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Brief Communication: Future avenues for permafrost science from the perspective of early career researchers

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Abstract

Accelerating climate change and increased economic and environmental interest in permafrost-affected regions have resulted in an acute need for more directed permafrost research. In June 2014, 88 early career researchers convened to identify future priorities for permafrost research. This multidisciplinary forum concluded that five research topics deserve greatest attention: permafrost landscape dynamics; permafrost thermal modelling; integration of traditional knowledge; spatial analysis of permafrost types and vulnerability; and engineering issues. These topics underline the need for integrated research across a spectrum of permafrost-related domains and constitute a contribution to the Third International Conference on Arctic Research Planning (ICARP III).

1 Introduction

Permafrost is a major component of the cryosphere, occupying 24 % of the Northern Hemisphere's land surface (Zhang et al., 1999), as well as parts of Antarctica and alpine areas around the world. Due to rapid warming in the Arctic, permafrost areas are now changing, with global implications for the carbon cycle and climate feedback mechanisms. The World Meteorological Organization and the United Nations consider permafrost to be an essential climate variable. Despite the knowledge that permafrost areas contain twice as much carbon (~ 1100–1500 Pg) than is currently in the atmosphere (Hugelius et al., 2014) and that permafrost temperatures have increased significantly during the last 20–30 years (Romanovsky et al., 2010), climate projections in the IPCC Fifth Assessment Report (AR5) did not account for emissions from thawing permafrost and the effects of the permafrost carbon feedback on global climate (IPCC, 2013). Circumpolar permafrost areas in the Arctic have been used for settlements and hunting grounds for indigenous peoples for more than ten thousand years, resulting in a legacy of knowledge about these areas. However, conservation of cultural heritage sites and the construction of industrial and municipal infrastructure on permafrost are costly and intellectually challenging.

Over the past two decades, the International Arctic Science Committee (IASC) and the Scientific Committee on Antarctic Research (SCAR) have organized activities focused on international and interdisciplinary perspectives for advancing Arctic and Antarctic research cooperation and knowledge dissemination in many subject areas. For permafrost science, however, no consensus document exists as yet at the international level to identify future research priorities, although the International Permafrost Association (IPA) highlighted the need for such a document during the 24th IPA Council meeting in June 2012 (IPA, 2012).

This manuscript presents the outcome of an international and interdisciplinary effort conducted by early career researchers (ECRs) in 2014. Online community input and a conference workshop highlighted five priority research questions on the future avenues of permafrost science. This consensus statement has been formulated as a contribution to the Third International Conference on Arctic Research Planning (ICARP III), to raise permafrost issues to the prominent position that they urgently deserve.

2 Community consultation process

Community input exercises are increasingly viewed as a valuable step towards elaborating future research priorities or research questions in a well-defined scientific community (e.g. Kennicutt et al., 2014; Seddon et al., 2014). We aimed to meet our goals of hosting an effective large group dialogue by means of online question development followed by a World Café conversational process (Brown and Isaacs, 2001). This process has been continually evaluated following the research question guidelines presented by Sutherland et al. (2011). An overview of the process is provided in Fig. 1.

This activity took place as part of an ECR Workshop held prior to the 4th European Conference on Permafrost (EUCOP) in Évora, Portugal. It was proceeded by breakout sessions hosted by senior scientist from IASC, the IPA and other organizations.

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For this activity, participants were provided with live instructions (Supplement S3). This activity format was selected due to its flexibility, prior positive experiences of workshop organizers, and highly collaborative nature. Throughout the workshop, each individual participant had the opportunity to work with more than 20 different members of the ECR permafrost research community, and to view a variety of research topics, many of which were outside their own field of expertise.

3 Breadth of questions

The submitted questions covered a broad range of topics that focused on the physical environment (32), biogeochemistry (14), social interactions and impacts (9), engineering (9), ecology (4), and modelling (3) (Supplement Table S1). Of the 20 questions that received votes at the end of the World Café, 11 were associated with permafrost degradation or change in permafrost properties (Supplement Table S4). This highlights the current changing nature of the terrestrial cryosphere environment and is directly linked to the trending research topics on thermokarst, active-layer monitoring and drivers of change. Tied for second were keywords "ground ice" and "carbon", which are linked to two distinct trends in permafrost research. Ground ice research hints at a more classical, geocryological approach to permafrost science and is concerned mostly with distribution, formation and sensitivity at thaw, while carbon research follows a younger trend, linking permafrost dynamics to carbon cycling by investigating its abundance, distribution and vulnerability. Research topics such as "permafrost distribution", "process-related" questions, "hydrology" and "subsea permafrost" followed these three, and expressed less frequent but nonetheless important research avenues.

TCD
9, 1209–1225, 2015

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4 Highlighted research questions for permafrost science

4.1 How does permafrost degradation affect landscape dynamics at different spatial and temporal scales? (Q1)

Recent climate change in many cold-climate regions on Earth is entailing significant environmental consequences, particularly in permafrost regions. This is the case of permafrost degradation in (sub)Arctic, Antarctic, high plateaus and mountain environments, where some of the edaphic, ecological, and geomorphological processes, which shape the landscape, are changing in magnitude, and in some cases even reinforce permafrost thawing through positive feedback effects. While some of the processes may react to long-term changes, others may respond rapidly, sometimes abruptly, to threshold crossing (Rowland et al., 2010).

Permafrost thawing has wide social and economic implications for northern communities (Schaefer et al., 2012). With the extension of permafrost warming to greater areas of the Arctic, subarctic and mountain landscapes (Haeberli et al., 2010; Romanovsky et al., 2010), the interactions and feedbacks among the different processes causing degradation, and those being affected by it, need to be better understood. These processes operate at different spatio-temporal scales and can involve remarkable changes on the landscape dynamics. Thermo-erosion and mass movements can affect sediment, nutrient and soil organic carbon fluxes (Bowden et al., 2008; Grosse et al., 2011). Melting of ground ice and the evolution of thaw lakes will affect the water composition, hydrological transport and water storage capacity of the land (Grosse et al., 2007). These changes also interact with vegetation and snow cover, in a series of complex positive and negative feedbacks in the ground surface as well as in the active layer of the permafrost.

More precise knowledge on the causes and consequences of permafrost degradation will help to better assess community planning and landscape evolution models. Future research should focus on the identification and quantitative description of processes affecting different types of landscapes and integrating/applying the results at

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multiple spatial scales. The identification and quantification of tipping points and long-term monitoring of currently degrading sites will provide useful information on the development and recovery of the landscape. This knowledge will further enable the development of conceptual models that can help to understand the timeframe, scale and frequency at which these processes operate. This information is crucial to form a more solid foundation for predicting and modelling the long-term evolution of the landscape morphology along with aquatic and atmospheric fluxes.

4.2 How can ground temperature models be improved to better reflect permafrost dynamics at high spatial resolution? (Q2)

In the rapidly warming Arctic, better monitoring and prediction of permafrost degradation at a variety of spatial scales is critical for providing a range of stakeholders, from scientist to local government and industry, with the tools they need to observe and plan for the effect on environmental and human activities. While models capable of representing many of the important processes at relevant scales have been recently developed, they remain too complex to be used by others than modelling experts and for more than generic scenarios. On global to regional scales, a number of approaches have facilitated mapping of the ground thermal regime and its evolution over time in the past years (e.g. Gruber, 2012; Westermann et al., 2013). However, on the local scale, presently existing tools are either too simplistic or too complex to provide answers to many of the local problems that Arctic communities will be facing in the near future. Hereby, a main problem is the availability of forcing data sets at such scales, which requires permafrost modeling in conjunction with downscaling approaches (e.g. Zhang et al., 2012; Gruber, 2012). Future research should be focused on identifying which processes are most important for a variety of scales and problems, so that usable models with varying levels of complexity can be developed for all arctic stakeholders. Hereby, in particular the evolution of permafrost soils with high ground ice content poses a challenge for modeling, with thermokarst, ground subsidence and in general a modification of the hydrological regime over time. These processes are controlled by factors with

TCD
9, 1209–1225, 2015

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high spatial variability, such as the type and density of vegetation, snow cover, soil moisture, human activity, which are in many cases interdependent of each other (e.g. Painter et al., 2013). Developing model representations for these processes is among the most urgent challenges for future permafrost research, both on local scales to better inform stakeholders e.g. on ground stability, as well as on large scales to improve the projections on the fate of permafrost ecosystems and their carbon cycle.

4.3 How can traditional environmental knowledge be integrated in permafrost research? (Q3)

The circumpolar Arctic is inhabited by indigenous peoples, such as Inupiat, Aletus and Alutiiq in Alaska; Inuit, Dene and Athabaskans in northern Canada; Kalaallit in Greenland; Sami in Fennoscandinavia and Chukchi, Yupiaq and Sakha in Russian Siberia. Having lived in close contact to the nature in the Arctic for a long time, indigenous people have observed the consequences of the variations in permafrost conditions that could provide valuable information to scientists. Traditional Environmental Knowledge (TEK) incorporates practice and belief and evolves by adaptive processes which are handed down through generations by cultural transmission. The highly specialized knowledge about the harsh permafrost-underlain environment of the Arctic is thus preserved in the collective memory (Henry et al., 2013 and references therein).

The ways environmental processes and events are described by the non-scientific community, including indigenous people, often differ from those within the scientific community. It is challenging for the scientific community to incorporate TEK into existing scientific methods and to find ways to build up trust for communication. Indigenous observations and concerns have been taken into account increasingly in the literature and recent initiatives exist where the northern communities actively participate in research projects (Bennett and Lantz, 2014; Bull and Juutilainen, 2014; Tondu et al., 2014).

Although there are examples of successful applications and integration of TEK in the Arctic for the purpose of co-management of natural resources, studies related to

TCD
9, 1209–1225, 2015

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wildfire and forestry, sea-ice monitoring and ecology (Bennett and Lantz, 2014; Tondu et al., 2014), increased effort is still needed to involve TEK into the permafrost community. Further integration and application of TEK with science is needed to evaluate Arctic communities' resilience in general (Henry et al., 2013). Successful adaptation to environmental changes demands a holistic system perspective, to which permafrost science in the case of the Arctic clearly can and should contribute. For the scientific community to document and assess traditional knowledge, as well as for adaptation in the socio-ecological and economical systems in the Arctic, finding ways to work together in mutually beneficial and respectful ways seems to be the key to succeed with communication.

4.4 What is the spatial distribution of different ground ice types and how susceptible is ice-rich permafrost to future environmental change? (Q4)

Ground ice is a fundamental component of permafrost soils. In the Arctic lowlands of Eurasia and North America ground ice can occupy up to 80 % of the soil volume in the upper 20–30 m of permafrost (Brown et al., 1998). The amount of ice and its vertical and lateral distribution are central parameters controlling the thermal, physical and geochemical properties of permafrost deposits as well as their behavior at thaw. The presence of excess ice and massive ice is a key factor affecting the vulnerability of permafrost to warmer temperatures and mechanical disturbance, as ice melt will give rise to surface subsidence and thermal collapse, also known as thermokarst (Czudek and Demek, 1970). Although many field studies characterize cryostructures, measure ground ice content and map ground ice distribution, a concerted and organized mapping initiative that feeds into international databases is still lacking. Differentiating between epigenetic and syngenetic ground ice development could become a key to classify and map the susceptibility of ground-ice bearing permafrost landscapes to warming, thaw, ground ice melt and finally to landscape reorganisation. The localization of massive ice bodies such as ice wedges and buried glacier would be essential to create sensitivity maps to upcoming environmental changes. Until now, the National

TCD
9, 1209–1225, 2015

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Snow and Ice Data Center (NSIDC) has been the principal database on ground ice conditions, but it does not support the direct input of field-based information by international researchers. Similarly, the Global Terrestrial Network for Permafrost (GTN-P) is the primary international program concerned with monitoring permafrost parameters (http://gtnp.arcticportal.org/index.php/about-the-gtnp), but it does not include or provide information on ground ice.

Efforts to address this issue should focus on remote sensing applications for landform classification and on geophysical tools and drilling for the detection of subsurface ice. Ground-ice-related information should be integrated in a dedicated database, such as GTN-P, opening the door to regional extrapolation by integrating these data into climate models.

4.5 What is the influence of infrastructures on the thermal regime and stability of permafrost in different environmental settings? (Q5)

The economic development of the Arctic and subarctic, as well as of mountain permafrost regions at lower latitudes, are facing numerous engineering challenges since the performance of engineering structures and transportation systems are reliant on the strength of permanently frozen soil and bedrock. Numerous examples exist, where the combined effects of climate change and inappropriate technical solutions due to lack of knowledge led to irreversible damages or have required intensive maintenance, adaptation and premature reconstruction (Bommer et al., 2010 and references therein).

National guidelines and recommendations have recently been developed to adapt infrastructures in permafrost areas (e.g. Bommer et al., 2010; McGregor et al., 2010). Still, long-term evaluations of these practices are needed to establish reliable tools and standardized guidelines. In order to facilitate the evaluation of the construction and performance of the infrastructure in their specific environmental context, future research needs to integrate permafrost engineering with earth sciences. This could be done through a geosystem approach to assess the potential for natural hazards caused by human activity (USARC, 2003). A main challenge is to improve predictions of the

TCD
9, 1209–1225, 2015

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behavior and performance of structures and to act prior to unstable permafrost conditions. Monitoring new test infrastructures in problematic permafrost sites is one way to work on this challenge. Furthermore, it helps bridging the gap between meteorological and permafrost monitoring data which are useful for risk assessments and recurrence interval projections of extreme events (Instanes et al., 2005). Sites characterized by the presence of warm ice-rich permafrost, poorly drained soils and active water flow should be prioritized. Overall, integrating engineering knowledge with other fields of science would benefit from and contribute to the impact assessments, socio-economic scenarios and adaptation strategies (USARC, 2003; Vincent et al., 2013).

5 Synthesis

The top five questions presented in this article cover a wide range of topics in permafrost research and are often interrelated. One example for topical diversity and interrelationship is the lack of a carbon-specific question among the top five, although permafrost carbon and its feedback dynamics is one of the most popular topics in our research field today, based on the number of publications and citations. However, questions Q1, Q2, and Q4 are all indirectly related to carbon dynamics and Q9, Q13, Q14, and Q16 (Supplement Table S4) directly deal with this topic. This merely indicates a fragmentation and specialization of our field as it grows rather than lack of interest, and there is a need for integration across disciplines (Vincent et al., 2013).

The required framework to answer the raised questions was already outlined by Kennicutt et al. (2014) as a result of the first SCAR Antarctic and Southern Ocean Science Horizon Scan. It can directly be adapted to permafrost research priorities in the polar areas and alpine regions. We require predictable and stable funding; year-round and multinational access to research stations in permafrost areas; improved and continuous satellite observation, transparent national licensing procedures, application of emerging technologies; transdisciplinary international cooperation; and improved communication among all interested parties (cf. Kennicutt et al., 2014). As the next generation of

TCD
9, 1209–1225, 2015

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permafrost researchers, we see the need and the opportunity to participate in framing this process. Across the polar sciences ECRs have built powerful networks, such as APECS and PYRN, which have enabled us to efficiently consult with the community. Many participants of this community input exercise will be involved and also affected by the Arctic science priorities for the next decade within permafrost research. Therefore, we need to (i) actively frame this process, (ii) contribute our insights into larger efforts of the community such as the Permafrost Research Priorities initiative by the Climate and Cryosphere (CliC) Project together with the IPA (http://www.climate-cryosphere.org/activities/targeted/permafrost-research-priorities); and (iii) help identifying relevant gaps and a suitable roadmap for the future of Arctic research. To critically evaluate the progress made since ICARP II and to revisit the science plans and recommendations will be crucial.

IASC and the IPA, together with SCAR on bipolar activities, should coordinate the research agendas in a proactive manner engaging all partners, including funders and policy makers. Disseminating the knowledge, i.e. to communicate our main findings into society for a dialogue between research and the public, is a priority. Special emphasis must be given to indigenous peoples living on permafrost, where knowledge exchange creates a mutual benefit for science and local communities. The ICARP III process is an opportunity to better communicate the global importance of permafrost to policy makers and the public and how permafrost affects and is influenced by people's daily lives.

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TCD
9, 1209–1225, 2015

Future avenues for permafrost science from the perspective of early career researchers

M. Fritz et al.

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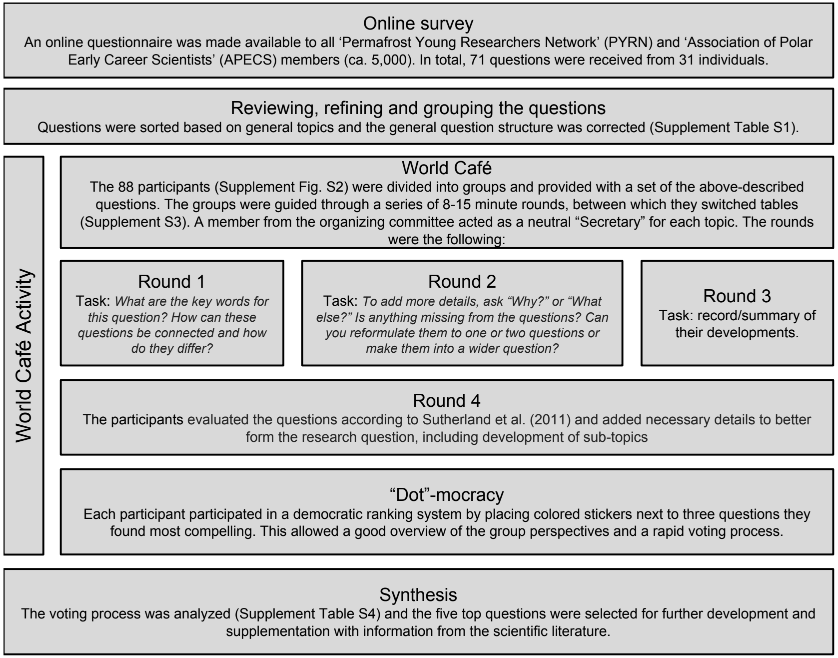

Figure 1. Flowchart of the process used to develop and refine future research questions. Questions were initially developed via an online survey. After some refinement, the process continued with an on-site World Café (Brown and Isaacs, 2001) workshop. Questions asked throughout the World Café enabled participants via group discussion to consider structure, breadth and depth of the questions (Sutherland et al., 2011). Workshop participants voted to identify the questions they believed to be the most compelling as a final step in the on-site activities. Based on votes, five questions were selected for further development and dissemination. The collaborative nature of the activities, coupled with substantial interest from all participating ECRs, enabled high levels of participation and thoughtful discussions about the future of permafrost research. Detailed workshop guidelines are given in Supplement S3.

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