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EDITORIAL

Changing permafrost in a warming world and feedbacks to the Earth system

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Abstract

The permafrost component of the cryosphere is changing dramatically, but the permafrost region is not well monitored and the consequences of change are not well understood. Changing permafrost interacts with ecosystems and climate on various spatial and temporal scales. The feedbacks resulting from these interactions range from local impacts on topography, hydrology, and biology to complex influences on global scale biogeochemical cycling. This review contributes to this focus issue by synthesizing its 28 multidisciplinary studies which provide field evidence, remote sensing observations, and modeling results on various scales. We synthesize study results from a diverse range of permafrost landscapes and ecosystems by reporting key observations and modeling outcomes for permafrost thaw dynamics, identifying feedbacks between permafrost and ecosystem processes, and highlighting biogeochemical feedbacks from permafrost thaw. We complete our synthesis by discussing the progress made, stressing remaining challenges and knowledge gaps, and providing an outlook on future needs and research opportunities in the study of permafrost–ecosystem–climate interactions.

1. Introduction

Permafrost regions, which cover about a quarter of the Northern Hemisphere land surface (Zhang *et al* 1999), are characterized by a mosaic of ecosystems shaped by very diverse landscapes and climate histories. Permafrost, defined by sub-zero ground temperatures for at least two consecutive years, consists of a highly diverse range of substrates with different geological backgrounds and depositional histories. In addition, observed and projected climate change is not uniform throughout the permafrost region and may result in the crossing of permafrost stability thresholds in high latitude ecosystems (Grosse *et al* 2011, Hinzman *et al* 2013). The combination of these complex permafrost-ecosystem-climate factors and interactions in a warming world will cause a broad range of successional trajectories in northern permafrost regions and affect the overall feedbacks and impacts of permafrost changes to the Earth system. While many of these impacts will be of predominantly local or regional nature, such as changing hydrology, vegetation, and topography, some may have far-reaching implications. In particular, the substantial frozen soil organic carbon pool in permafrost regions may cause climate impacts on global scales upon thaw and mobilization (Schuur *et al* 2015).

In recognition of this importance, permafrost has been added as an Essential Climate Variable (ECV) in the Global Climate Observing System (GCOS) of the World Meteorological Organization (WMO), which requires broad-scale research and systematic observations to support the Intergovernmental Panel on Climate Change (IPCC) and United Nations Framework Convention on Climate Change (UNFCC) in their assessments of the state of the global climate system and its variability. In addition, the United Nations Environmental Programme (UNEP) has supported the publication of a report highlighting the potential role of permafrost as a climate-shaping factor in a warming Arctic (Schaefer *et al* 2012).

A better understanding is required for permafrost characteristics, aspects of permafrost landscape dynamics, and the feedbacks from changing

Table 1. Research emphasis of all 28 studies within the focus issue on permafrost.

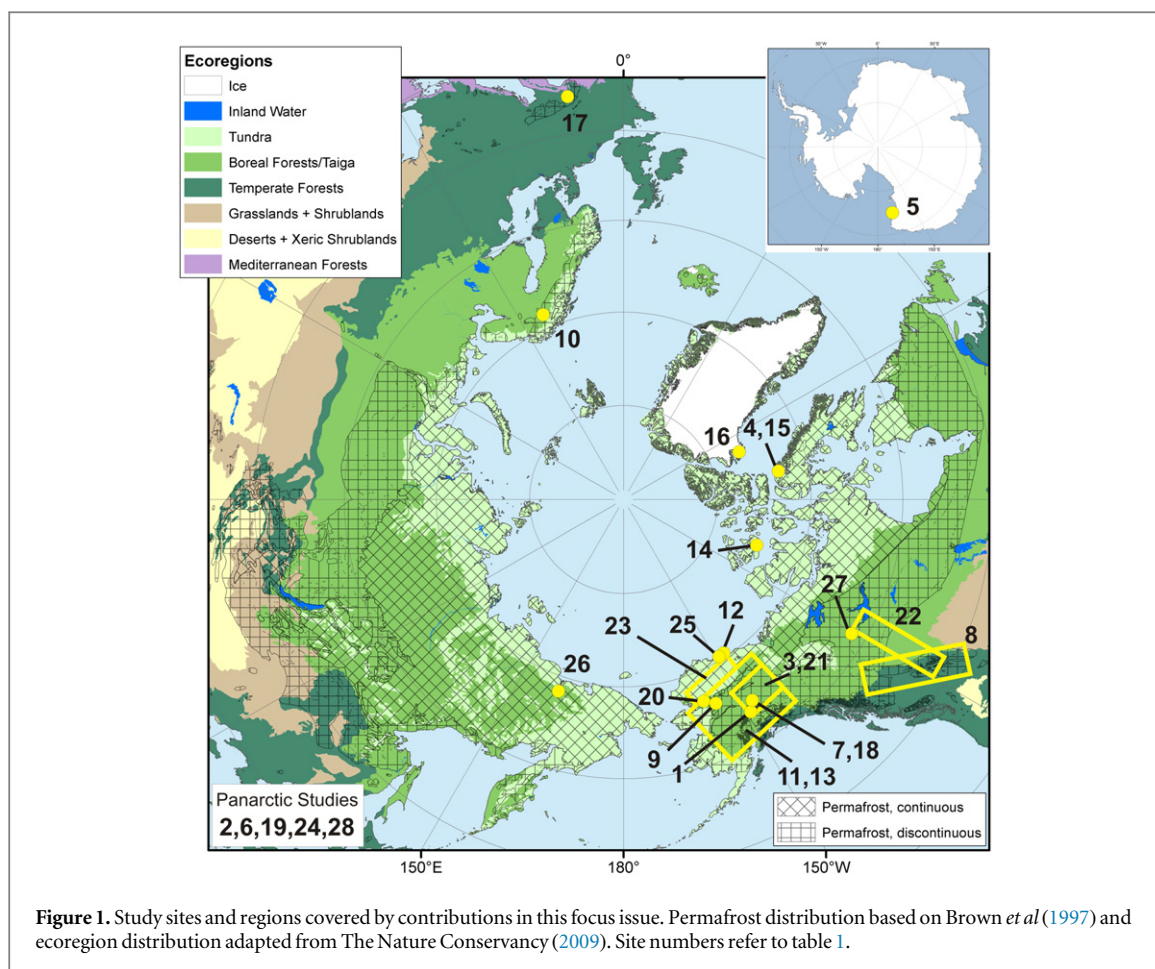| #	Study	Spatial scale[a]	Temporal scale[b]	Field study	Remote sensing	Numerical modeling	Main science fields[c]
1	Belshe *et al* (2013)	L	SN	X	X		GEO, SOIL
2	Gao *et al* (2013)	G	D			X	BGC
3	Genet *et al* (2013)	R	D			X	GEO, SOIL
4	Godin *et al* (2014)	L	A, D	X	X		HYD, GEO
5	Guglielmin *et al* (2014)	L	A	X			GEO, BIO
6	Hayes *et al* (2014)	G	S, D			X	BGC
7	Jafarov *et al* (2013)	L	S, D			X	GEO, SOIL
8	James *et al* (2013)	R	D	X			GEO
9	Jensen *et al* (2014)	L	S, A	X			GEO, SOIL, BGC
10	Johansson *et al* (2013)	L	A	X			GEO, SOIL, BIO
11	Johnson *et al* (2013)	R	SN			X	SOIL
12	Jones *et al* (2013)	R	A	X	X		GEO
13	Jorgenson *et al* (2013)	R	SN, D	X			GEO, HYD, SOIL, BIO
14	Lamoureux and Lafrenière (2014)	R	S	X			HYD, BGC
15	Laurion and Mladenov (2013)	L	S	X			HYD, BGC
16	Leffler and Welker (2013)	L	S, A	X			HYD, BGC
17	Marmy *et al* (2013)	L	S, D			X	GEO
18	McConnell *et al* (2013)	L	S	X			SOIL, BIO, BGC
19	Mishra *et al* (2013)	G	SN			X	SOIL
20	Necsoiu *et al* (2013)	R	D		X		HYD, GEO
21	Nossov *et al* (2013)	R	SN, S	X			SOIL, BIO, GEO
22	Olefeldt *et al* (2014)	R	SN	X			HYD, BGC
23	Pizano *et al* (2014)	R	D	X			BGC, SOIL, BIO
24	Schaefer *et al* (2014)	G	SN, D			X	BGC, POL
25	Tape *et al* (2013)	R	D	X	X		HYD, SOIL, BIO
26	Vonk *et al* (2013)	L	SN, S	X			HYD, BGC
27	Williams *et al* (2013)	L	S, D	X	X	X	GEO, HYD, POL
28	Zhu *et al* (2013)	G	D			X	BGC
	Total	12 × L 11 × R 5 × G	8 × SN 11 × S 6 × A 14 × D	18	6	10	14 × GEO, 12 × SOIL 10 × HYD, 7 × BIO 12 × BGC, 2 × POL

[a] L—local, R—regional, G—Panarctic/global.
[b] SN—snapshot, S—seasonal, A—multi-annual, D—multi-decadal.
[c] GEO—geophysics and geomorphology, SOIL—soil sciences, HYD—hydrology, BIO—biology, BGC—biogeochemistry, POL–policy.

permafrost that may act on local to global scales. It is important to use multi-disciplinary approaches on various scales and across research themes to develop a more complete understanding of ecosystem interactions in permafrost regions. This focus issue brings together 28 studies from a total of 129 individual authors covering diverse thematic perspectives on permafrost interactions with the Earth system. The studies envelop a wide range of spatial and temporal scales and they include field investigations, remote sensing approaches, and numerical modeling (table 1). The studies cover many of the important permafrost regions (Alaska, Canada, Northeast Siberia, and Antarctica) and settings and demonstrate the breadth of environmental diversity, as well as research approaches, in permafrost regions (figure 1). By bringing these studies together, this focus issue also offers insights into the complexity of environmental dynamics in permafrost regions and remaining knowledge gaps. The aim of our synthesis is to provide an overview of the studies in this focus issue and to place their findings in a broader context of permafrost–ecosystem–climate dynamics. Our overview is organized into three sections that focus on studies that were primarily relevant to (1) observations and modeling of permafrost thaw dynamics, (2) feedbacks between permafrost and ecosystem processes, and (3) biogeochemical feedbacks to the climate system from permafrost thaw. We then discuss the key collective advances made in each of these areas by the studies in this focus

Figure 1. Study sites and regions covered by contributions in this focus issue. Permafrost distribution based on Brown *et al* (1997) and ecoregion distribution adapted from The Nature Conservancy (2009). Site numbers refer to table 1.

issue. Finally, we conclude by providing insights on remaining challenges ahead as well as an outlook on promising new approaches for regional scale assessments of how permafrost distribution and permafrost change affect ecosystem dynamics.

2. Observations and modeling of permafrost thaw dynamics

Permafrost thaw has been observed in most permafrost regions across the globe and various processes have been identified that play an important role, including gradual top-down thaw and active layer deepening, thermokarst and talik formation, and thermo-erosion (Romanovsky *et al* 2010, Jorgenson 2013). In this focus issue, several studies focused on permafrost degradation and its direct consequences for terrain surface and hydrology. Jones *et al* (2013) used multi-temporal Light Detection and Ranging (LiDAR) elevation models to calculate surface deformation between 2006 and 2010 in a coastal lowland stretch along the Alaska Beaufort Sea. For the 100 km^2 study area they find significant change (>0.55 m vertical change) in 0.3% of the study area over the 4 year period. The change was mainly associated with eroding coastal, lake, and river bluffs, as well as thawing ice wedges and erosion gullies. Also relying on

remote sensing data in combination with field studies, Godin *et al* (2014) investigated the development of a thermo-erosional gully network on Bylot Island, Nunavut (Canada) in fine detail over the 1972–2013 period. The observed erosion rates were as high as 90 m yr^{-1} or 2900 m^2 yr^{-1} (1999–2007 interval), with significant impacts on local hydrology such as changes in channel configuration, flow rates, and increased hydrological connectivity. A single gully in their study region mobilized about 32 000 m^3 soil volume over the 1999–2013 period. Necsoiu *et al* (2013) used remote sensing and analyzed a time series of aerial and Quickbird satellite images from 1951–2005 to detect thermokarst lake changes and transition of low center polygons to high center polygons due to ice wedge degradation in the Kobuk Valley National Park in NW Alaska. In a study for the Fort Simpson region, Northwest Territories in Canada, Williams *et al* (2013) analyzed LiDAR digital elevation data and field data to quantify the distribution of linear disturbance features that developed from ground subsidence following geophysical exploration activities in the 1960s and 1980s. They find significantly decreased surface elevations and increased thaw depths and soil moisture in the disturbed zones, affecting hydrological flow direction. Combining mechanical probing, ground temperature monitoring, boreholes, and geophysical surveys, James *et al* (2013) revisited a 1964 survey of

permafrost distribution along the southern boundary of permafrost distribution in the Alaska Highway corridor of NW Canada. They find that about half of the 55 sites have lost permafrost over about 40 years, while sites with remaining warm permafrost are generally found in areas with peat or thick organic mats.

One modeling study analyzed the thermal dynamics of permafrost in different settings of mountainous regions. Marmy *et al* (2013) used a permafrost process model and conducted climate-driven sensitivity analyses to test the impacts of seasonal and long-term changes in air temperature and precipitation on a low ice-content permafrost site in the Swiss Alps typical for high mountain permafrost regions. They suggest that autumn changes have the largest thermal effects on permafrost conditions and that snow cover duration and timing are key factors for variability. The observations and modeling results reported in these studies indicate that permafrost thaw is occurring under a range of environmental conditions and disturbance regimes, and collectively these studies indicate that the potential for widespread permafrost retreat is likely under further climate warming and accelerating rates and severity of disturbances.

3. Feedbacks between permafrost and ecosystem processes

The rate of permafrost thaw depends on interactions between permafrost and ecosystem processes. Several papers in this focus issue examined feedbacks between permafrost and ecosystem structure and how disturbance alters those interactions. Johnson *et al* (2013) analyzed variability in permafrost occurrence and organic layer thickness (OLT) using more than 3000 soil pedons across a mean annual temperature (MAT) gradient in Alaska. The probability of observing permafrost was 32% higher for every 10 cm OLT increase in shallow OLT soils (<28 cm) due to the summer insulation effect of OLT. In deeper OLT soils, the probability of observing permafrost was 6% lower for every 10 cm increase because deeper OLT was more likely to occur in wetlands where the higher thermal conductivity of water may lead to permafrost degradation. Furthermore, across the MAT gradient, the probability of permafrost in sandy soils varied little, but the probability of permafrost in loamy and silty soils decreased substantially from cooler to warmer temperatures.

To address the complexity of how interactions between permafrost histories and successional changes after disturbance (fire and thermokarst) influence ecosystem dynamics in boreal regions, Jorgenson *et al* (2013) used a chronosequence approach to assess changes in vegetation composition, water storage and soil organic carbon (SOC) stocks along successional gradients within four landscapes. The study found that

permafrost thaw led to the reorganization of vegetation, water storage and flow paths, and patterns of SOC accumulation. However, changes have occurred over different timescales among landscapes: over decades in rocky uplands and gravelly–sandy lowlands in response to fire and lake drainage, over decades to centuries in peaty–silty lowlands with a legacy of complicated Holocene landscape changes, and over centuries in silty uplands where ice-rich soil and ecological recovery protect permafrost.

Nossov *et al* (2013) offer a detailed assessment of the factors that affect permafrost degradation after wildfire by comparing vegetation composition and soil properties between recently burned and unburned sites across three soil landscapes (rocky uplands, silty uplands, and sandy lowlands) situated within the Yukon Flats and Yukon-Tanana Uplands in interior Alaska. The study found that degradation of the upper permafrost occurred at all burned sites, but differences in soil texture and moisture among soil landscapes allowed permafrost to persist beneath the active layer in the silty uplands, whereas a talik of unknown depth developed in the rocky uplands and a thin talik developed in the sandy lowlands. These results have implications for the stability of permafrost after fire. To understand the vulnerability of permafrost in silty uplands and lowlands to fire severity and future climate change, Jafarov *et al* (2013) modeled the impact of fire disturbance on boreal permafrost with black spruce forests in silty uplands and lowlands of interior Alaska. The comparison of lowland sites with thicker organic layers versus upland sites with thinner organic layers showed that, depending on burn severity, permafrost in upland sites is significantly more vulnerable to loss, while permafrost in lowland sites may persist even under climate warming. For instance, their study suggests that an 18 m thick upland permafrost column may thaw within 120 years under current climate. Genet *et al* (2013) developed a modeling approach to estimate how warming and fire regime may influence spatial and temporal changes in active layer and carbon dynamics across a boreal forest landscape in interior Alaska. To address this question, they (1) developed and tested a predictive model of the effect of fire severity on soil organic horizons that depends on landscape-level conditions and (2) used this model to evaluate the long-term consequences of warming and changes in fire regime on active layer and soil carbon dynamics of black spruce forests across interior Alaska. Similar to Jafarov *et al* (2013), Genet *et al* (2013) concluded that lowlands were more resistant to severe fires and climate warming, showing smaller increases in active layer thickness and soil carbon loss compared to drier flat uplands and slopes.

Tape *et al* (2013) investigated the impacts of vegetation and geomorphological changes in a coastal permafrost lowland along the Alaska Beaufort Sea using aerial image time series from 1948–2010. The authors found that decadal-scale permafrost thaw subsidence

led to a shift from non-saline vegetation to salt-tolerant vegetation communities due to enhanced inundation from the sea, thereby altering the distribution of goose habitat. Belshe *et al* (2013) used high resolution Ikonos remote sensing images to investigate how linear thermokarst features affected vegetation and organic layer thickness in an upland setting with ice-rich permafrost in interior Alaska. Their image and elevation model-based land cover classification together with field data analysis revealed that 12% of the landscape is already affected by thermokarst in the study region. Both thaw depth and organic layer thickness were significantly larger in the thermokarst-dominated land cover categories. In a manipulation experiment, Johansson *et al* (2013) investigated how artificially increased snow cover impacts permafrost peat plateaus in northern Sweden. Following a multi-annual snow thickness manipulation, the mean winter ground temperatures increased by 1.5 °C in the plots with thicker snow, while minimum winter temperatures were even up to 9 °C higher. As a result active layers increased and graminoid vegetation types expanded in the manipulated plots, changing vegetation composition, structure, and phenology cycle, highlighting the role of snow cover properties for both permafrost conditions and ecosystem characteristics.

While all other studies in this focus issue target northern hemisphere permafrost regions, Guglielmin *et al* (2014) provided rare but valuable insights into permafrost changes in continental Antarctica. They reported active layer increases of 0.3 cm yr^{-1} since field monitoring started in 2000 at their study sites in Victoria Land, with impacts on soil moisture conditions and on the generally sparse vegetation layer of mosses and lichen.

4. Biogeochemical feedbacks to the climate system from permafrost thaw

In this section, we review both field-based and modeling studies that specifically focused on evaluating the effects permafrost thaw on biogeochemical feedbacks to the climate system. An analysis of 18 sites disturbed by retrogressive thaw slumps in the Arctic foothills of Alaska indicated that carbon (3 kg m^{-2}) and nitrogen (0.2 kg m^{-2}) pools were displaced from the soil organic layer during the disturbance but also that the disturbance did not change the pools of the upper 15 cm of mineral layer (Pizano *et al* 2014). At recovered sites, the soil carbon pools re-accumulated rapidly (32+/−10 g C m^{-2} yr) within 60 years after the disturbance had ceased and succession started. Overall, the recovery of the observed thaw slump disturbances resulted in vegetation succession shifting from graminoid communities to tall deciduous shrubs that in turn likely increased primary productivity, biomass accumulation, and nutrient cycling. Jensen *et al* (2014) also studied the impacts of retrogressive

thaw slumps on carbon cycling. By investigating a chronosequence of thaw slumps in Northwest Alaska they found that peak growing season soil CO_2 fluxes from active slumps were consistently less than half (1.8 and 0.9 g CO_2-C m^{-2} d^{-1} in 2011 and 2012, respectively) compared to undisturbed or stabilized thaw slumps (5.2 and 3.2 g CO_2-C m^{-2} d^{-1} in 2011 and 2012, respectively). Interestingly, environmental factors such as soil temperature and moisture did not exert strong control on the CO_2 efflux. The authors suggested that low organic matter content in the slumped material, lack of stable vegetation, and larger increases in bulk densities in the upper slump sediments may be a limiting factor to CO_2 efflux.

McConnell *et al* (2013) predicted that wetland vegetation communities with permafrost would have reduced ecosystem respiration (ER) but greater temperature sensitivity than communities without permafrost. These predictions were partially supported. The results of the study suggest that ER across a permafrost/wetland gradient was temperature-limited, until conditions became so wet that respiration became oxygen-limited and influenced less by temperature. But even in sites with similar hydrology and thaw depth, ER varied significantly likely based on factors such as soil redox status and vegetation composition.

In a study of feedbacks from changing winter precipitation on vegetation biochemistry in permafrost regions, Leffler and Welker (2013) reported impacts of a changed snow regime on plant biochemistry at a snow fence site over continuous permafrost in High Arctic Northwest Greenland. They found that vegetation affected by enhanced snow conditions for 10 years featured higher leaf nitrogen, photosynthetic rate, and more enriched leaf δ^{15}N. This local-scale study may represent an interesting perspective on changing snow-vegetation-biochemistry feedbacks in permafrost regions since thawing permafrost is often related to geomorphic change causing alteration of snow regimes due to thaw subsidence.

Another study investigated the impacts of slope permafrost disturbances on changes in particulate organic carbon (POC) fluxes from low-order coastal watersheds in the continuous permafrost of Melville Island in the Canadian High Arctic (Lamoureux and Lafrenière 2014). Radiocarbon analysis of the POC suggested that fresh disturbances delivered old POC to the aquatic system and that localized disturbances had a measurable impact on POC age downstream. In addition, POC from such disturbances dominated total POC (up to 78%) during summer baseflow. The findings suggest that POC sources and pathways need to be considered when scaling carbon fluxes across large watersheds affected by disturbances. Following a 900 km long transect crossing from non-permafrost into the discontinuous permafrost zone of western Canada, Olefeldt *et al* (2014) sampled dissolved organic carbon (DOC) and dissolved organic matter (DOM) concentrations in 65 streams with different

permafrost and peatland characteristics in their catchments. The study demonstrated that DOC concentration and DOM chemical composition, and thus biogeochemical cycling in hydrological systems, were significantly influenced by presence or absence of peatlands and permafrost in the river catchments. In particular, DOC concentrations increased with catchment peatland cover but were found to be consistently lower in the permafrost zone. Laurion and Mladenov (2013) in turn looked at how sunlight impacts DOM in thaw ponds by photodegradation. Sampling of ponds was performed over a 12-day summer period in the continuous permafrost region of Bylot Island, High Arctic Canada, to study changes in DOM characteristics over time. Color and fluorescence decayed relatively fast at the pond surface, in particular for humic-like components, but only insignificant losses of DOC occurred over the observation period. Direct DOM mineralization through photochemical production of CO_2 was minor compared to the photochemical transformation of DOM into less chromophoric and likely more labile molecules. DOM photolysis was considered a catalytic mechanism that can accelerate microbial turnover of DOM in thaw ponds. Melt of massive ice wedges in Yedoma deposits in Northeast Siberia were found to enhance degradation of organic carbon from Yedoma in experimental incubation assays where increasing amounts of ice wedge melt water were added to thawed Yedoma sediment (Vonk *et al* 2013). In these experiments, DOM from ice wedge meltwater enhanced the biolability of Yedoma DOM over time. The enhanced loss of DOM was attributed to the presence of low-molecular weight compounds and low initial phenolic content in the organic matter enclosed in ice wedge ice, thereby providing a readily available substrate promoting degradation of Yedoma organic carbon. This inoculation effect of ice wedge-bound organic matter for overall decomposition rates underlines the important role of ice wedge-rich Yedoma deposits for a positive permafrost-carbon feedback.

Several studies have used modeling as a tool to make progress towards quantifying the magnitude and timing of biogeochemical feedbacks from permafrost thaw to the climate system across large spatial scales. Mishra *et al* (2013) noted that substantial differences exist between empirical and modeling estimates of the quantity and distribution of permafrost-region soil organic carbon, and that reducing these uncertainties is important to making better predictions of carbon–climate feedbacks under future warming. The study identifies research challenges that constrain current assessments of the distribution and potential decomposability of soil OC stocks in the northern permafrost region and suggest priorities for future empirical and modeling studies to address these challenges. Several modeling studies in this focus issue have attempted to address these research challenges. In a retrospective analysis, Hayes *et al* (2014) employed a process-based

model simulation experiment to assess the net effect of active layer dynamics on the 'permafrost carbon feedback' from 1970 to 2006 over the circumpolar domain of continuous and discontinuous permafrost. These experiments indicate that the mobilization of previously frozen carbon resulted in an estimated cumulative net source of 3.7 Pg C to the atmosphere since 1970 and was directly tied to active layer dynamics. Three studies used modeling approaches to evaluate the permafrost carbon feedback to the climate system in the 21st Century and beyond. Using an integrated Earth-system model framework, Zhu *et al* (2013) used a coupled hydrology–biogeochemistry model to make estimates of these carbon exchanges with two contrasting climate change scenarios (no-policy versus policy) over the 21st century, by considering detailed water table dynamics and permafrost-thawing effects. Thawing permafrost has a small effect on the greenhouse gas sink under the policy scenario; however, under the no-policy scenario, about two thirds of the accumulated greenhouse gas sink over the 21st century has been offset by the carbon losses as CH_4 and CO_2 from thawing permafrost. Over the century, nearly all CO_2-induced greenhouse sink through photosynthesis has been undone by CH_4-induced greenhouse gas source. Gao *et al* (2013) examined the degradation of near-surface permafrost, the temporal dynamics of inundation (lakes and wetlands) induced by hydro-climatic change, subsequent methane emission, and potential climate feedbacks. The result of this model application indicates that additional warming, across the range of climate policy and uncertainties in the climate-system response, would be no greater than 0.1 °C by 2100. However, there is much uncertainty among the magnitude of the permafrost climate feedback simulated by the different models that have been used for this purpose. Schaefer *et al* (2014) conducted a synthetic analysis to evaluate this uncertainty and found that under a no policy scenario (representative concentration pathway 8.5) the permafrost carbon feedback would result in 0.29 $+/-0.21$ °C additional warming. However, under a policy scenario consistent with representative concentration pathway 4.5, they found that the permafrost carbon feedback would result in 0.1$+/-0.05$ °C additional warming. An important result from this synthesis is that any substantial warming results in long-term carbon release from thawing permafrost as 60% of emissions would occur after 2100.

5. Discussion

Many studies, including those in this focus issue, demonstrate with observations and data that in a warming world permafrost is currently changing and, in some cases, rapidly. While permafrost landscapes have always been dynamic and continuously affected by aggradation and degradation of frozen ground, the

amplification of natural and anthropogenic stressors due to anthropogenic warming and increased economic usage of these regions results in increased disturbance frequencies and magnitudes. The intensification of disturbance impacts leads to substantial permafrost retreat and a multitude of associated physical, ecological and biogeochemical feedbacks. Consequences of widespread permafrost thaw often are irreversible on human time scales and may impact the character of ecosystems, hydrology, and carbon cycling for centuries to millennia.

The physical processes that may be associated with permafrost degradation can be diverse including permafrost warming, phase transition from ice to water and increase in liquid pore water availability, volume loss due to melting ground ice and thaw subsidence (thermokarst), and loss of substrate stability and various forms of erosion. Hence, observations of permafrost thaw may focus on different approaches such as ground-based measurements of multi-annual increases in ground temperature, mechanical probing of long-term active layer or talik deepening, various types of geophysical surveys of permafrost conditions and permafrost extent and continuity, and geodetic surveys of long-term thaw subsidence or erosion. Approaches of observing permafrost thaw highlighted in this focus issue include for example quantitative surveys of thaw slumps, thermo-erosional gullies, ice wedge degradation, thaw subsidence, active layer deepening, and soil wetting as well as geophysical surveys of subsurface conditions. In addition, modeling on various scales was used to capture the impacts of disturbances on permafrost and resulting large-scale ecosystem feedbacks. Increasingly, remote sensing tools are used for observations of thaw subsidence, erosion, and even subsurface conditions and some studies in this focus issue use such tools to quantify changes in permafrost landscapes.

The studies in this focus issue indicate that much progress has been made in better understanding key feedbacks between permafrost and ecosystem processes. The thickness of the organic layer controls the stability of permafrost (Johnson *et al* 2013), but disturbance can substantially alter the stability of permafrost through either the removal of the organic layer by fire or through inundation associated with thermokarst disturbance and subsequent subsidence that renders the organic layer less effective at insulating permafrost from warm summer air temperatures (Genet *et al* 2013, Jafarov *et al* 2013, Johnson *et al* 2013, Jorgenson *et al* 2013, Nossov *et al* 2013). The studies also indicate that the vulnerability of permafrost to disturbance depends on snow depth, which insulates permafrost from cold winter air temperatures, and on soil texture, as sandy soils generally have less ice content and are less likely to be inundated. The improved understanding of these interactions is leading to the development of landscape models of permafrost vulnerability to warming that can consider non-linear

relationships between permafrost and ecosystem processes.

Because of the importance of the carbon cycle for global climate, studies on biogeochemical feedbacks from permafrost thaw largely concentrate on repercussions to the carbon cycle through changes in permafrost soil carbon storage, the fate of DOC and DOM in hydrological systems, and changes in permafrost region greenhouse gas dynamics. Particular attention is being placed on the association of soil carbon stocks with specific permafrost-landscape-ecosystem settings, and on how the representation of these carbon pools may be enhanced in large scale models. Several of the studies in this issue highlight advances in these fields but also indicate that much remains to be learned about the characteristics (quantity, quality, and distribution) and dynamics of the permafrost soil carbon pool that is required to project future climate feedbacks and thus address climate policy implications. A key step taken here is the constraint of state-of-the-art models with enhanced, observation-driven carbon pool data (Koven *et al* 2015). In addition, recent studies for example have been able to implement thermokarst dynamics in permafrost carbon models to better understand how thermokarst lakes may contribute significantly to future atmospheric methane concentrations (Schneider von Deimling *et al* 2015). In future studies, the dynamics of soil nitrogen will also need to have a larger role to understand how interactions between changing permafrost and vegetation may impact above and below ground carbon pools (Harden *et al* 2012).

6. Conclusions and outlook

Permafrost and its dynamics are important components of the cryosphere as well as the Earth system as a whole. New insights into the ecosystem-climate feedbacks resulting from permafrost changes on local to global scales have significantly raised the awareness for this component of Earth's cryosphere in the view of stakeholders, decision makers, and the public over the last few years. The studies collected in this focus issue have contributed significant pieces of knowledge to the overall understanding of permafrost-ecosystem dynamics and form an important base for future work such as the impacts of thaw on ecosystem processes, biogeochemical cycling in permafrost-affected hydrological systems, and the modelling of climate feedbacks from permafrost change.

Despite the strong progress made, significant challenges remain for the study of permafrost ecosystems, which are distributed across vast and remote high latitude regions with difficult access. Current permafrost data collection still focuses on limited areas across the ~23 million km^2 northern hemisphere permafrost domain. A range of permafrost variables that determine permafrost vulnerability, such as ground ice

content and distribution, are still poorly documented in the Arctic due to the difficulties associated with their local quantification and their scaling to larger regions. Though major steps have been taken in the quantification of soil organic carbon pools, other variables that determine climate feedbacks and impacts from permafrost changes in a warming world still need further assessments through mapping and data synthesis, in particular biogeochemical dynamics associated with carbon, nitrogen, and various nutrients or contaminants. For example, studies of carbon quality and availability are limited to a small number of specific settings that may not reflect the full variability of feedback dynamics across the large permafrost domain. At the same time, some permafrost-ecosystem feedbacks in a changing Arctic are incompletely understood, such as the importance of various disturbances regimes for widespread permafrost degradation, vegetation feedbacks with changes in the active layer thickness, and the interaction of geomorphic change due to permafrost thaw with hydrology and soil moisture regimes. An important factor in the outcome will be the different temporal dynamics of interacting processes and the presence or absence of gradual versus threshold-based changes.

To improve understanding of the current and future changes in permafrost and permafrost-associated ecosystem dynamics across this large domain, a tighter coupling between field data collection and upscaling with remote sensing and modeling is necessary. The recent formalization of the Global Terrestrial Network for Permafrost (GTN-P), with its two components on monitoring permafrost temperatures and the active layer, is an excellent first step towards enhanced data access and uniform data reporting for ground temperature records (Biskaborn *et al* 2015). Similar synthesis efforts increase the availability of panarctic datasets and strongly ease the use of such data by Earth System modelers and other scientific communities. An excellent example is the Northern Circumpolar Soil Carbon Database (NCSCD) (Hugelius *et al* 2013) which provides a synthesis of permafrost-region soil pedon and carbon data in the form of both vectorized and gridded datasets that can be readily incorporated into models. These databases have been expanded and accessibility enhanced through the work of the Permafrost Carbon Network (Schuur *et al* 2015; http://www.permafrostcarbon.org), which aims to use science synthesis to link empirical datasets at the panarctic scale to modeling efforts aimed at simulating future conditions. Database curation and expansion, as well as science synthesis, remain important tools for enabling networks of scientists that are creating new knowledge about this important region.

The development of remote sensing datasets, tools, and techniques is accelerating and is leading to faster progress in permafrost research (NRC 2014, Westermann *et al* 2015a). Longer homogeneous time

series of image data, new sensors systems, finer spatial and temporal resolutions, and easier and freer data access all have lead to the development of new innovative remote sensing products that are allowing the scientific community to make substantial progress in understanding and quantifying changes in permafrost landscapes (e.g., Fraser *et al* 2014, Jones *et al* 2015). Increasingly, direct implementation of remotely sensed, spatially homogeneous geophysical observations, along with ecosystem and land cover datasets across large regions into permafrost models is leading to improved spatio-temporal insights (Pastik *et al* 2015, Westermann *et al* 2015b). A further implementation of these approaches and the testing of new remote sensing techniques hold the promise of better quantification of future permafrost-climate feedbacks in the Earth system. Ongoing efforts like NASA's Arctic Boreal Vulnerability Experiment (ABoVE) (http://above.nasa.gov), ESA's GlobPermafrost (www.globpermafrost.info), DOE's Next-Generation Ecosystem Experiment (NGEE) Arctic (http://ngee-arctic.ornl.gov), and the permafrost research activities of Study of Environmental Arctic Change (SEARCH) (www.arcus.org/search-program/permafrost) will help to build upon the advances reported in this focus issue. Such broad and international research efforts are required to understand and project how permafrost-affected ecosystems, covering tens of millions of km^2 or about a quarter of the northern landmass, will change in a warming Arctic and influence global climate in a rapidly changing Earth system.

Acknowledgments

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