



*Supplement of*

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

**M. Fritz et al.**

*Correspondence to:* M. Fritz (michael.fritz@awi.de)

The copyright of individual parts of the supplement might differ from the CC-BY 3.0 licence.

Table S1. Original permafrost research questions (n=71) submitted by early career researchers through an online questionnaire and grouped according to research topics.

No.	Physical processes (n=32)
1	What are the biggest changes that should be included into a new permafrost map of the northern hemisphere?
2	Which new techniques can be used to identify ice wedges and permafrost in the southern permafrost zone?
3	Can permafrost effectively be used to dispose tailings and other toxic materials?
4	Can the Landsat 8 Thermal band be used to detect frozen ground?
5	What are the specific contributions of 'non warming' factors (e.g., human activity, surface disturbance, forest fires, hydrology, precipitation changes) on permafrost degradation? Can we disentangle and quantify these at different spatial and temporal scales?
6	How can we better capture small-scale processes in permafrost regions on the larger scale of global land surface models?
7	How can we better determine the portion of observed methane levels that are attributed to decomposing submarine permafrost vs. decomposing gas hydrates?
8	How can we deepen our investigation to better model soil temperatures at greater depth?
9	How can we detect circum-polar permafrost related changes using satellite data?
10	How can we improve methods to express permafrost distribution?
11	How can we improve the information on ground ice distribution?
12	How can we use geophysics to effectively delineate and monitor periglacial properties including ground ice, wetlands, seasonal ice (related to heave, subsidence) and drainage networks?
13	How do density-driven flows, such as salt fingering in marine sediments, affect the stability of submarine permafrost and the formation of taliks in submarine permafrost?
14	How do variations in submarine groundwater discharge affect offshore submarine permafrost evolution and how can we measure or observe evidence of submarine groundwater discharge?
15	How does climate change impact sediment movement in permafrost landscapes (terrestrial and hydrological)?
16	How does decomposing submarine permafrost on the circum-Arctic shelf contribute to the seawater methane concentration in shallow Arctic waters?
17	How important is subsurface denudation for landscape evolution in permafrost environments?

- 18 How much of the Arctic shelf is underlain by subsea permafrost?
- 19 How quickly does bedrock permafrost in steep rock faces react to rising temperatures?
- 20 How strong is/will be the permafrost carbon feedback?
- 21 How will permafrost thaw affect freshwater fluxes to the Arctic ocean in the next 10 to 100 years?
- 22 How will thawing permafrost in combination with changes in the components of the hydrological cycle affect wetland areas in the next 50 years?
- 23 How will the components of the surface energy balance of arctic ecosystems respond to predicted future climate scenarios and what will be the feedback exerted on the climate system?
- 24 Is submarine groundwater discharge fundamentally different in the coastal Arctic due to the influence of a permafrost layer?
- 25 What have been the rates of coastal erosion in permafrost areas since the end of the last ice age?
- 26 What impacts do ice lenses in the seasonal snowpack have on the surface offset between air and ground surface temperatures?
- 27 What is the best way to conduct continuous measurements in remote permafrost environments while accounting for limited funding?
- 28 What is the role of ground ice for the resilience and vulnerability of permafrost against rising air temperatures and thermal degradation?
- 29 What is the role of volcanic ashes for preserving glacial ice and permafrost?
- 30 Where does new permafrost formation take place?
- 31 Which paleoclimate signals are stored in different kinds of ground ice and how can this information be used as a substantial contribution to the permafrost community and to paleoclimate research for defined time periods and regions?
- 32 How does the stability of permafrost-affected rock faces react to recent climate warming?

#### **Biogeochemistry (n=14)**

- 33 How can we assess the relative importance of lateral transport, storage, burial and mineralization of carbon in short- and long-term reservoirs resulting in delayed or attenuated GHG emissions and their impacts on greenhouse gas emissions? At what spatial and temporal scales?
- 34 How can we better model soil carbon distribution and dynamics?
- 35 What are the future steps required to produce quality soil carbon models?
- 36 How do changes in active layer thickness and permafrost coverage influence ecosystem-scale carbon budgets and what are the impacts of these changes on vegetation patterns and productivity on the one hand and decomposition of soil

organic matter on the other hand?

- 37 How do soil organic matter mineralization rates and nutrient availability for plants (with particular attention to nitrogen) change?
- 38 How much carbon, nutrients and sediments are expected to be delivered to the Arctic Ocean due to coastal erosion under different IPCC scenarios?
- 39 How will the hydrological part of the carbon cycle be affected by climate change across spatial scales?
- 40 Is degrading permafrost altering riverine fluxes of major elements to the polar oceans, and if there is a change, is it significant enough to alter global biogeochemical cycling?
- 41 Is degrading permafrost increasing riverine fluxes of organic and inorganic carbon (and other nutrients) to the Arctic Ocean?
- 42 What are the best methods of quantifying balance dynamics between the methanogenesis and methanotrophy in the water column of thermokarst lakes? What are the key determinants of these dynamics?
- 43 What are the impacts of thawing permafrost on aquatic ecosystems (ponds, streams, lakes)?
- 44 What are the rates of carbon turnover in warming and deepening active layers?
- 45 What is the role of ground ice as a potential source of carbon and nutrients upon permafrost degradation?
- 46 What will be the role of subsea permafrost in the global carbon cycle in the next 100 years?

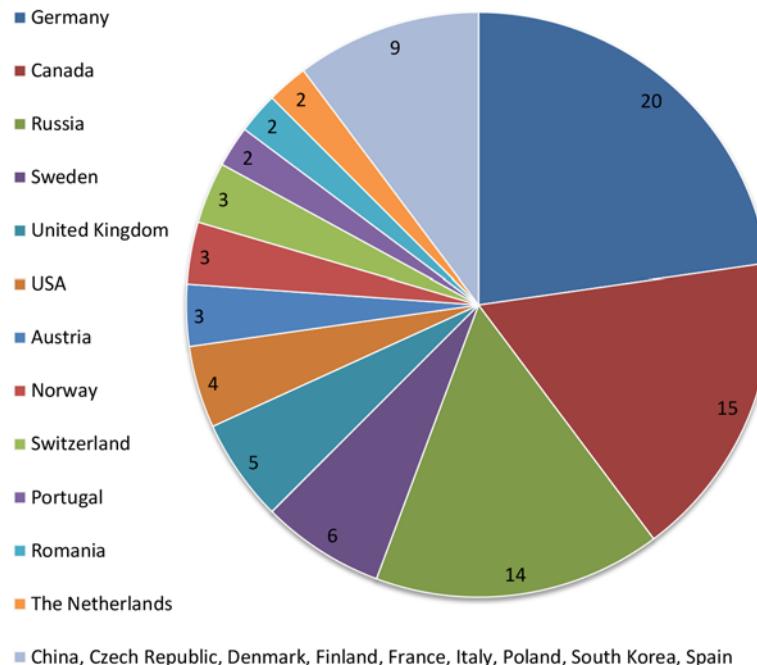
#### **Social Interactions and impacts (n=9)**

- 47 How have indigenous people actively shaped certain permafrost landscapes in the past and what will be the impact of increasing land use on permafrost degradation processes?
- 48 How are indigenous people in southern permafrost zone dealing with climate changes?
- 49 How can indigenous people living on permafrost adapt to or mitigate the degradation of natural resources, settlement areas and hunting/fishing grounds due to thermal and mechanical permafrost degradation?
- 50 How can the predicted increased rockfall risk for permafrost-affected rock faces be implemented within the risk management cycle?
- 51 How can we evaluate of the potential land use of high latitude regions under climate change and vulnerability of existing infrastructures.
- 52 How is present climate change likely to change permafrost landscapes and indigenous land use and what are the possibilities for local communities to adapt to these changes?
- 53 Is it possible to technically involve people living on permafrost in field studies, in particular the indigenous populations?

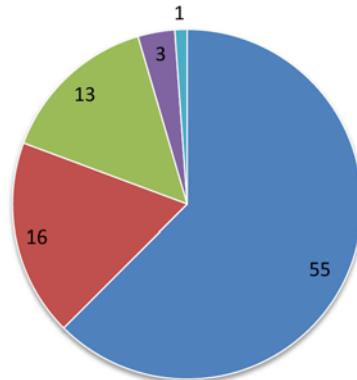
- 54 What is the best way to transfer scientific knowledge to policy makers and the general public?
- 55 Where and how was periglacial research funding distributed (spatially and by topic)? What was the long-term impact of this funding?
- Engineering (n=9)**
- 56 What is the influence of transport infrastructure on permafrost degradation?
- 57 How will an expected expansion in infrastructure in the Arctic be affected by degrading permafrost in the next 50 years?
- 58 How are the locations of roads in cold climate regions reacting on the influence of seasonal frost penetration?
- 59 How can the seismic risk be considered in the design of northern infrastructures built on permafrost?
- 60 How can we make the chilling system of thermopiles changeable with minimum loss of its efficiency?
- 61 How exactly are the mechanical properties of frozen rock containing ice altered by an increase of temperature?
- 62 How is the deformation mode of soil changing during the process of frost heaving?
- 63 How to optimally freeze soil layers defined by their grain-size using thermosyphones?
- 64 What is required to adapt available thermo-hydro-mechanical models for simulating pile-heaving soil interactions?
- Ecology (n=4)**
- 65 How will climate change affect the specific composition, vegetation cover fraction and primary productivity of the arctic terrestrial biome?
- 66 What are the feedbacks of change in landscape-scale permafrost hydrology on vegetation dynamics and how are these feedbacks controlled by degrading permafrost?
- 67 What impacts do changes in permafrost have on the grazing and migration patterns of caribou?
- 68 How can we connect permafrost thawing with eco-hydrological degradations in boreal forest regions?
- Modelling (n=3)**
- 69 What is the best way (algorithms, models, approach) to simulate coupled permafrost-hydrological systems for the past and future?
- 70 How can we monitor and survey carbon-rich permafrost tundra lowlands and transfer observations into transient meso-scale models?
- 71 Is permafrost likely to completely disappear in the future?

## Workshop statistics

Participants by country



Participants by career level



Participants by gender

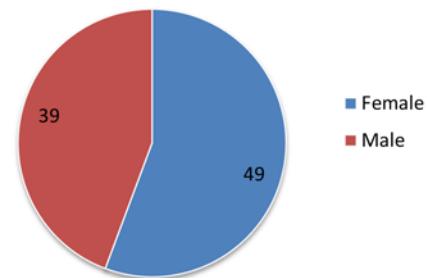


Figure S2. Statistics of workshop participants (n=88) grouped by country, career level, and gender.

## S3: World Café Guidelines

### Overall Purpose

- Diversify thinking and ideas regarding key permafrost research questions for the next decade, encourage out-of-the-box and unique ideas to emerge
- Expand thinking and ideas regarding the topics and questions posed
- Provide an opportunity for Permafrost Young Researchers to interact in a unique environment
- Link, connect and share ideas to promote multi-disciplinary, cross-disciplinary and inter-disciplinary thinking
- Produce a final set of questions to be part of a Permafrost Priority Sheet to define early-career researchers perspective on:
  - Permafrost science priorities for the next decade & research agendas
  - Informing policy makers, people who live in or near the Arctic and the global community
  - Building constructive relationships between producers and users of knowledge.
  - Integrating priorities for forward-looking, collaborative, interdisciplinary permafrost research and observing
  - Establishing an inventory of recent and current synthesis documents and major developments in permafrost research.

#### *Guidelines for all participants:*

- Focus on what matters
- Contribute your thinking
- Speak your mind
- Listen actively to understand
- Link and connect ideas
- Listen together for insights and deeper questions
- Play, doodle, draw; Have fun

#### *Guidelines for table moderators:*

- Take notes to record what happens at your table
- Ensure participation from all members of your table
- Try to balance open sharing and brain-storming with staying focused on what matters

## Criteria for research questions

Please read through the questions at your table and identify if they fulfill the following criteria (Sutherland et al., 2011). If they do not fulfill the criteria, feel free to adjust, edit, combine or eliminate questions if necessary.

- Answerable through a realistic research design,
- Not answerable with "it all depends",
- Should not be answerable by "yes" or "no",
- Addresses important gaps in knowledge,
- Of a spatial and temporal scope that reasonably could be addressed by a research team,
- Have a factual answer that does not depend on value judgments,
- Not formulated as a general topic area,
- If related to impact and interventions, contains a subject, an intervention, and a measurable outcome.

*Sutherland, W. J., Fleishman, E., Mascia, M. B., Pretty, J., and Rudd, M. A.: Methods for collaboratively identifying research priorities and emerging issues in science and policy, Methods in Ecology and Evolution, 2, 238-247, 10.1111/j.2041-210X.2010.00083.x, 2011.*

Table S4. Permafrost research questions (n=20) that received votes during the World Café process (“Dot”-mocracy), including the top five priority research questions, which were developed further.

No.	Question	Weighted votes
1	<b>How does permafrost degradation affect landscape dynamics at different spatio-temporal scales? Which are the most important processes?</b>	88
2	<b>How can ground temperature models be improved to better reflect factors affecting degradation/preservation/aggradation of permafrost at high spatial resolution? (factors: ground ice, snow cover, volcanic ashes, vegetation, other insulating layers, moisture, ground physical properties, climate, human impact)</b>	85
3	<b>In what ways can traditional environment knowledge be quantified and used in scientific research?</b>	52
4	<b>What is the spatial distribution of: a) massive ground ice, b) syngenetic ground ice, c) epigenetic ground ice? What is the vertical distribution of: a) massive ground ice, b) syngenetic ground ice, c) epigenetic ground ice? And how susceptible is it to thaw and warming?</b>	45
5	<b>What is the influence of different types of infrastructure on the permafrost thermal regime and stability in different environmental settings?</b>	43
6	How to create a georeferenced database of permafrost distribution that is easy to contribute to and continuously updated?	36
7	What geophysical methods can be used to validate remotely-sensed ground ice data?	33
8	What are the impacts of thawing permafrost on aquatic ecosystems?	29
9	What are the most significant feedback mechanisms between permafrost changes and wildlife, hydrology, the carbon cycle, and vegetation dynamics?	27
10	What is the past and future of permafrost distribution?	25
11	How can we standardize techniques to determine permafrost distribution while including key local factors?	25
12	Which processes control new permafrost aggradation and where does it occur?	23
13	What are the turnover rates of carbon and nutrients in warming and deepening active layers (including lateral and vertical fluxes)?	19
14	How can we obtain soil carbon distribution and model dynamics and which are the key parameters that need improvement?	14
15	What are the magnitudes of feedbacks between changing permafrost and hydrology?	13

16	What is the role of ground ice as a potential source of carbon and nutrients on permafrost degradation?	12
17	Under which climatological and geological conditions is ground ice forming today?	9
18	How do variations in submarine groundwater discharge affect offshore submarine permafrost evolution? How does decomposing subsea permafrost and circum-arctic shelf contribute to the seawater methane concentration in shallow arctic waters?	9
19	What are the most important parameters to use in permafrost models to capture the interactions between permafrost and the hydrological cycle?	7
20	What increases the likelihood of subsea permafrost thaw and its extent?	2