global average. Warming is causing normally frozen ground to thaw, exposing significant quantities of organic carbon to decomposition by soil microbes. This **permafrost carbon** is the remnants of plants and animals accumulated in perennially frozen soil over thousands of years, and it holds twice as much carbon as currently in the atmosphere. Release of just a fraction of this frozen carbon pool as the greenhouse gases carbon dioxide and methane into the atmosphere would dramatically increase the rate of future global climate warming. A key societal question is whether there are tipping points, global carbon cycle surprises such as the release of permafrost carbon that will make climate change effects such as sea-level rise, extreme weather, droughts, and impacts on agriculture occur faster than currently projected by models.

The **Permafrost Carbon Network** was formed out of the urgent need to address these issues. One simple question dictates the future effect of permafrost carbon on climate: *How much, how fast, and in what form will permafrost carbon be released to the atmosphere in a warmer world?* Answering this question at the scale of the circumpolar region, however, requires a large and sustained effort drawing on a range of scientific disciplines. The Permafrost Carbon Network is a grass-roots effort designed to bring ideas and people together to create new knowledge through science synthesis. One driving concept of the network is that it takes the science community to interpret and distill the findings of the primary literature into higher-level science synthesis publications that can effectively articulate the cutting-edge state of the science on this topic. Creating this type of science synthesis then opens the door for synthesis reports, agency briefings, media interviews, and other non-science communication outlets that deliver information to decision-makers and the wider public who can drive real action on the issue of our changing Earth.

The content of this report highlights the results of this approach. After a short description of the network, the report covers three synthesis efforts that use different approaches to assess the potential climate feedback from permafrost carbon. The Nature review article (Schuur et al. 2015) summarizes the findings across a range of individual synthesis products produced by the Permafrost Carbon Network. The Philosophical Transactions of the Royal Society paper (Koven et al. 2015) combines a number of individual synthesis products with Earth System Model projections of future climate and permafrost thaw. The Permafrost Carbon Model Intercomparison Project (McGuire et al.) projects both the response of permafrost carbon and the offsetting response of plant carbon uptake across a range of land surface models under scenarios of global change. These highest-level synthesis papers are followed by an example of using expert assessment, made possible by the development of the network. The report then highlights some of the individual synthesis papers, with other citations at the end of the report and on the website. After the science highlights, there are details about the workshops and the efforts of the network to develop the science community through engagement of early career scientists, and the various outreach products that have arisen from the network.

The efforts of the Permafrost Carbon Network build upon a foundation tirelessly laid by others that have come before, and draws upon a wide variety of resources and people that engage in bringing science knowledge to action. Core support has been provided by the National Science Foundation initially as a Research Coordination Network and now through the Study of Environmental Arctic Change. This represents just a few of the key agencies that provided resources that allowed individual scientists to ultimately participate. In the end, the Permafrost Carbon Network is open, and is created and shaped by its members. It is all of us who contribute time, energy, and enthusiasm towards helping answer big science questions that help society meet the challenges of creating a sustainable way of life on Earth this century and beyond.

In closing, we want to thank all the participants for their individual and collective contributions to the Permafrost Carbon Network, and hope to engage with you into the future.

Ted Schuur & Dave McGuire,

Lead Investigators for the Permafrost Carbon Network

BACKGROUND

What is the magnitude, timing, and form of permafrost carbon release to the atmosphere in a warmer world?

The Permafrost Carbon Network is an international scientific effort linking research focused on the biological carbon cycle to the physical sciences, focused on the thermal state of permafrost.

Approximately 1670 Pg of soil carbon (1 Pg = 1 billion tons) are estimated to be stored in soils and permafrost of high latitude ecosystems which is twice as much carbon as is currently contained in the atmosphere. In a warmer world permafrost thawing and decomposition of previously frozen organic carbon is more likely to amplify climate warming by releasing more carbon into the atmosphere. Although ground temperature increases in permafrost regions are well documented there is a knowledge gap in the response of permafrost carbon to climate change.

The main objectives of this network are to synthesize and link existing research about permafrost carbon and climate in a format that can be assimilated by biospheric and climate models, and that will contribute to future assessments of the Intergovernmental Panel on Climate Change (IPCC).

Network activities include a series of meetings and working groups designed to synthesize ongoing permafrost carbon research, which will produce important new knowledge to quantify the role of permafrost carbon in contributing to climate change in the 21st century and beyond.

The network includes more than 300 scientists from 130 research institutions located in 21 countries. It is structured into five working groups that focus on improving our understanding of 1) the size of permafrost carbon pools, 2) the decomposability of thawed permafrost soil organic matter, 3) the fate of permafrost carbon from 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 Permafrost Carbon Network is part of the Study of Environmental Arctic Change (SEARCH) project. The SEARCH project, led by the University of Alaska Fairbanks as the lead institution and Northern Arizona University as a collaborating institution, is a global-scale, cross-disciplinary research program that seeks to connect the science of Arctic change to decision makers. Three Action Teams comprise a core structural aspect of SEARCH, each focused on data synthesis and model development with projections used to advance current knowledge of a changing Arctic. The Permafrost Action Team, led by Ted Schuur will, in part, support activities developed by the Permafrost Carbon Network.

In addition to synthesis research, the Permafrost Carbon Network has been highly active in training early career scientists in synthesis research, organizing a series of sessions at national and international scientific meetings, and communicating new results through scientific presentations, news articles, interviews, and blog posts. The network has a website (www.permafrostcarbon.org) that serves as a portal for research coordination, media outreach, and education on permafrost carbon.

NETWORK ORGANIZATION

Dr. Edward (Ted) A.G. Schuur
Northern Arizona University, Flagstaff, AZ, USA

Ted is the Principle Investigator of the Permafrost Carbon Network and the lead of the Permafrost Action Team. He is a professor of Ecosystem Ecology with a special focus on the response of Arctic ecosystems in a warmer world.

Dr. A. David McGuire
U.S. Geological Survey, University of Alaska Fairbanks, Fairbanks, AK, USA

Dave is the co-Principal Investigator of the Permafrost Carbon Network , professor of Ecology and a senior scientist at the U.S. Geological Survey. He is an expert on arctic and boreal terrestrial ecosystems in the climate system.

Dr. Christina Schädel
Northern Arizona University, Flagstaff, AZ, USA

Christina is the lead coordinator of the Permafrost Carbon Network and works as a Research Associate at Northern Arizona University. She conducts data synthesis focused on the decomposability of permafrost carbon.

Dr. Josep (Pep) Canadell
Global Carbon Project, CSIRO Canberra, Australia

Pep is a steering committee member of the Permafrost Carbon Network and the Executive director of the Global Carbon Project with the goal to develop a complete picture of the global carbon cycle, including biophysical and human dimensions.

Dr. Jennifer Harden
U.S. Geological Survey, Menlo Park, CA, USA

Jen is a steering committee member of the Permafrost Carbon Network and Scientist Emeritus at the U.S. Geological Survey. Her current research focuses on carbon and nutrient cycling, with an emphasis on landscape disturbance such as permafrost degradation.

Dr. Peter Kuhry
Stockholm University, Stockholm, Sweden

Peter is a steering committee member of the Permafrost Carbon Network and professor of Physical Geography. His research mainly focuses on carbon pools in soils and peat of permafrost-affected terrain.

Dr. Vladimir E. Romanovsky
University of Alaska Fairbanks, Fairbanks, AK, USA

Vladimir is a steering committee member of the Permafrost Carbon Network and Professor of Geophysics. He is interested in environmental and engineering problems involving permafrost and ice.

Dr. Merritt R. Turetsky
University of Guelph, Guelph, Canada

Merritt is a steering committee member of the Permafrost Carbon Network and professor of Ecosystem Ecology. Her research centers on ecosystem analysis with emphasis on the interactions among soil, water, plants, and the atmosphere.

NETWORK STRUCTURE

Participation in the Permafrost Carbon Network has increased from 45 in 2011 to more than 300 by the end of 2015. Participants are distributed across 130 institutions and 21 countries and early career scientists are particularly well represented throughout our synthesis activities. The network is structured into five working groups that couple information to develop more reliable projections of permafrost carbon dynamics, and to reduce uncertainty about permafrost carbon feedbacks to the climate system.

Over the years, cross-group synthesis activities have combined elements from multiple working groups and provided additional predictive capabilities for CO_2 and CH_4 release from thawing permafrost.

1) PERMAFROST CARBON QUANTITY

The Carbon Quantity working group has updated, reformatted and published the Northern Circumpolar Soil Carbon Database (http://bolin.su.se/data/ncscd/). This database includes spatially distributed datasets of soil coverage and soil carbon storage in the northern permafrost region. Other products include a spatial database of Siberian Yedoma distribution, maps of soil organic-horizon thickness for the northern circumpolar permafrost and other related topics.

2) PERMAFROST CARBON QUALITY

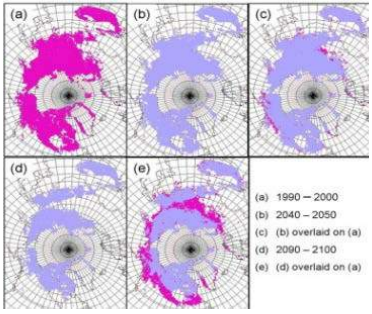
The Carbon Quality working group has estimated the vulnerability of permafrost carbon to decomposition upon thaw and evaluated large-scale controls of anaerobic CO_2 and CH_4 production, while comparing the relative importance of landscape-level factors. Additionally, the effects of environmental controls (e.g. temperature and soil moisture) on permafrost carbon release have been estimated.

3) ANAEROBIC/AEROBIC ISSUES

Activities of the Anaerobic/Aerobic working group have included a synthesis of chamber-based CH_4 data from wetland ecosystems across the permafrost zone to estimate CH_4 emissions from the permafrost zone. Other products in progress focus on the contribution of lakes to CH_4 emissions across high latitude permafrost landscapes, and estimation of stream and river processing of dissolved organic permafrost carbon for the Arctic Ocean watershed.

4) THERMOKARST AND THERMAL EROSION

The Thermokarst and Thermal Erosion working group has focused on synthesizing thermokarst and thermo-erosion rates, estimating thermokarst abundance and distribution at local scales, identifying and characterizing panarctic regions vulnerable to thermokarst, and the effects of thermokarst on soil carbon cycling.



5) MODELING INTEGRATION

The Modeling Integration working group has worked to improve modeling of the permafrost carbon feedback. These improvements are ongoing and are intended for incorporation in new generations of Earth System Model Simulations used for assessments by the Intergovernmental Panel on Climate Change (IPCC). Development of benchmark data sets for model evaluation and coordinated model experiments are an important part of the modeling integration working group.

CLIMATE CHANGE AND THE PERMAFROST CARBON FEEDBACK

Schuur, EAG, McGuire AD, Schädel C, Grosse G., Harden JW, Hayes DJ, Hugelius G, Koven CD, Kuhry P, Lawrence DM, Natali SM, Olefeldt C, Romanovsky VE, Schaefer K, Turetsky MR, Treat CC and Vonk JE (2015). *Nature* 520 (7546): 171-179. doi:10.1038/nature14338

Large quantities of organic carbon are stored in frozen soils (permafrost) within Arctic and sub-Arctic regions. A warming climate can induce environmental changes that accelerate the microbial breakdown of organic carbon and the release of the greenhouse gases carbon dioxide and methane. This feedback can accelerate climate change, but the magnitude and timing of greenhouse gas emission from these regions and their impact on climate change remain uncertain. Here we find that current evidence suggests a gradual and prolonged release of greenhouse gas emissions in a warming climate and present a research strategy with which to target poorly understood aspects of permafrost carbon dynamics.

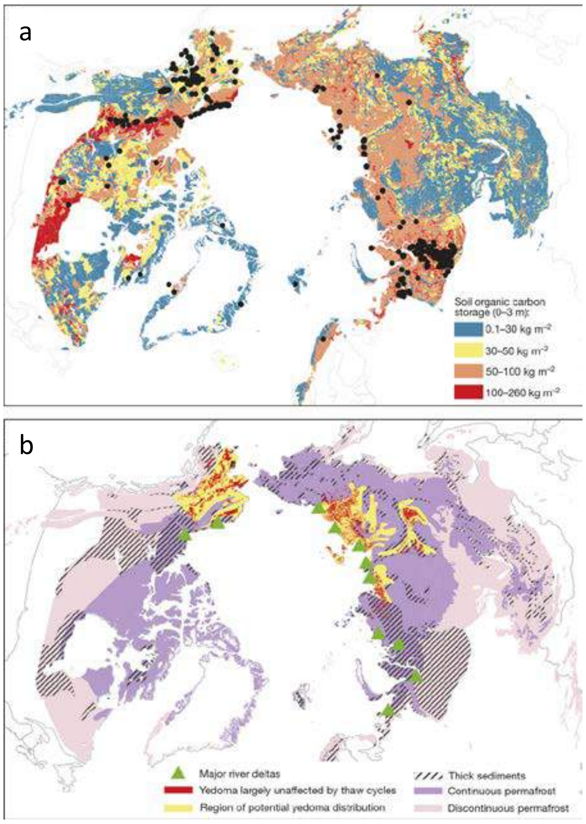


Figure 1, above| Soil organic carbon maps. **a**, Soil organic carbon pool (kg C m^{-2}) contained in the 0–3 m depth interval of the northern circumpolar permafrost zone. Points show field site locations for 0–3 m depth carbon inventory measurements; **b**, Deep permafrost carbon pools (>3 m), including the location of major permafrost-affected river deltas (green triangles), the extent of the yedoma region previously used to estimate the carbon content of these deposits (yellow), the current extent of yedoma region soils largely unaffected by thaw-lake cycles that alter the original carbon content (red), and the extent of thick sediments overlying bedrock (black hashed).

Figure 2, below| Potential cumulative carbon release. Data are given as a percentage of initial carbon. **a**, Cumulative carbon release after ten years of aerobic incubation at a constant temperature of 5 °C. Thick solid lines are averages for organic (red) and mineral soils (blue) and thin solid lines represent individual soils to show the response of individual soils. Dotted lines are the averages of the 97.5% CI for each soil type. **b**, Cumulative carbon release after one year of aerobic and anaerobic incubations (at 5 °C). Darker colours represent cumulative CH_4-carbon calculated as CO_2-carbon equivalent (for anaerobic soils) on a 100-year timescale. Positive error bars are upper 97.5% CI for CO_2-carbon and negative error bars are lower 97.5% CI for CH_4-carbon

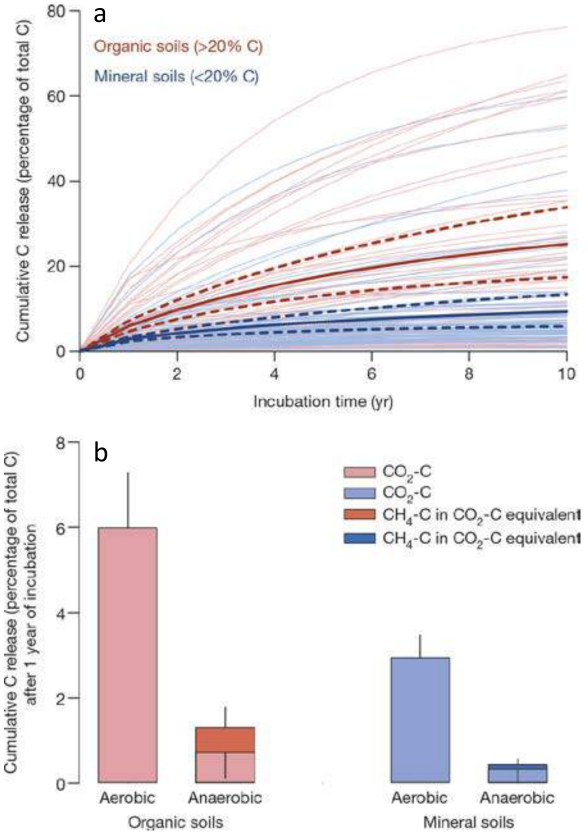


Figure 3| Model estimates of potential cumulative carbon release from thawing permafrost by 2100, 2200, and 2300**.**

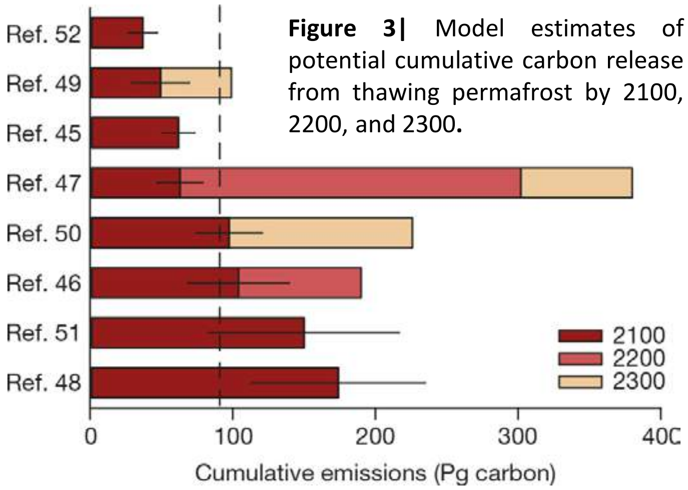


Figure 3| All estimates except those of refs 50 and 46 are based on RCP 8.5 or its equivalent in the AR4 (ref. 97), the A2 scenario. Error bars show uncertainties for each estimate that are based on an ensemble of simulations assuming different warming rates for each scenario and different amounts of initial frozen carbon in permafrost. The vertical dashed line shows the mean of all models under the current warming trajectory by 2100.

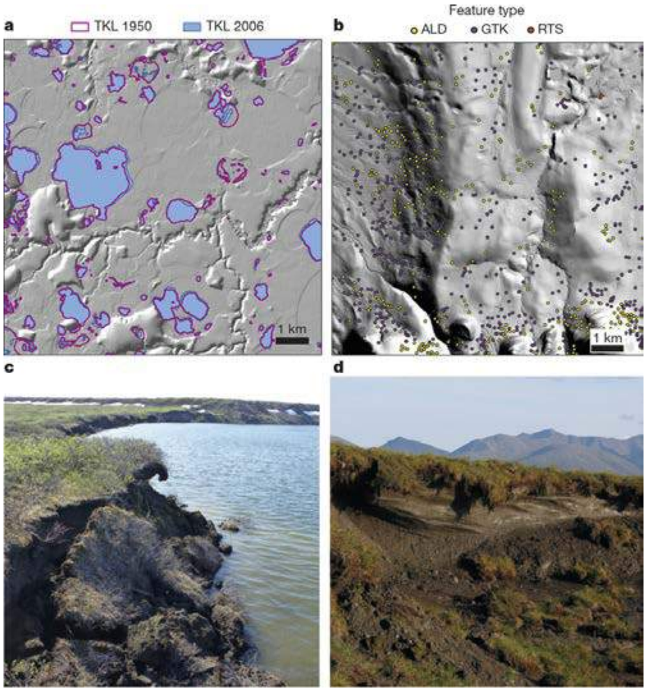
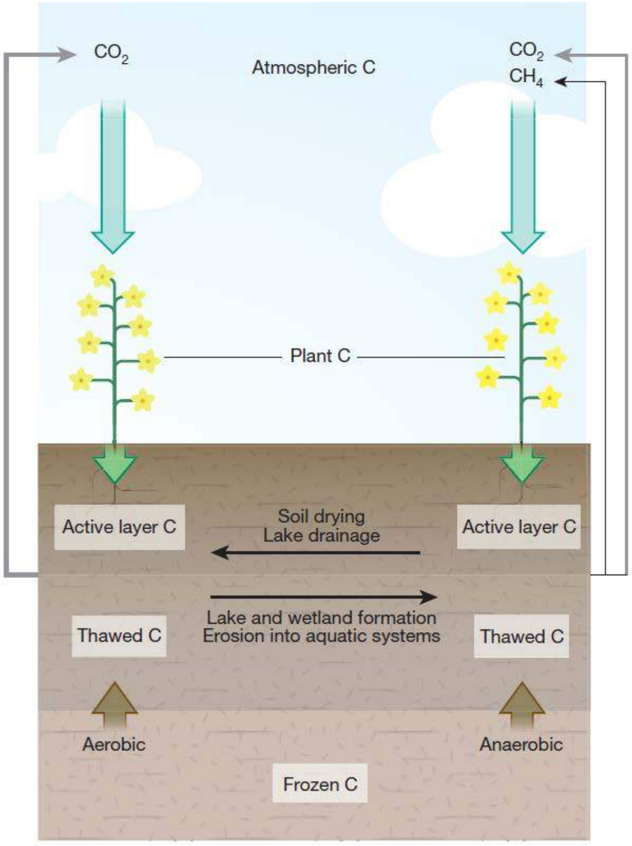


Figure 4| Abundance of abrupt thaw features in lowland and upland settings in Alaska.

Figure 4| Left panels (**a, c**) show thermokarst lake (TKL) abundance, expansion, and drainage on the Seward Peninsula, Northwest Alaska, between 1950 and 2006, with collapsing permafrost banks (photo credit G.G.). Right panels (**b, d**) show extensive distribution of ground collapse and erosion features (ALD, active layer detachment slide; RTS, retrogressive thaw slump; GTK, thermal erosion gullies) in upland tundra in a hill slope region in Northwest Alaska, and thawing icy soils in a retrogressive thaw slump (photo credit E.A.G.S.).

As shown in **Box 1 Figure** carbon stored frozen in permafrost, once thawed, can enter ecosystems that have either predominantly aerobic (oxygen present) or predominantly anaerobic (oxygen limited) soil conditions. Across the permafrost region, there is a gradient of water saturation that ranges from mostly aerobic upland ecosystems to mostly anaerobic lowland lakes and wetlands. In aerobic soils, CO_2 is released by microbial decomposition of soil organic carbon, whereas both CO_2 and CH_4 are released from anaerobic soils and sediments. Microbial breakdown of soil organic carbon can happen in the surface active layer, which thaws each summer and refreezes in the winter, and in the subsurface as newly thawed carbon becomes available for decomposition after it has emerged from the perennially frozen pool. The decomposability of soil organic carbon varies across the landscape depending in part on the plant inputs as well as the soil environment, and also with depth in the soil profile. The landscape mosaic of water saturation is also affected by permafrost thaw. Gradual and abrupt thaw processes such as top-down thawing of permafrost (increasing the thickness of the active layer) and lake draining can expose more carbon to aerobic conditions. Alternatively, abrupt thaw processes can create wetter anaerobic conditions as the ground surface subsides, attracting local water. Carbon can also be mobilized by erosion or by leaching from upland soils into aquatic systems or sediments. Plant carbon uptake can be stored in increased plant biomass or deposited in the surface soils, which in part can offset losses from soils.

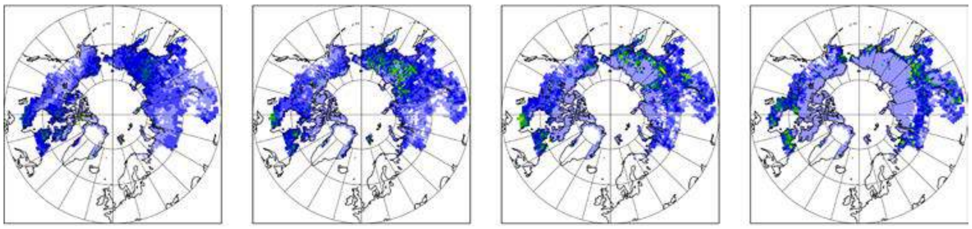


Box 1 | Key features regulating the permafrost carbon feedback to climate from new, synthesized observations.

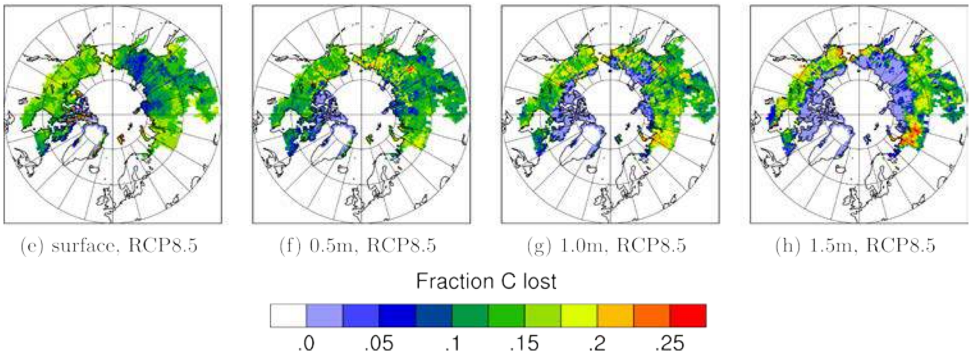
A SIMPLIFIED, DATA-CONSTRAINED APPROACH TO ESTIMATE THE PERMAFROST CARBON–CLIMATE FEEDBACK

Koven CD, Schuur EAG, Schädel C, Bohn TJ, Burke EJ, Chen G, Chen X, Ciais P, Grosse G, Harden JW, Hayes DJ, Hugelius G, Jafarov EE, Krinner G, Kuhry P, Lawrence DM, Macdougall AH, Marchenko SS, Mcguire AD, Natali SM, Nicolsky DJ, Olefeldt D, Peng S, Romanovsky VE, Schaefer KM, Strauss J, Treat CC, Turetsky M (2015. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences,* 373. doi: 10.1098/rsta.2014.0423

We present an approach to estimate the feedback from large-scale thawing of permafrost soils using a simplified, data-constrained model that combines three elements: soil carbon maps and profiles to identify the distribution and type of carbon in permafrost soils; incubation experiments to quantify the rates of carbon lost after thaw; and models of soil thermal dynamics in response to climate warming. We call the approach the Permafrost Carbon Network Incubation–Panarctic Thermal scaling approach (PInc-PanTher). The approach assumes that carbon stocks do not decompose at all when frozen, but once thawed follow set decomposition trajectories as a function of soil temperature. The trajectories are determined according to a three-pool decomposition model fitted to incubation data using parameters specific to soil horizon types. We calculate litterfall carbon inputs required to maintain steady-state carbon balance for the current climate, and hold those inputs constant. Soil temperatures are taken from the soil thermal modules of ecosystem model simulations forced by a common set of future climate change anomalies under two warming scenarios over the period 2010 to 2100. Under a medium warming scenario (RCP4.5), the approach projects permafrost soil carbon losses of 12.2–33.4 Pg carbon ; under a high warming scenario (RCP8.5), the approach projects carbon losses of 27.9–112.6 Pg carbon. Projected carbon losses are roughly linearly proportional to global temperature changes across the two scenarios. These results indicate a global sensitivity of frozen soil carbon to climate change (γ sensitivity) of −14 to −19 Pg carbon $^{\circ}C^{-1}$ on a 100 year time scale. For CH_4 emissions, our approach assumes a fixed saturated area and that increases in CH_4 emissions are related to increased heterotrophic respiration in anoxic soil, yielding CH_4 emission increases of 7% and 35% for the RCP4.5 and RCP8.5 scenarios, respectively, which add an additional greenhouse gas forcing of approximately 10–18%. The simplified approach presented here neglects many important processes that may amplify or mitigate carbon release from permafrost soils, but serves as a data-constrained estimate on the forced, large-scale permafrost carbon response to warming.



(a) surface, RCP4.5 (b) 0.5m, RCP4.5 (c) 1.0m, RCP4.5 (d) 1.5m, RCP4.5



(e) surface, RCP8.5 (f) 0.5m, RCP8.5 (g) 1.0m, RCP8.5 (h) 1.5m, RCP8.5

(*a*–*h*) Maps of fractional C losses over the period 2010–2100 calculated by the PInc-PanTher scaling approach at four depths (surface=1 cm, 0.5 m, 1.0 m and 1.5 m) and two warming scenarios (RCP4.5 and RCP8.5) using CLM4.5 soil temperatures as an example driving soil climate dataset. Losses are fairly uniform at the surface because of widespread lengthening of the unfrozen decomposing season and summertime soil warming; at depth C losses are zero in the area that remains permafrost and greatest at the margins of the permafrost zone where thaw leads to permanently unfrozen ground that allows continuous decomposition.

PERMAFROST CARBON MODEL INTERCOMPARISON PROJECT

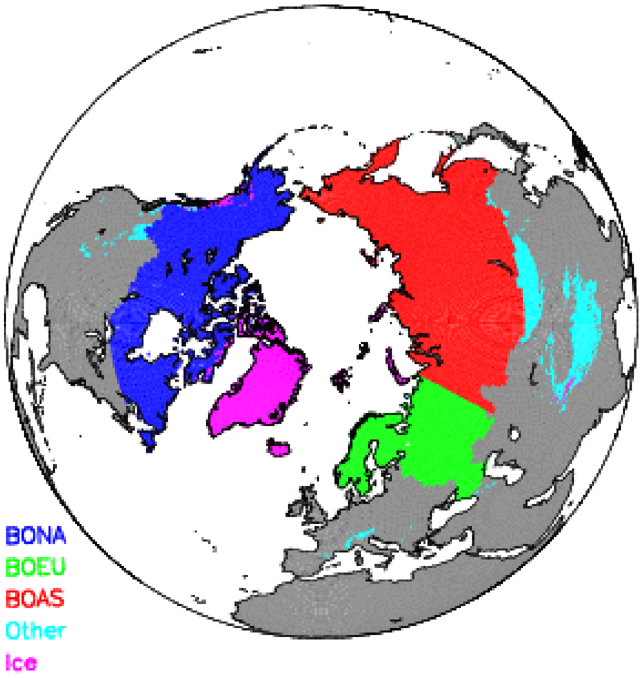
This project evaluates model projections of vulnerability of the permafrost region by comparing 15 land surface model simulations including carbon cycle processes and permafrost for two time periods. A retrospective analysis of the period 1960-2009 forms **Product 1**, along with a number of ancillary papers that focus on model output for individual variables or subregions. **Product 2** projects future vulnerability of the permafrost region for the period 2010 to 2299 using common driving data sets for future climate. Results from this model intercomparison help evaluate how differences in model structure and parameterization influence projected uptake and release of carbon for the permafrost region in the current and future climate.

PRODUCT 1:

A Model Based Analysis of the Vulnerability of Carbon in the Permafrost Region Between 1960 and 2009. McGuire AD, Koven CD, Lawrence DM, Clein JS, Xia J, Beer C, Burke E, Chen G, Chen X, Delire C, Jafarov EE, MacDougall A, Marchenko SS, Nicolsky DJ, Peng S, Rinke A, Saito K, Zhang W, Alkama R, Bohn TJ, Ciais P, Decharme B, Hayes DJ, Ekici A, Gouttevin I, Hajima T, Ji D, Krinner G, Lettenmaier DP, Luo Y, Miller PA, Moore JC, Romanovsky VE, Schädel C, Schaefer K, Schuur EAG, Smith B, Sueyoshi T, Zhuang Q (*to be submitted 12/2015*)

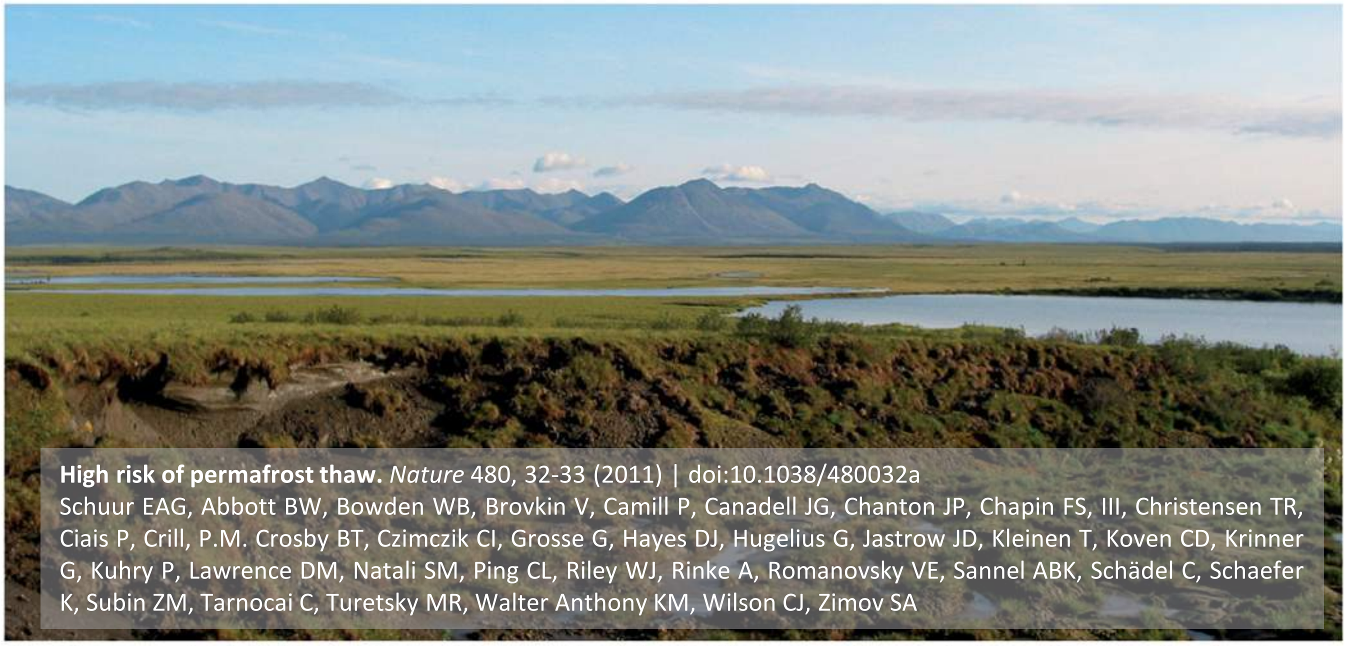
PRODUCT 2:

A Model Based Analysis of the Vulnerability of Carbon in the Permafrost Region Between 2010 and 2299. McGuire AD, et al. (*to be submitted 2016*)



The spatial extent of the permafrost region in the Northern Hemisphere defined in this study. Sub-regions include boreal Asia (BOAS), boreal Europe (BOEU), boreal North America (BONA), Glaciers and Ice Sheets (Ice), and other permafrost areas (Other).

Planning phases of model runs at the 1st and 3rd Annual Meeting, San Francisco, CA. Photos: Ben Abbott



High risk of permafrost thaw. *Nature* 480, 32-33 (2011) | doi:10.1038/480032a
Schuur EAG, Abbott BW, Bowden WB, Brovkin V, Camill P, Canadell JG, Chanton JP, Chapin FS, III, Christensen TR, Ciais P, Crill, P.M. Crosby BT, Czimczik CI, Grosse G, Hayes DJ, Hugelius G, Jastrow JD, Kleinen T, Koven CD, Krinner G, Kuhry P, Lawrence DM, Natali SM, Ping CL, Riley WJ, Rinke A, Romanovsky VE, Sannel ABK, Schädel C, Schaefer K, Subin ZM, Tarnocai C, Turetsky MR, Walter Anthony KM, Wilson CJ, Zimov SA

Abrupt thaw, as seen here in Alaska's Noatak National Preserve, causes the land to collapse, accelerating permafrost degradation and carbon release.

High risk of permafrost thaw

Northern soils will release huge amounts of carbon in a warmer world, say **Edward A. G. Schuur, Benjamin Abbott** and the Permafrost Carbon Network.

Arctic temperatures are rising fast, and permafrost is thawing. Carbon released into the atmosphere from permafrost soils will accelerate climate change, but the magnitude of this effect remains highly uncertain. Our collective estimate is that carbon will be released more quickly than models suggest, and at levels that are cause for serious concern.

We calculate that permafrost thaw will release the same order of magnitude of carbon as deforestation if current rates of deforestation continue. But because these emissions include significant quantities of methane, the overall effect on climate could be 2.5 times larger.

Recent years have brought reports from the far north of tundra fires[1], the release of ancient carbon[2], CH_4 bubbling out of lakes[3] and gigantic stores of frozen soil carbon[4]. The latest estimate is that some 18.8 million square kilometres of northern soils hold about 1,700 billion tonnes of organic carbon[4] — the remains of plants and animals that have been accumulating in the soil over thousands of years. That is about four times more than all the carbon emitted by human activity in modern times and twice as much as is present in the atmosphere now.

This soil carbon amount is more than three times higher than previous estimates, largely because of the realization that organic carbon is stored much deeper in frozen soils than was thought. Inventories typically measure carbon in the top metre of soil. But the physical mixing during freeze–thaw cycles, in combination with sediment deposition over hundreds and thousands of years, has buried permafrost carbon many metres deep.

The answers to three key questions will determine the extent to which the emission of this carbon will affect climate change: How much is vulnerable to release into the atmosphere? In what form it will be released? And how fast will it be released? These questions are easily framed, but challenging to answer.

KNOWN UNKNOWNS

As soils defrost, microbes decompose the ancient carbon and release CH_4 and carbon dioxide. Not all carbon is equally vulnerable to release: some soil carbon is easily metabolized and transformed to gas, but more complex molecules are harder to break down. The bulk of permafrost carbon will be released slowly over decades after thaw, but a smaller fraction could remain within the soil for centuries or longer. The type of gas released also affects the heat-trapping potential of the emissions. Waterlogged, low-oxygen environments are likely to contain microbes that produce CH_4 — a potent greenhouse gas with about 25 times more warming potential than CO_2 over a 100-year period. However, waterlogged environments also tend to retain more carbon within the soil. It is not yet understood how these factors will act together to affect future climate.

The ability to project how much carbon will be released is hampered both by the fact that models do not account for some important processes, and by a lack of data to inform the models. For example, most large-scale models project that permafrost warming depends on how much the air is warming above them. This warming then boosts microbial activity and carbon release. But this is a simplification. Abrupt thaw processes can cause ice wedges to melt and the ground surface to collapse, accelerating the thaw of frozen ground[5]. Evidence of rapid thaw is widespread: you can see it in the 'drunken' trees that tip dangerously as a result of ground subsidence, and in collapsed hill slopes marked by scars from landslides. These are just some of the complex processes that models don't include.

At the same time, few data are available to support these models because of the difficulties of gathering data in extreme environments. Only a handful of remote field stations around the world are collecting data to support this research, even though the permafrost zone covers about almost one-quarter of the Northern Hemisphere's land area. The field studies that do exist confirm that permafrost thaw is tightly linked to ground subsidence and soil moisture as well as temperature. So modelling carbon emissions from permafrost thaw is much more complex than a simple response to temperature alone.

Models have flaws, but experts intimately familiar with these landscapes and processes have accumulated knowledge about what they expect to happen, based on quantitative data and qualitative understanding of these systems. We have attempted to quantify this expertise through a survey developed over several years.

SURVEY SAYS

Our survey asks what percentage of the surface permafrost is likely to thaw, how much carbon will be released, and how much of that carbon will be CH_4, for three time periods and under four warming scenarios that will be part of the Intergovernmental Panel on Climate Change Fifth Assessment Report. The lowest warming scenario projects 1.5 °C Arctic warming over the 1985–2004 average by the year 2040, ramping up to 2 °C by 2100; the highest warming scenario considers 2.5 °C by 2040, and 7.5 °C by 2100. In all cases, we posited that the temperature would remain steady from 2100 to 2300 so that we could assess opinions about the time lag in the response of permafrost carbon to temperature change.

The survey was filled out this year by 41 international scientists, listed as authors here, who publish on various aspects of permafrost. The results are striking. Collectively, we hypothesize that the high warming scenario will degrade 9–15% of the top 3 metres of permafrost by 2040, increasing to 47–61% by 2100 and 67–79% by 2300 (these ranges are the 95% confidence intervals around the group's mean estimate). The estimated carbon release from this degradation is 30 billion to 63 billion tonnes of carbon by 2040, reaching 232 billion to 380 billion tonnes by 2100 and 549 billion to 865 billion tonnes by 2300. These values, expressed in CO_2 equivalents, combine the effect of carbon released as both CO_2 and as CH_4.

Our estimate for the amount of carbon released by 2100 is 1.7–5.2 times larger than those reported in several recent modelling studies[6–8], all of which used a similar warming scenario. This reflects, in part, our perceived importance of the abrupt thaw processes, as well as our heightened awareness of deep carbon pools. Active research is aimed at incorporating these main issues, along with others, into models.

Are our projected rapid changes to the permafrost soil carbon pool plausible? The survey predicts a 7–11% drop in the size of the permafrost carbon pool by 2100 under the high-warming scenario. That scale of carbon loss has happened before: a 7–14% decrease has been measured in soil carbon inventories across thousands of sites in the temperate-zone United Kingdom as a result of climate change[9]. Also, data scaled up from a single permafrost field site point to a potential 5% loss over a century as a result of widespread permafrost thaw[2]. These field results generally agree with the collective carbon-loss projection made by this survey, so it should indeed be plausible.

Across all the warming scenarios, we project that most of the released carbon will be in the form of CO_2, with only about 2.7% in the form of CH_4. However, because CH_4 has a higher global-warming potential, almost half the effect of future permafrost-zone carbon emissions on climate forcing is likely to be from CH_4. That is roughly consistent with the tens of billions of tonnes of CH_4 thought to have come from oxygen-limited environments in northern ecosystems after the end of the last glacial period[10].

All this points towards significant carbon releases from permafrost-zone soils over policy-relevant timescales. It also highlights important lags whereby permafrost degradation and carbon emissions are expected to continue for decades or centuries after global temperatures stabilize at new, higher levels. Of course, temperatures might not reach such high levels. Our group's estimate for carbon release under the lowest warming scenario, although still quite sizeable, is about one-third of that predicted under the strongest warming scenario.

Knowing how much carbon will be released from the permafrost zone in this century and beyond is crucial for determining the appropriate response. But despite the massive amount of carbon in permafrost soils, emissions from these soils are unlikely to overshadow those from the burning of fossil fuels, which will continue to be the main source of climate forcing. Permafrost carbon release will still be an important amplifier of climate change, however, and is in some ways more problematic: it occurs in remote places, far from human influence, and is dispersed across the landscape. Trapping carbon emissions at the source — as one might do at power plants — is not an option. And once the soils thaw, emissions are likely to continue for decades, or even centuries.

The scientific community needs to collect more data and develop more-sophisticated models to test the hypotheses presented by this survey. Fortunately, awareness of the problem is increasing and these are starting to happen. The US Department of Energy, for example, has initiated a project called Next-Generation Ecosystem Experiments — Arctic, which aims to improve the representation of these processes in large-scale models. NASA is pursuing an Arctic–Boreal Vulnerability Experiment, which aims to improve satellite observations of this region. The Vulnerability of Permafrost Carbon Research Coordination Network funded by the US National Science Foundation, of which we are part, is bringing together people and observations to synthesize results and validate models. These are just some of the many international initiatives aimed at filling these research gaps.

In the meantime, our survey outlines the additional risk to society caused by thawing of the frozen north, and underscores the urgent need to reduce atmospheric emissions from fossil-fuel use and deforestation. This will help to keep permafrost carbon frozen in the ground. ■

'Drunken' trees reveal areas of subsidence.

VISUALS UNLIMITED/NATUREPL.COM

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e-mail: tschuur@ufl.edu

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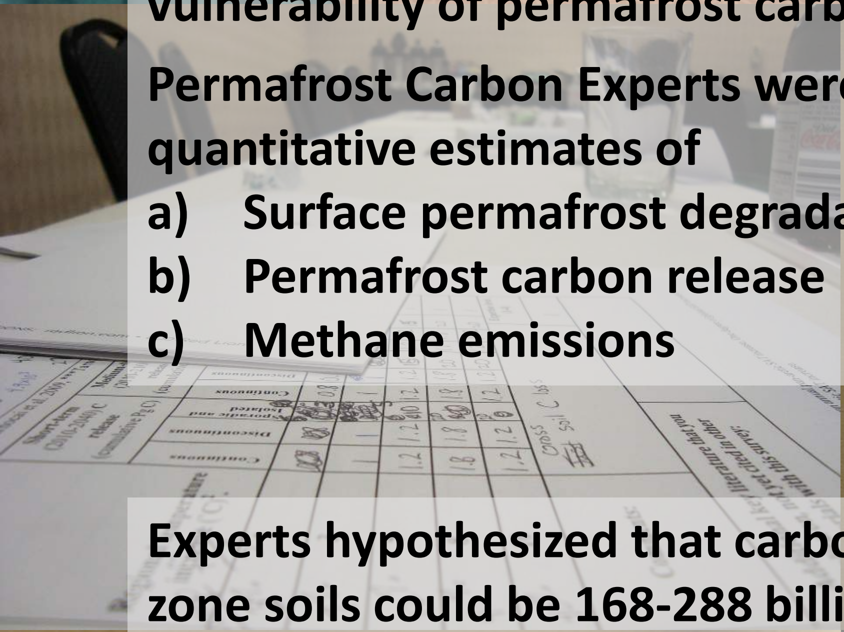
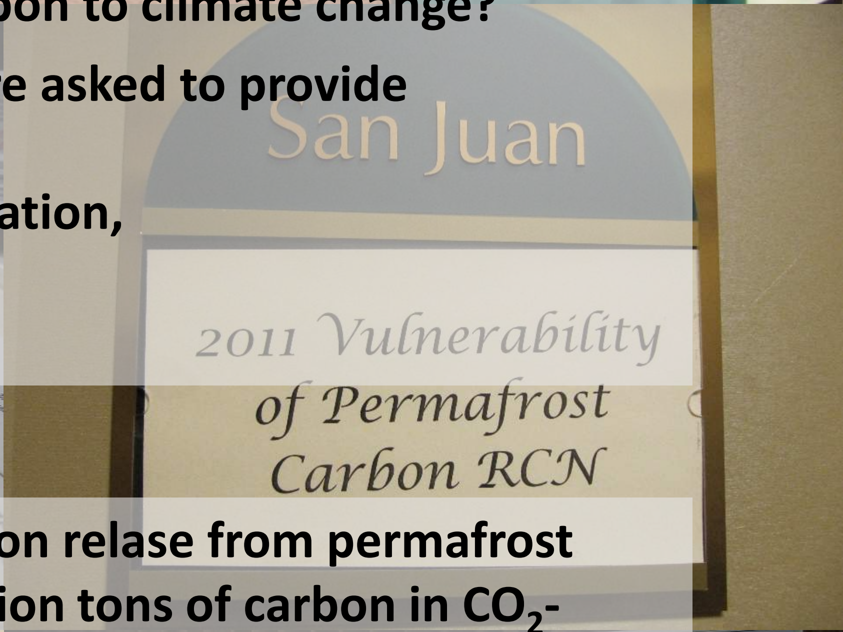
How can expert knowledge be used to assess the vulnerability of permafrost carbon to climate change?

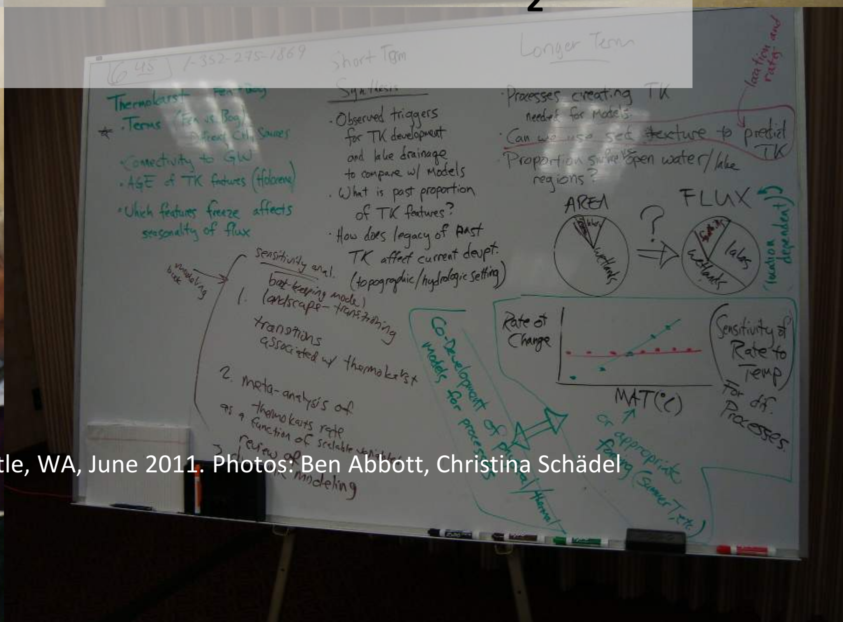
Permafrost Carbon Experts were asked to provide quantitative estimates of

- **a) Surface permafrost degradation,**
- **b) Permafrost carbon release**
- **c) Methane emissions**





Experts hypothesized that carbon relase from permafrost zone soils could be 168-288 billion tons of carbon in CO_2-equivalents by 2100.

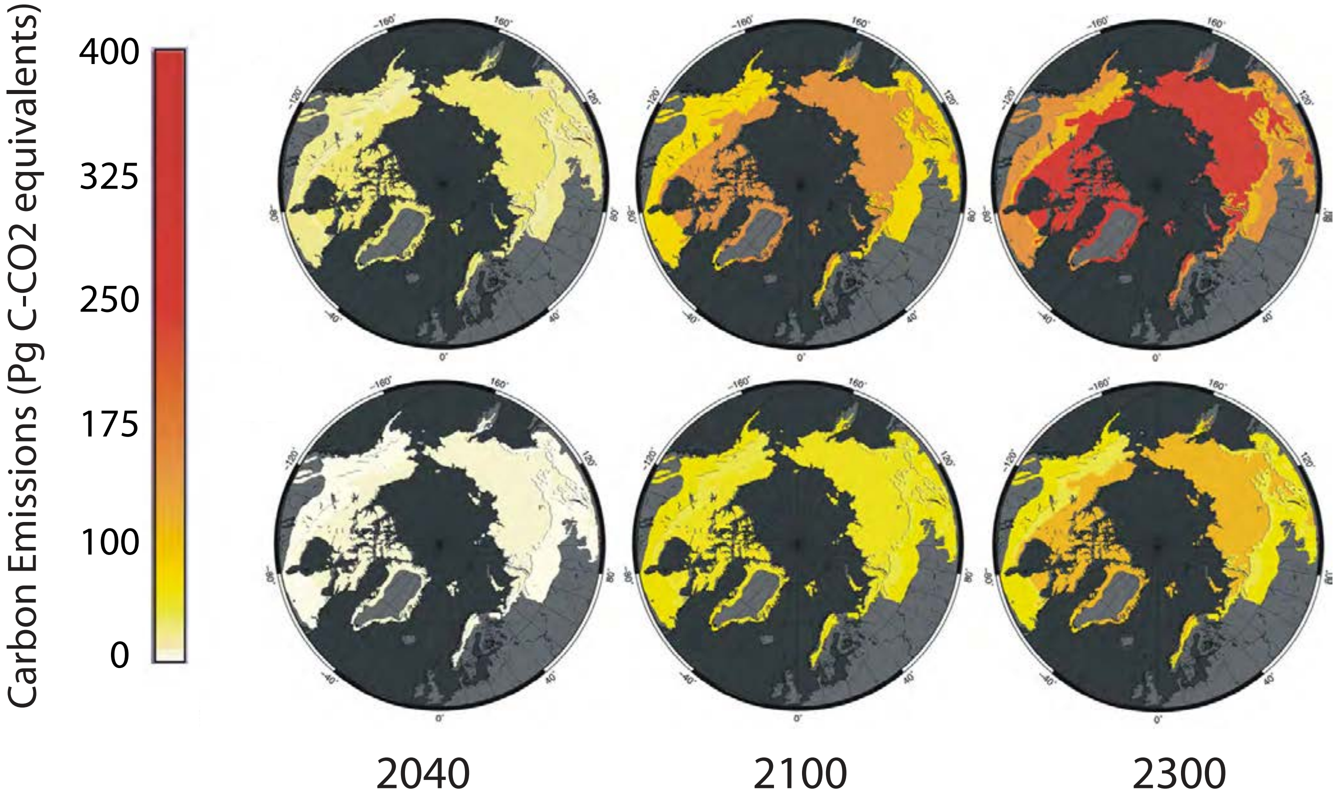


All photos: Permafrost Carbon Experts and meeting notes, Seattle, WA, June 2011. Photos: Ben Abbott, Christina Schädel

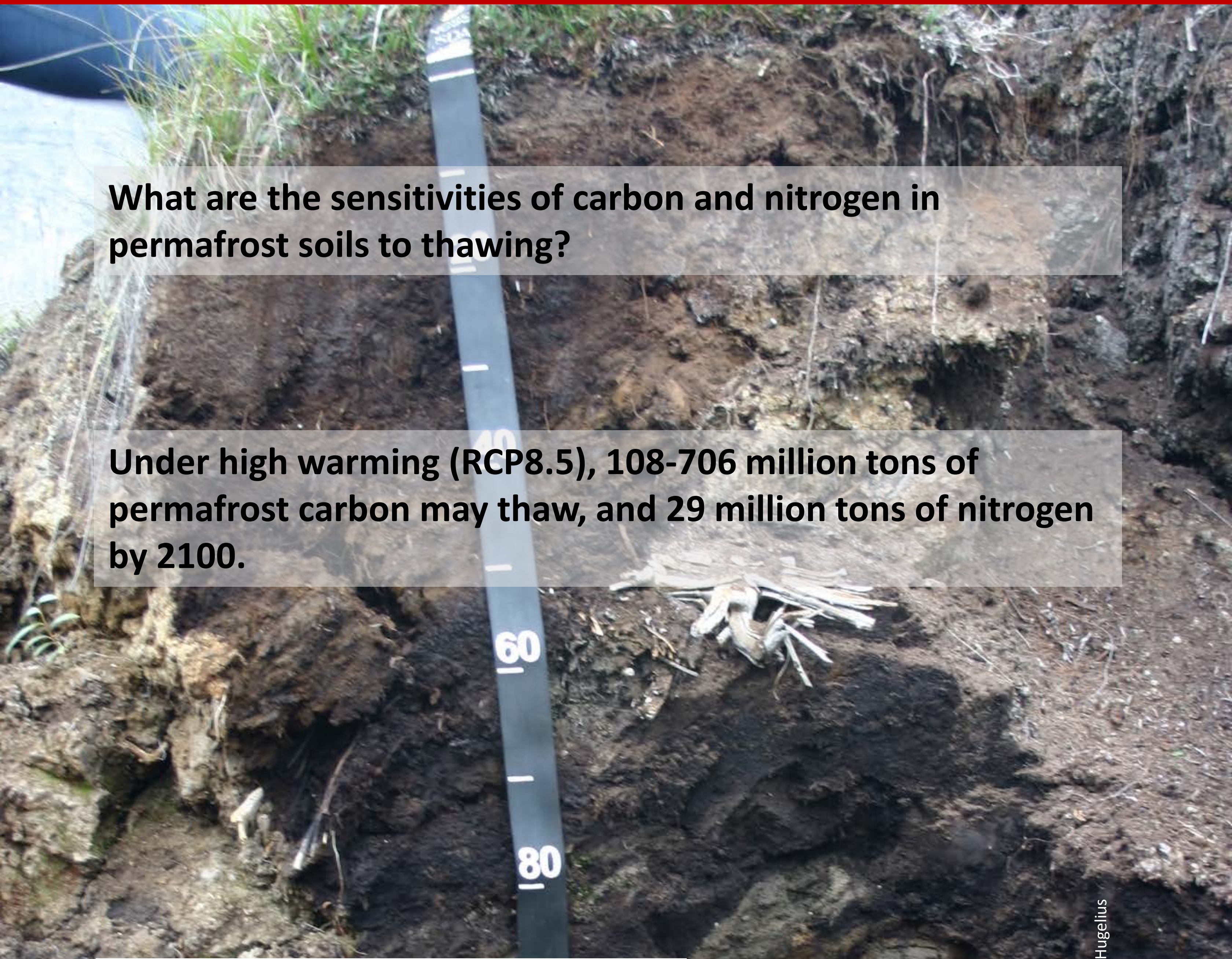
EXPERT ASSESSMENT OF VULNERABILITY OF PERMAFROST CARBON TO CLIMATE CHANGE

Schuur EAG, Abbott BW, Bowden WB, Brovkin V, Camill P, Canadell JG, Chanton JP, Chapin FS, III, Christensen TR, Ciais P, Crosby BT, Czimczik CI, Grosse G, Harden J, Hayes DJ, Hugelius G, Jastrow JD, Jones JB, Kleinen T, Koven CD, Krinner G, Kuhry P, Lawrence DM, McGuire AD, Natali SM, O'Donnell JA, Ping CL, Riley WJ, Rinke A, Romanovsky VE, Sannel ABK, Schädel C, Schaefer K, Sky J, Subin ZM, Tarnocai C, Turetsky MR, Waldrop MP, Walter Anthony KM, Wickland KP, Wilson CJ, Zimov SA (2013) *Climatic Change,* 119, 2. 359-374, doi: 10.1007/s10584-013-0730-7.

Abstract Approximately 1700 Pg of soil carbon are stored in the northern circumpolar permafrost zone, more than twice as much carbon than in the atmosphere. The overall amount, rate, and form of carbon released to the atmosphere in a warmer world will influence the strength of the permafrost carbon feedback to climate change. We used a survey to quantify variability in the perception of the vulnerability of permafrost carbon to climate change. Experts were asked to provide quantitative estimates of permafrost change in response to four scenarios of warming. For the highest warming scenario (RCP 8.5), experts hypothesized that carbon release from permafrost zone soils could be 19–45 Pg carbon by 2040, 162–288 Pg carbon by 2100, and 381–616 Pg carbon by 2300 in CO_2 equivalent using 100-year CH_4 global warming potential (GWP). These values become 50 % larger using 20-year CH4 GWP, with a third to a half of expected climate forcing coming from CH_4 even though CH_4 was only 2.3 % of the expected carbon release. Experts projected that two thirds of this release could be avoided under the lowest warming scenario (RCP 2.6). These results highlight the potential risk from permafrost thaw and serve to frame a hypothesis about the magnitude of this feedback to climate change. However, the level of emissions proposed here are unlikely to overshadow the impact of fossil fuel burning, which will continue to be the main source of carbon emissions and climate forcing.



Cumulative carbon emissions projected by experts as a result of warming climate for three different time horizons. Top figures represent a higher warming trajectory (2.5 °C at 2040, 7.5 °C at 2100, 7.5 °C at 2300), and bottom figures represent a lower warming trajectory (1.54 °C at 2040, 2.0 °C at 2100, 2.0 °C at 2300). Values are Pg C (CO_2 plus CH_4) expressed on a common scale as CO_2-equivalents (using 100-year GWP) and are shown as median values (to account estimates of zero flux) for the continuous, the discontinuous, and the sporadic plus isolated permafrost zones



What are the sensitivities of carbon and nitrogen in permafrost soils to thawing?

Under high warming (RCP8.5), 108-706 million tons of permafrost carbon may thaw, and 29 million tons of nitrogen by 2100.

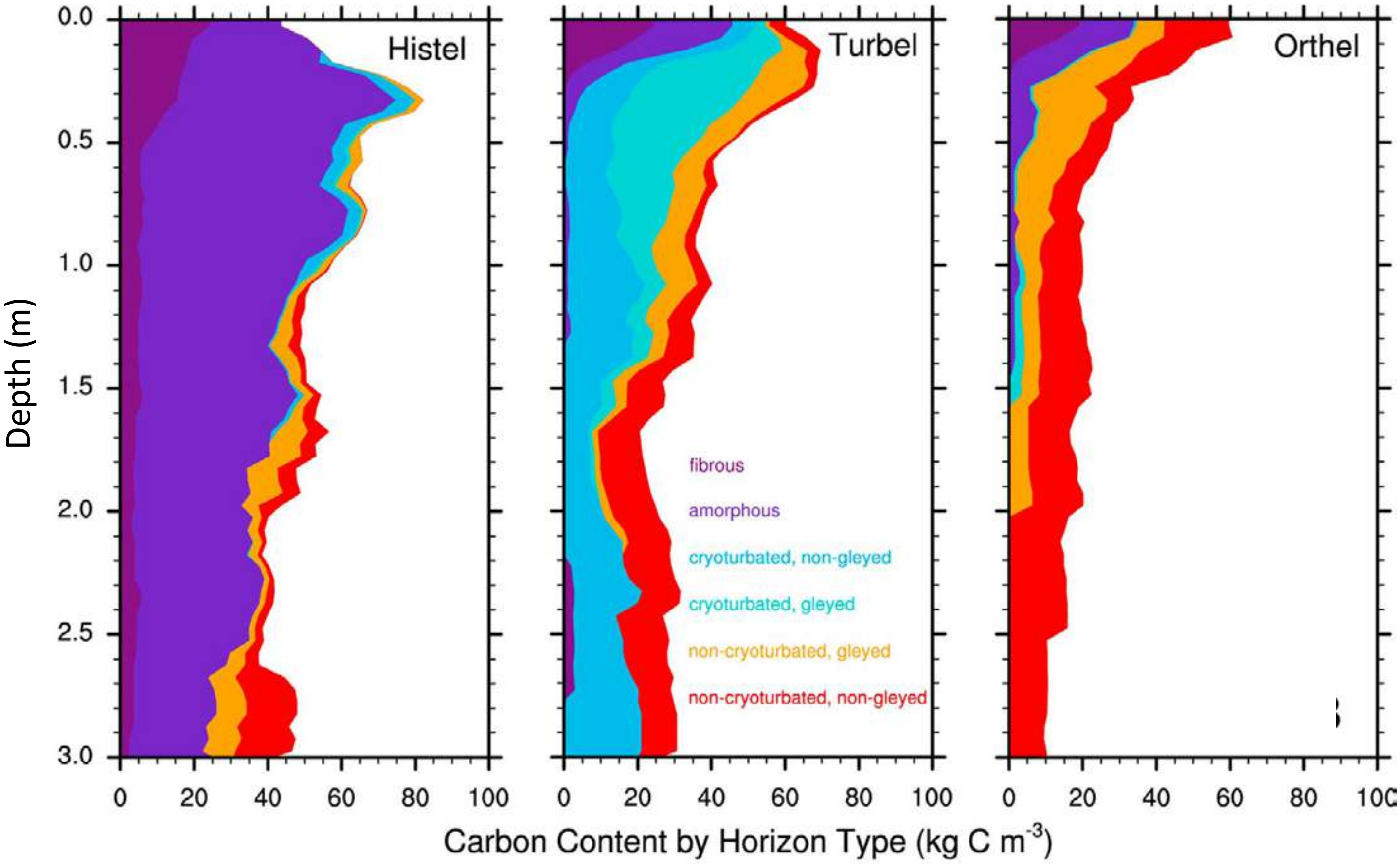
Ice-wedge in Yedoma, Cherskii, Russia. Photo: Gustaf Hugelius

Full-page: Cryoturbated soil, Cherskii, Russia. Photo: Gustaf Hugelius

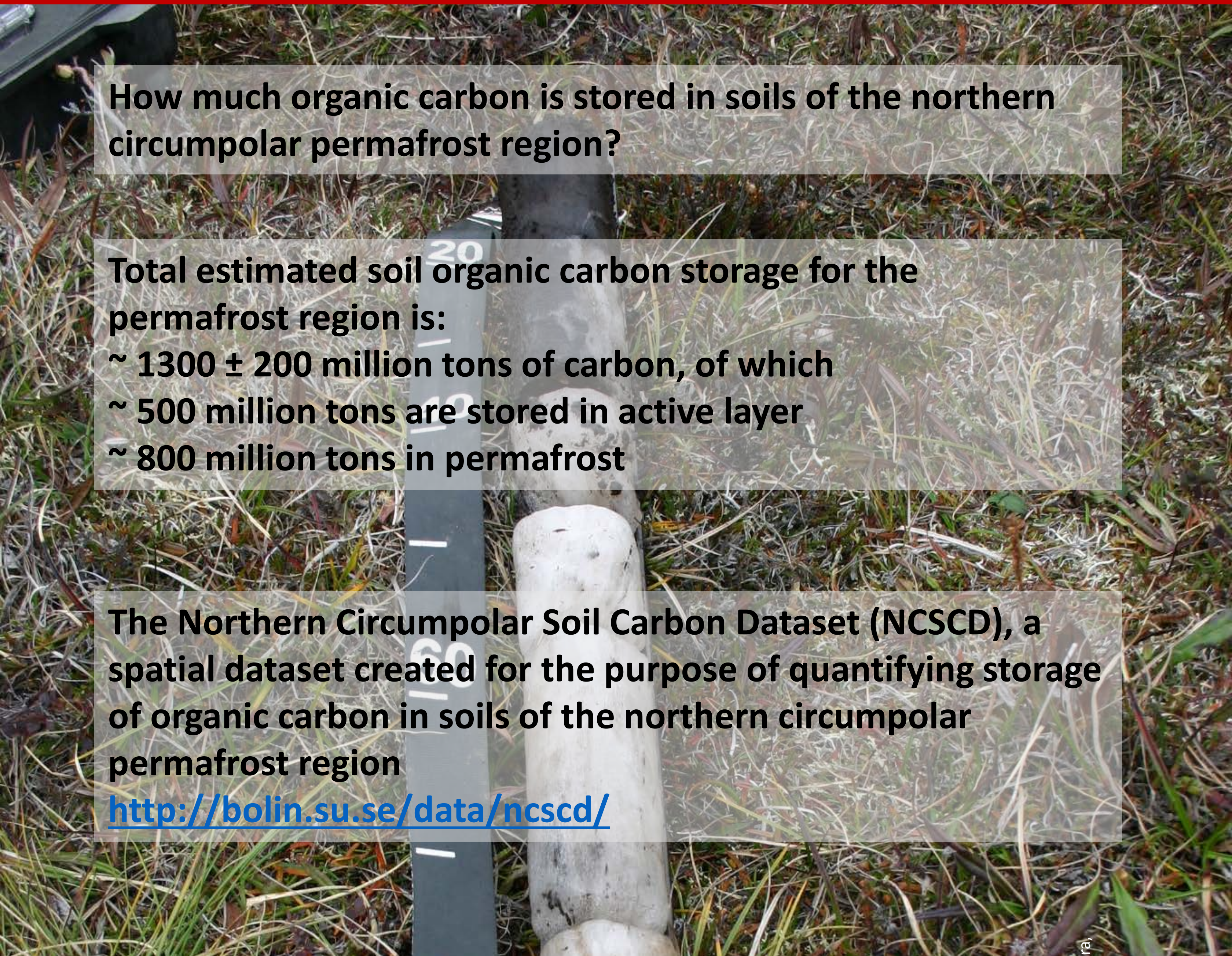
FIELD INFORMATION LINKS PERMAFROST CARBON TO PHYSICAL VULNERABILITIES OF THAWING

Harden JW, Koven CD, Ping C-L, Hugelius G, McGuire AD, Camill P, Jorgenson T, Kuhry P, Michaelson GJ, O'Donnell JA, Schuur EAG, Tarnocai C, Johnson K, Grosse G (2012). *Geophysical Research Letters,* 39, L15704.

Deep soil profiles containing permafrost (Gelisols) were characterized for organic carbon and total nitrogen stocks to 3 m depths. Using the Community Climate System Model (CCSM4) we calculate cumulative distributions of active layer thickness under current and future climates. The difference in cumulative active layer thickness distributions over time was multiplied by carbon and nitrogen contents of soil horizons in Gelisol suborders to calculate newly thawed carbon and nitrogen. Thawing ranged from 147 Pg carbon with 10 Pg nitgrogen by 2050 (representative concentration pathway RCP scenario 4.5) to 436 Pg carbon with 29 Pg nitrogen by 2100 (RCP 8.5). Organic horizons that thaw are vulnerable to combustion, and all horizon types are vulnerable to shifts in hydrology and decomposition. The rates and extent of such losses are unknown and can be further constrained by linking field and modelling approaches. These changes have the potential for strong additional loading to our atmosphere, water resources, and ecosystems.



Carbon-depth distribution of soil horizons in Histels, Turbels and Orthels.



How much organic carbon is stored in soils of the northern circumpolar permafrost region?

Total estimated soil organic carbon storage for the permafrost region is:
~ 1300 ± 200 million tons of carbon, of which
~ 500 million tons are stored in active layer
~ 800 million tons in permafrost

The Northern Circumpolar Soil Carbon Dataset (NCSCD), a spatial dataset created for the purpose of quantifying storage of organic carbon in soils of the northern circumpolar permafrost region
http://bolin.su.se/data/ncscd/

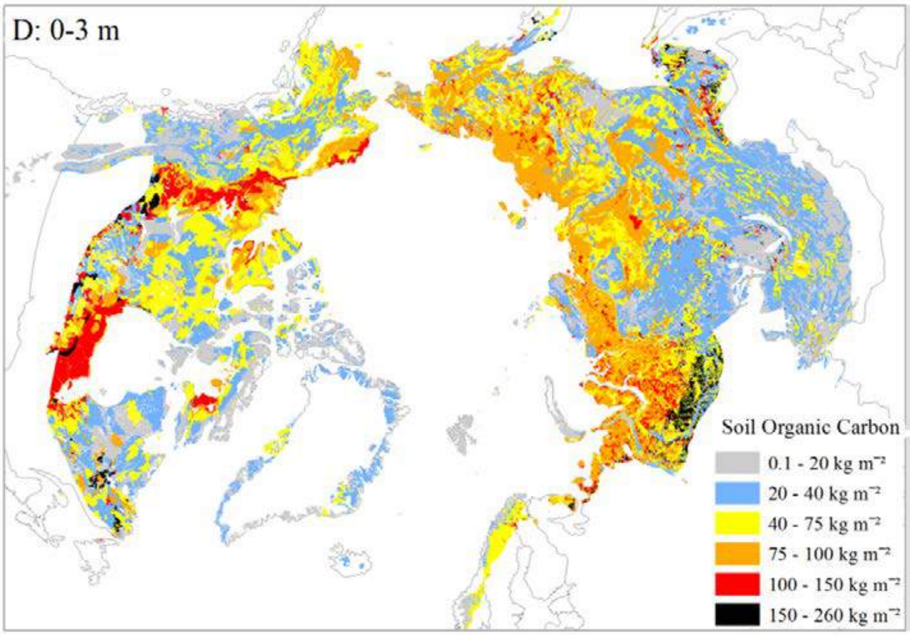
Ice lens from high centered polygon on the Arctic Coastal Plain. Photo: Marguerite Mauritz

Full page: oil core through an ice wedge in polygonated tundra, Arctic Coastal Plain. Photo: Marguerite Mauritz

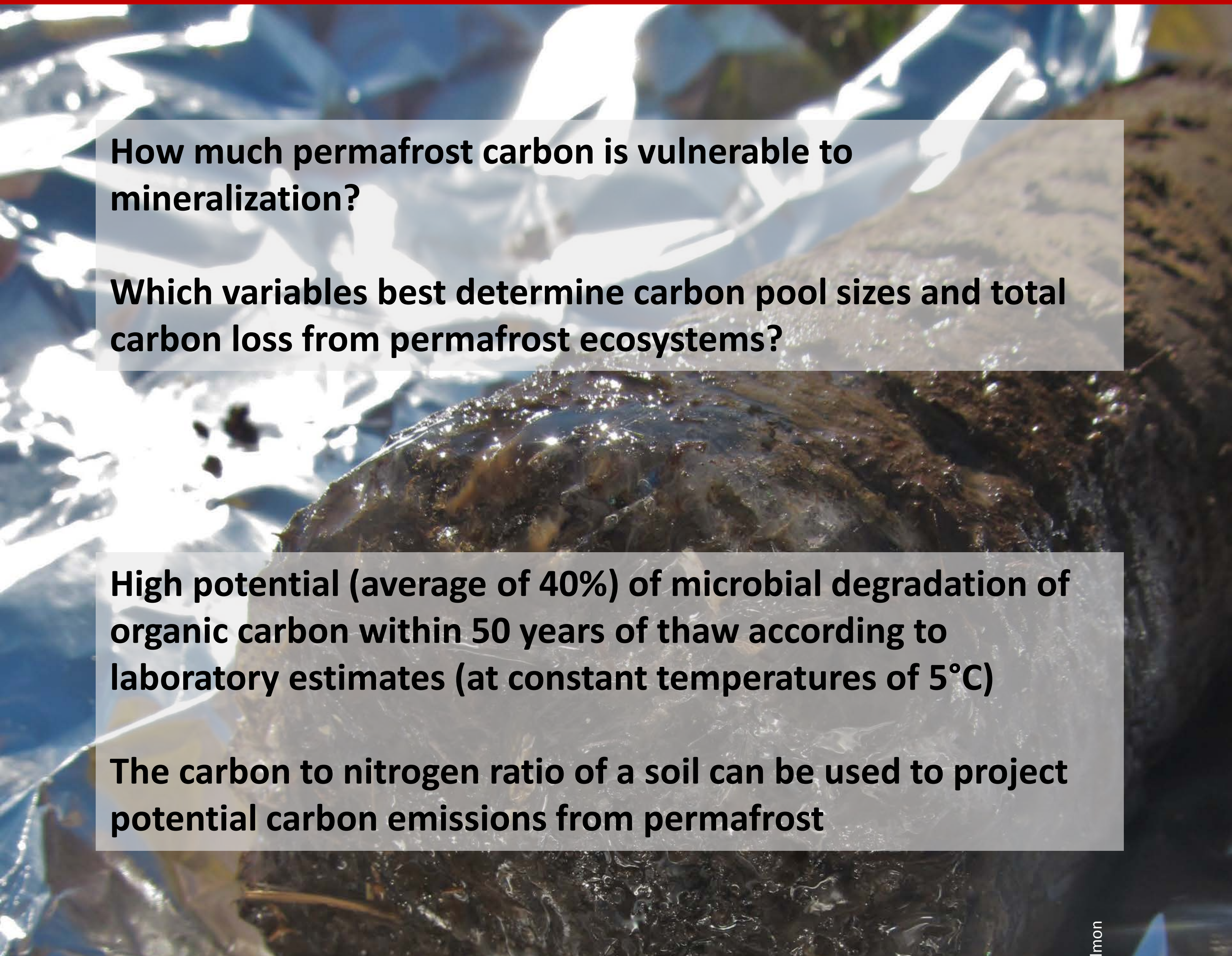
ESTIMATED STOCKS OF CIRCUMPOLAR PERMAFROST CARBON WITH QUANTIFIED UNCERTAINTY RANGES AND IDENTIFIED DATA GAPS

Hugelius G, Strauss J, Zubrzycki S, Harden JW, Schuur EAG, Ping CL, Schirrmeister L, Grosse G, Michaelson GJ, Koven CD, O'Donnell JA, Elberling B, Mishra U, Camill P, Yu Z, Palmtag J, Kuhry P (2014). *Biogeosciences,* **11**, 6573-6593. doi: 10.5194/bg-11-6573-2014

Soils and other unconsolidated deposits in the northern circumpolar permafrost region store large amounts of soil organic carbon (SOC). This SOC is potentially vulnerable to remobilization following soil warming and permafrost thaw, but SOC stock estimates were poorly constrained and quantitative error estimates were lacking. This study presents revised estimates of permafrost SOC stocks, including quantitative uncertainty estimates, in the 0–3m depth range in soils as well as for sediments deeper than 3m in deltaic deposits of major rivers and in the Yedoma region of Siberia and Alaska. Revised estimates are based on significantly larger databases compared to previous studies. Despite this there is evidence of significant remaining regional data gaps. Estimates remain particularly poorly constrained for soils in the High Arctic region and physiographic regions with thin sedimentary overburden (mountains, highlands and plateaus) as well as for deposits below 3mdepth in deltas and the Yedoma region. While some components of the revised SOC stocks are similar in magnitude to those previously reported for this region, there are substantial differences in other components, including the fraction of perennially frozen SOC. Upscaled based on regional soil maps, estimated permafrost region SOC stocks are 21712 and 47227 Pg for the 0–0.3 and 0–1m soil depths, respectively (95% confidence intervals). Storage of SOC in 0–3m of soils is estimated to 1035150 Pg. Of this, 3416 PgC is stored in poorly developed soils of the High Arctic. Based on generalized calculations, storage of SOC below 3m of surface soils in deltaic alluvium of major Arctic rivers is estimated as 9152 Pg. In the Yedoma region, estimated SOC stocks below 3mdepth are 18154 Pg, of which 7420 Pg is stored in intact Yedoma (late Pleistocene ice- and organic-rich silty sediments) with the remainder in refrozen thermokarst deposits. Total estimated SOC storage for the permafrost region is 1300 Pg with an uncertainty range of 1100 to 1500 Pg. Of this, 500 Pg is in non-permafrost soils, seasonally thawed in the active layer or in deeper taliks, while 800 Pg is perennially frozen. This represents a substantial 300 Pg lowering of the estimated perennially frozen SOC stock compared to previous estimates.



Map of estimated 0–3m SOC storage (kg carbon m^{-2}) in the northern circumpolar permafrost region.



How much permafrost carbon is vulnerable to mineralization?

Which variables best determine carbon pool sizes and total carbon loss from permafrost ecosystems?

High potential (average of 40%) of microbial degradation of organic carbon within 50 years of thaw according to laboratory estimates (at constant temperatures of 5°C)

The carbon to nitrogen ratio of a soil can be used to project potential carbon emissions from permafrost

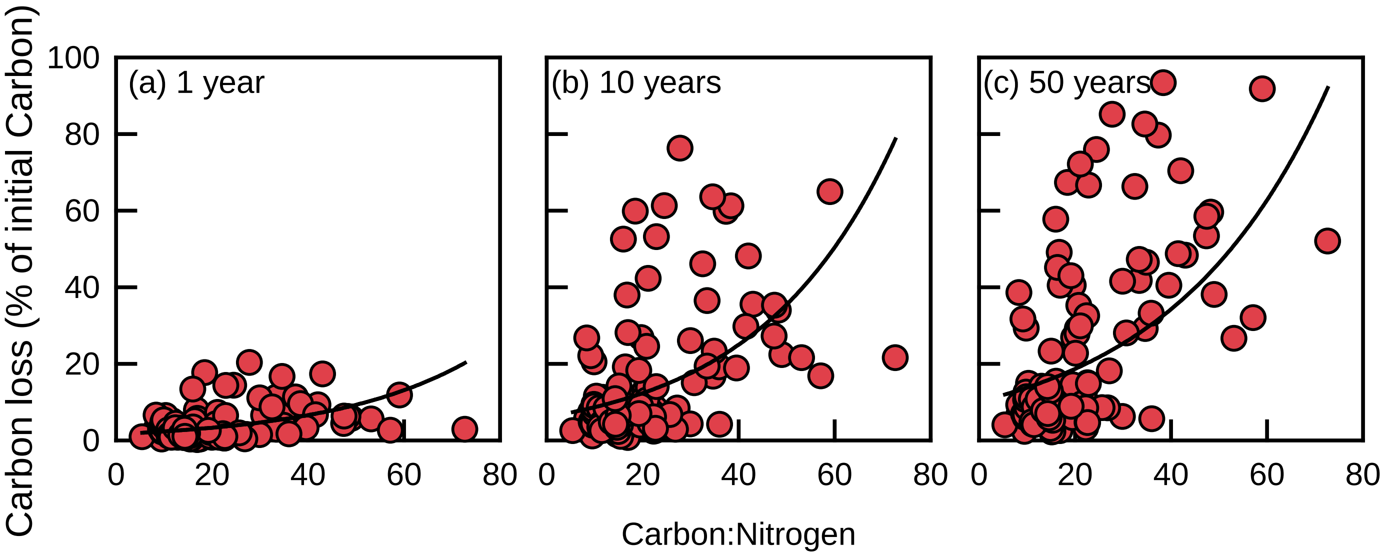
Incubation jars. Photo: Rosvel Bracho

age: Permafrost soil core with ice lens. Photo: Verity Salmon

CIRCUMPOLAR ASSESSMENT OF PERMAFROST CARBON QUALITY AND ITS VULNERABILITY OVER TIME USING LONG-TERM INCUBATION DATA

Schädel C, Schuur EAG, Bracho R, Elberling B, Knoblauch C, Lee H, Luo Y, Shaver GR, Turetsky MR (2014). *Global Change Biology,* 20, 641-652.

High-latitude ecosystems store approximately 1700 Pg of soil carbon, which is twice as much carbon as is currently contained in the atmosphere. Permafrost thaw and subsequent microbial decomposition of permafrost organic matter could add large amounts of carbon to the atmosphere, thereby influencing the global carbon cycle. The rates at which carbon is being released from the permafrost zone at different soil depths and across different physiographic regions are poorly understood but crucial in understanding future changes in permafrost carbon storage with climate change. We assessed the inherent decomposability of carbon from the permafrost zone by assembling a database of long-term (>1 year) aerobic soil incubations from 121 individual samples from 23 high-latitude ecosystems located across the northern circumpolar permafrost zone. Using a three-pool (i.e., fast, slow and passive) decomposition model, we estimated pool sizes for carbon fractions with different turnover times and their inherent decomposition rates using a reference temperature of 5 °C. Fast cycling C accounted for less than 5% of all carbon in both organic and mineral soils whereas the pool size of slow cycling carbon increased with C carbon : nitrogen. Turnover time at 5 ° carbon of fast cycling carbon typically was below 1 year, between 5 and 15 years for slow turning over carbon, and more than 500 years for passive carbon. We project that between 20 and 90% of the organic carbon could potentially be mineralized to CO_2 within 50 incubation years at a constant temperature of 5 °C, with vulnerability to loss increasing in soils with higher carbon : nitrogen. These results demonstrate the variation in the vulnerability of carbon stored in permafrost soils based on inherent differences in organic matter decomposability, and point toward carbon : nitrogen as an index of decomposability that has the potential to be used to scale permafrost carbon loss across landscapes.



Carbon loss (in percentage of initial carbon) in relation to initial Carbon : Nitrogen of total soil carbon after (a) 1 year of incubation, (b) 10 years of incubation and (c) 50 years of incubation; all at a constant incubation temperature of 5 °C. Carbon loss beyond the incubation period of at least 1 year represents potential carbon loss. Lines show the predicted relationship between carbon loss and initial Carbon : Nitrogen of total soil carbon.

How do environmental and ecological drivers affect CH_4 and anaerobic CO_2 production from soils of the permafrost region?

Maximum CH_4 and median anaerobic CO_2 production decreased with depth, while CO_2 to CH_4 production increased with depth. Maximum CH_4 production was highest in soils with herbaceous vegetation and soils that were either consistently or periodically inundated.

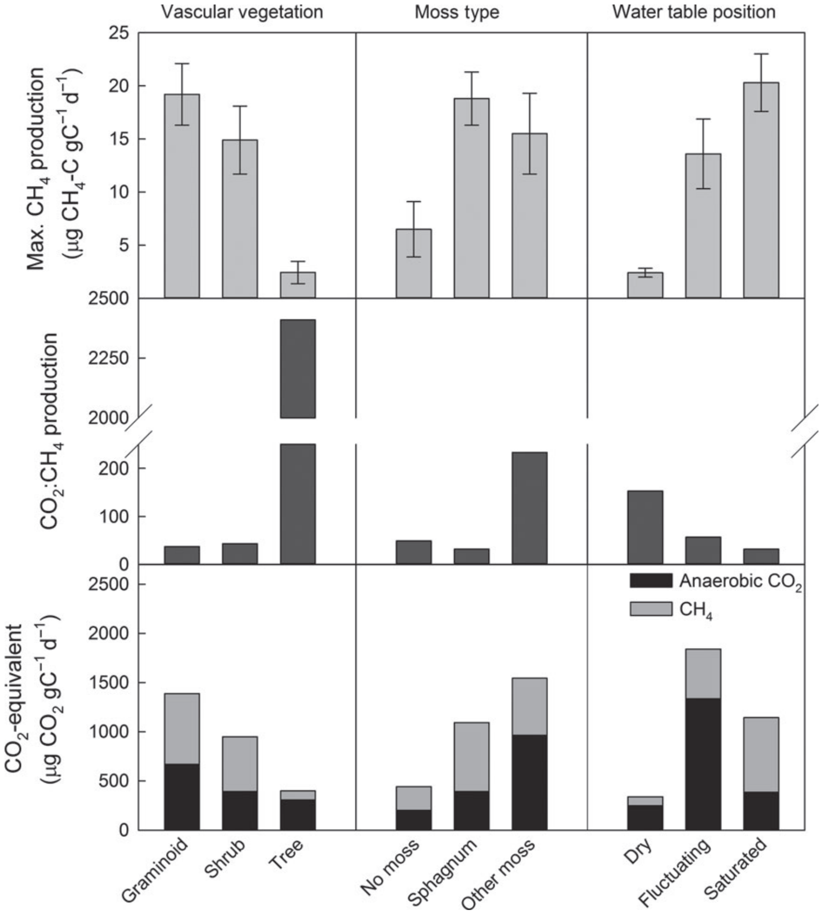
Ice lens and lenticular soil structure in organic layer of polygonated tundra, Arctic Coastal Plain. Photo: Marguerite Mauritz

Full-page: *Eriophorum vaginatum*. Photo: Christina Schädel

A PAN-ARCTIC SYNTHESIS OF CH_4 AND CO_2 PRODUCTION FROM ANOXIC SOIL INCUBATIONS

Treat CC, Natali SM, Ernakovich J, Iversen CM, Lupascu M, McGuire AD, Norby RJ, Roy Chowdhury T, Richter A, Šantrůčková H, Schädel C, Schuur EAG, Sloan VL, Turetsky MR, Waldrop MP (2015). *Global Change Biology,* 21, 2787-2803.

Permafrost thaw can alter the soil environment through changes in soil moisture, frequently resulting in soil saturation, a shift to anaerobic decomposition, and changes in the plant community. These changes, along with thawing of previously frozen organic material, can alter the form and magnitude of greenhouse gas production from permafrost ecosystems. We synthesized existing methane (CH_4) and carbon dioxide (CO_2) production measurements from anaerobic incubations of boreal and tundra soils from the geographic permafrost region to evaluate large-scale controls of anaerobic CO_2 and CH_4 production and compare the relative importance of landscape-level factors (e.g., vegetation type and landscape position), soil properties (e.g., pH, depth, and soil type), and soil environmental conditions (e.g., temperature and relative water table position). We found fivefold higher maximum CH_4 production per gram soil carbon from organic soils than mineral soils. Maximum CH_4 production from soils in the active layer (ground that thaws and refreezes annually) was nearly four times that of permafrost per gram soil carbon, and CH_4 production per gram soil carbon was two times greater from sites without permafrost than sites with permafrost. Maximum CH_4 and median anaerobic CO_2 production decreased with depth, while CH_4 production increased with depth. Maximum CH_4 production was highest in soils with herbaceous vegetation and soils that were either consistently or periodically inundated. This synthesis identifies the need to consider biome, landscape position, and vascular/moss vegetation types when modeling CH_4 production in permafrost ecosystems and suggests the need for longer-term anaerobic incubations to fully capture CH_4 dynamics. Our results demonstrate that as climate warms in arctic and boreal regions, rates of anaerobic CO_2 and CH_4 production will increase, not only as a result of increased temperature, but also from shifts in vegetation and increased ground saturation that will accompany permafrost thaw.

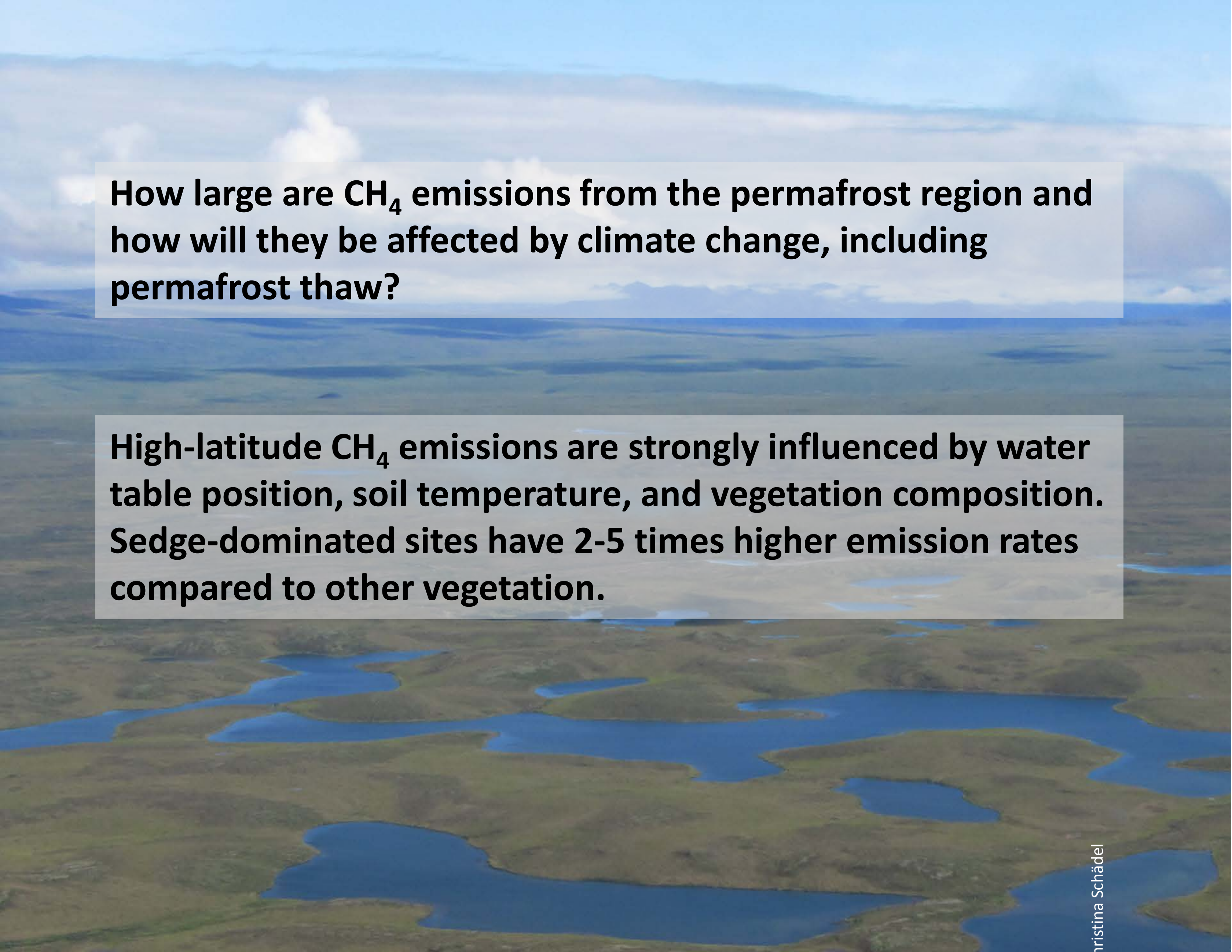


Maximum CH_4 production (a–c), median anaerobic CO_2:CH_4 production ratio (d–f), and CO_2 equivalent (CO_2e) (g–i) differed significantly between vascular plant type (left), moss type (center), and water table status (right). Error bars represent standard error. CO_2e calculated using a GWP of 28 kg CO_2 equivalents kg 1 CH_4 and a 100-year time horizon (Myhre et al., 2013).

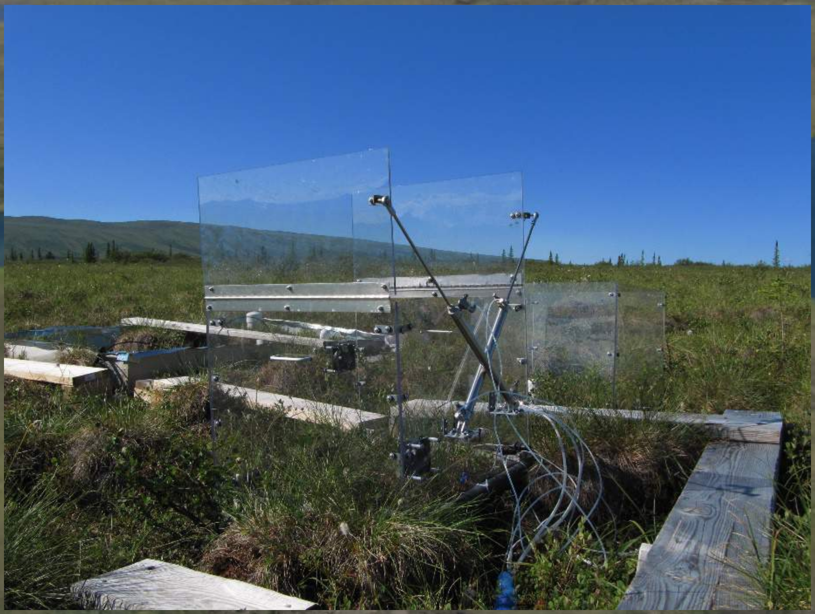
Drunken trees, Alaska. Photo: Claire Treat

How large are CH_4 emissions from the permafrost region and how will they be affected by climate change, including permafrost thaw?

High-latitude CH_4 emissions are strongly influenced by water table position, soil temperature, and vegetation composition. Sedge-dominated sites have 2-5 times higher emission rates compared to other vegetation.



Full-page: Thermokarst lakes, North Slope Alaska. Photo: Christina Schädel

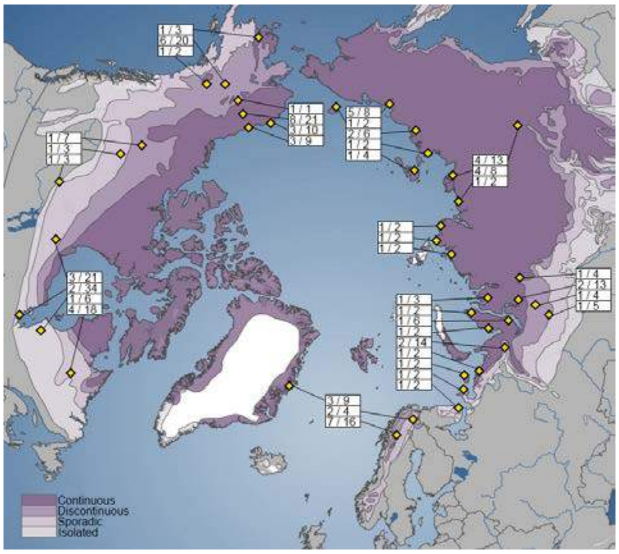


Gas flux chamber. Photo: Christina Schädel

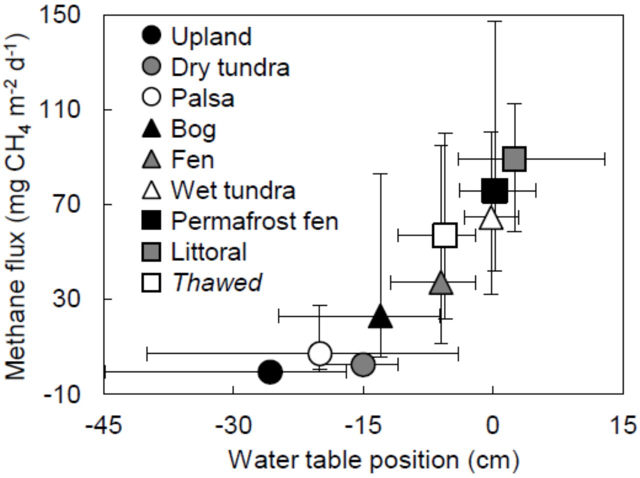
ENVIRONMENTAL AND PHYSICAL CONTROLS ON NORTHERN TERRESTRIAL METHANE EMISSIONS ACROSS PERMAFROST ZONES

Olefeldt D, Turetsky MR, Crill PM, McGuire AD (2013). *Global Change Biology,* 19, 589-603.

Methane (CH4) emissions from the northern high-latitude region represent potentially significant biogeochemical feedbacks to the climate system. We compiled a database of growing-season CH4 emissions from terrestrial ecosystems located across permafrost zones, including 303 sites described in 65 studies. Data on environmental and physical variables, including permafrost conditions, were used to assess controls on CH4 emissions. Water table position, soil temperature, and vegetation composition strongly influenced emissions and had interacting effects. Sites with a dense sedge cover had higher emissions than other sites at comparable water table positions, and this was an effect that was more pronounced at low soil temperatures. Sensitivity analysis suggested that CH4 emissions from ecosystems where the water table on average is at or above the soil surface (wet tundra, fen underlain by permafrost, and littoral ecosystems) are more sensitive to variability in soil temperature than drier ecosystems (palsa dry tundra, bog, and fen), whereas the latter ecosystems conversely are relatively more sensitive to changes of the water table position. Sites with near-surface permafrost had lower CH4 fluxes than sites without permafrost at comparable water table positions, a difference that was explained by lower soil temperatures. Neither the active layer depth nor the organic soil layer depth was related to CH4 emissions. Permafrost thaw in lowland regions is often associated with increased soil moisture, higher soil temperatures, and increased sedge cover. In our database, lowland thermokarst sites generally had higher emissions than adjacent sites with intact permafrost, but emissions from thermokarst sites were not statistically higher than emissions from permafrost-free sites with comparable environmental conditions. Overall, these results suggest that future changes to terrestrial high-latitude CH4 emissions will be more proximately related to changes in moisture, soil temperature, and vegetation composition than to increased availability of organic matter following permafrost thaw.



Map of permafrost zones with study locations indicated by diamonds. First number in boxes indicates how many studies from each location are included in our database, and the second number indicates how many sites these studies contributed. Shadings indicate permafrost zones, using delineations from Brown et al. (1998).



Relationship between median CH4 flux and median water table position for sites within each ecosystem. Whiskers represent 25th and 75th percentiles for both methane fluxes and water table position. The Thawed category does not represent a unique set of sites, but contains sites from the other ecosystem types that were described as thermokarst landforms that recently experienced complete near-surface permafrost thaw.

SYNTHESES IN PROGRESS

The citations on this page are select papers in review, in revision or in press that were prepared with considerable contribution by members of the Permafrost Carbon Network. There are many more publications in preparation, regular updates are provided on the website: http://www.permafrostcarbon.org/publications.html

Abbott BW, Jones BM, Schuur EAG, Chapin III FS, Bowden WB, Bret-Harte MS, Epstein H, Flannigan MD, Harms TK, Hollingsworth TN, Mack MC, McGuire AD, Natali SM, Rocha AV, Tank SE, Turetsky MR, Vonk JE, Wickland KP, Aiken GR, Alexander HD, Amon RMW, Benscoter BW, Bergeron Y, Bishop K, Blarquez O, Bond-Lamberty B, Breen AL, Buffam I, Cai Y, Carcaillet C, Carey SK, Chen JM, Chen H, Christensen TR, Cooper LW, Cornelissen JHC, de Groot WJ, DeLuca TH, Dorrepaal E, Fetcher N, Finlay JC, Forbes BC, French NHF, Gauthier S, Girardin MP, Goetz SJ, Goldammer JG, Gough L, Grogan P, Guo L, Higuera PE, Hinzman L, Hu FS, Hugelius G, Jafarov EE, Jandt RR, Johnston JF, Karlsson J, Kasischke ES, Kattner G, Kelly J, Keuper F, Kling GW, Kortelainen PL, Kouki J, Kuhry P, Laudon H, Laurion I, Macdonald RW, Mann PJ, Martikainen PJ, McClelland JW, Molau U, Oberbauer SF, Olefeldt D, Paré D, Parisien M-A, Payette S, Peng C, Pokrovsky OS, Rastetter EB, Raymond PA, Raynolds MK, Rein G, Reynolds JF, Robards M, Rogers BM, Schädel C, Schaefer K, Schmidt IK, Shvidenko A, Sky J, Spencer RGM, Striegl RG, Tank SE, Teisserenc R, Tranvik LJ, Virtanen T, Welker JM, Zimov S *(in review)* Biomass offsets little or none of permafrost carbon release from soils, streams, and wildfire. An expert assessment.

Olefeldt D, Goswami S, Grosse G, Hayes D, Hugelius G, Kuhry P, McGuire AD, Romanovsky VE, Sannel ABK, Schuur E, Turetsky M (*in review*) Thermokarst terrain: circumpolar distribution and soil carbon vulnerability.

Schädel C, Bader MKF, Schuur EAG, Bracho R, Capek P, De Baets S, Diakova K, Ernakovich J, Estop-Aragones C, Graham DE, Hartley IP, Iversen CM, Kane ES, Knoblauch C, Lupascu M, Natali SM, Norby RJ, O'Donnell JA, Roy Chowdhury T, Santruckova H, Shaver G, Sloan VL, Treat CC, Turetsky MR, Waldrop M, Wickland KP (*in revision*) Potential carbon emissions dominated by carbon dioxide from thawed permafrost soils.

Vonk JE, Tank SE, Bowden WB, Laurion I, Vincent WF, Alekseychik P, Amyot M, Billet MF, Canário J, Cory RM, Deshpande BN, Helbig M, Jammet M, Karlsson J, Larouche J, MacMillan G, M. R, Walter Anthony KM, Wickland KP (*in revision*) Effects of permafrost thaw on arctic aquatic ecosystems.

Wik M, Varner RK, Walter Anthony K, Macintyre S, Bastviken D (*in press*) Northern methane release dominated by climate sensitive lake and pond source.

Alaska Range, Alaska. Photo: Christina Schädel

MEETINGS

We have organized a series of meetings and workshops (co-sponsored by Climate and Cryosphere, International Permafrost Association, International Arctic Science Committee, U.S. Geological Survey, and Department of Energy) to bring together leading network participants spanning various stages of career levels. Those meetings are used to design and present progress of individual synthesis products, link findings of products from individual working groups into cross-group synthesis activities, and to discuss missing gaps and future opportunities. Our lead and co-lead meetings have taken place in: Seattle, WA, June 2011, St Pete Beach, FL, May 2012, Captiva Island, FL, May 2013, Stockholm, Sweden, May 2014, Flagstaff, AZ, May 2015.

Every year before the Fall Meeting of the American Geophysical Union in San Francisco, CA, we hold the Annual Meeting of the Permafrost Carbon Network, which is a one-day meeting open to all interested members.

Leads and co-leads, Stockholm, Sweden 2014

Leads and co-leads, Flagstaff, AZ 2015

INVOLVEMENT OF EARLY CAREER SCIENTISTS

The Permafrost Carbon Network is highly engaged in training early career scientists and we have engaged multiple junior scientists from various institutions and countries to work with more senior scientists by leading a synthesis activity thereby offering key training and exposure to early career scientists. This pairing is a structural feature of the Permafrost Carbon Network and serves to integrate new researchers into science synthesis.

Benjamin Abbott
Post-Doc
Université de Rennes

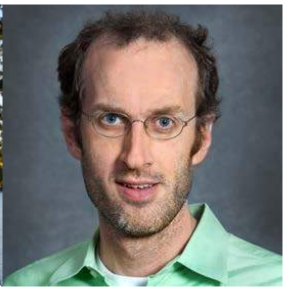
Cristian Estop-Aragones
Post-Doc
University of Alberta

Jennifer Frederick
Staff Scientist
Sandia National Lab

Guido Grosse
Research Scientist
AWI Potsdam

Dan Hayes
Assistant Professor
University of Maine

Gustaf Hugelius
Researcher
Stockholm University



Charles Koven
Research Scientist
Lawrence Berkeley Lab

Mike Loranty
Assistant Professor
Colgate University

Umakant Mishra
Staff Scientist
Argonne National Lab

Sue Natali
Assistant Scientist
Woods Hole Research Center

David Olefeldt
Assistant Profesor
University of Alberta

Britta Sannel
Lecturer
Stockholm University

Christina Schädel
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Northern Arizona University

Jens Strauss
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AWI Potsdam

Claire Treat
Post-Doc
USGS Menlo Park

Jorien Vonk
Researcher
Utrecht University

Martin Wik
PhD student
Stockholm University

SCIENTIFIC OUTREACH AND ENGAGEMENT

The Permafrost Carbon Network is an open network encouraging interested scientists to participate in all ongoing synthesis activities. Members of the steering committee have given numerous presentations at national and international conference presenting activities and results from synthesis activities of the Permafrost Carbon Network. A broad scientific audience is being reached by organizing permafrost focused sessions at national and international research conferences. Over the last five years, the Permafrost Carbon Network has organized ten different sessions and will continue hosting sessions at upcoming conferences. Steering committee members were also part of a special issue on permafrost in a warming world in Environmental Research Letter.

SESSION ORGANIZATION:

American Geophysical Union 2011-2015, San Francisco, CA, USA
Vulnerability of Permafrost Carbon to Climate Change

European Geosciences Union 2012-2014, Vienna, Austria
Assessing the effects of global warming on permafrost degradation - contributions from field studies, remote sensing and modelling

Our Common Future under Climate Change 2015, Paris, France
Biogeochemical Feedbacks to Climate Change

XI. International Conference on Permafrost 2016, Potsdam, Germany
Climate Change and the Permafrost Carbon Feedback: Past, Present and Future

GUEST EDITORS FOR SPECIAL ISSUE:

Focus on Changing Permafrost in a Warming World: Observation and Implication
Environmental Research Letters: Published papers: 25+

Guest Editors:
Edward AG Schuur, Guido Grosse, A. David McGuire, Vladimir Romanovsky, Scott Goetz

FROSTBYTES:

Early career scientists that were sponsored by Climate and Cryosphere to attend a lead and co-lead workshop have prepared ‘FrostBytes’, a so called soundbites of cool research. They can be viewed here: http://www.climate-cryosphere.org/categories/138-frostbytes

- Vulnerability of permafrost carbon to climate change *by Christina Schädel*
- Mapping thermokarst pre-disposition at the pan-arctic scale *by David Olefeldt*
- Methane Exchange within permafrost landscapes-contribution of lakes *by Martin Wik*
- Permafrost carbon on its journey from land-to-ocean *by Jorien Vonk*
- Thermokarst lake dynamics in permafrost peatlands during recent decades *by Britta Sannel*
- Permafrost carbon and climate change *by Sue Natali*
- Detecting permafrost aggradation in peatland ecosystems to understand the effects of climate *by Claire Treat*
- Organic carbon stocks in ice-rich permafrost of the Yedoma region *by Jens Strauss*
- Permafrost sub-system in the Earth’s eco-climate system *by Kazuyuki Saito*

PUBLIC ENGAGEMENT

As part of our outreach activities, members of the steering committee and the entire Permafrost Carbon Network have given input to many press releases, interviews and have written articles and blog posts for a broad audience. News articles have appeared in news services such as *The Washington Post, The New York Times, The Globe and Mail, Sydney Morning Herald, The Guardian, Science Magazine, Daily Californian, The Economist, The Alaskan Dispatch News* and many more. The items listed below are an extract only of public engagement activities related to Permafrost Carbon Network activities.

PRESS RELEASES:

Climate Change: High risk of permafrost thaw
> 18 news articles and blog posts

Climate Change and the Permafrost Carbon Feedback:
> 71 news articles published

A simplified, data-constrained approach to estimate the permafrost carbon-climate feedback:
6 news articles published

INTERVIEWS (2015 ONLY):

Atlantic Magazine:
In Alaska, Too Many Fires, Not Enough Snow

National Public Radio:
Beneath Alaskan Wildfires, A Hidden Threat: Long-Frozen Carbon's Thaw

Washington Post:
Alaska's Terrifying Wildfire Season and What it Says About Climate Change

BBC:
Permafrost Warming in Parts of Alaska 'Is Accelerating'. Oct 2015

Daily Californian:
Berkeley Lab scientists create model to map permafrost carbon, climate feedback

ARTICLES AND BLOGPOSTS

Frozen Ground
Research coordination network on the vulnerability of permafrost carbon, 2011;
Short communication on network related activities: research coordination network on the vulnerability of permafrost carbon, 2013

The Carbon Brief:
What the latest science says about thawing permafrost, 2015

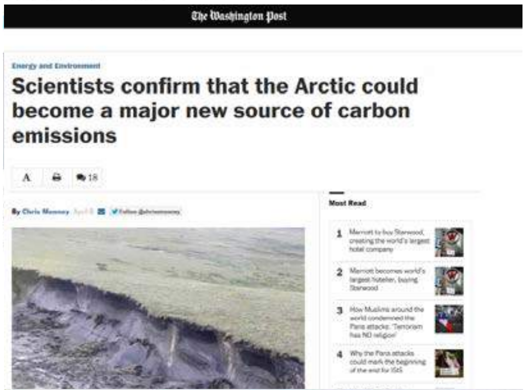
World Wildlife Foundation.
The Circle. Permafrost carbon and climate change, 2015.

Witness the Arctic:
Sensitivity of tundra carbon balance to warming and permafrost thaw

News > Climate > Ticking Arctic Carbon Bomb May Be Bigger Than Thought

LATEST NEWS

Ticking Arctic Carbon Bomb May Be Bigger Than Thought



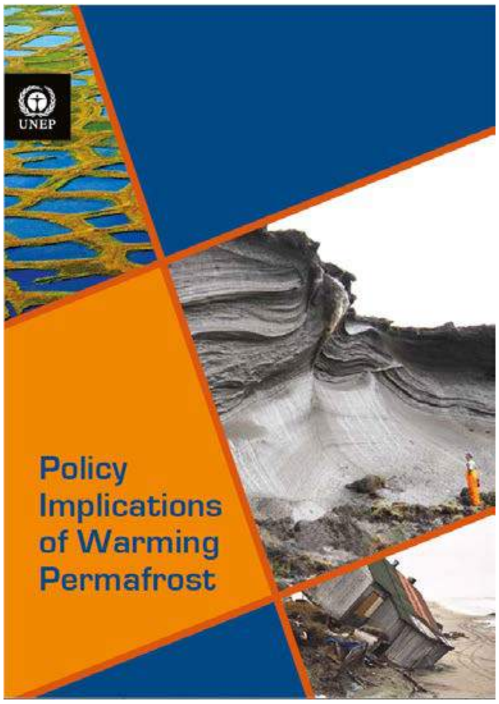
Scientists confirm that the Arctic could become a major new source of carbon emissions

In Alaska: Too Many Fires, Not Enough Snow

The state nearly set a record for number of acres burned this year, while the Iditarod once more had to be moved north.

DECISION MAKER SUPPORT

The Permafrost Carbon Network has been very active in reaching out to the public, the scientific community and also to decision makers. Over the last five years, members of the steering committee have contributed to multiple reports such as 'Policy Implications of Warming Permafrost' (report published by United Nations Environment Program in November 2012) and have participated in the 'Climate Science Day' on Capitol Hill (2013), which was organized by the American Geophysical Union to develop ongoing relationships between policy makers and scientists.



NATIONAL AND INTERNATIONAL SYNTHESIS SCIENCE REPORTS:

The report '**Policy Implications of Warming Permafrost**' has been written in a way to inform a broad audience about permafrost and to communicate to decision-makers and the general public the implications of changing permafrost in a warming climate. The report can be downloaded as a pdf:
http://www.unep.org/pdf/permafrost.pdf

Other reports involving contributions by members of the Permafrost Carbon Network include:

Snow, Ice, Water, and Permafrost in the Arctic (SWIPA), prepared by the Arctic Monitoring and Assessment Program, Arctic Council.

The State of the Carbon Cycle Report (SOCCR), released as a U.S. Climate Change Science Program Synthesis and Assessment Product

International Panel on Climate Change (IPCC), Working Group I – Chapter 6 Carbon

BRIEFING REPORTS:

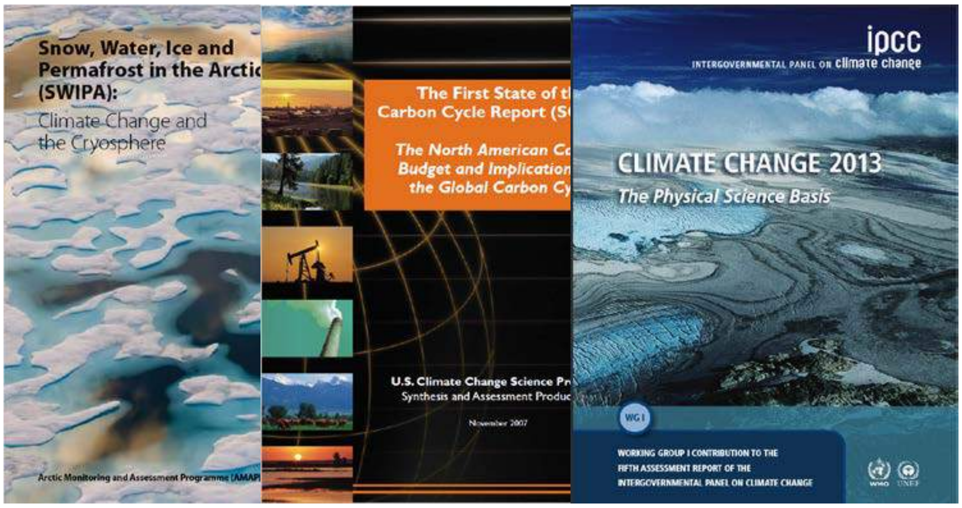
International Permafrost Association (IPA) – Study of Environmental Arctic Change and the Permafrost Carbon Network

National Academies Polar Research Board – Rapid Change at the Poles

Interagency Arctic Research Policy Committee (IARPC) – Permafrost Carbon Research Coordination Network Progress on Milestone 3.2.3

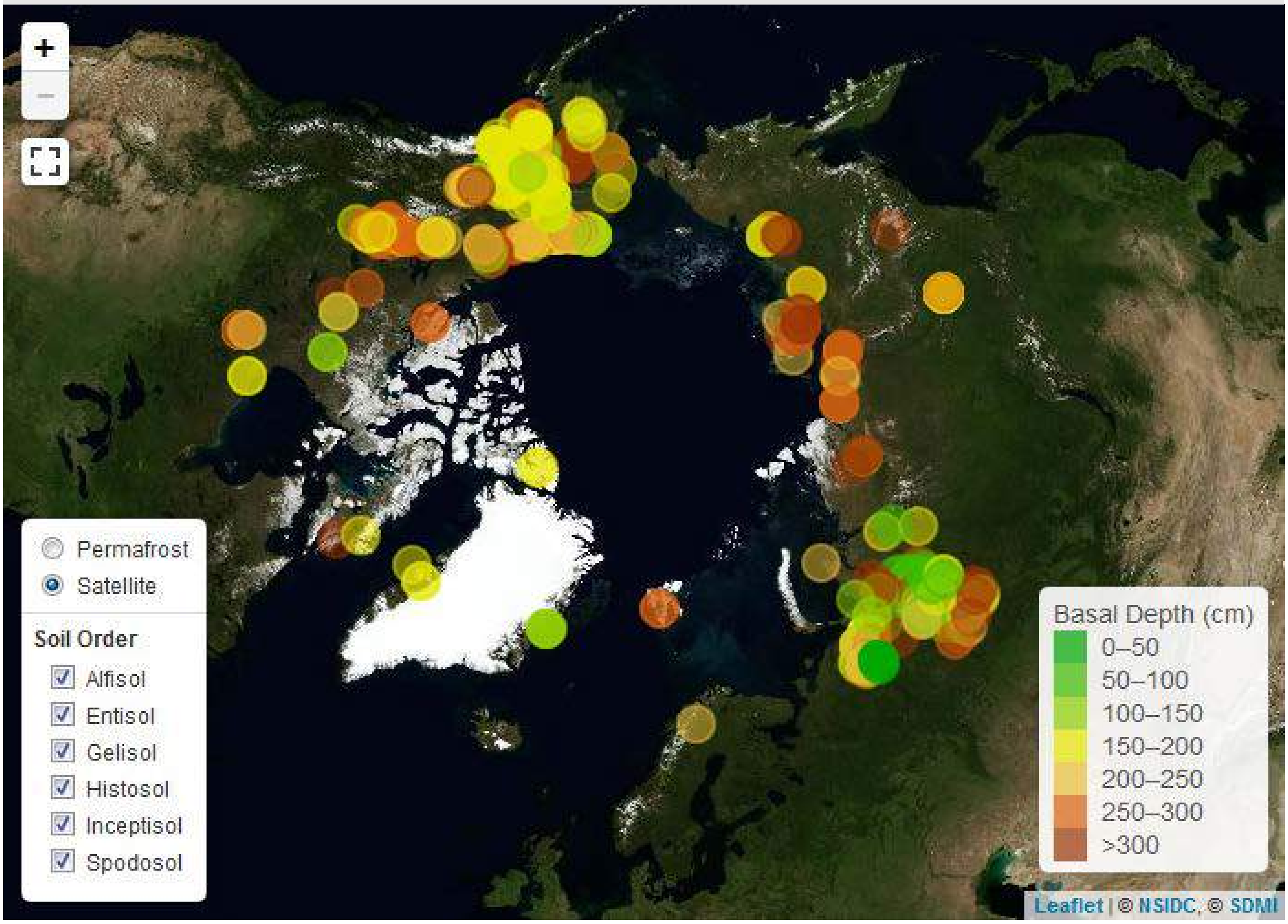
OTHER DECISION MAKER SUPPORT

Material provided to U.S. Global Change Research Program (USGCRP) and State Department in Advance of President Obama's presentation at the GLACIER conference
https://www.whitehouse.gov/2015-alaska-trip?sid=123

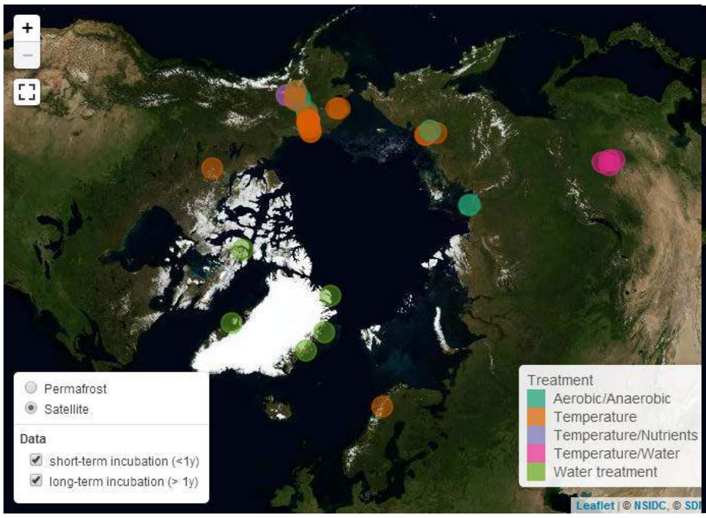


DATA VISUALIZATION

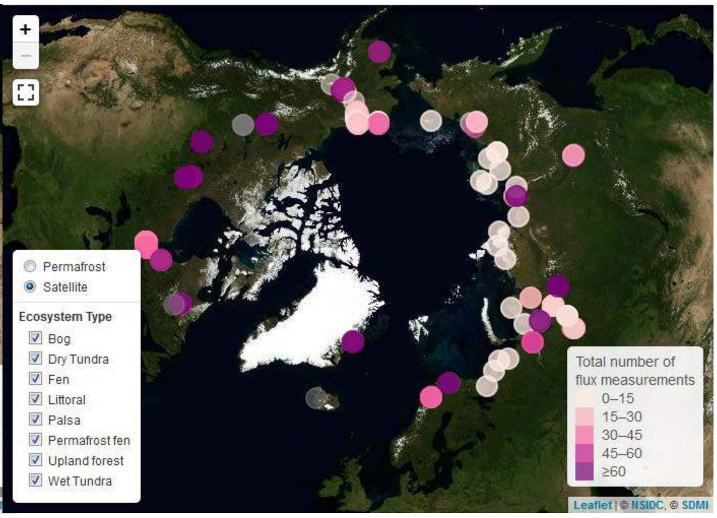
Sampling sites and measurement locations for various syntheses are available on the website of the Permafrost Carbon Network and allow any user to find more detailed information for one specific sampling site or soil core. http://www.permafrostcarbon.org/maps.html



Sampling sites for soil pedons of the northern circumpolar permafrost region.



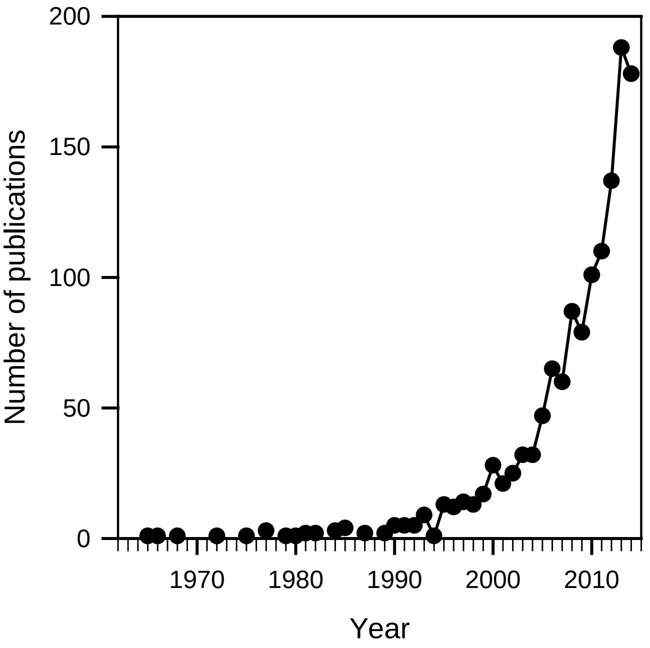
Study locations for incubated soil samples as used in Schädel et al. 2014



Study locations for CH_4 measurements as featured in Olefeldt et al. 2013

PUBLICATIONS

Publications including the terms ‘permafrost and carbon’ have dramatically increased over the last 20 years. Here is a list of publications (incomprehensive) on the topic of permafrost and carbon that are related to activities of the Permafrost Carbon Network (starting in 2011).



Number of citations per year at Web of Science (ISI) with the search terms “permafrost and carbon" in full text. (Schädel, Pegoraro, Schuur 2014)

2011 and earlier

Euskirchen ES, McGuire AD, Kicklighter DW *et al.*(2006) Importance of recent shifts in soil thermal dynamics on growing season length, productivity, and carbon sequestration in terrestrial high-latitude ecosystems. *Global Change Biology,* 12, 731-750. doi:10.1111/j.1365-2486.2006.01113.x

Grosse G, Harden J, Turetsky M *et al.* (2011) Vulnerability of high-latitude soil organic carbon in North America to disturbance. *Journal of Geophysical Research-Biogeosciences,* 116. doi:10.1029/2010jg001507

Hugelius G, Virtanen T, Kaverin D *et al.* (2011) High-resolution mapping of ecosystem carbon storage and potential effects of permafrost thaw in periglacial terrain, European Russian Arctic. *Journal of Geophysical Research-Biogeosciences,* 116. doi:10.1029/2010JG001606

Jorgenson MT, Shur YL, Pullman ER (2006) Abrupt increase in permafrost degradation in Arctic Alaska. *Geophysical Research Letters,* 33. doi:10.1029/2005gl024960

Koven CD, Ringeval B, Friedlingstein P *et al.* (2011) Permafrost carbon-climate feedbacks accelerate global warming. *Proceedings of the National Academy of Sciences,* 108, 14769-14774. doi:10.1073/pnas.1103910108

Lawrence DM, Slater AG, Romanovsky VE, Nicolsky DJ (2008) Sensitivity of a model projection of near-surface permafrost degradation to soil column depth and representation of soil organic matter. *Journal of Geophysical Research-Earth Surface,* 113. doi: 10.1029/2007jf000883

McGuire AD, Hayes DJ, Kicklighter DW *et al.* (2010a) An analysis of the carbon balance of the Arctic Basin from 1997 to 2006. *Tellus Series B-Chemical and Physical Meteorology,* 62, 455-474. doi:10.1111/j.1600-0889.2010.00497.x

McGuire AD, Macdonald RW, Schuur EAG *et al.* (2010b) The carbon budget of the northern cryosphere region. *Current Opinion in Environmental Sustainability,* 2, 231-236. doi:10.1016/j.cosust.2010.05.003

Michaelson GJ, Ping CL (2003) Soil organic carbon and CO2 respiration at subzero temperature in soils of Arctic Alaska. *Journal of Geophysical Research-Atmospheres,* 108. doi:10.1029/2001jd000920

Osterkamp TE (2007) Characteristics of the recent warming of permafrost in Alaska. *Journal of Geophysical Research-Earth Surface,* 112. doi:10.1029/2006JF000578

Ping C-L, Michaelson GJ, Jorgenson MT *et al.* (2008) High stocks of soil organic carbon in the North American Arctic region. *Nature Geoscience,* 1, 615-619. doi:10.1038/ ngeo284

Schaefer K, Zhang T, Bruhwiler L, Barrett AP (2011) Amount and timing of permafrost carbon release in response to climate warming. *Tellus Series B-Chemical and Physical Meteorology,* 63, 165-180. doi:10.1111/j.1600-0889.2011. 00527.x

Schirrmeister L, Grosse G, Wetterich S *et al.* (2011) Fossil organic matter characteristics in permafrost deposits of the northeast Siberian Arctic. *Journal of Geophysical Research-Biogeosciences,* 116. doi: 10.1029/2011jg001647

Schirrmeister L, Siegert C, Kunitzky VV, Grootes PM, Erlenkeuser H (2002) Late Quaternary ice-rich permafrost sequences as a paleoenvironmental archive for the Laptev Sea Region in northern Siberia. *International Journal of Earth Sciences,* 91, 154-167. doi:10.1007/s005310100205

Schuur EAG, Bockheim J, Canadell JG *et al.* (2008) Vulnerability of permafrost carbon to climate change: Implications for the global carbon cycle. *Bioscience,* 58, 701-714. doi:10.1641/b580807

Schuur EAG, Vogel JG, Crummer KG *et al.* (2009) The effect of permafrost thaw on old carbon release and net carbon exchange from tundra. *Nature,* 459, 556-559. doi:10.1038/nature08031

Tarnocai C, Canadell JG, Schuur EAG *et al.* (2009) Soil organic carbon pools in the northern circumpolar permafrost region. *Global Biogeochemical Cycles,* 23. doi:10.1029/2008gb003327

Turetsky MR, Kane ES, Harden JW *et al.* (2011) Recent acceleration of biomass burning and carbon losses in Alaskan forests and peatlands. *Nature Geoscience,* 4, 27-31. doi:10.1038/ngeo1027

Walter KM, Zimov SA, Chanton JP, Verbyla D, Chapin FS, III (2006) Methane bubbling from Siberian thaw lakes as a positive feedback to climate warming. *Nature,* 443, 71-75. doi:10.1038/nature05040

Zhuang Q, Melillo JM, Sarofim MC *et al.* (2006) CO2 and CH4 exchanges between land ecosystems and the atmosphere in northern high latitudes over the 21st century. *Geophysical Research Letters,* 33. doi:10.1029/2006gl026972

Zimov SA, Schuur EAG, Chapin FS (2006) Permafrost and the global carbon budget. *Science,* 312, 1612-1613. doi:10.1126/science.1128908

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Anthony KMW, Anthony P, Grosse G, Chanton J (2012) Geologic methane seeps along boundaries of Arctic permafrost thaw and melting glaciers. *Nature Geoscience,* 5, 419-426. doi:10.1038/ngeo1480

Belshe EF, Schuur EAG, Bolker BM, Bracho R (2012) Incorporating spatial heterogeneity created by permafrost thaw into a landscape carbon estimate. *Journal of Geophysical Research-Biogeosciences,* 117. doi:10.1029/ 2011jg001836

Burke EJ, Hartley IP, Jones CD (2012) Uncertainties in the global temperature change caused by carbon release from permafrost thawing. *Cryosphere,* 6, 1063-1076. doi: 10.5194/tc-6-1063-2012

DeConto RM, Galeotti S, Pagani M *et al.* (2012) Past extreme warming events linked to massive carbon release from thawing permafrost. *Nature,* 484, 87-91. doi:10.1038/ nature10929

Gouttevin I, Menegoz M, Domine F *et al.* (2012) How the insulating properties of snow affect soil carbon distribution in the continental pan-Arctic area. *Journal of Geophysical Research-Biogeosciences,* 117. doi: 10.1029/2011JG001916

Harden JW, Koven CD, Ping C-L *et al.* (2012) Field information links permafrost carbon to physical vulnerabilities of thawing. *Geophysical Research Letters,* 39. doi:10.1029/2012gl051958

Hicks Pries CE, Schuur EAG, Crummer KG (2012) Holocene Carbon Stocks and Carbon Accumulation Rates Altered in Soils Undergoing Permafrost Thaw. *Ecosystems,* 15, 162-173. doi: 10.1007/s10021-011-9500-4

Hugelius G (2012) Spatial upscaling using thematic maps: An analysis of uncertainties in permafrost soil carbon estimates. *Global Biogeochem. Cycles,* 26, GB2026. doi: 10.1029/2011GB004154

Hugelius G, Routh J, Kuhry P, Crill P (2012) Mapping the degree of decomposition and thaw remobilization potential of soil organic matter in discontinuous permafrost terrain. *Journal of Geophysical Research-Biogeosciences,* 117. doi:10.1029/2011jg001873

Jones MC, Grosse G, Jones BM, Walter Anthony K (2012) Peat accumulation in drained thermokarst lake basins in continuous, ice-rich permafrost, northern Seward Peninsula, Alaska. *J. Geophys. Res.,* 117, G00M07. doi:10.1029/2011jg001766

Lee H, Schuur EAG, Inglett KS, Lavoie M, Chanton JP (2012) The rate of permafrost carbon release under aerobic and anaerobic conditions and its potential effects on climate. *Global Change Biology,* 18, 515-527. doi: 10.1111/j.1365-2486.2011.02519.x

MacDougall AH, Avis CA, Weaver AJ (2012) Significant contribution to climate warming from the permafrost carbon feedback. *Nature Geoscience,* 5, 719-721. doi:10.1038/ngeo1573

Mishra U, Riley WJ (2012) Alaskan soil carbon stocks: spatial variability and dependence on environmental factors. *Biogeosciences,* **9**, 3637-3645. doi:10.5194/bg-9-3637-2012

Natali SM, Schuur EAG, Rubin RL (2012) Increased plant productivity in Alaskan tundra as a result of experimental warming of soil and permafrost. *Journal of Ecology,* 100, 488-498. doi: 10.1111/j.1365-2745.2011.01925.x

Olefeldt D, Roulet NT, Bergeron O *et al.* (2012) Net carbon accumulation of a high-latitude permafrost palsa mire similar to permafrost-free peatlands. *Geophys. Res. Lett.,* 39, L03501. doi: 10.1029/ 2011GL050355

Olefeldt, D. & Roulet, N. T. Effects of permafrost and hydrology on the composition and transport of dissolved organic carbon in a subarctic peatland complex. *J. Geophys. Res.* 117, G01005, (2012). doi: 10.1029/2011JG001819

Schneider von Deimling T, Meinshausen M, Levermann A, *et al.* (2012) Estimating the near-surface permafrost-carbon feedback on global warming. *Biogeosciences,* 9, 649-665. doi:10.5194/bg-9-649-2012

Strauss J, Schirrmeister L, Wetterich S, Borchers A, Davydov SP (2012) Grain-size properties and organic-carbon stock of Yedoma Ice Complex permafrost from the Kolyma lowland, northeastern Siberia. *Global Biogeochemical Cycles,* 26. doi:10.1029/2011gb004104

Trucco C, Schuur EAG, Natali *SM et al.* (2012) Seven-year trends of CO2 exchange in a tundra ecosystem affected by long-term permafrost thaw. *Journal of Geophysical Research: Biogeosciences,* 117, G02031. doi: 10.1029/ 2011JG001907

Vonk JE, Alling V, Rahm L *et al.* (2012a) A centennial record of fluvial organic matter input from the discontinuous permafrost catchment of Lake Tornetrask. *Journal of Geophysical Research-Biogeosciences,* 117. doi:10.1029/ 2011JG001887

Vonk JE, Sanchez-Garcia L, van Dongen BE *et al.* (2012b) Activation of old carbon by erosion of coastal and subsea permafrost in Arctic Siberia. *Nature,* 489, 137-140. doi:10.1038/nature11392

2013

Belshe EF, Schuur EAG, Bolker BM (2013a) Tundra ecosystems observed to be CO2 sources due to differential amplification of the carbon cycle. *Ecology Letters*, doi:10.1111/ele.12164

Belshe EF, Schuur EAG, Grosse G (2013b) Quantification of upland thermokarst features with high resolution remote sensing. *Environmental Research Letters,* 8, 3. 035016, doi:10.1088/1748-9326/8/3/035016

Burke EJ, Jones CD, Koven CD (2013) Estimating the permafrost-carbon climate response in the CMIP5 climate models using a simplified approach. *Journal of Climate,* 26, 14. 4897-4909, doi:10.1175/jcli-d-12-00550.1

Cory RM, Crump BC, Dobkowski JA, Kling GW (2013) Surface exposure to sunlight stimulates CO2 release from permafrost soil carbon in the Arctic. *Proceedings of the National Academy of Sciences*, doi: 10.1073/pnas.1214104110

Elberling B, Michelsen A, Schädel C *et al.* (2013) Long-term CO2 production following permafrost thaw. *Nature Clim. Change,* 3, 10. 890-894, doi: 10.1038/ nclimate1955

Feng X, Vonk JE, van Dongen BE *et al.* (2013) Differential mobilization of terrestrial carbon pools in Eurasian Arctic river basins. *Proceedings of the National Academy of Sciences of the United States of America,* 110, 35. 14168-14173, doi: 10.1073/pnas.1307031110

Grosse G, Robinson JE, Bryant R *et al.* (2013) Distribution of late Pleistocene ice-rich syngenetic permafrost of the Yedoma Suite in east and central Siberia, Russia. *U.S. Geological Survey Open File report,* 2013-1078, 37 pp.

Hicks Pries CE, Schuur EAG, Crummer KG (2013a) Thawing permafrost increases old soil and autotrophic respiration in tundra: Partitioning ecosystem respiration using δ13C and Δ14C. *Global Change Biology,* 19, 2. 649-661, doi: 10.1111/gcb.12058

Hicks Pries CE, Schuur EAG, Vogel JG, Natali SM (2013b) Moisture drives surface decomposition in thawing tundra. *Journal of Geophysical Research: Biogeosciences,* 118, 3. 1133-1143, doi: 10.1002/ jgrg.20089

Hugelius G, Tarnocai C, Broll G *et al.* (2013) The Northern Circumpolar Soil Carbon Database: spatially distributed datasets of soil coverage and soil carbon storage in the northern permafrost regions. *Earth System Science Data,* 5, 1. doi: 10.5194/essd-5-3-2013

Johnson KD, Harden JW, McGuire *AD et al.* (2013) Permafrost and organic layer interactions over a climate gradient in a discontinuous permafrost zone. *Environmental Research Letters,* 8, 3. 035028, doi:10.1088/1748-9326/8/3/035028

Jones BM, Breen AL, Gaglioti BV *et al.* (2013) Identification of unrecognized tundra fire events on the north slope of Alaska. *Journal of Geophysical Research-Biogeosciences,* 118, 3. 1334-1344, doi: 10.1002/jgrg.20113

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