SEVENTH FRAMEWORK PROGRAMME

INTERACT

International Network for Terrestrial Research and Monitoring in the Arctic

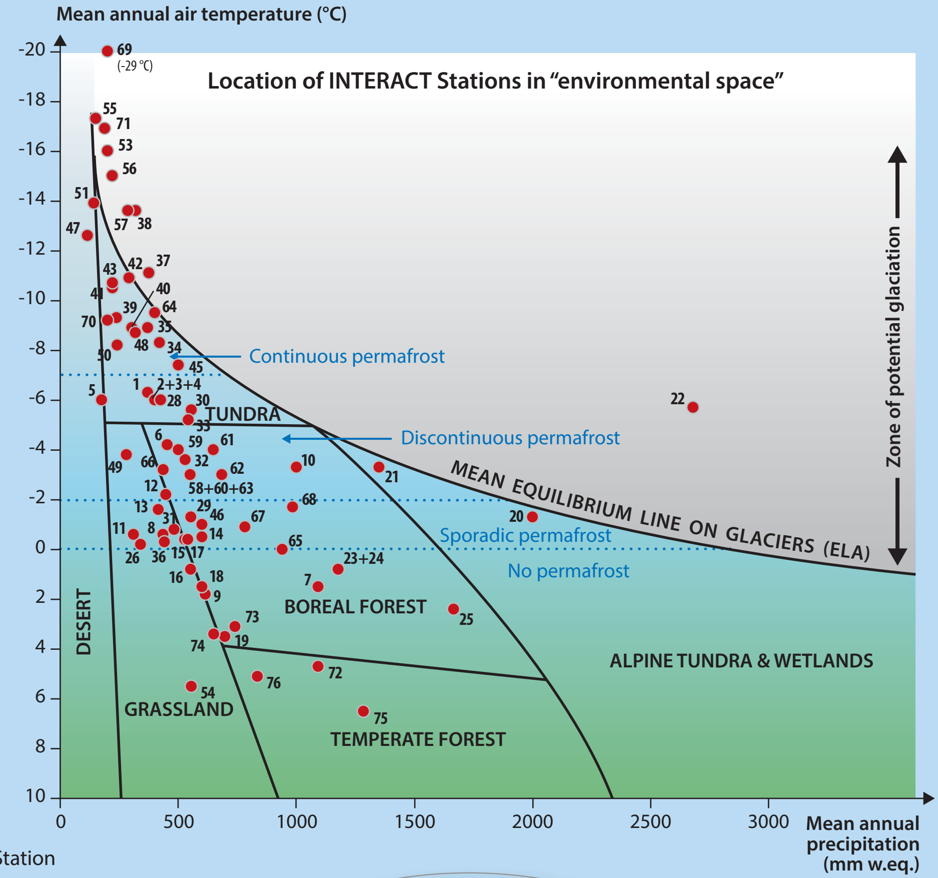
Stories of Arctic Science

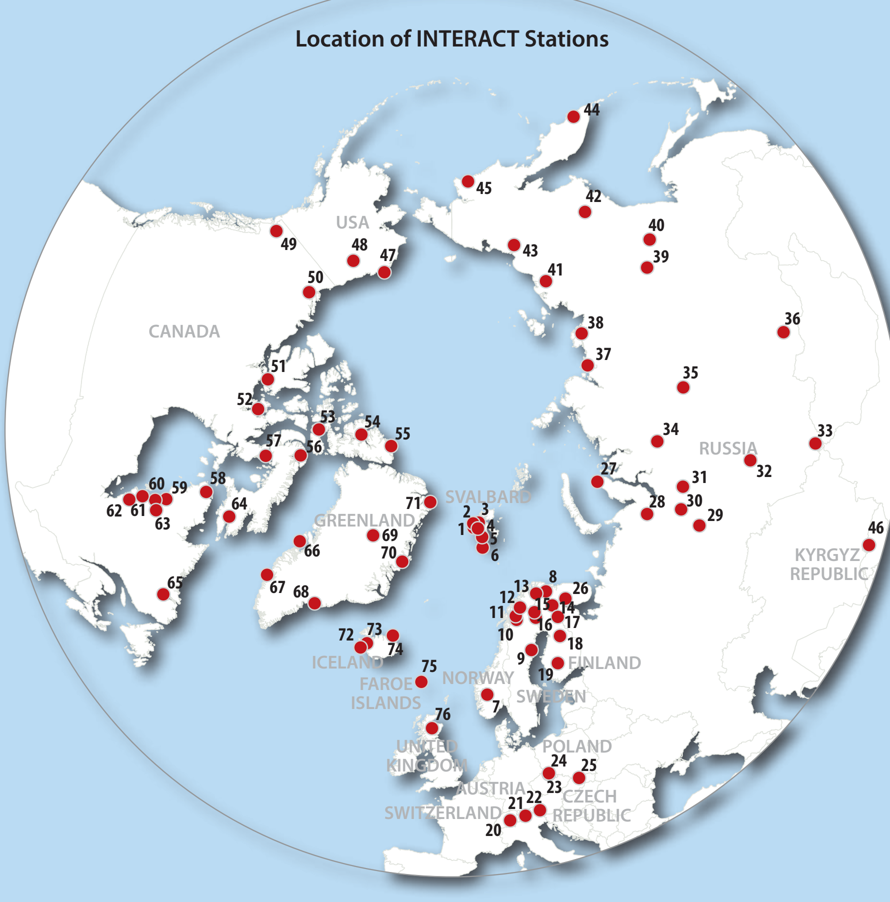
INTERACT Stations

1 Sverdrup Research Station
2 Netherlands' Arctic Station
3 UK Arctic Research Station
4 CNR Arctic Station "Dirigibile Italia"
5 Czech Arctic Research Station of Josef Svoboda
6 Polish Polar Station Hornsund
7 Finse Alpine Research Centre
8 Bioforsk Svanhovd Research Station
9 Svartberget Research Station
10 Tarfala Research Station
11 Abisko Scientific Research Station
12 Kilpisjärvi Biological Station
13 Kevo Subarctic Research Station
14 Värriö Subarctic Research Station
15 Pallas-Sodankylä Stations
16 Kolari Research Unit
17 Oulanka Research Station
18 Kainuu Fisheries Research Station
19 Hyytiälä Forest Research Station (SMEAR II)
20 Alpine Research and Education Station Furka
21 Station Hintereis
22 Sonnblick Observatory
23 Krkonoše Mountains National Park
24 Karkonosze National Park
25 M&M Kłapa Research Station
26 Khibiny Educational and Scientific Station
27 Beliy Island Research Station
28 Labytnangi Ecological Research Station
29 Mukhrino Field Station
30 Numto Park Station
31 Kajbasovo Research Station
32 Khanymey Research Station
33 Aktru Research Station
34 Igarka Geocryology Laboratory
35 Evenkian Field Station
36 International Ecological Educational Center "Istomino"
37 Willem Barents Biological Station
38 Research Station Samoylov Island
39 Spasskaya Pad Scientific Forest Station
40 Elgeeii Scientific Forest Station
41 Chokurdakh Scientific Tundra Station
42 Orotuk Field Station
43 North-East Science Station
44 Avachinsky Volcano Field Station
45 Meinypil'gyno Community Based Biological Station
46 Adygine Research Station
47 Barrow Arctic Research Center/ Barrow Environmental Observatory
48 Toolik Field Station
49 Kluane Lake Research Station
50 Western Arctic Research Centre
51 Canadian High Arctic Research Station
52 M'Clintock Channel Polar Research Cabins
53 Flashline Mars Arctic Research Station
54 Polar Environment Atmospheric Research Laboratory
55 CEN Ward Hunt Island Research Station
56 CEN Bylot Island Field Station
57 Igloolik Research Center
58 CEN Salluit Research Station
59 CEN Boniface River Field Station
60 CEN Umiujaq Research Station
61 CEN Whapmagoostui-Kuujjuarapik Research Station
62 CEN Radisson Ecological Research Station
63 CEN Clearwater Lake Research Station
64 Nunavut Research Institute
65 Labrador Institute Research Station
66 Arctic Station
67 Greenland Institute of Natural Resources
68 Sermilik Research Station
69 EGRIP Field Station
70 Zackenberg Research Station
71 Villum Research Station
72 Sudurnes Science and Learning Center
73 Litla-Skard
74 RIF Field Station
75 Faroe Islands Nature Investigation
76 ECN Cairngorms

INTERACT is a circumarctic network of terrestrial field bases in Arctic, alpine and neighbouring forested areas. The network is funded for 2011-2015 by EU's Seventh Framework Programme as "Integrating Activity" under the theme "Research Infrastructures for Polar Research".

INTERACT has an overarching concept of strategically sampling the great environmental variation throughout northern areas. This concept is illustrated in the graphic below which shows the location of the **INTERACT** Stations within environmental space, defined by temperature and precipitation ranges. Much of research within this book seeks to understand how this environmental space is changing.





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INTERACT
Stories of Arctic Science

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Terry V. Callaghan
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INTERACT Stories of Arctic Science

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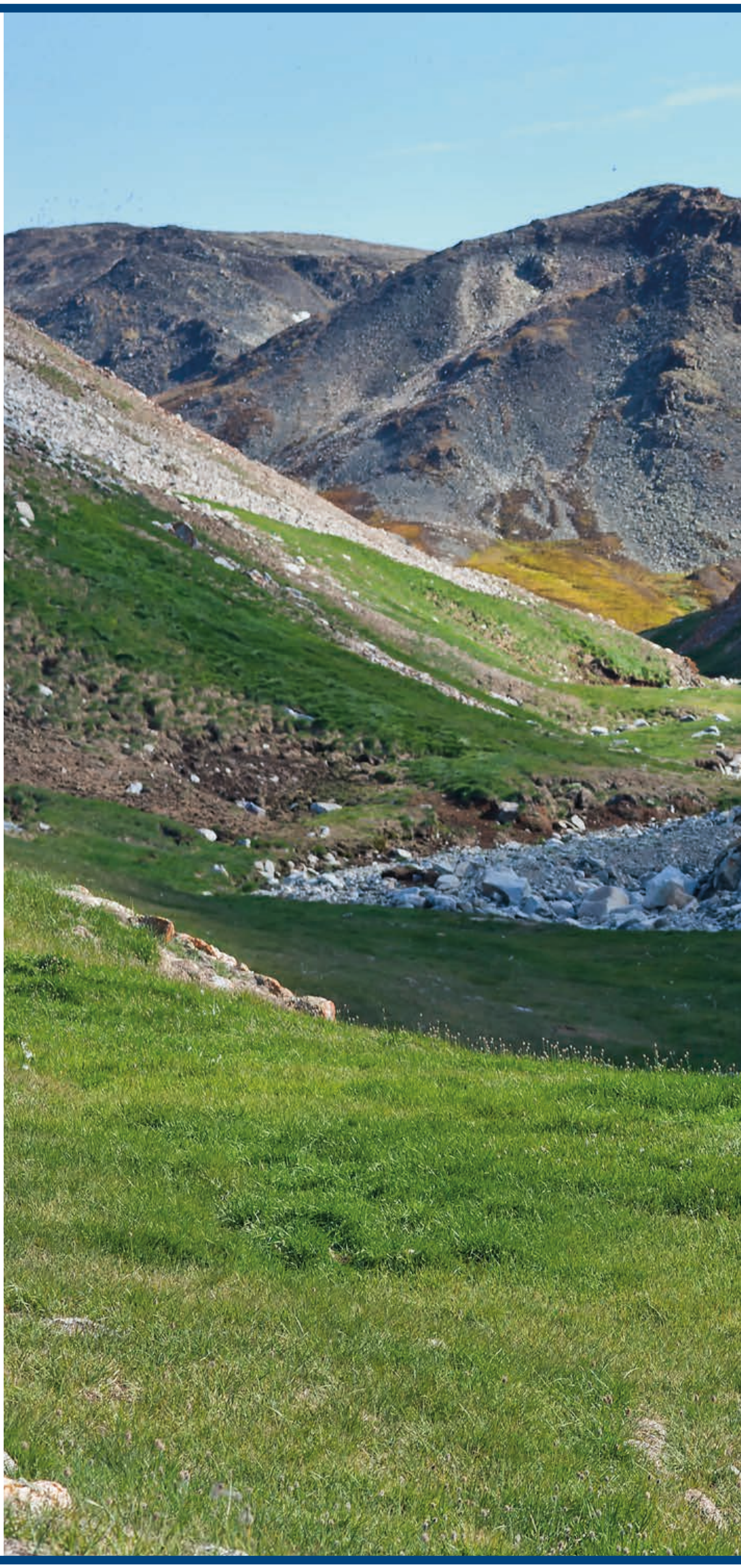


Carsten Egevang/Arc-pic.com

Her Royal Highness Crown Princess Victoria of Sweden

I have had the privilege to make several trips to the Arctic to experience its remarkable nature and wild life, meeting with local residents as well as learning first-hand from researchers working in the field. This experience has given me a deeper appreciation of the importance of understanding and protecting this northern frontier of the planet Earth.

Most importantly, the breadth of research activities, and the long term commitments to observations and measurements are critical for providing solutions to how to predict, prevent, adapt to and mitigate the environmental changes. During my visits to Abisko, and other research stations in the North I have also come to understand the importance of good infrastructure and state-of-the-art technology.

Her Royal Highness Crown Princess Victoria of Sweden and INTERACT Coordinator Terry V. Callaghan pictured at Abisko Scientific Research Station in Sweden (Peter Rosen).

The INTERACT network connects research stations in 17 countries and enables experience and knowledge to be shared. These collective efforts are well reflected in this book. It presents short research stories from around the Arctic and provides a source of knowledge about the fundamental environmental issues of global concern that are taking place there. These stories give a wealth of information about Arctic science in a format which hopefully will inspire new generations of Arctic scientists as well as providing decision makers, teachers and interested readers with essential information.

My hope is that like me you will find this book "INTERACT Stories of Arctic Science" stimulating and a link to further insights and a broader appreciation of the Arctic and its role in a global context.

Katrine Raundrup

Content

Foreword

The Arctic is a vast area with beautiful unspoiled landscapes and a stunning but fragile biodiversity. The Arctic is home to Indigenous Peoples who have been and to a great extent still are depending on resources from the natural environment. In the past decade, the Arctic has gained widespread attention from scientists, the public and politicians because of the rapid changes occurring there. The Arctic's climate is changing faster than climate elsewhere while at the same time many other changes are taking place. These include globalization, exploitation of renewable and non-renewable resources and dramatically increased access. All of these changes provide opportunities as well as challenges to the residents of the Arctic. However, the Arctic is not isolated: the changes occurring in the Arctic have effects on the rest of the world. Retreating glaciers and shrinking ice caps increase global sea level rise that threatens many coastal areas and the people that live there, and carbon-based greenhouse gases released from thawing permafrost could potentially amplify global warming. However, new transport routes could lead to better access for exploiting new resources.

To maximize the opportunities at the same time as responding to challenges requires a well-developed observational record of environmental change together with process understanding that will allow us to predict future changes. Unfortunately, however, the Arctic lands are vast and the human population is small. It is therefore a challenge to document and predict the changes.

In 2001, a small group of nine research stations in the European Arctic came together to share experiences and to develop a more efficient framework for observation and research. This SCANNET network was financed by the European Commission's 5th Framework Programme. Since then, SCANNET has grown, and in 2010 the network consisted of 32 research stations. Together with some research institutions outside the Arctic, the research stations proposed a new collaborative project to the European Commission's 7th Framework Programme. This was the start of INTERACT.

INTERACT started in 2010 as a circumarctic network of 32 terrestrial field bases in Arctic and northern alpine areas of Europe, Asia and North America. However, by 2015, it had grown to 76 research stations. Its main objective is to build capacity for identifying, understanding, predicting and responding to diverse environmental changes throughout the wide environmental and land-use envelopes of the Arctic. Together, the INTERACT stations host many thousands of scientists from around the world working in multiple disciplines, and INTERACT collaborates with many research consortia and international research and monitoring networks. This book presents a fraction of the research projects undertaken at INTERACT stations and shows the great span of scientific activities and the thrilling adventures endured by the visiting scientists.

It is a pleasure to thank all those who were involved in the production of the book and we hope it can educate and inspire the general public and the next generation of scientists to follow in the footsteps of more experienced researchers involved in Arctic science.

On behalf of INTERACT

Terry V. Callaghan[1,2,3], Coordinator of INTERACT
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Telling stories of Arctic science

INTRODUCTION

Terry V. Callaghan & Hannele Savela

WHAT AND WHERE IS THE ARCTIC?

This book is about research into the changing environment of Arctic lands. Everyone has pre-conceived ideas of what the Arctic is and where it is: it is north, it is cold, it is isolated, it is dark and there are few people living there – it is an area of great barren lands covered by ice and snow. However, the Arctic is very diverse and it is very difficult to define. Somewhat surprisingly, definitions depend on the perspective of a scientific discipline or even on government decisions.

Northern lights in October on Lake Dlinnoe, Khibiny Mountains, Kola Peninsula, Russia
(Valentin Zhiganov).

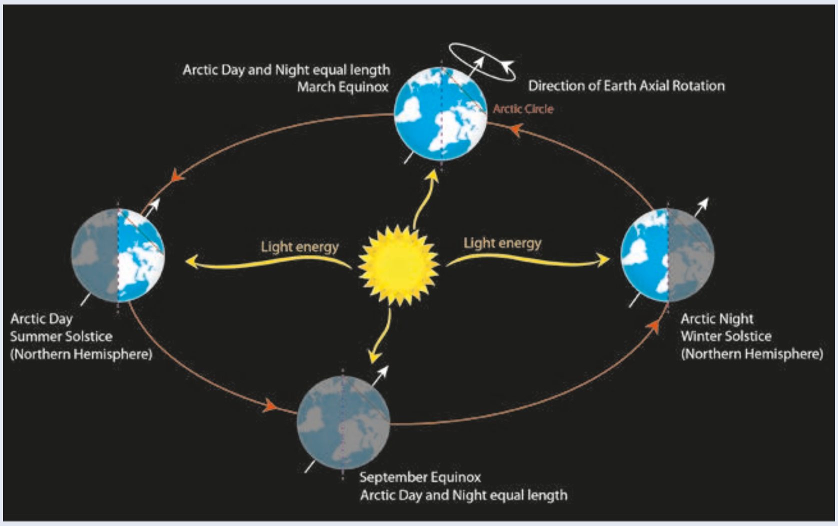


Figure 1. Polar climates are fundamentally controlled by the Earth's tilted axis. At midnight during the summer solstice, the Arctic experiences midnight sun whereas during the winter solstice, the Sun is below the horizon at midday.
Graphic by Hannele Heikkilä-Tuomaala.

Astronomically, the Arctic is the geographic area north of 66.7° N (The Arctic Circle). Beyond that latitude, the Sun is visible at mid-night on mid-summer's day and cannot be seen above the horizon at mid-day on mid-winter's day. These distinct patterns of daylight lead to long, cold winters and brief warm summers (Figure 1). However, a tour around the Arctic teaches us that climate and environmental conditions vary enormously, even at the same latitude, depending on where we are.

At 70° N in northern Norway, Sweden and Finland, there are birch forests and even agriculture. In complete contrast, polar bears and *tundra* (treeless areas) are found at 58° N in Canada – a latitude south of Stockholm, Helsinki and St. Petersburg! (Figure 2) Why? The reason for the environmental contrasts are caused by differences in climate which in turn, are caused by ocean currents (including the Gulf Stream) that bring warm waters from the tropics along the eastern seaboard of the North Atlantic Ocean thereby warming the lands as far east as the

Figure 2. Scenery from two locations of similar latitude (a) Wapusk National Park, Manitoba, Canada, 57 °N (Ansgar Falk/Wikimedia Commons /Creative Commons Attribution 2.5 Generic), **(b) Helsinki, Finland, 60 °N** (Flaneurin/Flickr/ CC BY-NC 2.0).

Figure 3. An environmental definition of the Arctic is the latitudinal *treeline* beyond which trees cannot grow or grow as shrubs (Sergey Kirpotin).

western Russian Arctic. At the same time, cold currents return along the eastern Canadian seaboard thereby cooling the land.

Another difference in climate depends on distance to an ocean. Land areas react much more quickly to changing temperatures than oceans. This results in smaller differences in temperature between summer and winter in islands and coastal areas than in interior land masses where temperatures differ by as much as the record of 100 °C (from +30 °C in summer to -70 °C in winter at Verkhoyansk in the Sakha Republic, Russia). Temperatures also decrease with height above sea level so high mountain areas can be "Arctic-like", for example with glaciers. Elevation therefore "blurs" the southern boundary of the Arctic.

Environmental researchers tend to define the Arctic as the area north of the latitudinal treeline. This definition uses a natural phenomenon as an indicator – the severity of climate that prevents trees from growing. The treeline (Figure 3) is very important because it separates the major "*biomes*" (vegetation-climate zones) of the great coniferous boreal forest (the taiga) from the Arctic tundra and takes into account all those local effects that modify the general climate north and south of the Arctic Circle. North of the treeline, there are relatively few plant species, production is slow, land use is not intensive and there are few people and only a few cities. South of the treeline, we find agriculture, forestry and major cities such as capitals.

In this book, we use a definition of the Arctic in the environmental sense but we do not exclude the areas further south. We cannot understand what is going on in one area when climate is warming without knowing the processes in neighbouring southern areas. Although environmental issues are also important in the atmosphere and at sea, the stories included in this book focus on research on land, including frozen ground, lakes and ponds; from polar deserts in the far North to the vast forests of the *taiga* in the South (Figure 4).

Figure 4. This book includes stories of science from Arctic landscapes including frozen ground, lakes and ponds, from polar deserts in (a) the far North to (b) the vast forests of the taiga in the South ((a) Warwick F. Vincent, (b) Sergey Kirpotin)).

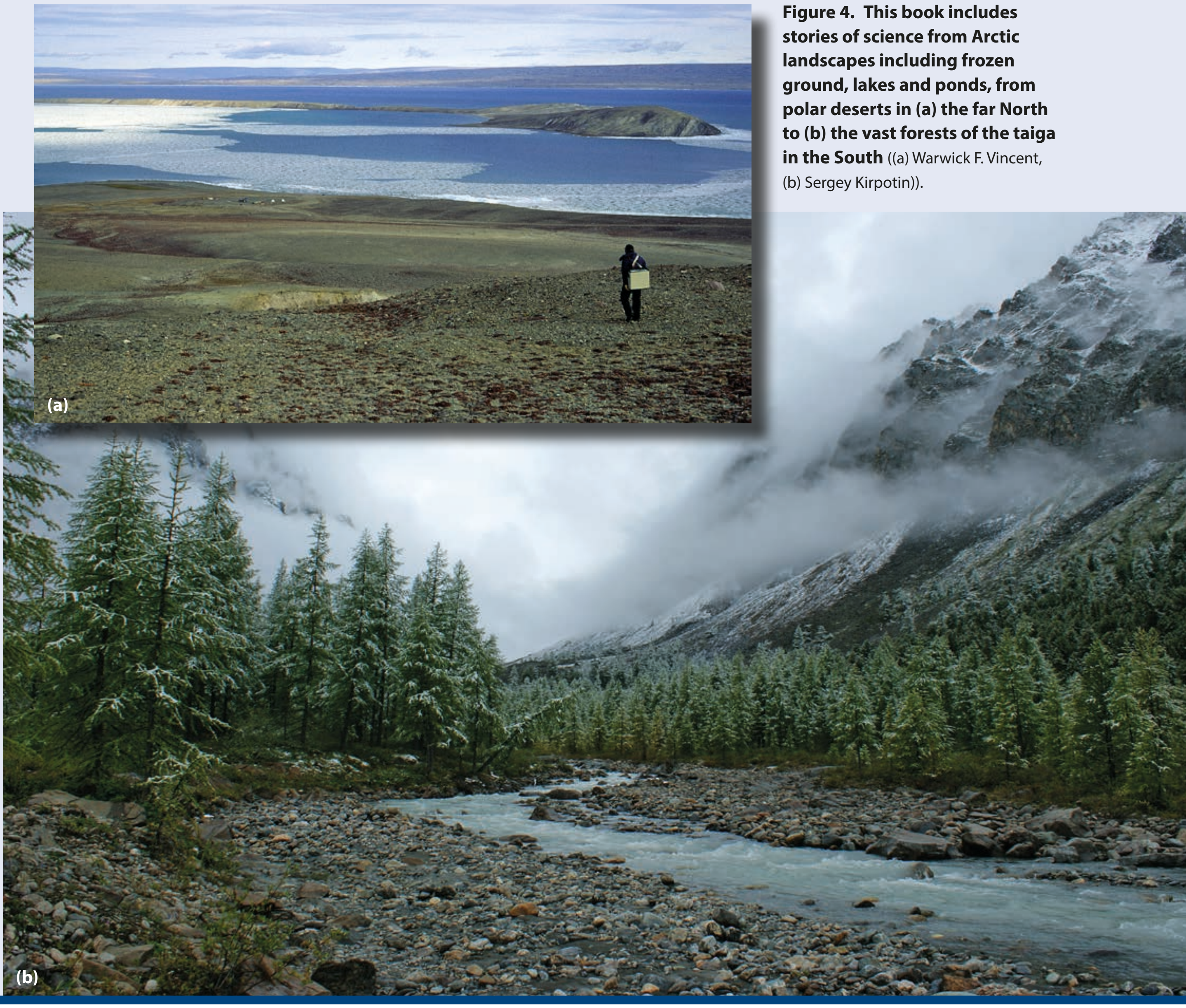


Figure 5. During the last Ice Age, giant herbivores and their predators inhabited vast Arctic plains, many of which are now submerged under the Arctic Ocean (Mauricio Antón/Wikimedia Commons/Creative Commons Attribution 25 Generic).

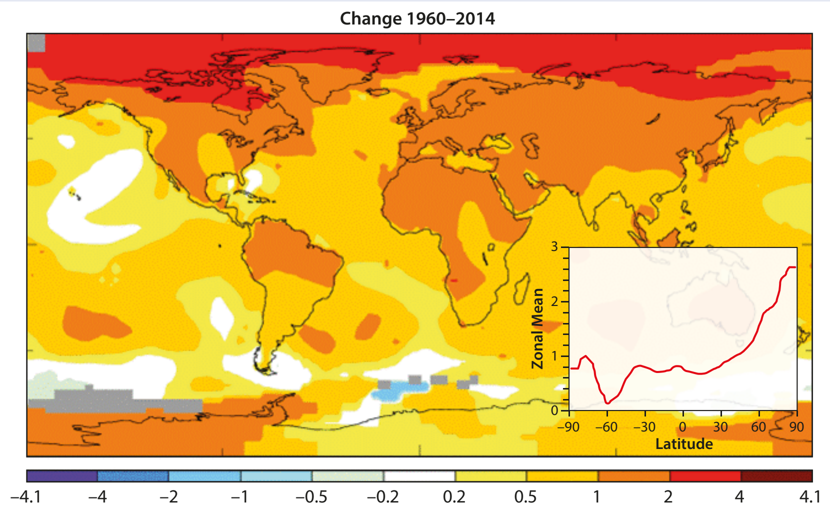
WHY PRODUCE A BOOK ABOUT ARCTIC RESEARCH?

Like in other areas of the world, the landscapes of the Arctic are ever-changing. Eighteen thousand years ago, during the last Ice Age, ice sheets were at their greatest extent. Most of North America, Europe and western Russia were covered by ice sheets, sea level was 120 m lower than today, tundra *ecosystems* stretched much further to the north than today, and giant herbivores (vegetation-eating animals such as the woolly mammoths) and their predators (flesh-eating animals such as sabre-toothed tigers and lions) inhabited the vast tundra and *tundra-steppe* plains (Figure 5). As the ice retreated, its marks on the landscape were revealed: scars on bedrock, *moraines* of debris that glaciers had carried to their fronts, and rivers, streams, soil and vegetation where there was once ice. Vast lowland areas underlain by *permafrost* (permanently frozen ground) developed surface features such as *patterned ground* and *thaw lakes*, and preserved carbon captured by plants over millennia (Figure 6). However, not all areas of the Arctic were covered by ice: parts of Alaska and large areas of central and eastern Russia remained ice-free because of a dry climate. In these areas, deep organic (carbon-rich) soils accumulated mainly through water- and wind-related *sedimentation* processes. Learning about these past processes not only helps us to understand how Arctic landscapes were formed, but gives us an understanding of how these landscapes might also change in the future. Past processes can also help us to understand how future changes might amplify climate warming, for example through the release of carbon preserved in soils as a *greenhouse gas* to the atmosphere (Figure 7).

Figure 6. Vast lowland areas underlain by permafrost (permanently frozen ground) developed surface features such as *palsas*, patterned ground and thaw lakes, and preserved carbon captured by plants over millennia (Anna Konopzcak).

Figure 7. Tower measuring exchanges of carbon dioxide between the land surface and atmosphere (Torben R. Christensen).

Figure 8. Amplified temperature warming in the Arctic (NASA GISS, retrieved from http://nsidc.org/cryosphere/arctic-meteorology/climate_change.html).

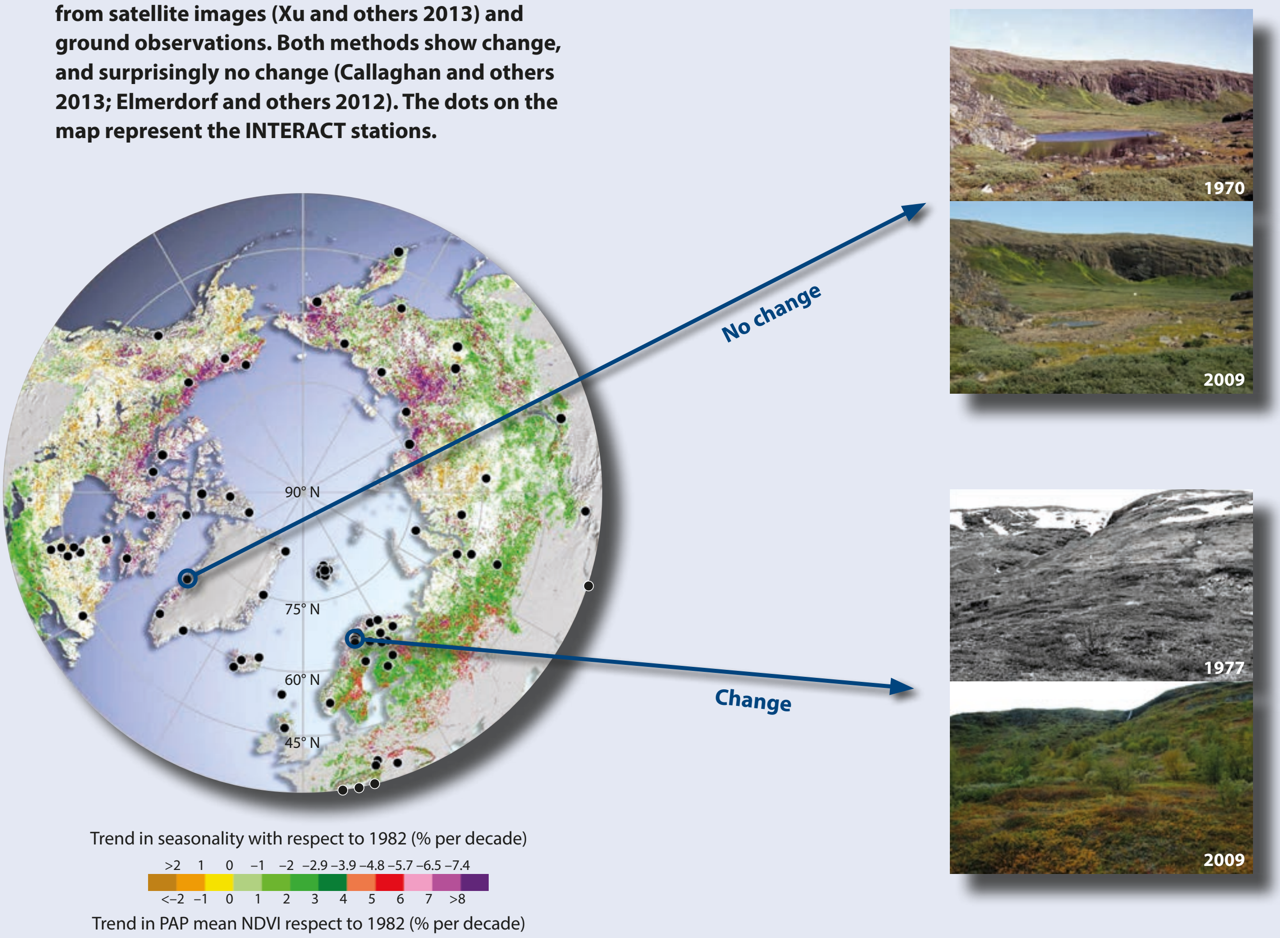


Currently, the environment and ecology of the Arctic and neighbouring territories are changing dramatically. Several different factors are occurring together such as climate change, globalisation of economies and increased use of resources. The changes have been studied in comprehensive international studies (called assessments) such as the Arctic Climate Impacts Assessment (ACIA: www.acia.uaf.edu) in 2005, the Snow, Water, Ice, Permafrost in the Arctic Report (SWIPA: www.amap.no/swipa) in 2011, the Polar Chapter in the Intergovernmental Panel on Climate Change assessment (IPCC: www.ipcc.ch) of 2014, and the Arctic *Biodiversity* Assessment (Meltofte and others 2013).

Climate warming in the Arctic is occurring at over twice the rate as global warming: between 1960 and 2011 mean annual temperatures in the Arctic have risen up to 4 °C (Figure 8) and by the end of the current century they are expected to increase up to 5 °C, compared with present. The recent changes have resulted in decreases in sea ice extent and thickness, ice volume stored in glaciers and snow cover duration. They have also resulted in increases of permafrost temperature and *active layer* thickness (the top layer of soil above permafrost that freezes and thaws each year) and they have affected the dynamics of lake and pond formation and drainage. These changes affect the ecology of the Arctic and ecosystem services to people. Three types of ecosystem services are "provisioning" (for example services that supply food), "regulatory" (services that affect water sources and climate) and "cultural" (services that affect sense of identity) (Millennium Assessment of Ecosystems, www.millenniumassessment.org).

Evidence for ecological changes on land comes from *remote sensing*, from ground-based measurements around the Arctic and local observations (Figure 9). Information on changes is extremely important for local residents who must adapt to changes in their physical environment and in ecosystem services they have previously relied on (Figure 10). However, the changes in the Arctic also have great implications for the global community as the Arctic is linked with the rest of the Earth. Historically, processes called *feedbacks* from Arctic lands to the global climate systems have been cooling the planet. However, during warming there is concern that changes in

Figure 9. Information on ecosystem change comes from satellite images (Xu and others 2013) and ground observations. Both methods show change, and surprisingly no change (Callaghan and others 2013; Elmerdorf and others 2012). The dots on the map represent the INTERACT stations.



the cooling effects will lead to increased global warming. The processes leading to these effects include storage and release of carbon in tundra soils, and changes in the ways in which the Arctic landscape reflects heat energy from the Sun when the duration of snow and sea ice decreases and tall vegetation invades low tundra. Also, loss of ice on land and drainage of water from glaciers and ice sheets contribute to increases in sea level rise. It has been estimated that about 140 million people will suffer from coastal flooding with a sea level rise of 44 cm (assuming no remedial action) and this is expected to take place within the next 50 years (Figure 10).

The changes that are occurring in the Arctic provide both opportunities and challenges to Arctic residents and the global population. Challenges to the local population include changes in traditional ecosystem services such as access to food, insecure travel conditions, potential spread of disease and species invading from the South, while the challenges to the global population are dominated by increasing sea level and possible displacement of substantial populations. In contrast, opportunities to Arctic residents include possible introduction of forestry and agriculture while opportunities to the global community include improved access to oil and gas and more cost-effective shipping routes between Europe and Asia. Unfortunately, the challenges and opportunities are distributed unevenly between disadvantaged populations and trans-border corporations. Such inequalities together with trans-border problems of access to resources and their future availability are likely to have future geo-political implications, and already some minor geo-political disputes have arisen in the North. Understanding change, so that we can live peacefully with it, is becoming ever more important as is the need to work together across borders –a key feature of the INTERACT network of friends that has produced this book.

WHY WRITE STORIES?

There are an increasing number of books, newspaper and magazine articles and scientific papers produced about the Arctic, reflecting the growing interest by the public, students, scientists and politicians. However, they range from very technical books written for specialists to popular natural history books written for the public. Here, we try to produce something of interest to all of these audiences. Stunning pictures provide immediate access to the spectacular and diverse environments of the Arctic, its wildlife and people; overviews provide accessible and up-to-date introductions to complex environmental issues that will inform students and the general public; numerous short stories concisely present on-going research activities in easy-to-understand language to inform the public and even experts of a wide range of current research activities and important topics being studied in the Arctic. Arctic research is also about adventures in beautiful areas. To reflect this, we have added some words in each science story about the excitement of working in the Arctic (Figure 11).

We hope that this book will not just inform as many people as possible, but that it will also inspire you to become involved in protecting this unique environment – either indirectly by taking measures to reduce our carbon footprints, or directly by becoming involved in citizen science (www.eu-interact.org/outreach2/local-engagement/interact-examples/). We also hope the book will be an encouragement to decision makers

Figure 10. Arctic change affects local people and the global community (Arctic fishing (a): EHRENBERG Kommunikation/Flickr/CC BY-SA 2.0. Flooding (b): Stockbyte/World Bank/Flickr/CC BY-NC-SA 2.0).

Figure 11. Adventure – polar bear near the solarimeters by the Polish Polar Station Hornsund (•6), in Svalbard (Marek Szymocha).

to be more active in protecting the Arctic and in ensuring that any development in this fragile area will be sympathetic to the environment, its peoples and its wildlife. Also, we hope the book and its stories, photographs and adventures, will excite and help to recruit the next generation of Arctic researchers. Remember, the Arctic is sparsely populated, is changing rapidly and we need to understand and value the importance of what we have before it changes for ever. Finally, for thousands of years, the Arctic's resilient Indigenous Peoples have shared their extremely important knowledge from generation to generation by telling stories: we have learned from them and adopted this highly successful method of communication in this book (Figure 12).

WHAT IS INTERACT'S ROLE?

The research in this book was supported and facilitated by INTERACT (www.eu-interact.org), an EU-funded Network for Terrestrial Research and Monitoring in the Arctic with contributions from Canada and the USA. The main building blocks of INTERACT are 76 research stations located throughout all the Arctic countries and many neighbouring countries with mountains and/or forests (Figure 9). These research stations are described in a catalogue available on the INTERACT web site (www.eu-interact.org/station-managers-forum/publications/station-catalogue/). INTERACT crosses all national borders in the North and is enthusiastically endorsed at high political levels while working with many Arctic and global environmental organisations. Furthermore, INTERACT is unique in establishing contacts among northern cultures and many sectors of society.

Despite the importance of the changes taking place in the Arctic, our observing power is very low as the Arctic is vast and sparsely populated. Although there are many ways of identifying environmental change in the North, for example by analysing images from satellites, a deep understanding of the changes is often only possible from local knowledge, research on the ground and sophisticated experiments that require research station facilities. Also, it is becoming evident that short-term extreme events such as rain in winter rather than snow, can override long-term trends. These winter events kill animals and plants but unfortunately, we cannot guarantee being in the right place at the right time to observe and understand a short-lived, yet important extreme event. Perhaps surprisingly, there is a large variability in response of ecological processes to climate warming throughout the whole Arctic and even within small areas of the Arctic. As knowledge-based management of environment, biodiversity and resources depends on identifying, understanding and predicting changes, low observing power and even lower predictive power in the Arctic currently limits effective management.

The INTERACT research stations play a fundamental role in improving our knowledge on environmental change and its causes and consequences in the Arctic and neighbouring areas. The stations do this by running long-term monitoring programmes – some of which have been operating for over 100 years – and by hosting researchers from around the world who visit the stations to carry out intensive studies, measurements and experiments (www.eu-interact.org/station-managers-forum/publications/research-and-monitoring/ (Figure 13). INTERACT monitoring and research volume). The stations are therefore "hot spots" of research activity within remote, harsh environments. By networking, the stations share experiences (www.eu-interact.org/station-managers-forum/publications/station-management/) so that measurements throughout the network can be made in the same way and compared. Together, the stations strategically sample the wide "environmental envelope" of the North (the sum of all the varied environments found in the Arctic and neighbouring territories). In addition, the stations also sample the diverse changes – and sometimes surprisingly the lack of changes – that are occurring throughout the Arctic (Figure 9).

Figure 12. Story telling by Arctic Peoples passes knowledge and skills down through the generations. The Sámi family Blind from the Laevas Sameby (Sámi village) prepares firewood at their summer village for next summer's needs (Anna Sarri).

Figure 13. Intensive experiments can only be carried out in harsh conditions with appropriate infrastructure such as that provided by INTERACT research stations (Adam Nawrot).

INTERACT operates by bringing station managers together in a Station Managers' Forum, by contributing to international organisations to communicate and improve science, and by developing new technologies to improve the way we monitor the environment and make the data and results available. In addition, INTERACT gives outreach at all levels, from young school children to state leaders, and provides opportunities to researchers, particularly early career scientists, to visit and work at research stations in harsh and often dangerous environments, but in comparatively safe working conditions established by experienced station staff (Figure 11). This book is an important part of INTERACT's outreach activities and it is based largely on the INTERACT *Transnational Access* programme that enables many researchers to visit some of INTERACT's research stations (Figure 14). Between 2011 and 2014, INTERACT funded 500 researchers to visit research stations in every Arctic country and many neighbouring countries. This book could not include stories from all the projects that were funded. Instead, we have chosen stories that give an indication of the vast range of studies that were supported and that contribute importantly to our improved understanding of the North. All TA projects are listed in the Appendix and described at www.eu-interact.org.

HOW TO USE THIS BOOK?

The book is divided into seven sections that take the reader on a journey of understanding through the Arctic. It includes the processes that form the landscapes, the frozen glaciers and permafrost environments, the ground processes that store and release greenhouse gases, the ecology of land and freshwater and eventually the Peoples of the Arctic. Of course all of these topics are interconnected and together contribute to the "Arctic System" and this, in turn, is part of the "Earth System". To aid communication we refer the reader wherever possible to relevant connections between sections of the book.

Each section starts with an overview written by experts on the topic. The language is for non-experts and there is an abundance of illustrations. After the overviews, there is a series of between 5 and 7 individual stories on a particular detailed aspect of science written by active researchers. Each story is presented in a standard two-page spread for ease of understanding. Contact details and further information sources are given for those who want to know more. A red dot and a number (•#) refers to the location of the station that can be seen on the back side of the front cover flap.

The book cannot of course cover all of the research in the Arctic but it does provide an introduction to the most pressing issues on land. Importantly, and for potential future scientists in particular, it gives snapshots of how research is done and the field conditions that researchers both endure and enjoy. On the other hand, for the specialist, a complete list of environmental research and monitoring activities at INTERACT research stations since the year 2000 can be found at eu-interact.org.

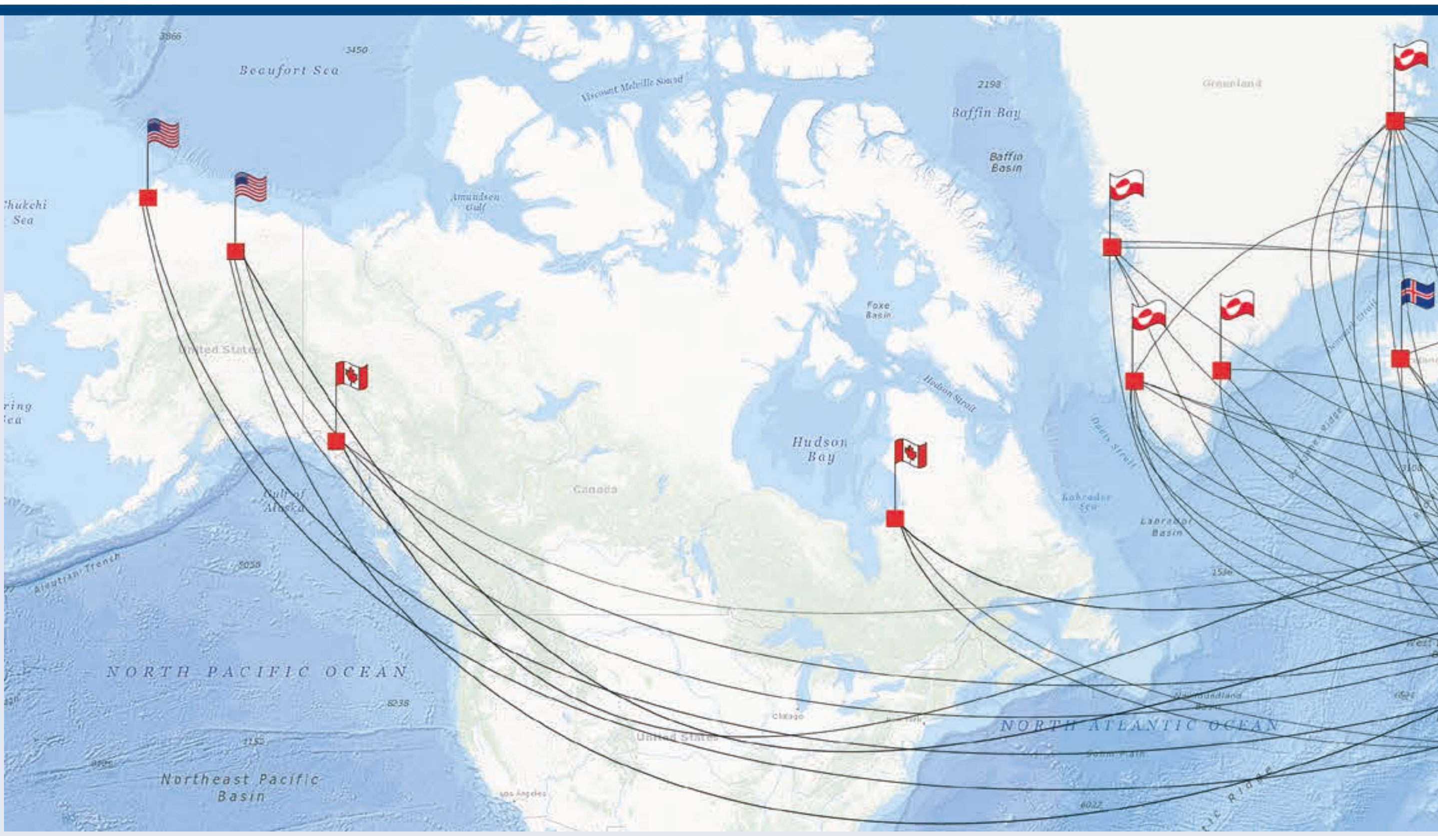


Figure 14. INTERACT's Transnational Access program supported 500 scientists from 19 countries to work at 24 research stations located all over the Arctic for 7300 days in 2011-2015 (Hannele Heikkilä-Tuomaala).

The last story in the book shows how scientific research – in this case studies of permafrost – is essential to calculate the vulnerability of settlements in the Arctic to climate change. Only with this type of knowledge can communities adapt to the changes that are to come.

LEARNING MORE

A book such as this cannot avoid the use of specific terminology but we try to use it carefully and try to explain the terms we use. Specific terms are denoted by italicised font at its first mention in each section and then explained in parentheses or in an on-line glossary of terms and a supporting photo gallery at www.eu-interact.org. For educators, more information can be obtained by direct contact with INTERACT or authors of this book.

The contents of the book will also be presented in an on-line distance learning course "The Changing Arctic Landscape" arranged by Tomsk State University (Russia), INTERACT and the University of the Arctic. More details will be available on the web pages of these institutions. In addition, it is intended to produce this book as an e-book that helps communication even more by presenting video clips and animations of key environmental processes and immediate links via internet to a glossary of terms and a photo-gallery. While this first edition is produced in English, a Russian translation will be available in early 2016.

Acknowledgements

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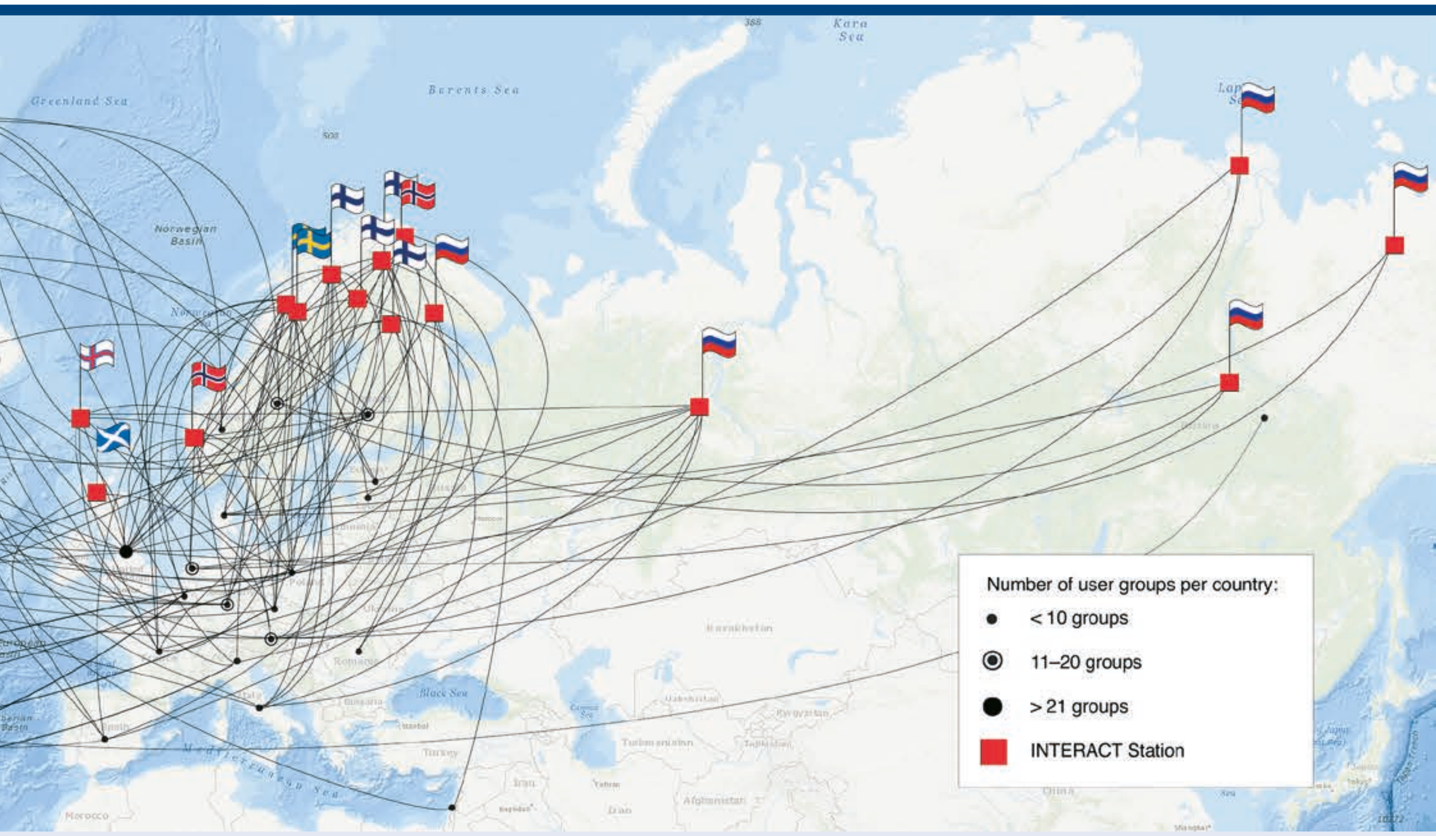

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1 Landscapes and land-forming processes

SECTION OVERVIEW

Wladimir Bleuten & Christer Jonasson

Northern Arctic and sub-Arctic areas include magnificent almost pristine landscapes with large ice caps, glaciers, spectacular U-shaped valleys, wide rivers, waterfalls, wetlands, extensive bogs, *tundra* and *treeline* forests. These landscapes show the effects of *erosion* (break down of rocks by frost, thaw and temperature changes) and *sedimentation* (transport and deposition of these materials by glacial ice, water and wind) during glaciations of the Pleistocene (2.5 million to 12 thousand years ago) followed by the *Holocene* (the last 11 thousand years) post glacial geomorphological (land-forming) processes. The cold Arctic climate and relative lack of environmental "engineering" by plants enable previously developed landforms to remain intact for a long time. For example, granite outcrops in northern Norway have weathered at about 2 mm per 1,000 years and have remained without a vegetation cover for about 10,000 years. In many places the processes, which created these landforms, are still active or can be seen in comparable areas nearby.

Some *geomorphological* processes are unique for Arctic areas, such as those connected with ground frost and *permafrost* and an intense snow-melt period where precipitation accumulated over several months is discharged during only a few weeks, leading to flooding and *slush avalanches*.

In general, geomorphological processes in the mountain areas of the Arctic are more intense than in temperate areas because of frost and snowmelt and lack of protective vegetation. As global warming is amplified in the Arctic, significant changes are expected in geomorphological processes there, and the Arctic is becoming a major natural laboratory for scientific studies of climate-driven landscape-changing processes.

Mountain side features in Kong Oscar Fjord, Northeast Greenland (Morten Rasch).

The landscapes of Arctic mountains and of high mountains in temperate and even in tropical areas are formed by extensive and deep glacial erosion that typically results in U-shaped valleys and fjords. Examples can be found along the coasts of Greenland and Norway. Flat-topped mountains remain where ice-caps melted away but some jagged rocks (*nunataks*) protrude above such high plateaus showing erosion marks and indicate the level of the former glacier ice. Landscapes of lower Arctic mountain ranges (e.g. Central and East Siberia) show the effects of *periglacial* conditions ("periglacial" refers to landscapes with a tundra climate (summer temperature below 10 °C) close to ice sheets and glaciers and in other high latitude areas not covered by ice-sheets: French, 2007) that have led to the formation of gentle slopes with *stone stripes* (linear features where rock fragments create channels or elongated hills/mounds) and *rock glaciers* ("rivers" of frozen rocks slowly moving downslope) at the higher levels and *solifluction tongues* (movement of wet soil above a permafrost layer) at the lower levels. In contrast to mountains, the landforms in lowland areas have been formed mainly from sedimentation by rivers in deltas and wide floodplains. The resulting landforms of r*iver terraces, mires* (peat accumulating vegetation) and extensive plains are then transformed by periglacial processes resulting from permafrost dynamics (Section 2) and wind action. As a result of climate warming after the last glaciation, mires developed in depressions on flat areas on *water divides*, on river terraces and floodplains far from river channels. These mires became extensive during the Holocene, particularly in Canada and Siberia. Mire vegetation, and in particular *Sphagnum* mosses, have sequestered atmospheric carbon dioxide through photosynthesis and historically, this has provided a negative *feedback* (dampening) of past climate warming. However, current climate warming could change this feedback into an amplification of warming (Section 4).

In this section, the appearance, properties and dynamics of landforms are presented as a framework in which to understand the dynamics of physical and biological processes in relation to climate warming. The geomorphological processes are being studied on the ground and by *remote sensing* techniques (e.g. Science Story 1.1).

LANDFORMS OF ARCTIC MOUNTAIN AREAS

In Arctic and sub-Arctic mountain areas, it is possible to study the landforms resulting from glaciers that excavate valleys and lead to accumulation of sediments while in action. During several glaciation periods of the Pleistocene, great parts of northern Europe, Asia and northern America were covered with ice caps and ice sheets. However, because of the dry Arctic climate in central and eastern parts of Siberia, vast areas were not covered by ice-sheets (Figure 1.1). Instead, these areas experienced harsh climatic conditions and deep and widespread permafrost developed. After the last glaciation, which ended ca. 12,000 years BP (before present), most of the ice sheets covering lowland areas gradually disappeared, leaving today a few ice caps on mountain areas (in Alaska, Canada, Scandinavia, Svalbard and the Russian Arctic islands) and the extensive Greenland Ice Sheet.

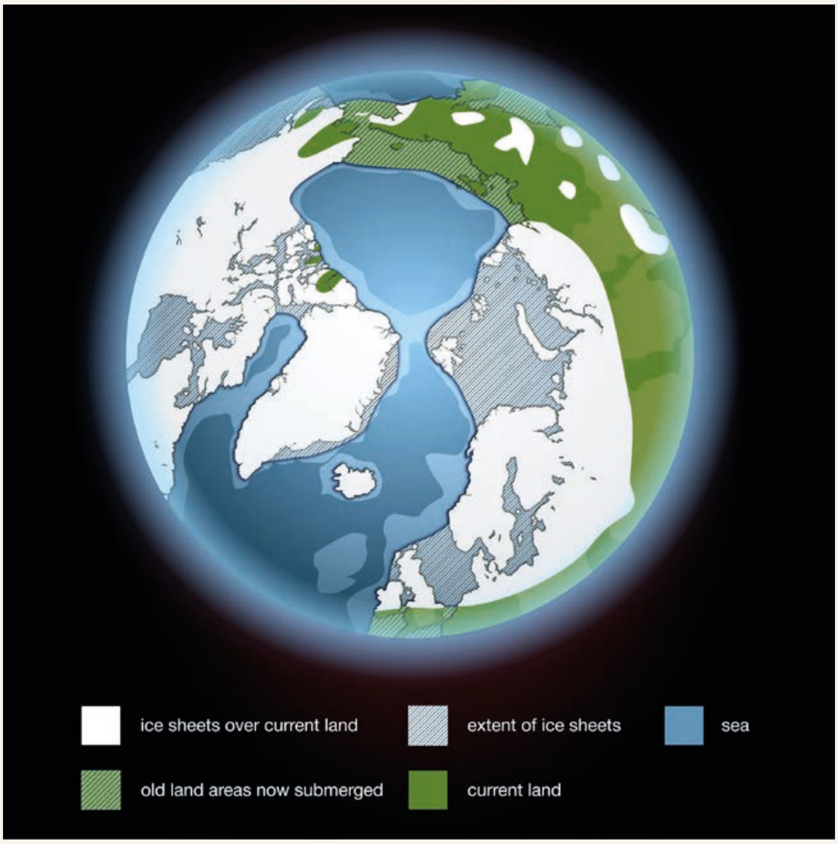

Figure 1.1 Map of glacial areas 18,000 years ago when the last Ice Age was at its height. Sea level was 120 m lower than today, eastern Asia was connected to North America and the Siberian coastline extended far north of today's coastline (Arview, Tomsk, Russia).

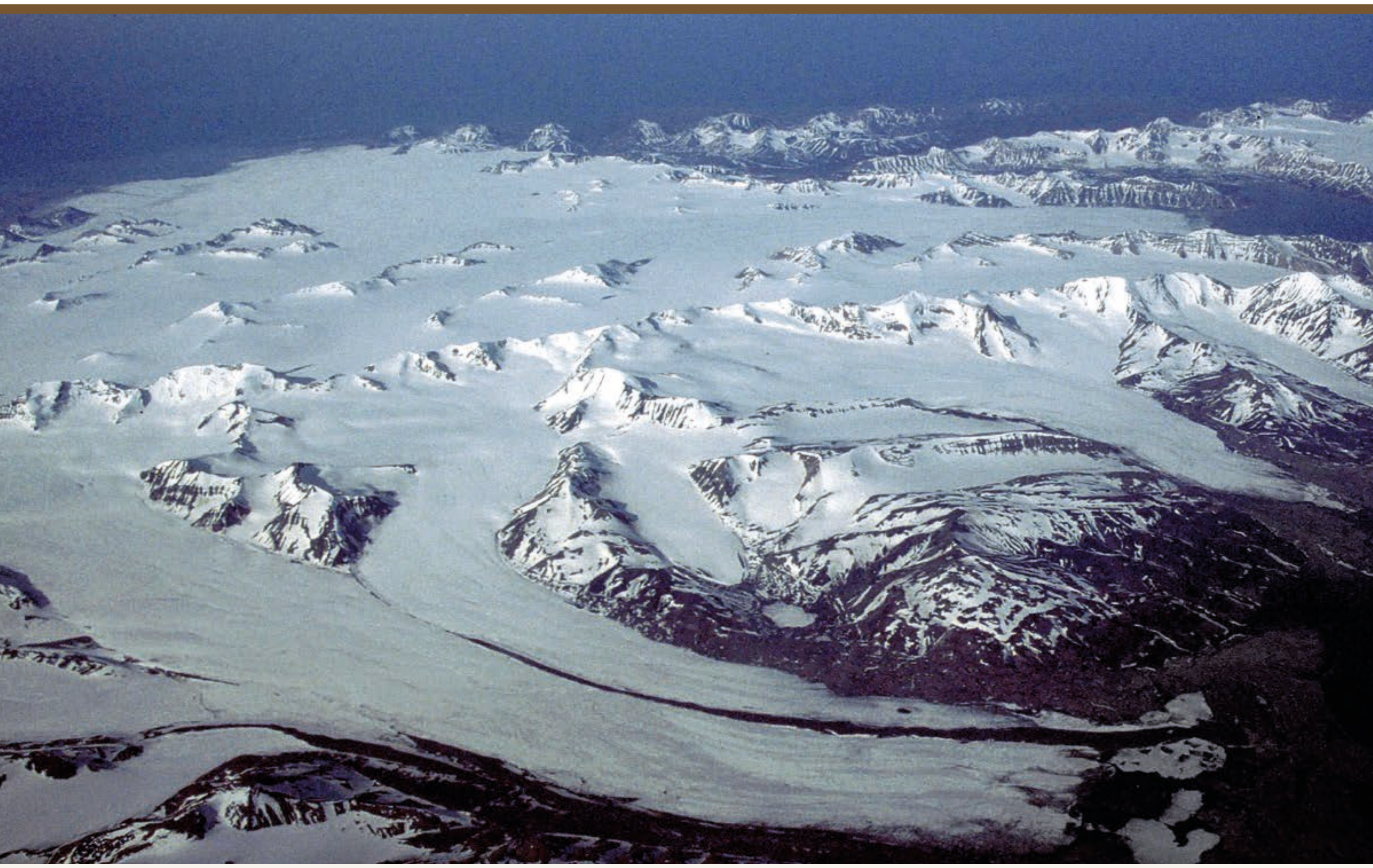

Figure 1.2 Mountain side rock debris is transported inside or in front of glaciers. Where glaciers from different valleys join, dark bands of debris can be seen. Nunataks (ice-free mountain tops) can be seen in the middle of the ice cap (Terry V. Callaghan).

Ice caps are formed by the accumulation of snow, which changes into ice by compression under its own weight (Section 3). The ice layers developed are overlaid with more and more snow and ice layers. The resulting pressure makes the ice plastic and it flows slowly downhill at outlet points as glaciers. Little is known about what happens to the *subglacial* land surfaces at the interface between ice and rocks. Consequently, evidence of subglacial erosion was looked for on the Finnish-Russian Kola Peninsula (Science Story 1.2). This area has a flat-topped granite dome which was covered with an ice-cap during the last glaciation.

At the margins of the ice caps, "outlet" glaciers are formed in valleys that were already present before the ice caps developed. Compared to the central parts of the ice-caps, the ice flow rates at the glacier bottom increases substantially. Locally, the temperature at the glacier bottom may rise above the freezing point either for a short period or continuously: in these conditions, the glacier is called a "warm glacier". The sequential freezing and thawing at the glacier bottom, combined with the force of the moving ice-mass, excavate rock and loose material on the valley bottom and side slopes and this is transported by the moving ice to the lower end of the glacier. There, by *ablation* (evaporation of melted ice and run-off of melt water) of the glacier ice, the transported rock material is deposited at the glacier sides and front. Where valley slopes rise above the glaciers, rock material may fall on top of the glacier and this material is then transported within and in front of the ice (Figure 1.2). Along the lower parts of the glacier, elongated *side-moraines* are formed (Section 3), consisting of rock material of both the valley floor glacial deposits (*tills*) and valley slope debris. At the glacier front, banana shaped *end-moraines* are formed (Figure 1.3). Both moraine types contain *ice lenses* as well as boulders and till. Such ice lenses have been studied in Science Story 1.3 and 1.4. The moraines formed are most prominent during periods when the glacier front is stationary and the supply of glacier ice equals melting rate.

When the snow accumulation on ice-caps and glacier head zones (*firn zones*) decreases, for example through climate warming, glacier fronts retreat (Section 3) leaving moraines behind. Glaciers in mountains without ice-caps generally move ice from the highest parts (*cirques*) down slope through the glacial valleys and develop moraine landforms comparable to those of outlet-glaciers. Study of the location of successive moraine ridges reveals glacial stages which can be related

Figure 1.3 Cirques are bowls resulting from ice scouring near the heads of glaciers. Below the glacier is a pro-glacial lake dammed by moraines. The glacier is Vaktpostglaciären, situated in the Valley Unna Räitavaggen in northern Sweden (P. Holmlund, taken in August 2011).

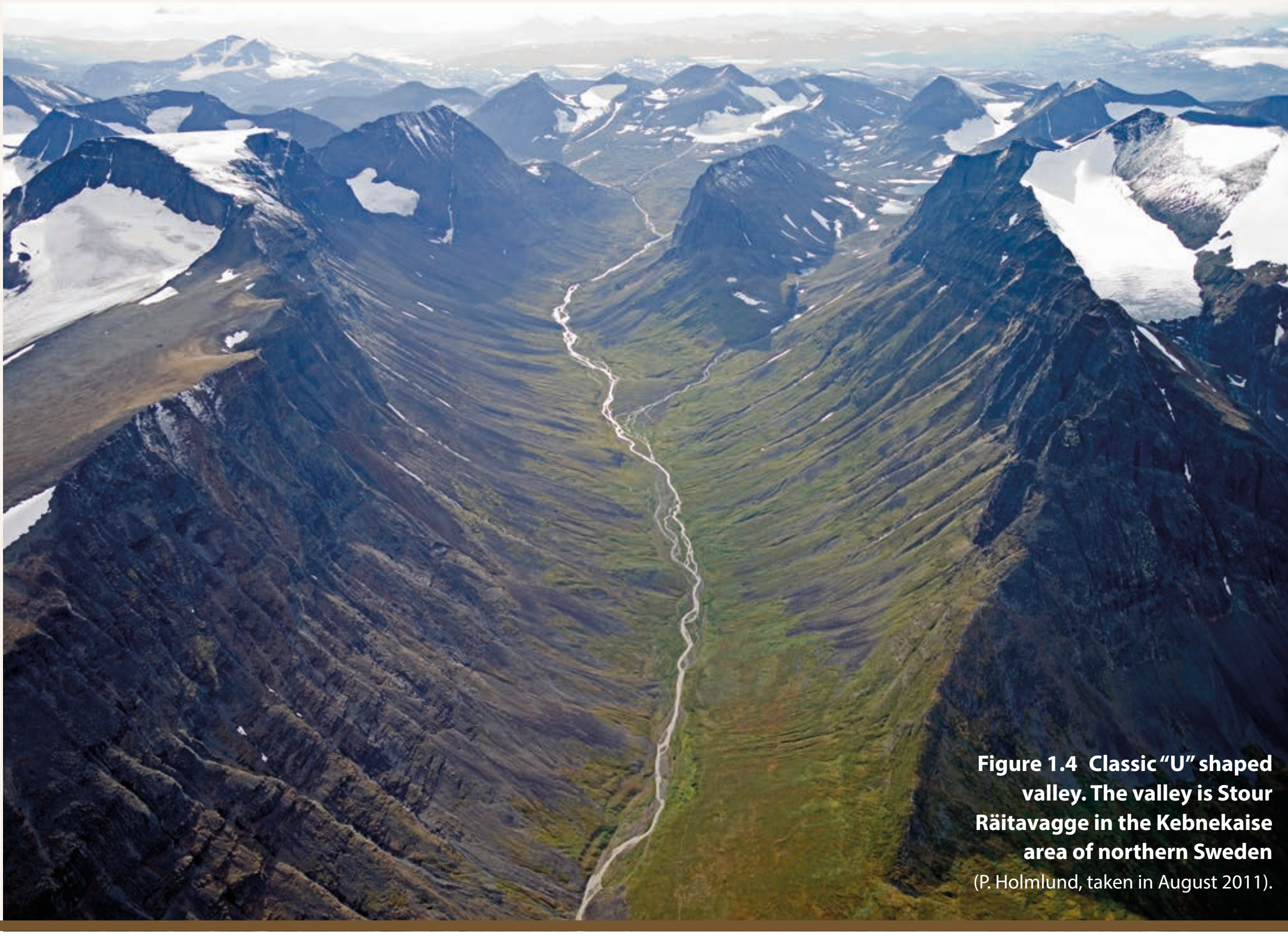

Figure 1.4 Classic "U" shaped valley. The valley is Stour Räitavagge in the Kebnekaise area of northern Sweden (P. Holmlund, taken in August 2011).

to climate changes. The entire process of glacial erosion leads to the development of the typical *U-shaped* glacial valleys which appear after glacier retreat (Figure 1.4). It also leads to the erosion of the mountains in the head zones where cirque glaciers break up mountain ridges (Figure 1.3).

At the end of the last glacial period, some of the ice caps, for example in sub-Arctic Scandinavia, melted and the former land-forms covered with ice in the glacial period were released as relicts. Also, during the last glaciation, many Arctic mountain ridges were covered with snow and ice with only sporadic "nunataks" protruding through (Figure 1.2). As climate warmed, the slopes below the nunataks became ice free and the nunataks joined together forming rocky, snow-free mountain ridges. Sometimes, glaciers connected ice-free areas to the mainland and when they melted, former peninsulas became islands. These processes can be seen on Svalbard (Ziaja and Ostafin 2014).

Sometimes, the Pleistocene ice sheets in Scandinavia, Greenland, and North America were very thick (several kilometers) and exerted sufficient pressure to push the Earth's crust down. After the end of the last Pleistocene glaciation that pressure decreased, resulting in a slow rebound of the Earth's crust called "*isostatic uplift*". This uplift is active still today. In some places it compensates for, or even exceeds the sea level rise, for example in parts of Greenland and Scandinavia.

In certain locations, lakes may develop where water flows toward a glacier via side-valleys. Such lakes may gradually fill up with sediments. After the glacier melts, these deposits remain as *kame-terraces*, having almost flat top surface and steep scarps (slopes) at the margins. The internal orientation of debris, structure of layers and presence of ice lenses has been studied in Science Story 1.4 to determine the date of sediment deposition and glacier stage.

In addition to glacial processes, different kinds of weathering and mass movements have sculptured the Arctic mountain slopes. Also, frost action creates landforms like *patterned ground* where rock fragments are sorted and moved by soil freezing and thawing. These processes result in *sorted steps, stone stripes* and other kinds of linear features where rock fragments create channels or elongated hills. A typical Arctic mountain slope (Figure 1.5) consists of a free face, which is affected by frost action and physical weathering, creating a *talus* slope beneath. Below the talus slopes, slow mass movement processes are normally active. These include *solifluction,* slow slope movement called *creep*. Several studies have shown that the geomorphological development of Arctic mountain slopes is dominated by rapid mass movements like avalanches, *slush avalanches*, *slides* and *debris flows*. These processes seldom occur but they have a high intensity as extreme events which can be triggered by an intense snowmelt or rainfall.

Figure 1.5 Mountain side features in Adventdalen, Svalbard (Terry V. Callaghan).

Figure 1.6 A classic braided meltwater stream from Ruotesjekna entering Ruotesvagge in Sarek, northern Sweden (P. Holmlund, taken in August 2012).

Meltwater discharge from glaciers form multi-channel, shallow streams (*braided streams:* Figure 1.6), which transport high masses of gravel, sand and *silt* material, sometimes extending across the complete valley floor. Lower valley depressions as well as reservoirs can be filled up rapidly by these sediments.

Climate warming is leading to the melting of glaciers (Section 3) and increased fresh water flow to the oceans. This contributes to increased sea level that will lead to worldwide coastal flooding. Calculating the volume of glacier ice that can be melted by a unit temperature rise is one of the important issues in this field of geosciences. Such melting rate estimates are based on mass volume of the glaciers (and ice-caps feeding these glaciers), snow accumulation, solar insulation and top-ice temperature. The volume of ice that is prone to melting also depends on sub-ice temperature which is an important factor determining ice flow velocity. Intensive research efforts have been made and are still continuing to quantify the snow and ice mass balances of glaciers and ice sheets that cover the highlands of the Arctic. The Science Story 1.3 describes how sediments present in valley head depressions (cirques) have been studied for the estimation of ice mass volumes.

The thawing of glacier ice is also affected by ice-thickness and *sub-ice relief*. Unlike the downstream slope of rivers, the subglacial valley floor undulates in the down-flow direction. Deeply excavated valley floor sections are followed by higher, less eroded areas downslope. These form "thresholds" for subglacial water flow. Further retreat of these fronts can result in sudden catastrophic peak discharge of subglacial lakes present in depressions when thresholds are freed from ice and breached. Glacier melting as a result of climate warming can make glacial lakes a threat downhill because of the risk of sudden massive water release through the formation of subglacial siphons and by collapse of moraine ridges as studied in Science Story 1.5 and the publication by Rudoy in 2002.

Another impact caused by enhanced temperatures is the melting of mountain permafrost, which might lead to increased mass movement activity and risk of damage to infrastructure such as roads and railroads. Mountain sides, freshly freed from glacier ice, may be unstable after release of their support by glacial ice. In particular, kame terraces, side- and end-moraines and valley slopes become prone to mass movements. Furthermore, the raised melt-water peak discharge of river water that contains a high amount of transported sediments, may give rise to downstream floods and bury existing land surfaces. Such high river discharges alternate with gentle flows that produce sediment layers of variable thickness and grain size (*varves*) on lake beds. By coring the sediments, the "*hydro-dynamic*" conditions during the deposition of these varves can be reconstructed, quantified and related to climate changes (Section 6).

The processes that form the mountain landscapes of the North have been studied at INTERACT research stations from high Arctic glaciated areas to ice-free sub-Arctic areas and these stations are a resource for further studies.

LANDFORMS OF ARCTIC LOWLAND AREAS

In Arctic lowland areas, the traces of the last or even earlier ice-sheet processes can be studied. The high pressure from prolonged movements of ice sheets over lowland areas produces wide ice-tongue depressions from where the loose soil materials have been pushed forward. Today, these depressions are often filled with large lakes. Together with the transported *subglacial tills* and rocks on top of the ice sheets, these soil materials formed series of ice-pushed moraine hills. These hills form ridges that can be recognized in large areas of Europe, Canada, Alaska and Russia.

Moraine ridges representing stationary stages of ice-sheet fronts are the best locations for dating the deglaciation stages and for comparing these stages with climate change derived from other climate approximations dating from the same time period. Remnants of subglacial meltwater courses from below the ice-sheets are preserved as narrow, but elongated, sometimes meandering hills (*eskers*) and their size and sediment properties may help identify the source areas of the ice-sheet and estimate the ice volume during their formation. Many elongated and sometimes very deep lakes in the areas formerly covered by ice-sheets occupy former subglacial river beds and further carving by flowing ice. These lakes contain very interesting varve sediments, which can be used to reconstruct past climates. Other important geomorphological features of landscapes formed by ice-sheets are *glacial tills* and so called "*dead-ice"* hollows. Glacial tills that consist of unsorted sediments (mixtures of boulders, gravel, sand, silt and clay), left behind after disappearance of the ice sheet, can be present over large areas. Tills with high loam and clay content can cause water ponding and lead to peat accumulation above. Dead-ice hollows are formed where isolated remnants of sheet-ice remain after general ice melting. Where such ice blocks were present near the ice-sheet front, the deposition of sediments was prevented. Later, when the ice sheet front had retreated further, the sediment supply diminished, the dead-ice melted, and depressions remained. Many lakes have been formed in this way, in particular in the area in front of the glacier where gravel and sand were transported and deposited by multi-channel overland flow (by the braided streams and rivers). Where lakes are not present, *sandr's* form. These are gently sloping surfaces (ideal places for airport runways) in front of the ice-sheet and downhill from the end-moraine ridges (Figures 1.3 and 1.5). They can cover zones tens of kilometres wide and up to hundreds of kilometres long (in West Siberia) and are common in formerly glaciated areas of the Arctic and sub-Arctic zones.

In periglacial areas, because of low temperatures, most of the soils and rocks near the surface are frozen (Section 2) and only a thin superficial layer thaws in summer (the "*active layer*"). Vegetation of these periglacial areas is scarce and bare, and

Figure 1.7 Stone circles in polar desert on Cornwallis Island, high Arctic Canada (Terry V. Callaghan).

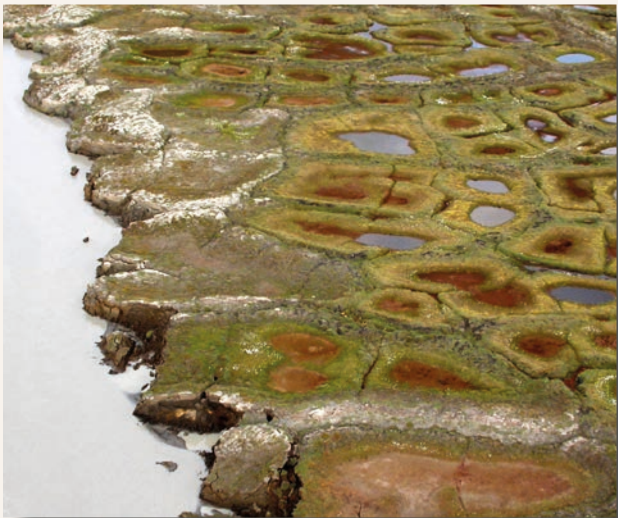

Figure 1.8 Tundra polygons on Bylot Island, Canada (Isabelle Laurion).

Figure 1.9 Yedoma (soils with high carbon content resulting from wind-blown soil deposits) Duvannyi Yar, Russia (Jorien Vonk).

gravelly soils are common. Such periglacial environments are called polar deserts and semi-deserts and can be found and studied today in the surroundings of high Arctic INTERACT stations. In such lowland regions sedimentation processes have been dominating during the post-glacial period. Both seasonal ground frost and permafrost create distinct landforms in Arctic lowland areas. The frost action creates different kinds of patterned ground phenomena, like *stone rings* (networks of sorted stones creating circles) in polar deserts (Figure 1.7), *ice-wedges,* and *tundra polygons* (see Sections 2 and 6 and Figure 1.8) in vegetated, tundra areas.

In peat areas, *palsas* may develop. These are local permafrost features caused by intense cooling during winter periods, when ice-lenses are developed that lift the surface of the peat forming mounds (Section 2). These mounds can be more than 10 metres high and are underlain by permafrost. In summertime, the uplifted peat layer becomes dry, thereby insulating and protecting the ice layers below.

The continental tundra climate is generally very dry because of low precipitation and low evaporation. Therefore, after snow melt, the top soil becomes dry and susceptible to wind erosion. Wind erosion was very active during the Pleistocene glaciations when a broad zone of Europe, Asia, and North America had a tundra climate and the land mass extended over what is now submerged continental shelves. Windblown sand and in particular silt (grain size 50 µm) was deposited in downwind areas and in lee areas of valleys. The material deposited (*loess*) covered wide areas and formed very thick *Yedoma deposits* in Siberia (Figure 1.9). These deposits include relatively high contents of easily decomposable organic matter preserved by permafrost after being covered by succeeding windblown sediments (Science Story 4.2).

In areas where large quantities of windblown sands and silts were deposited, the drainage networks, except for the big rivers, are disturbed and/or weakly developed. The permafrost hinders the development of valleys and a river network. The water from snowmelt and summer rainfall cannot infiltrate into the soil and consequently flows overland (*sheet flow*) and downhill to existing rivers. Frequently, sheet flows and mass movements of super-saturated water-sediment mixtures move down slope and fill up small river tributaries. As a result of such periglacial processes, valley slopes become concave in cross section in contrast to convex valley slopes resulting from river erosion under moderate climates.

Typical periglacial rivers are shallow, have many channels and transport relatively high masses of sediments, particularly in spring. The numerous Arctic lakes developed by collapses in both mineral and peat soils (*thermokarst*) (Figure 1.10) delays the development of river networks for long periods. Because of these hydrological conditions the resulting landscapes have very wet soils.

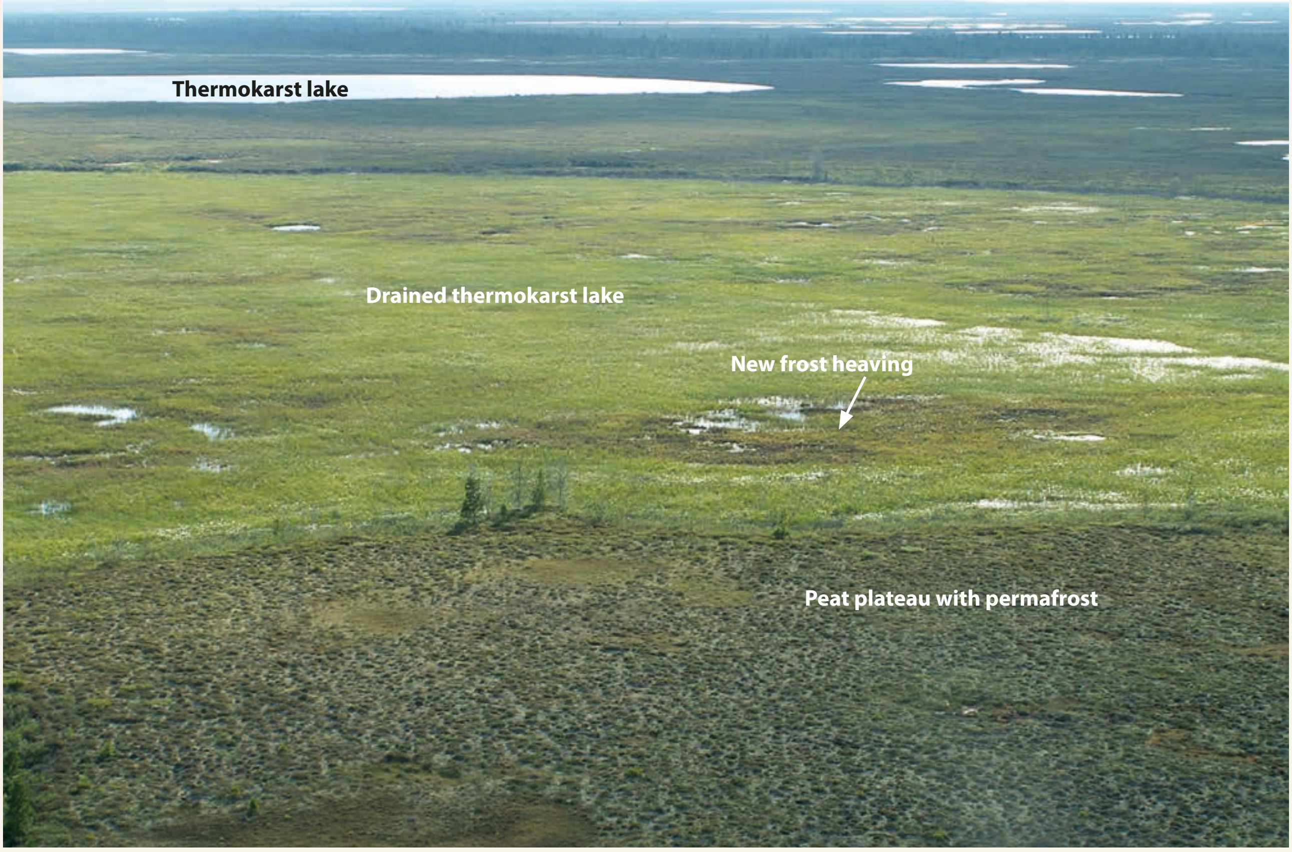

Figure 1.10 Stages of thermokarst lake development in Siberia (N 64.7° N, 75.4° E). Peat plateaus erode as permafrost thaws to form thermokarst lakes which drain to form khasyrei, which then accumulate permafrost to form palsa plateaus (Wladimir Bleuten).

At the beginning of the Holocene, the climate became warmer but the surface remained very wet because permafrost was still present and there was a lack of an efficient drainage system. Such conditions promote the development of peat accumulating vegetation (mires) with *Sphagnum* mosses, sedges, cotton grass, dwarf shrubs and, in slightly drier places, stunted trees. The mires spread far to the north up to the Arctic Ocean during the *Holocene Thermal Maximum* period (HTM) and the following wet, cool period (10 to 5 thousand years BP) (Hunt and others 2013). These peat layers became frozen during colder periods after the HTM when ice-lenses formed in the peat. These ice lenses and pore ice in the peat lifted up the surface of the peat to form *peat plateaus*, intersected by shallow rivers. Later rises in temperature caused parts of the peat plateaus to thaw and collapse (resulting in "thermokarst" features: see Section 2). The resulting depressions filled up with water forming numerous lakes typical for the Arctic and sub-Arctic circumpolar zones. Frost action and thawing and collapse ("slumping") of the lake shores enlarge the areas of these thermokarst lakes which eventually join each other. However, if the permafrost below the lakes thaws or surface connections between thermokarst lakes and draining rivers form, the thermokarst lakes can drain and become dry forming "*khasyrei*". The beds of these drained lakes can freeze again and lift the lake beds (Figure 1.10; Kirpotin and others 2007). It is expected that this cycling process will be broken by on-going and predicted future global temperature rise and already, areas of lake disappearance have been observed in permafrost areas in Arctic North America (Hinzman and others 2005) and Russia (Smith and others 2005), although some lake formation has also been observed (but to a lesser degree particularly in areas of continuous permafrost in Siberia).

The peat accumulation by Arctic and sub-Arctic mires that occurred over large, former periglacial areas during the Holocene is still active in pristine (undisturbed and un-polluted) areas (Figure 1.11). This peat accumulation has preserved the hydrological conditions with widely spaced river tributaries throughout the entire Holocene. Consequently, the accumulated peat layers form an archive of past climate and provide very good possibilities to reconstruct the climate changes during the Holocene through analysis of the macro fossils of plants, mosses and micro-organisms at varying depths from the young surface peat layers to the old bottom layers. Current and future climate warming may result in the decomposition of the organic matter stored in peat and mineral soil (Yedoma in Siberia) and the release of the *greenhouse gases* carbon dioxide and methane into the atmosphere (Section 4 and Science Story 4.2). This process results in a positive feedback (amplification) on climate warming. However, where moisture conditions are favorable, peat accumulation may continue at rates sufficient to give a negative feedback (dampening) on climate warming.

The discharge dynamics of the very large rivers characteristic of the Russian Arctic (e.g. the Siberian rivers Ob, Yenissei, Lena) with catchment areas consisting for a great part of mires and mire-lake complexes, is suppressed by the high water retention capacity of mires. River floodplains and adjacent hinterlands of the middle and lower river sections as well as coastal lowland areas are at risk of enhanced frequency and duration of flooding when mires degrade because of climate warming, and if there is large scale artificial draining and peat mining. This flooding risk is increased by the rapid rate of glacier thaw and snow melt in the head waters of the rivers far to the South (Narozhniy and Zemtsov 2011). The large Russian rivers are unusual because they flow great distances from warm regions, where temperatures above 30 °C are not uncommon, to the Arctic Ocean carrying heat energy.

Geomorphological and hydrological studies of Arctic and sub-Arctic lowland areas are scarce relative to the vast surface area they occupy. However, the INTERACT program has enabled substantial scientific progress in these fields.

Figure 1.11 Complex of mires with permafrost and lakes in the Forest Tundra Zone of West Siberia (Sergey Kirpotin).

Key messages and needs for further research

- Stability analyses of valley slopes, recently released from glacier ice, is an important issue in mountain areas in the Arctic as well as in lower latitudes, but little studied yet.
- Special attention is needed to quantify the spatial and depth distribution of windblown sandy and silty deposits widespread in the Arctic regions of Siberia (Yedoma deposits). These sediments include layers with relatively high concentrations of easily decomposable organic material because they were deposited during periglacial climatic conditions.
- Hydrological dynamics of rivers draining large mires in the sub-Arctic zones have been simulated by *stochastic modeling* but quantitative knowledge of the cause-effect relationships is missing. Likewise, ground truth data of the occurrence and mechanisms of river blocking by ice-dams are missing, which also limits the prediction of the occurrence of floods by real-time modeling.
- Although the natural cycles of lake formation and drainage have been described, the balance between lake drainage and formation due to permafrost thaw remains to be determined because it is important for people, wildlife, and land-atmosphere links of energy and greenhouse gases.

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Evaluating radar remote sensing data for Arctic tundra landscapes

Jennifer Sobiech-Wolf

Radar remote sensing is a technique that allows remote and cost efficient observation of natural environments and is thus an important tool to observe uninhabited regions such as the Arctic. However, the radar images are not easy to interpret, since the radar signal is influenced by various factors such as the soil and vegetation water content as well as the structure of the surface, for example if the surface is smooth or rough, and if herbs and grasses or woody vegetation is on top. Thus, we have to compare in situ field data with the satellite data to "translate" the signal to environmental information.


Soil moisture measurements in the field (Tobias Ullmann).

AIMS OF THE PROJECT

Our goal was to find out which environmental parameters in Arctic tundra landscapes can be detected with radar remote sensing.

WHAT DID WE DO?

In the field, we mapped the spatial distribution of vegetation types and the structure of the surface, measured soil moisture at more than 4,000 points, and determined the *biomass* and vegetation water content at 20 different locations. All measurements were repeated after one year. At home in the office, we analyzed the corresponding satellite images and explored correlations between the radar signals and the natural conditions in the study area.

WHERE DID WE WORK?

We worked at the Zackenberg Research Station (•70) in Northeast Greenland. The station is located in a valley which is dominated by permafrost and covered by different tundra vegetation types and contains several wetlands. We chose this location, as we could reach various vegetation zones easily from the station by hiking. Furthermore, an automatic weather station is situated nearby and environmental data such as vegetation *phenology* (timing of events such as bud-burst) and soil moisture are measured from spring to fall by the station staff. Those data were made available for our study.

WHAT DID WE FIND?

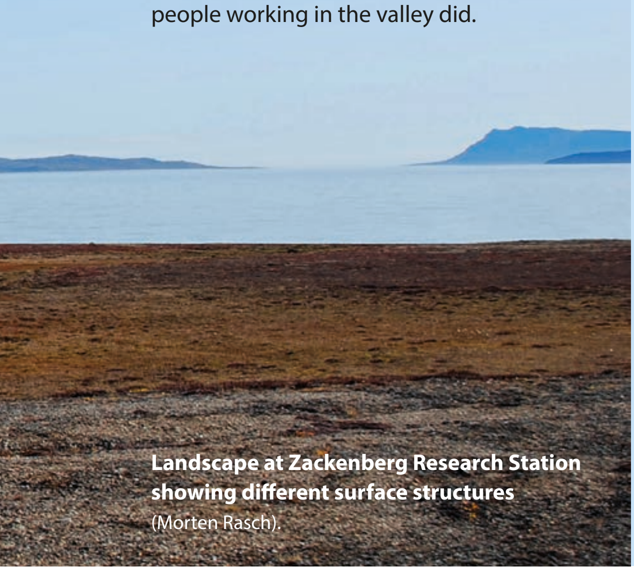
We analyzed the signal of the TerraSAR-X radar satellite (*X-band*, radar wavelength 3.1 cm) for our first investigations. We observed strong variations from time to time and place to place of the radar signals during the year. We found that the spatial signal variations neither match the main vegetation distribution in the valley nor the soil moisture distribution. Future analysis will show if the biomass water content or the surface roughness (structure) is the dominating factor influencing the signal or if the X-band signal is a mixture of too many parameters to get spatial environmental information out of short-wave radar images.

WHY ARE THE RESULTS IMPORTANT?

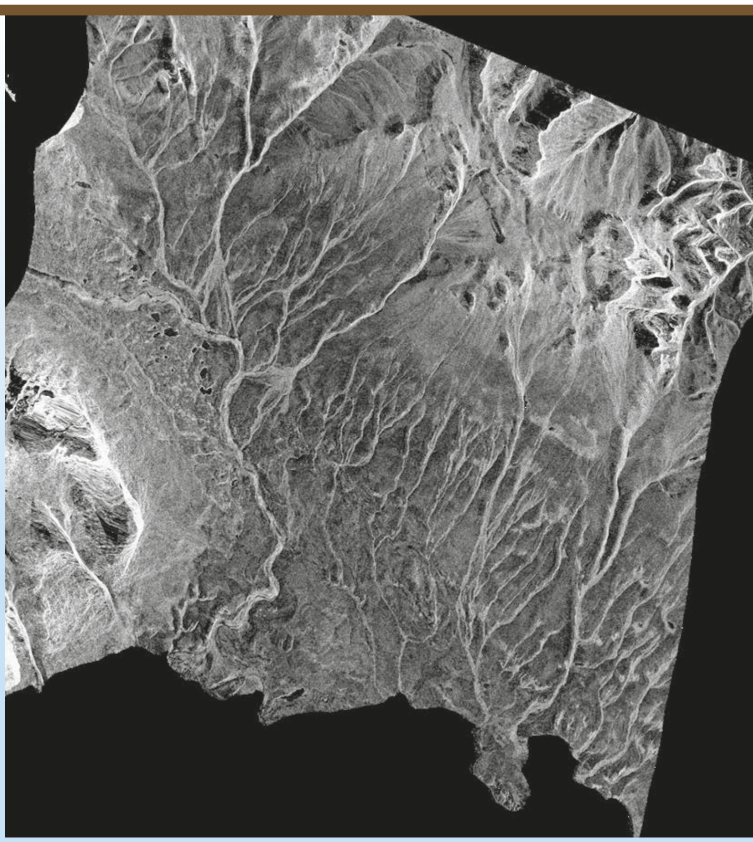
It is important to explore possible relationships between remote sensing data and natural environmental parameters. Such relationships can then be used for providing maps, for climate modelling, or for weather forecasting over areas far larger than those which can be covered by in situ measurements.

THE ADVENTURE

The journey to Zackenberg is an adventure itself. The exciting flight from southern to northern Greenland takes place in a small Twin Otter type of aircraft. We flew through the valleys along the coast, having the steep mountain ridges close to both sides of the plane. Around Zackenberg, a lot of wildlife is present. We could observe muskox almost everywhere and often had to walk some extra minutes to keep our distance. We also saw Arctic foxes, which were surprisingly confiding. Polar bears are also frequently present in the area, thus we had to scan our surrounding constantly. Unfortunately – or luckily? – we never saw one ourselves, although other people working in the valley did.



Landscape at Zackenberg Research Station showing different surface structures (Morten Rasch).



Zackenberg valley in the radar perspective. Filtered and geocoded TerraSAR-X image recorded 17.06.2013. ©DLR 2013.

Equipment for field measurements and safety (Jennifer Sobiech-Wolf).

Further information

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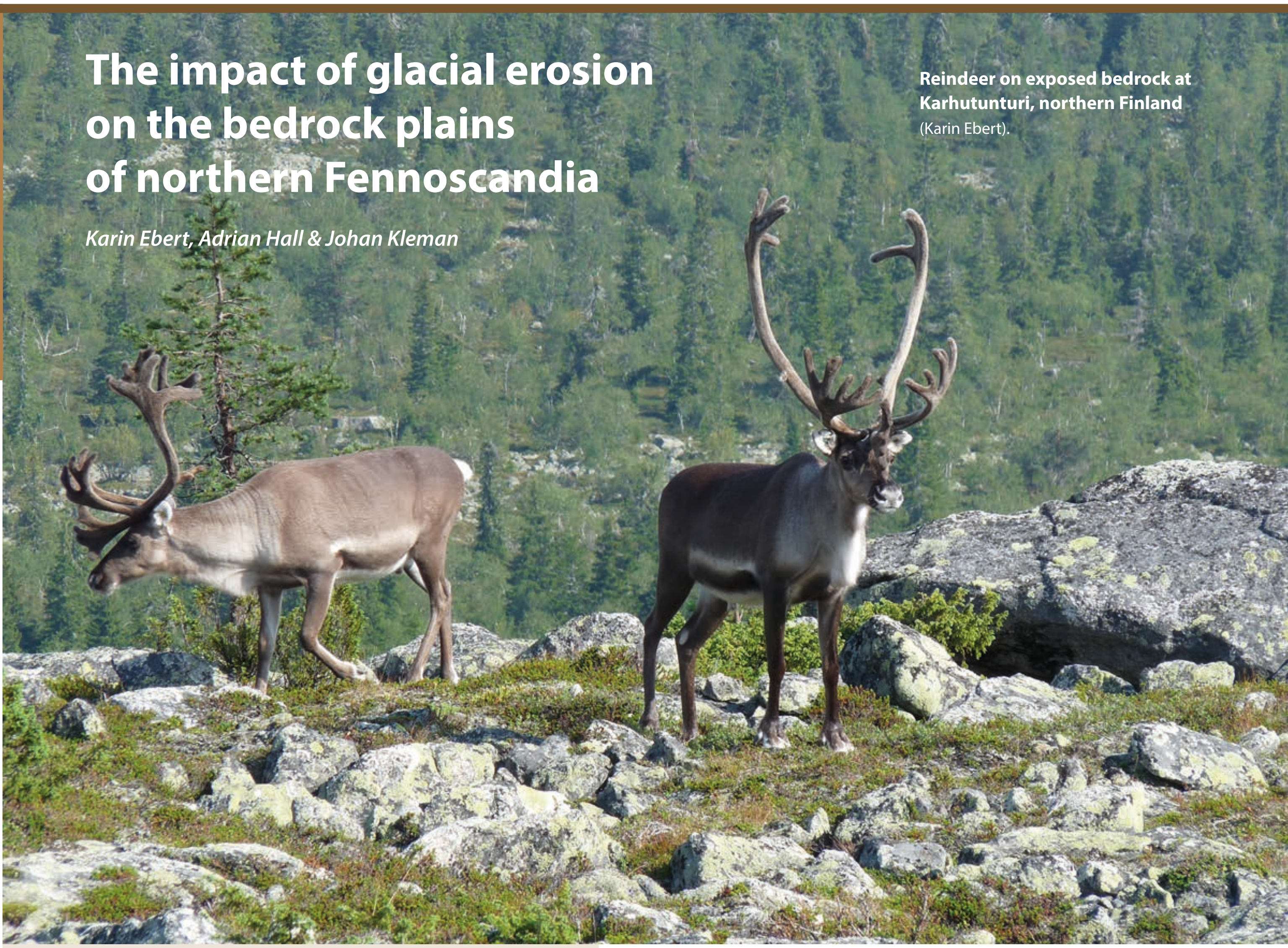
The impact of glacial erosion on the bedrock plains of northern Fennoscandia

Karin Ebert, Adrian Hall & Johan Kleman



Reindeer on exposed bedrock at Karhutunturi, northern Finland (Karin Ebert).

In the areas of the Northern Hemishere that have been covered by ice during the ice age, geomorphological research is dominated by ice-age related studies. However, before the ice age, we had hundreds of million years of other processes, e.g. fluvial (river-related) processes and weathering, that formed the landscapes. Many of these pre-glacial –formed before the ice age – landforms have not been destroyed by the ice. We are interested in finding the areas that are best preserved, to be able to find out about landscape development before the ice age and we looked in Fennoscandia (northern Norway, Sweden, Finland and northwestern Russia). The bedrock plains of northern Fennoscandia mainly consist of bedrock belonging to the "Fennoscandian Shield". Shields are the hundreds of million years old stable cores of our continents. They consist of bedrock types that are extremely resistant to erosion. The shield surface usually is comparatively flat, with low relief. During the last 2.6 million years, the northern shields, like the Canadian and the Fennoscandian shields, have been covered many times by kilometre-thick ice sheets. While there is intense research on how ice behaves and erodes in mountainous terrain, research about the impact of ice erosion on flat, resistant bedrock surfaces is only in its beginnings.

AIMS OF THE PROJECT

We wanted to know what impact many thousands of years of ice sheet cover had on the bedrock surface of the northern Fennoscandian Shield. Also, we continuously develop different analyses in *Geographical Information Systems* (GIS), in combination with fieldwork, to visualize the pattern of ice sheet erosion.

WHAT DID WE DO?

We visited field sites and opencast mines. We looked for evidence for either glacial erosion by warm-based ice or the preservation of old, weathered bedrock (soil) under cold-based ice. Warm-based ice is thick, heavy, and fast flowing. The ice melts at the bottom and water and particles erode the underlying landscape. Cold-based ice is thinner and frozen to the ground – it effectively preserves the underlying landscape. In areas of warm-based ice we find that the bedrock surface shows traces of erosion like many lakes, bare and scraped bedrock surfaces, and bedrock types from other areas that have been transported into the area. In cold-based areas, the pre-glacial soils that existed before the glaciers formed, are preserved and have not been scraped away by ice. The field work was combined with studies using Geographical Information Systems (GIS).

WHERE DID WE WORK?

We visited three different research stations – Kolari Research Unit (•16), Kilpisjärvi Biological Station (•12) and KEVO Sub-arctic Research Station (•13) in northern Finland, to see as much shield area as possible, as well as several mines. Mines give the rare opportunity to see a cut downwards into the shield. We drove all across the area by car and did many long hikes to viewpoints and areas with bare bedrock. Getting higher up on hills is important to get an overview, as the *taiga* forest in the lower areas makes an overview difficult.

WHAT DID WE FIND?

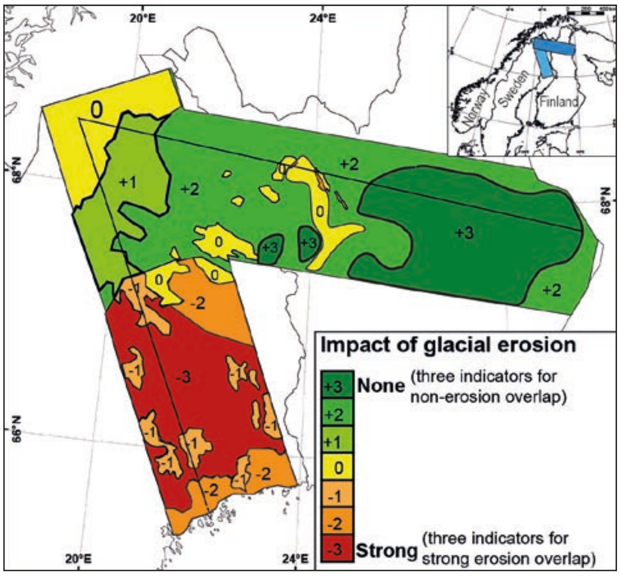
We found that ice sheet erosion had little impact on the shield surface. Valleys that are positioned in the former ice-flow direction are overdeepened by glacial erosion, and bedrock hills in areas of most intense erosion seem streamlined, because the ice deposited loose material in the lee side of the hill (lee of ice flow direction). In some areas, the pre-glacial landscape is practically intact. Here, the valleys are not overdeepened, the hills do not appear to be streamlined, and old soil and pre-glacially weathered rock, so-called "*saprolite*" covers the landscape. In areas of glacial erosion, this comparatively soft saprolite, was stripped away.

WHY ARE THE RESULTS IMPORTANT?

Hitherto it was not known how much rock was removed from the Fennoscandian Shield during the Ice Age. Knowledge about the impact of ice sheet erosion is a first important step to determine this. The shields cover areas of thousands of square kilometres, and their contribution of sediment and their susceptibility to surface processes are important to understand all kinds of global dynamics. For example, if soil is stripped away, new soil will form by weathering. Weathering needs carbon dioxide so weathering across huge areas like the shields will have an impact on the Earth's carbon dioxide budget.

THE ADVENTURE

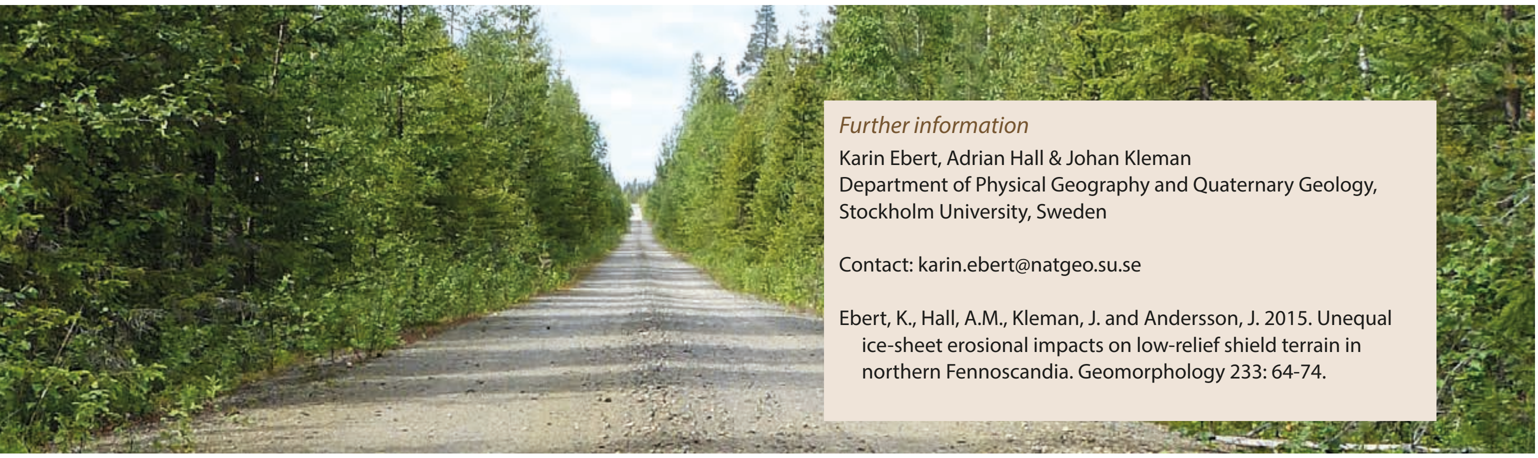
The adventure included long drives, long hikes, mosquitoes and reindeer – and many new discoveries.



Impact of glacial erosion on the shield bedrock. Even "strong" erosion impact that moved around a lot of material on the shield surface did not transform the large-scale bedrock forms of the shield (Modified from Ebert and others 2015).

Discussions at Pahtavaara between Adrian Hall and mine geologists about ice dynamics. In this location, we find only local bedrock, and the local boulders were not transported far, which means that glacial erosion was moderate (Karin Ebert).

Road on the huge Fennoscandian bedrock plains (Karin Ebert).



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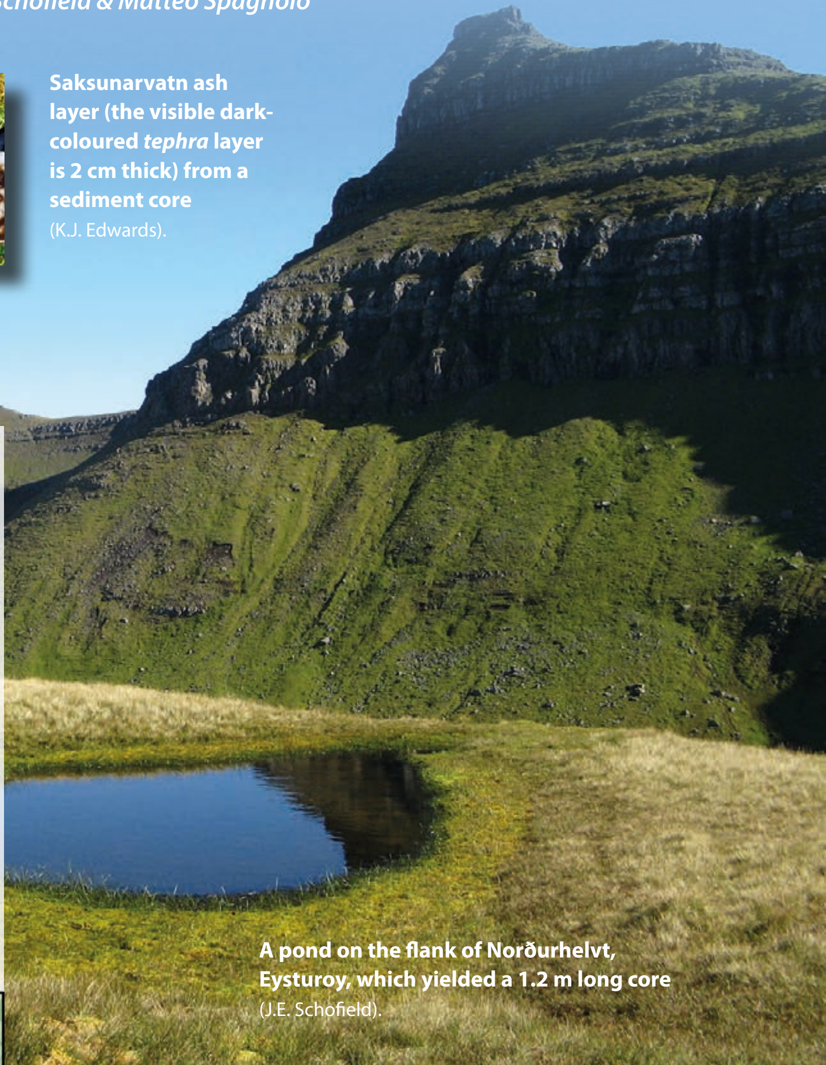
Past climate of the Faroe Islands during the late glacial period

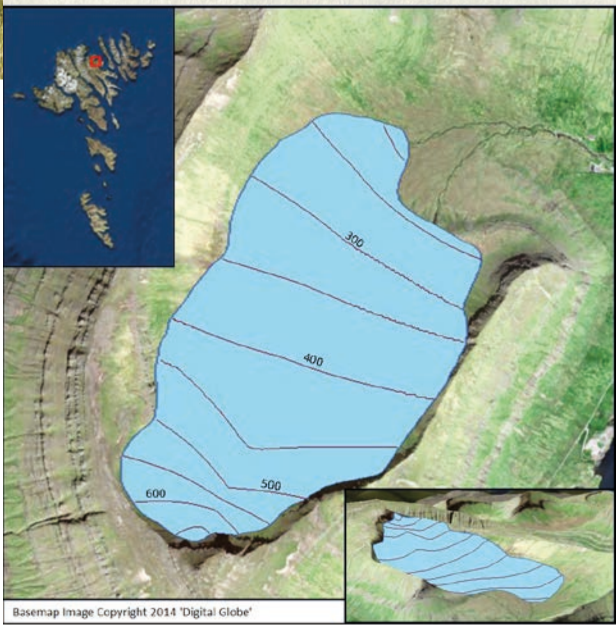
Brice R. Rea, Kevin J. Edwards, Craig R. Frew, J. Edward Schofield & Matteo Spagnolo

Saksunarvatn ash layer (the visible dark-coloured *tephra* layer is 2 cm thick) from a sediment core (K.J. Edwards).

The Greenland Ice Sheet and ice masses around the North Atlantic Ocean are diminishing, returning stored water to the oceans and contributing to sea-level rise. Freshwater input into the North Atlantic Ocean has the potential to disrupt the Meridional Overturning Circulation (MOC) of which the Gulf Stream is part, resulting in a significant climate cooling in Europe, and a southward shift of the Polar Front. It is therefore important to study a past event that is similar to the possible freshening of the North Atlantic Ocean which could occur in the future. This "analogue" happened during the Younger Dryas climatic phase, about 12.9-11.7 thousand years BP (Before Present), at the end of the last glaciation when there was a reorganisation of the MOC and rapid climate cooling. Palaeoecology and palaeoglaciology provide ideal proxies (indicators) for developing a better understanding of the climate changes resulting from this ocean-atmosphere-cryosphere feedback.



A pond on the flank of Norðurhelvt, Eysturoy, which yielded a 1.2 m long core (J.E. Schofield).



Reconstructed (probable) Younger Dryas glacier in Vatnsdalur, Eysturoy, overlaid on Google Earth map. Contour values refer to elevation above sea level of the reconstructed glacier.

AIMS OF THE PROJECT

Glacier Equilibrium Line Altitudes (ELA – the elevation on a glacier at which snowfall equals snowmelt over a single year: Section 3) from reconstructed Younger Dryas palaeo-glaciers in Ireland, Britain and Norway show a clear south to north lowering interrupted by a step-change in altitude between about 59-62° N. This increase in altitude of the ELA reflects the position of the Polar Front, north of which a permanent sea-ice cover would significantly reduce snowfall, raising ELAs. The Faroe Islands are ideally located to better estimate the location of the Polar Front during the Younger Dryas. Palaeoecological archives preserved, for instance, as pollen, other plant remains and invertebrates, in organic deposits record the palaeoenvironment and palaeoclimate at the time of their formation. We aimed to determine the ELAs of Younger Dryas palaeo-glaciers and combine these with palaeoecologically-derived climate information, to construct a more detailed picture of the climate in the region at that time.

WHAT DID WE DO?

We undertook a two-week field campaign in 2013. Through map-based analyses, the cirques (see the Overview) most likely to have hosted glaciers during the Younger Dryas were identified. Approximately 40 cirques were investigated on foot, moraine systems were mapped using hand-held GPS receivers, and samples for dating the moraines were collected. Crystals in boulders exposed to cosmic radiation have increased concentrations of certain isotopes that are directly proportional to the time the boulders have been exposed at the Earth surface, i.e. consistent with the age of the moraines.

For palaeoecologial purposes, sediment cores were obtained adjacent to the high altitude moraine systems and from beyond them, focusing upon material at and below the visible Saksunarvatn *tephra* layer (a 10,350 calendar years BP volcanic ash deposit). Data from these will provide the opportunity to generate high resolution palaeoecological and palaeoclimatic records for the Faroe Islands.

WHERE DID WE WORK?

Our project “FaroeICE” was undertaken in the Faroe Islands under the hospitality of the Faroe Islands Nature Investigation (•75). The archipelago was chosen due to its location (at a latitude between northern Scotland and southern Norway, where the altitudinal jump in ELA has been verified), and the fact that previous work on the islands had demonstrated that our research strategy could be successfully applied. Nine of the 18 islands were investigated during the project.

WHAT DID WE FIND?

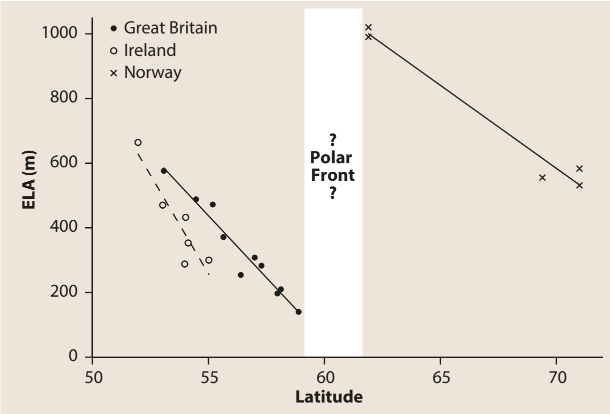
Glacial depositional landforms are generally unspectacular and relatively sparse. Some large hummocky and retreat moraine systems were identified along the main fjords and valleys but only a minority of cirques had any moraines in them. In total, nine separate moraine systems were mapped and 26 sites were sampled for cosmogenic dating. Reconstruction of the cirque glaciers is ongoing but initial results indicate an ELA of about 385 m. Only one site was identified with the potential to yield fossiliferous material in proximity to a moraine system. This was found close to the summit of Slættaratindur (882 m), the highest mountain in the Faroe Islands, and consisted of about 1.2 m of dark brown coarse detritus mud (*gyttja*) contained within a small pond. In addition, efforts were made to identify sites containing records of considerable longevity. This task is hindered by lack of suitable late glacial/early Holocene deposits. A particularly promising sequence was recovered from a palaeo-lake site, Hoydalur, on the north side of Tórshavn. Here, a 6.35 m deep core was taken which contained the Saksunarvatn ash centred at 4.64 m in the deepest part of the basin. Pollen, chironomid and sedimentological analyses are being undertaken for this core. These will provide information about vegetation dynamics, past temperatures, and the stability of catchment soils respectively over the period of interest.

WHY ARE THE RESULTS IMPORTANT?

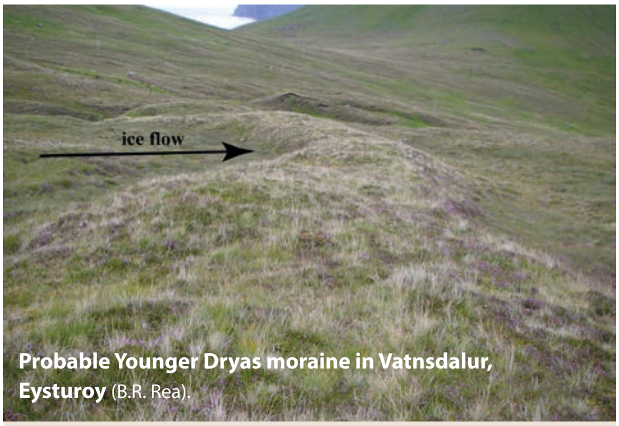
The final results from this project will be important as they will elucidate the palaeoclimate of the Faroe Islands during the Younger Dryas. This is not only of interest in its own right, but the geographical provenance of these data will help to pin down the location of the Polar Front, and also the moisture regime of the islands. This is critical because it will indicate the presence or absence of sea-ice around the islands. Sea-ice provides a major control on large-scale atmospheric circulation patterns, on down-wind climate, and has also been implicated in possible rapid insolation-driven early deglaciation on the northwest seaboard of Europe during the Younger Dryas.

THE ADVENTURE

The Faroe Islands provide a spectacular backdrop for scientific research. The weather is often wet and the steep slopes, precipitous cliff paths and ridge walks provide a challenging environment in which to work. When the clouds part and the Sun shines, the landscape is transformed.



Younger Dryas ELAs from Ireland, Britain and Norway and the likely location of the Polar Front.



Probable Younger Dryas moraine in Vatnsdalur, Eysturoy (B.R. Rea).

Further information

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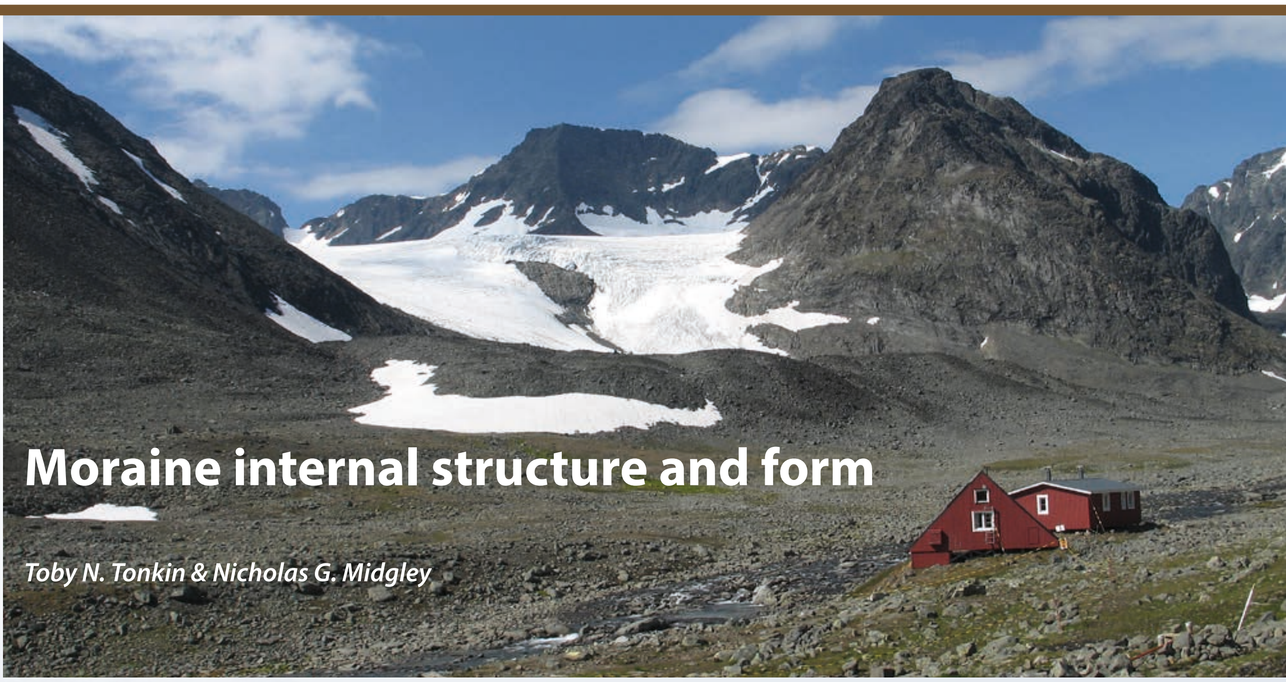


Moraine internal structure and form

Toby N. Tonkin & Nicholas G. Midgley

Isfallsglaciären and its prominent snowbanked lateral-frontal moraines. Tarfala Research Station can be seen in the foreground (Toby N. Tonkin).

Moraines are ridges or mounds of unconsolidated sediment (loose, deposited materials) that develop at the margins of glaciers. Whilst the glaciers of the Tarfala valley in northern Sweden are well studied in terms of their glaciology, the moraines are less well understood. The sedimentary composition, internal structure and morphology (shape) of moraines is related to a range of glaciological and surface processes. Therefore these landforms can be seen as an archive of past glacier characteristics and activity. Studies of these landforms may contribute to our understanding of the character and behaviour of these glaciers over a range of timescales and therefore merit further investigation.

AIM OF THE PROJECT

To investigate the internal structure, morphology and sedimentary composition of lateral-frontal moraines (moraines that accumulate around the margin of a glacier) formed by Arctic glaciers.

WHAT DID WE DO?

Our research took the form of two visits to the Tarfala Research Station (•10). The first was during winter-conditions, when we used a geophysical technique called ground-penetrating radar to identify internal structure within the moraines. We returned in the summer to document the sedimentary composition of the moraines and to collect low-level aerial imagery using an unmanned aerial vehicle (UAV). The aerial images were then used to produce *digital-elevation* models (DEMs) using a technique called *photogrammetry*. DEMs are representations of the terrain's relief, which help us to interpret the significance of the landforms.

Using ground-penetrating radar to investigate the internal structure of the Isfallsglaciären moraines under winter-conditions (Gunhild Rosquist).

A 3D model of the Isfallsglaciären northern lateral-frontal moraine produced using imagery acquired from an unmanned aerial vehicle (UAV). The UAV is shown in the bottom right (Toby N. Tonkin). **Approximate former ice-flow direction is also indicated.**

WHERE DID WE WORK?

We worked at Tarfala Research Station (•10) in northern Sweden. Tarfala was chosen due to its close proximity to a range of valley glaciers and interesting glacial landforms. Our study site at Isfallsglaciären was a short walk (ca. 500 metres) from the research station allowing us to easily keep our equipment charged and therefore stay productive.

WHAT DID WE FIND?

The results of our geophysical surveys appear to delimit the extent of buried-ice within the moraines and the depth at which this ice is buried, as well as revealing some of the internal structure of the landforms. Lateral cross-sections of the landforms show some distinct differences in terms of their sedimentary composition, subsurface structure and morphology in comparison to frontal sections. The moraines appear to have developed as a result of more than one period of glacier expansion and therefore provide a sedimentary record of glacier change.

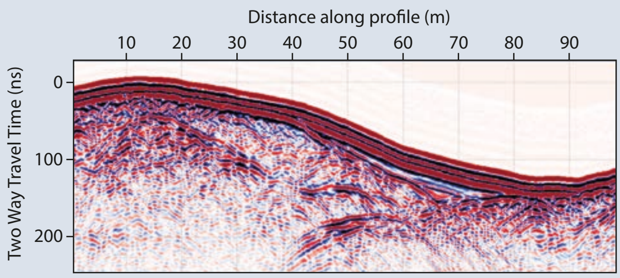
WHY ARE THE RESULTS IMPORTANT?

Studies investigating these landforms are important for a variety of reasons. Firstly, it helps aid our understanding of relict features in the geomorphological (landform) record and their glaciological and climatic significance. Secondly, by documenting the internal structure and morphology of these landforms, we can understand how the glacier has changed over timescales well in excess of direct monitoring studies. Furthermore, by determining the ice-content and sedimentology of ice-cored moraines in sub-Arctic Sweden we can get a better understanding of how the morphology of these features will potentially evolve under a warming climate.

THE ADVENTURE

Due to the isolated location of the research station, under winter-conditions travelling to Tarfala required a snow scooter ride into the mountains. During the summer we arrived and departed via helicopter which enabled us to transport bulky equipment to and from our field site. We were lucky enough to catch the *Aurora Borealis* during our first visit. Tarfala is an amazing location to conduct research.

A 100 MHz ground-penetrating radar profile displaying the internal structure of the Isfallsglaciären southern lateral moraine.



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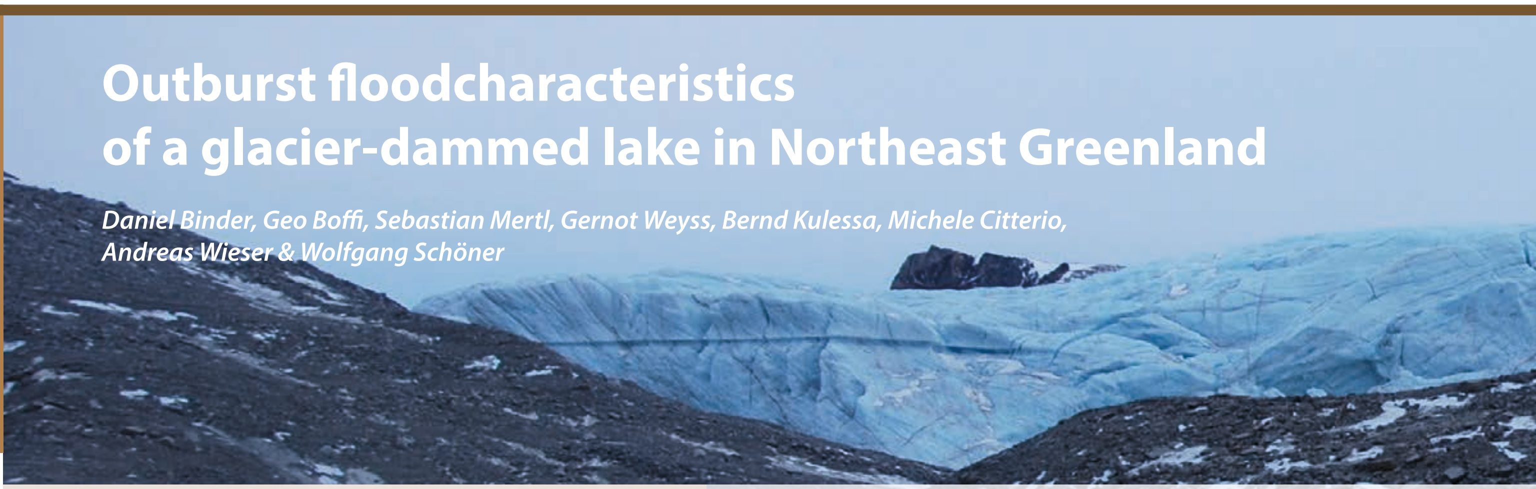


Outburst floodcharacteristics of a glacier-dammed lake in Northeast Greenland

Daniel Binder, Geo Boffi, Sebastian Mertl, Gernot Weyss, Bernd Kulessa, Michele Citterio, Andreas Wieser & Wolfgang Schöner

During the annual melting period, a glacier-dammed side valley is filled with meltwater from snow and ice of the surrounding glaciers. A significant but at the same time short-lived lake is built up in about two months. Eventually, the lake water overcomes the icy barrier and is totally drained in just several hours. Consequently, a catastrophic flood wave rushes through the valley.

This glacial phenomenon is described by the Icelandic term "jökulhlaup", respectively "glacial lake outburst flood *(GLOF)". The classic GLOF-theory just covers the slowly-rising type, which exhibits an exponentially rising flood discharge over days and weeks. The more catastrophic, rapid-rising GLOFs show a linear rising flood discharge over hours and days and cannot be explained by the classic theory. Thus process-orientated studies are needed.*

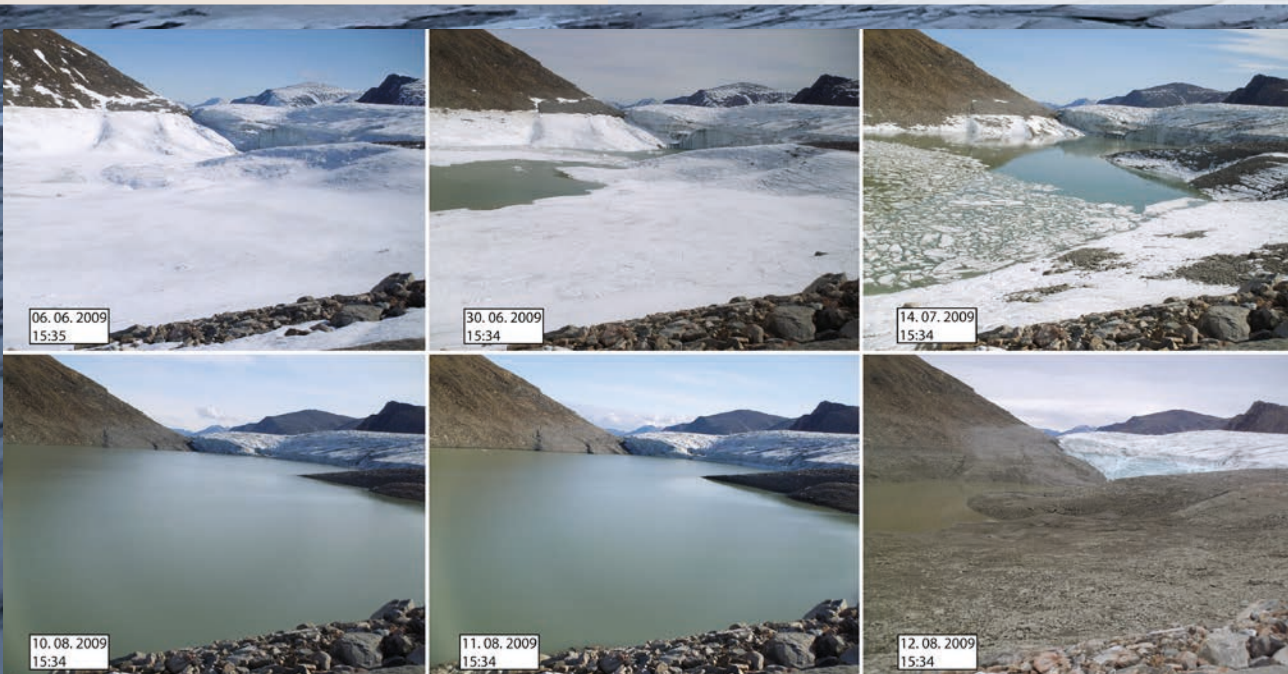
A project called "GlacioBurst" followed a continuous GPS and geophysical monitoring strategy over the whole fill- and drain cycle in 2012. The data set gathered shows a highly active initiation and outburst phase, typical for the rapid-rising GLOF type.

AIMS OF THE PROJECT

The overall aim of the project was to gain a deep insight into the driving mechanism(s) of the observed GLOF. Therefore, a GPS and geophysical monitoring programme was initiated to register the seismic activity as well as the corresponding glacier surface dynamics due to the infiltrating lake water. Furthermore, a ground-penetrating radar (GPR) survey was conducted in spring 2012 to get some information on the present state from inside the glacier's ice mass (*englacial*) as well as from the glacier's bed (subglacial). Based on the derived dataset, a conceptual model is currently being developed.

WHAT DID WE DO?

In April 2012 we installed the geophysical (passive seismics) and GPS monitoring network on the investigated glacier. Besides setting up the monitoring stations at the glacier surface, we drilled three metres deep boreholes to sink the seismic sensors and covered the boreholes with an insulating geotextile to avoid an untimely melt out. Parallel to the installation of the all-year round monitoring network, we conducted a GPR survey to receive an actual snapshot of the englacial and subglacial conditions.



At the bottom of the drained ice-dammed side valley at the A.P. Olsen Ice Cap (Daniel Binder).

WHERE DID WE WORK?

We worked at the SE outlet glacier of the predominantly cold-based A.P. Olsen Ice Cap in Northeast Greenland, about 30 km inland from the Zackenberg Research Station (•70). During a past expedition in 2008, we already gathered highly interesting GPR data. The GPR data showed englacial and subglacial signals most likely closely related to the regular outburst floods. During the GPR data analysis the idea of the GPS and geophysical monitoring grew and was realized in 2012.

WHAT DID WE FIND?

Due to the very successful field campaign, we could gather a precious data set which is currently being analyzed by the project team. Beside the high quality GPR data, the passive seismic and GPS data reveal a highly active GLOF initiation phase, typical for a rapid-rising GLOF. The first results suggest the infiltration of a high-pressurised water sheet at the ice dam-glacier bed intersection at least one week before the outburst itself. The GPR survey revealed glacier bed characteristics pointing as well to a rather subglacial infiltration of the lake water and furthermore, uncovered highly interesting englacial structures closely related to the GLOF.

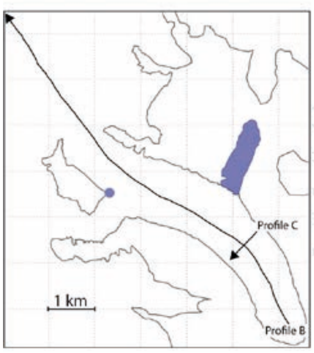
WHY ARE THE RESULTS IMPORTANT?

En- and subglacial hydrological processes are the key to understand fundamental glacial processes. Due to their inaccessibility, direct observations are sparse in time and space which results in a lack of process-oriented, quantitative understanding. Thus high quality field data are needed to test existing models and new hypotheses. Once the basic physics are understood, a quantitative model can be set up and can be tested for other settings.

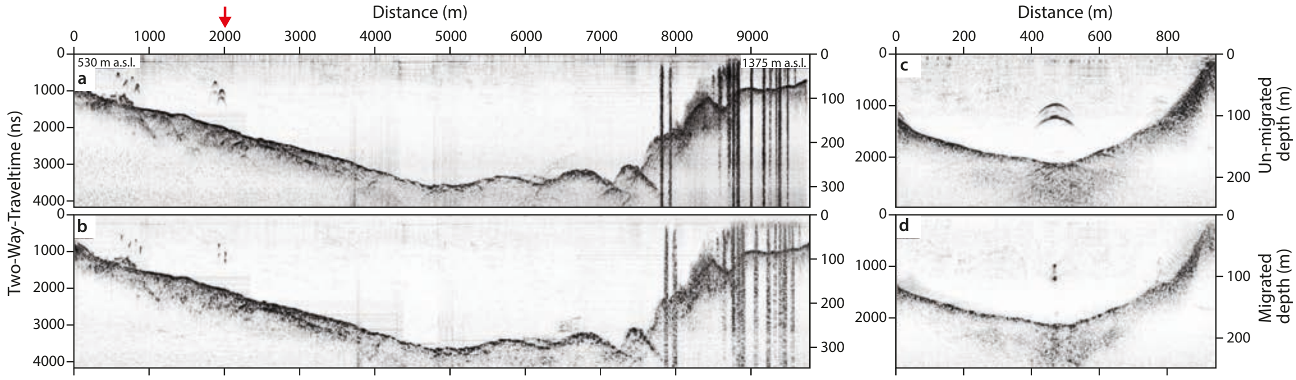
Besides the fundamental understanding of the driving physics, glacial flood waves are shaping the landscapes on different scales. *Heinrich Events* during the last glacial period are connected to the release of excessively large amounts of freshwater by the *Laurentide Ice Sheet* with an impact on the global climate. One hypothesis to explain the Heinrich Events and the large amounts of freshwater involved are rapid mega-GLOFs.

The origin of the pro-glacial river before (a) and during (b) the outburst on the 6th of August 2012. Please note for scale the person in the left, lower corner on the upper picture (Gernot Weyss).

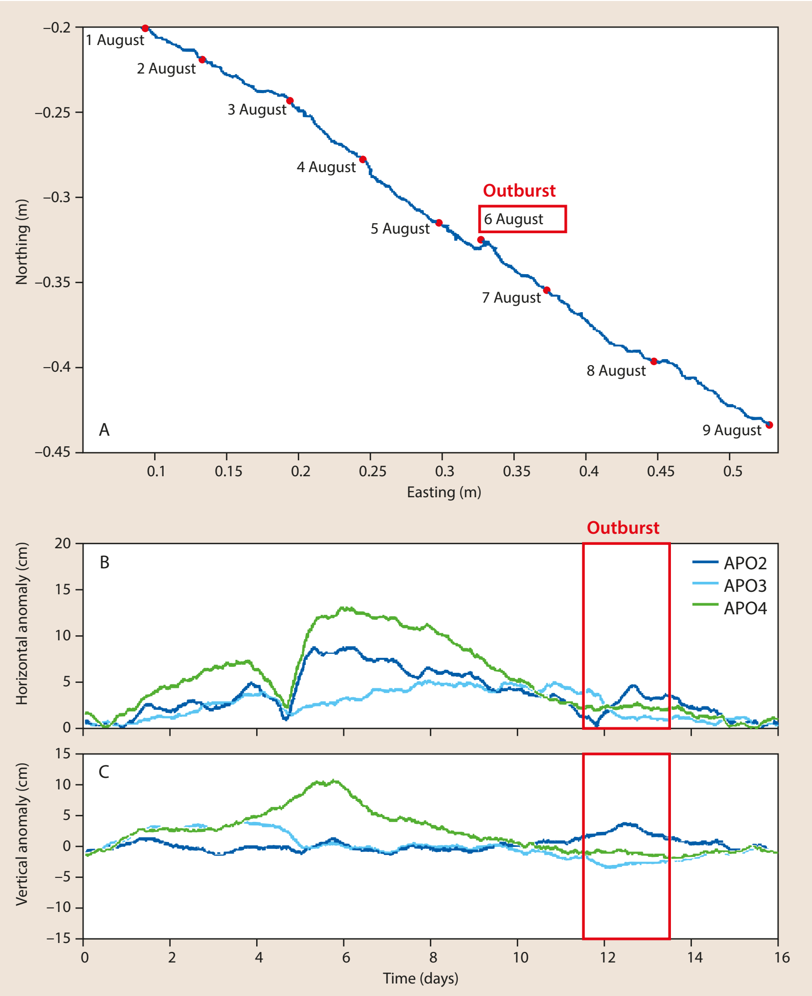
Evolution of the ice-dammed lake at the A.P. Olsen Ice Cap in the ablation (melt) period of 2009 showing the chronological sequence of the fill and drain cycle (GeoBasis, Aarhus University).



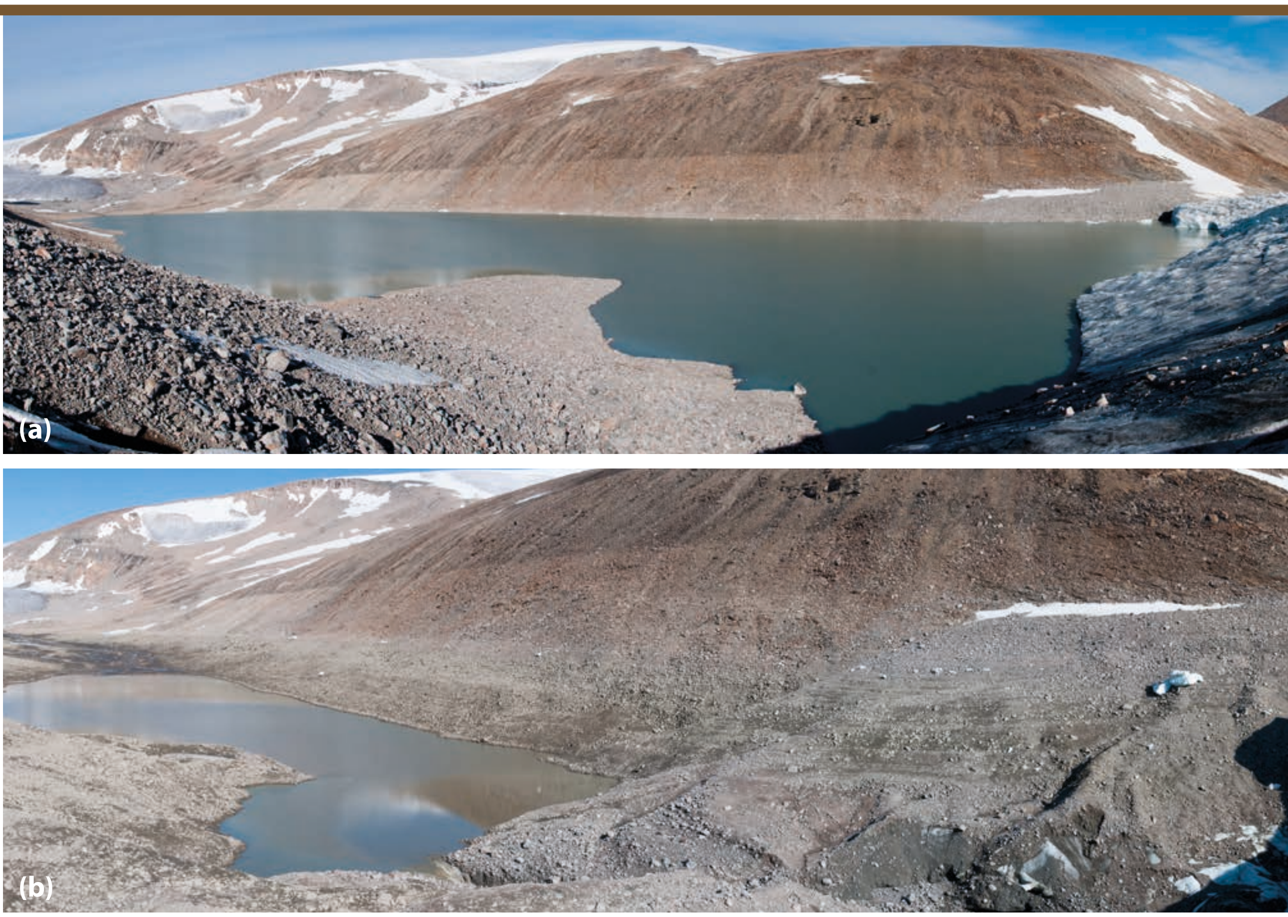
The left figure shows the outline of the investigated outlet glacier at the A.P. Olsen Ice Cap. The black arrowed lines represent locations and directions of selected GPR Profiles B and C. Blue areas show the ice-dammed lake and an active *glacier mill* (point).



Diagrammes (a) and (b) represent corresponding GPR data for Profile B (top figure). Diagrammes (c) and (d) are the corresponding migrated sections for Profile C (top figure). The red arrow in diagramme (a) indicates the crossing point of Profile C on Profile B.



First GPS Results. (A) shows the horizontal variation of the GPS station APO2. A clear reversal of flow direction can be distinguished during the GLOF on the 6th of August 2012. (B) and (C) illustrate the horizontal and vertical surface motion anomalies of GPS stations APO2-4, which reveal a highly active phase approximately1 week before the GLOF itself.



The ice-dammed side valley on the 5^{th} of August (a) and at the end (b) of the GLOF on the 6^{th} of August 2012. The GLOF took about 10 hours (Gernot Weyss).

Drilling of a borehole and deployment of a seismic sensor
(S. Mertl (a), G.Weys (b), D. Binder (c)).

THE ADVENTURE

Beating the odds, a GlacioBurst research team member witnessed the GLOF on the 6^{th} of August 2012. In the summer, the investigated glacier is just reachable by foot, which means an approximate 30 km hike in the wilderness of NE Greenland. The original mission was to stay one day at the glacier to get the data and do a basic station service. The two-persons field team arrived in the night-time of the 5^{th} of August and were woken up by sounds of a violent torrent in the morning of the 6^{th} of August. They instantly realized that the GLOF was happening just at that moment.

Further information

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The field trip was funded by EU FP7 INTERACT. Seismic devices were provided by SeisUK, a branch of the Natural Environment Research Council, UK. Borehole geophones were provided by the Department of Geophysics of the Vienna University of Technology.

2 Permafrost

SECTION OVERVIEW

Margareta Johansson

Permafrost is an integral part of many northern landscapes. It has profound implications for infrastructures and economies in the North and interacts with many *ecosystems*. Permafrost is any material that stays at or below 0 °C for two or more consecutive years. Permafrost can occur in soils or other ground surface materials (from peat or clay to boulders) and in bedrock. On top of the permafrost is an "*active layer*" which thaws and refreezes on a seasonal basis. Its thickness varies depending on climate, vegetation cover and soil type, from a few tens of centimetres in peat to more than several metres in areas with well-drained (and therefore poorly insulating) materials. The permafrost below can be everything from a few tens of centimetres thick to the record which is more than 1,400 m thick. As permafrost is mainly a product of cold climates, whenever the Earth's climate has been cold enough in the past, permafrost has formed. Most of the permafrost that exists today was formed during the past 100,000 years. During the Last Glacial Maximum (ca. 18,000 years ago) permafrost was more widespread than at present. In addition to air temperatures, local factors such as snow cover, vegetation, soil organic layer thickness, thermal (insulating) properties of the earth materials, soil moisture/ice content and drainage conditions are also important factors influencing the presence or absence of permafrost.

Yukon Coastal Plain (Anna Konopczak).

PERMAFROST DISTRIBUTION AND EXTENT

Permafrost currently underlays 20-25% of the landmasses in the Northern Hemisphere. It is widespread at high latitudes but also occurs at lower latitudes, where permafrost is mainly found in mountainous areas such as the Himalayas. Permafrost is usually divided into four different categories according to the proportion of the landscape it underlays; 1) continuous permafrost at the highest latitudes where 90-100% of the ground is underlain by permafrost (Figure 2.1) 2) discontinuous permafrost further south where 50-90% is underlain by permafrost 3) sporadic permafrost near the southern boundary of permafrost where 10-50% is underlain by permafrost and 4) isolated islands of permafrost at the boundary where 0-10% is underlain by permafrost. Figure 2.2 shows a conceptual transect from south to north illustrating the increasing extent of permafrost when moving north.

In addition to the vast areas of permafrost found on land in the Northern Hemisphere, permafrost is also found under the Arctic Ocean at the sea bottom. It is found below the continental shelves extending from the coastline of Siberia, in the Beringia area and in the northwest part of Canada. This permafrost was formed during the last glaciation, when the sea level was much lower than today and the continental shelves were landscapes above the sea. The cold temperatures in the Arctic Ocean have preserved the permafrost for thousands of years.

PERMAFROST-RELATED LANDFORMS

Unlike other cryospheric (frozen water) components such as snow, glaciers, sea-, river- and lake-ice, it is not always possible to see whether an area is underlain by permafrost or not. However, there are some specific landforms that are permafrost-related such as ice-wedge or tundra polygons that are probably the most widespread periglacial landforms (areas where frost action and permafrost related processes dominate) in lowland continuous and discontinuous permafrost areas (Section 2 cover photo). Ice wedges are formed during the coldest winter periods due to cracking resulting from contraction. In the same permafrost zones, another permafrost-related landform is found – the "pingo". Pingos are hills, typically conical in shape, that contain a core of massive ice. In the southern parts of the permafrost zone, a typical permafrost-related landform called "palsas" can be found. Palsas are peat mounds with a frozen core. Their position, elevated above their surroundings, keeps them cold during winter as snow is blown from the top and the ground is therefore not insulated.

WHY SHOULD WE STUDY PERMAFROST?

Increasing permafrost temperatures will have many major impacts such as on local hydrology, vegetation, biogeochemical and biogeophysical cycling (land-atmosphere linkages: Section 4), infrastructure and our possibility to learn more about old diseases, extinct animals and human cultures.

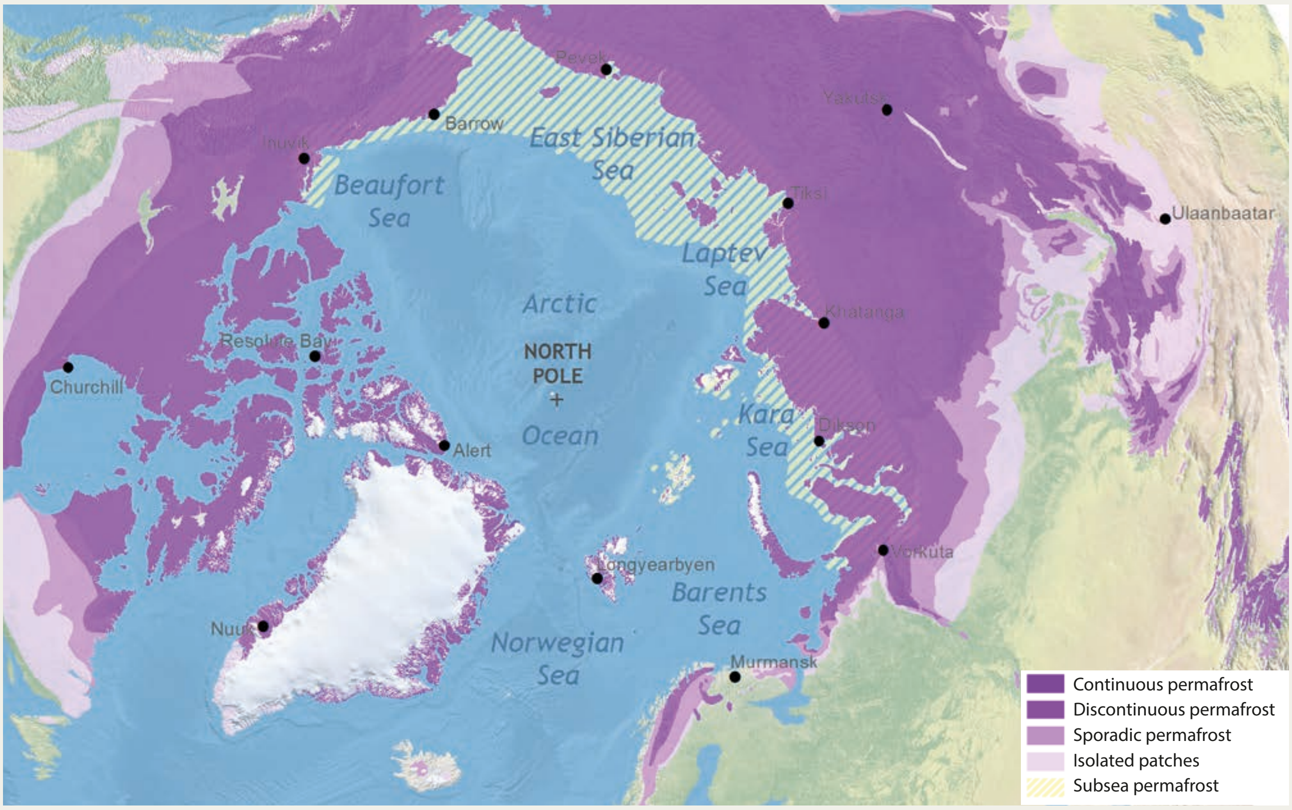

Figure 2.1 Permafrost is widespread in high latitude and high altitude areas. It also exists under the Arctic Ocean below the continental shelves (Hugues Lantuit . The data for creating the map was derived/modified from the original 1:10,000,000 paper map by Brown and others 1998).

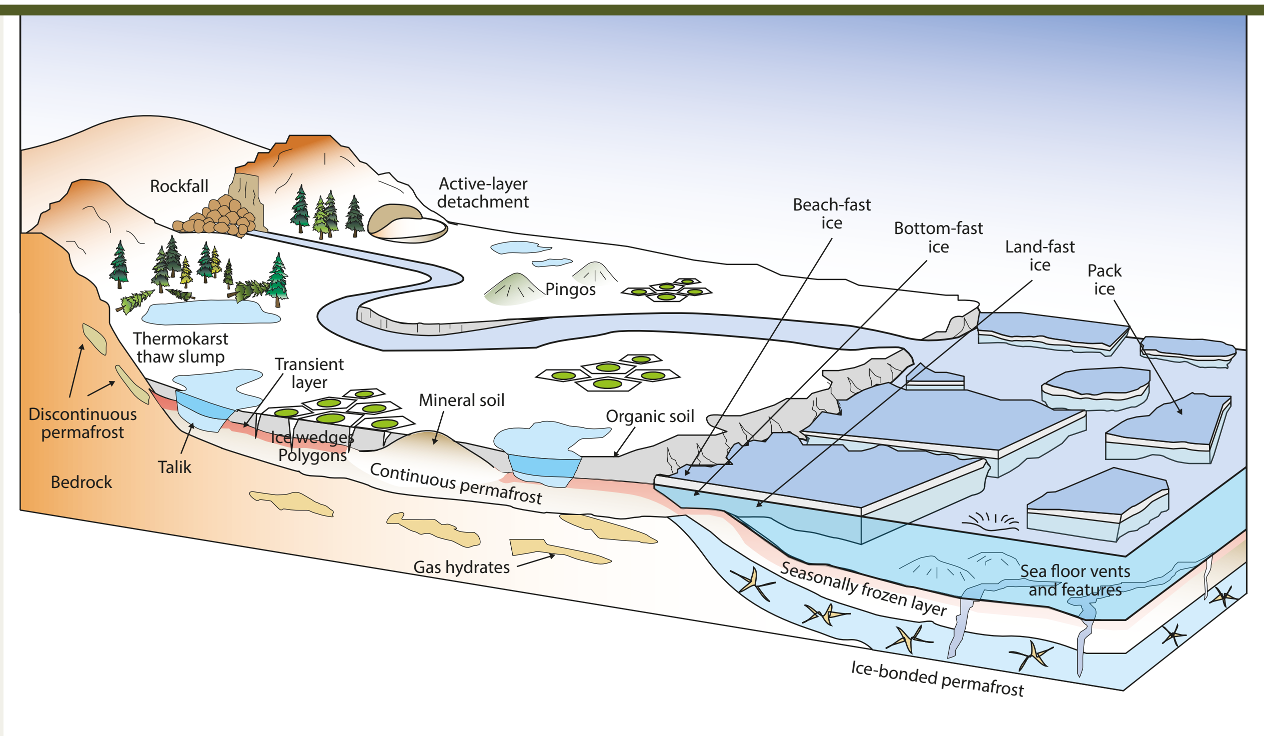

Figure 2.2 A conceptual transect of the distribution of permafrost and permafrost features from the sub-Arctic to the continental shelves (Callaghan and others 2011).

Hydrology: There are innumerous lakes in permafrost areas (Sections 1 and 6) but they constantly change in a warming climate. An increasing active layer can result in both pond formation as well as pond/lake disappearance. In some areas ponds dry out as the water can then find new pathways to drain. The opposite scenario with pond formation can occur in areas of ice-rich permafrost. When the active layer becomes thicker, the ice in the ground melts and the ground subsides. The depressed areas soon fill with water and a new pond (called a thermokarst pond) forms. As a consequence of new pond formation and pond drying out, the ecology of the freshwater systems is also affected (Section 6). Adamson and her group (Science Story 2.1) explored how the seasonal changes in active layer thickness would affect the location of meltwater streams from glaciers to downstream lakes and the type of materials that were transported.

Vegetation: Vegetation can vary greatly from polar desert to spruce forest in land areas underlain by permafrost. Vegetation changes are predicted for the future, some related to changes in permafrost others due to other factors (Section 5). Examples where ongoing changes in permafrost have affected the vegetation are "drunken forests" (Figure 2.3). Drunken forests occur when the active layer thickness increases and the ground becomes unstable. Trees with shallow roots such as spruce are particularly vulnerable and can fall. At the margins of permafrost existence where permafrost has started to thaw, vegetation changes have been reported from e.g. dwarf shrub dominated plant communities to a community dominated by graminoids (grasses, sedges and rushes) and this has an impact on berry production that in turn affects local people and wildlife such as bears. Dielissen and her group (Science Story 2.2) have studied the shift in plant community composition as a consequence of changes in permafrost.

Figure 2.3 Vegetation affected by permafrost thawing and ground subsidence – "Drunken Forest" (Trofim Maximov).

Biogeochemical cycling: Land areas underlain by permafrost store approximately twice as much carbon (e.g. decaying, old vegetation) as is currently in the atmosphere (Section 4). When permafrost temperatures and active layer thickness are increasing, organic material that has previously been frozen in the ground thaws and can be decomposed and its carbon emitted as either carbon dioxide (CO_2) or methane (CH_4). These greenhouse gases contribute to increases in the greenhouse effect in the atmosphere and hence amplify current climate changes (Section 4). Monitoring of carbon fluxes from land has been ongoing for more than a decade. However, to understand all the carbon cycling processes in a landscape it is important to monitor both the changes on land and also ongoing change in lakes. Lichens and shrubs from drier areas can become flooded when permafrost thaws and form a source of dissolved organic material in the new ponds. This material can then be released as carbon dioxide or methane to the atmosphere.

Jammet and her group have focused their study on monitoring both the land and lake fluxes of greenhouse gases (Science Story 2.3). The release of greenhouse gases results from the metabolism of soil microbes that occur in organic soils and the carbon isotopes in dead plant matter change in proportion as young, easily decomposed material is respired by microorganisms and older carbon is lost more slowly. Krüger and Alewell (Science Story 2.4) use the distribution of stable isotopes down through the peat to infer the development and degradation of palsas. In addition to the great carbon storage on land, the sub-sea permafrost also holds carbon (a reservoir expected to be almost as big as the carbon pool stored in land permafrost). However, it is not known how sensitive this carbon is to ongoing changes in sub-sea permafrost and to what extent it will actually be emitted. Because of the vast extent of permafrost in the North, it is necessary to develop remote sensing techniques with ground validation to observe change (Science Story 2.5).

Infrastructure: Infrastructure built on permafrost can be anything from roads and houses to pipelines that transport oil and natural gas from the North to the South. In areas of ice-rich permafrost, permafrost thawing can have severe impacts on infrastructure since surface subsidence can occur. It is necessary to adapt (Science Story 2.7) and use special building techniques to avoid affecting the temperature of the ground. Houses are for example, often built on pillars to allow air circulation underneath the building so that the heat from the building does not affect the ground underneath and cause the permafrost to thaw (Figure 2.4). An example where special building techniques have not been applied has resulted in an Arctic house competing with the leaning tower of Pisa (Figure 2.5)!

Villages in Alaska have had to re-locate due to coastal erosion (a combined effect of decreasing sea ice in the Arctic Ocean and changes in permafrost conditions). Consequently, permafrost scientists have an important role in advising communities (for example in Alaska) where to re-locate villages. They

Figure 2.4 House built on pillars in Barentsburg, Svalbard. These pillars allow air circulation underneath the building to protect the permafrost (Margareta Johansson).

Figure 2.5 Ice in the permafrost has melted and the ground has collapsed resulting in a house that is no longer possible to live in (Vladimir Romanovsky).

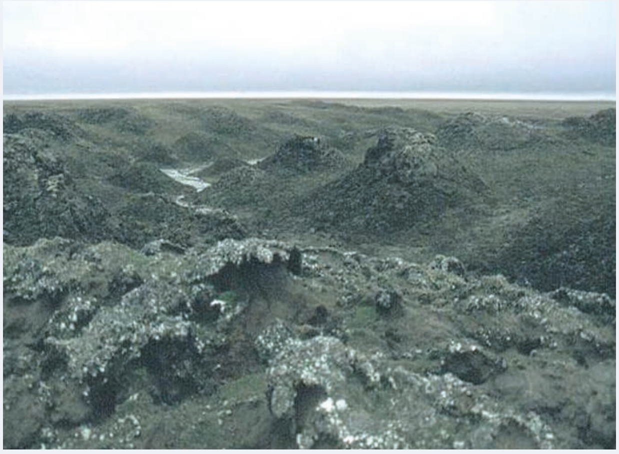

Figure 2.6 Landscape on the New Siberian Islands showing massive permafrost degradation that is so fast that vegetation cannot become established and remains of extinct animals are surfacing (Terry V. Callaghan, 1994).

need to avoid ice-rich ground that will result in very costly infrastructure development as special caution is needed when building new infrastructure. In some areas of Arctic Russia, erosion of the coast and hinterlands is particularly dramatic through permafrost thaw (Figure 2.6). In contrast to the vulnerable examples from Alaska, many coastal settlements in Greenland are built on bedrock and ground subsidence is not an issue there.

Old diseases, extinct animals and human cultures: People have been living in areas with permafrost for many centuries and people have been buried in the permafrost. As the permafrost acts as a big freezer, many bodies, clothing and artefacts have been preserved. When the active layer thickness increases, bodies that have been buried for centuries can start to thaw. This can of course in some areas pose problems to health but it is also an opportunity to learn more about ancient diseases and human cultures. Permafrost also preserves remains of extinct animals such as the woolly mammoths which are becoming evident along river banks where erosion takes place and in areas of rapid permafrost degradation.

HOW IS PERMAFROST MONITORED?

To detect what happens to the permafrost in a warming world there are two general factors that are monitored throughout the Arctic and beyond. The first factor being monitored to detect changes in permafrost during current climate change is permafrost temperatures. During the International Polar

Figure 2.7 Borehole drilling to initiate monitoring of permafrost temperatures (Jonas Åkerman).

Year (2007-2009) the project "Thermal State of Permafrost" developed a standardised method to record permafrost temperatures by drilling boreholes and measuring temperatures deep inside them. Many new boreholes were made during the project and temperatures were recorded according to the new methods developed (Figure 2.7). Permafrost temperature data showing changes over the years can be downloaded from the GTN-P database (http://gtnpdatabase.org).

The second factor being monitored is the active layer's thickness. This is recorded at least annually at the end of the summer season (when it is thickest) to measure how much of the upper soil has thawed during the summer (Figure 2.8). The Circumpolar Active Layer Monitoring Programme (CALM www.gwu.edu/~calm/) has developed a standardised methodology to record active layer thickness using a 100 m ground surface grid which is divided into 100 squares, each 10 by 10 m. Data from active layer measurements is available in the CALM database at www.gwu.edu/~calm/data/north.html .

Monitoring of active layer thickness and ground temperatures is done at a relatively small scale at particular sites. However, permafrost in large areas of the Arctic is not monitored. To get a better overview of what is going on at a larger scale, other methods are being used such as remote sensing (e.g. use of satellite images). The site monitoring is usually in turn used as ground truthing, i.e. checking the information taken from space at specific locations.

CURRENT AND FUTURE TRENDS

There are relatively few long-term (several decades) permafrost temperature series from the Arctic. From the few that exist, the general trend is that the permafrost temperatures have increased between 0.5 to 2 °C during the last three decades. The highest increases in temperatures are found in the zone of continuous permafrost. In some areas (such as in the Nordic countries, Northeast Greenland, the Russian European North), the trend in increasing temperatures has been accompanied by a trend in increasing active layer thickness. Where permafrost temperatures are very low, the consequences of warming permafrost are minor but where permafrost temperatures are close to the limit of permafrost, increasing temperatures can result in its loss.

The future fate of permafrost is being predicted by several models. Permafrost models rely on projections of Arctic warming calculated by general circulation models. Even though the detailed output of the models can vary from one model to another, they all predict a continued trend in warmer ground temperatures, thicker active layers and a continuing increase in permafrost thawing at its southernmost boundary by the end of the 21st century.

Key messages and needs for further research

Ongoing changes in climate affect the state of permafrost which can have profound implications for both the natural environment and on society. The Arctic Council's working group Arctic Monitoring and Assessment Programme (AMAP) presented in 2011 the Snow, Water, Ice and Permafrost in the Arctic (SWIPA) Assessment that had a specific chapter on permafrost that described ongoing changes, future changes, and impacts. This section also listed several key questions and future recommendations. An example was "a need to better integrate observing techniques including the further development of remote sensing to complement in situ observations and expansion of in situ observations to validate and explain information derived from remote sensing". This is what Elin Högström and her group (Science Story 2.5) have been addressing when visiting Siberia to retrieve information that could be used to validate information on soil moisture derived from satellites. Even though there are many key questions and recommendations yet to cover, INTERACT has actively contributed to solve some of the important issues.

Further information and references

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Figure 2.8 The thickness of the active layer is measured in northern Sweden at the end of the summer to record the maximum thaw depth for the season. A thermokarst pond is surrounded peatland vegetation and underlain by permafrost (Jonas Åkerman).

The influence of permafrost on glacial meltwater and sediment transfer

Kathryn Adamson & Tim Lane

Permafrost is ground that remains permanently frozen for at least two years. It underlies over 20% of the Earth's land surface in the Northern Hemisphere, and is very sensitive to changes in air temperature. On top of the permafrost is a layer that thaws in the summer, called the active layer. The response of permafrost and the active layer to climate change may have important impacts on Arctic landscapes. Many glaciers in the Arctic, and in mountain regions across the world, are located in areas of permafrost. The powerful meltwater streams draining the glaciers may be eroding the thawed active layer, leading to major changes in the glacial environment.

Annotated map of the Arctic Station, river crossing points, and GPR survey location (Background aerial photograph from Kort og Matrikelstyrelsen).

The GPR being used in front of the glacier snout during winter. The transect along which the survey has been taken can be seen behind the GPR. The photograph has been taken looking east (Kathryn Adamson).

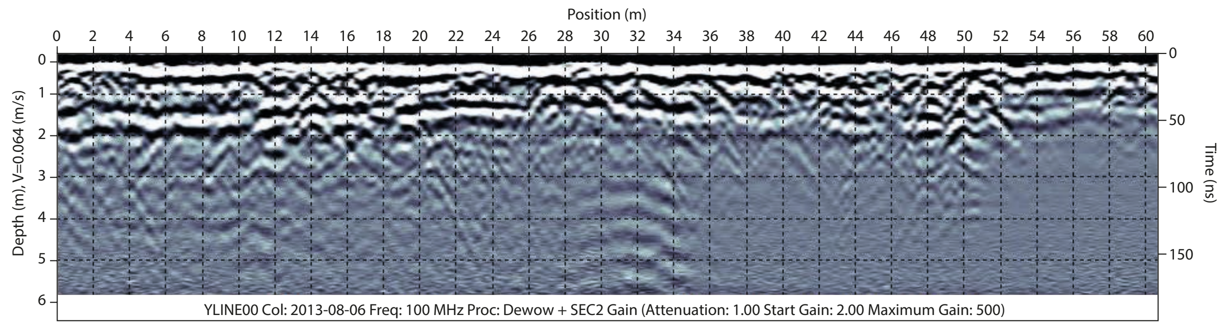
AIMS OF THE PROJECT

Our research aimed to investigate how seasonal changes in permafrost influence glacial meltwater streams (which carry water away from glaciers during the summer melt period). In particular, we wanted to answer two key questions:

- How do changes in permafrost affect the location of meltwater streams?
- And what does this mean for the type of material they carry?

To achieve our aim, we completed two field seasons, during winter and summer, at Lyngmarksbræen, an ice cap on Disko Island, West Greenland. We worked at an outlet glacier (a lobe of ice flowing from the main dome of the ice cap) on the east side of Lyngmarksbræen.

Printout of processed results from a GPR transect in front of the studied glacier.



WHAT DID WE DO?

To measure changes in the permafrost and active layer, we used ground penetrating radar (GPR). A GPR transmitter emits a signal into the ground that bounces off solid objects, such as rocks and ice, and is then detected by a receiver. The signal penetrates down to 6 m below ground. Without it, we would not know what the sub-surface looks like without digging lots of holes! In the field, we pulled the GPR behind us on a sledge, starting at the glacier snout and walking down the valley, taking measurements every 25 cm. We repeated this in the winter and the summer. Once the snow had melted in the summer we also mapped the meltwater streams draining from the ice cap. Back at the research station, we used computer software to process the data and develop an image of the sub-surface.

We also wanted to understand the type of sediment (e.g. pebbles, sand, and *silt*) that the meltwater streams were carrying and where this material had come from. We took sediment samples from the active layer and meltwater streams in the glacier foreland. We then analysed the grain size of these samples using a machine in the laboratory. We could then match the characteristics of the sediments in the stream to the different sample sites on the foreland – it is a kind of sediment "fingerprinting".

WHERE DID WE WORK?

Disko Island is just off the west coast of Greenland, in the same bay as Jakobshavn Isbræ – the fastest moving glacier in the world. We were lucky enough to stay at the Arctic Station (•66) – close to the town of Qeqertarsuaq, southern Disko. This area was ideal for our study because a number of ice caps and valley glaciers are located only a short (6 hours!) hike away from the station. The Arctic Station hosts international experts and during our stay we met other researchers: marine biologists, ecologists, and permafrost experts, among many others. It made for very interesting discussions over the dinner table!

The foreland of Lyngmarksbræen (Tim Lane).

WHAT DID WE FIND?

Although our analysis is on-going, we detected large changes in the state of the permafrost between the winter and summer. This is to be expected, as the "active layer" warms and thaws during the summer. At that time, the glacier is also in its melt phase, and the streams become very powerful, eroding and transporting large amounts of sediment that are frozen during the winter. Our analysis aims to establish whether enhanced thawing of the permafrost, due to climate change, might lead to greater erosion of permafrost in the glacier foreland.

We also collaborated with researchers from the University of Copenhagen, using the GPR to explore the ground close to the Arctic Station.

WHY ARE THE RESULTS IMPORTANT?

Our measurements can be combined with detailed climate records to investigate the impacts of climate change on the permafrost that could lead to major changes in the glacial environment.

THE ADVENTURE

All this makes the fieldwork sound easy! Travelling to Disko Island from the UK takes around three days, using an exciting mixture of planes, trains, helicopters, boats, and snowmobiles. The glacier was only 15 km away from Arctic Station, but getting there was a real adventure. In winter, temperatures were around -15°C and the snow was up to 1 m thick. Our rucksacks, which were filled with GPR equipment, weighed over 25 kg. Luckily, the meltwater streams were frozen and we could use crampons to walk on the ice. In summer, we still had the heavy rucksacks, but the meltwater streams had thawed into powerful, ice cold rivers – we crossed six of these during a 12 hour walk to the site. It was all worth it to camp only 500 m away from the glacier snout and eat our breakfast with such a fantastic view. After spending days living off rudimentary food cooked on our camping stove, we were always pleased to return to the comfort of the Arctic Station and share our experiences with the other researchers.

The Lyngmarksbræen meltwater stream in summer. The snout of the outlet glacier can be seen in the background (Tim Lane).

Further information

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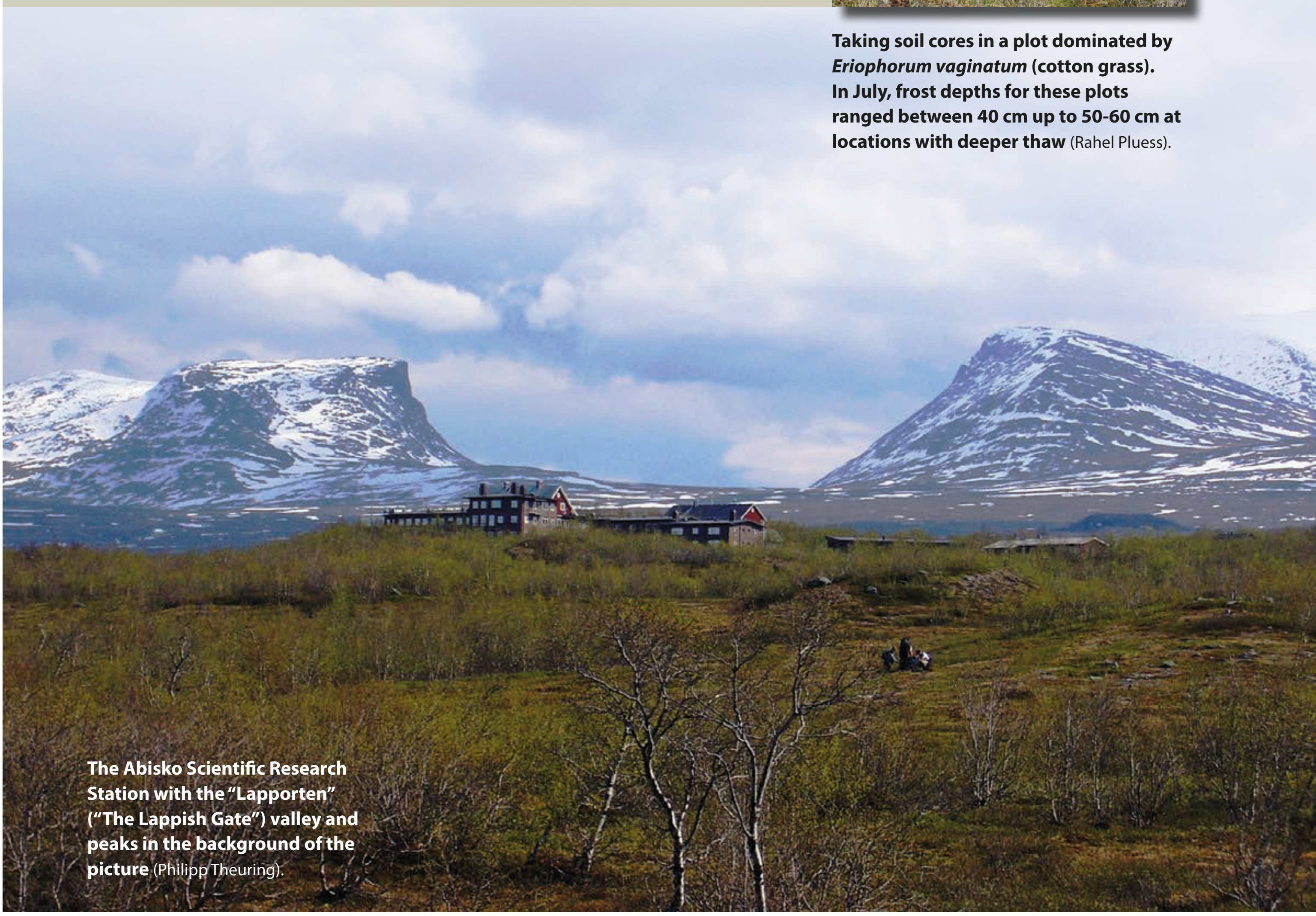
Plant community controls on thawing permafrost soils

Esther Dielissen, Bjorn J.M. Robroek & Ellen Dorrepaal

Permafrost (perennially frozen) soils underlay many of the world's boreal and Arctic peatlands. These frozen peat soils are generally nutrient poor, and potential plant and microbe–available nutrients are locked up in the ice. Climate-warming-induced soil thawing may unlock these nutrients, which then become available to plants and microbes. This could lead to positive climate feedbacks through greenhouse gas release from enhanced microbial decomposition. On the other hand, permafrost thawing could have negative feedbacks through increased plant nutrient uptake near the thaw front *(the position of a transition zone between deeper, frozen soil and shallower, unfrozen soil also called "active layer"), which results in increased sequestration of atmospheric carbon dioxide by stimulated plant growth (Section 4). Additionally, permafrost thawing provides more seasonally available unfrozen soil, offering opportunities for plants to further develop their root systems. Because plant species are likely to differ in their responses to these "opportunities", we envisaged that permafrost thawing changes plant interspecific interactions, ultimately leading to changes in plant community composition and ecosystem functioning.*

Taking soil cores in a plot dominated by *Eriophorum vaginatum* (cotton grass). In July, frost depths for these plots ranged between 40 cm up to 50-60 cm at locations with deeper thaw (Rahel Pluess).



The Abisko Scientific Research Station with the "Lapporten" ("The Lappish Gate") valley and peaks in the background of the picture (Philipp Theuring).

AIMS OF THE PROJECT

We aimed to investigate how plant community composition interacts with plant root distribution, plant root activity and microbial activity in thawing permafrost soils. Different plant communities were compared, varying from plant communities of several species (further referred to as "diverse" communities) to communities that were dominated by one species. In these communities, we tested if plant roots were able to reach the deeper soil layers near the thaw front. Additionally, we aimed to study the activity of the microbial community in releasing previously inaccessible nutrients (by studying enzymatic activities) and hence, the uptake of nutrients by plant roots (i.e. root activity).

WHAT DID WE DO?

We used local variation in active layer depth at the field site to simulate various degrees of permafrost thawing. Plots were laid out in "diverse" plant communities, and plots that were dominated by either dwarf birch *(Betula nana)*, crowberry *(Empetrum nigrum)* or cotton grass *(Eriophorum vaginatum)*.

From early July and late September (i.e. when a large part of the soil above the permafrost has seasonally thawed), soil cores were taken from each plot, and analyzed in the lab. From these soil samples we measured *enzyme* activities. Shortly, we measured *phosphatase* activity, an important enzyme involved in releasing phosphorus, and phenoloxidase, an indicator of microbial decomposition. Furthermore, we measured the abundance and mass of plant roots present at various peat soil depths to determine the vertical distribution of roots above the permafrost thaw front, which we assumed to be related to the presence of available nutrients.

WHERE DID WE WORK?

The fieldwork took place in permafrost tundra near the village of Abisko and the Abisko National Park in Swedish Lapland, about 200 km north of the Arctic Circle (68°21′ N, 18°49′ E). Our lab work was done at the Abisko Scientific Research Station (•11), a sub-Arctic and alpine field station. This field station attracts an international community of researchers who are specialized in climate change related subjects, due to its long history as a meteorological monitoring station, good accessibility, research facilities, and surroundings, which offer a high variability in hydrological, geological and ecological conditions.

WHAT DID WE FIND?

As expected, we found alive and active roots close to the permafrost, at a depth of 50-75 cm, especially in *Empetrum nigrum* dominated plots. Yet, microbial (enzyme) activity decreased with depth and was negligible at the permafrost thaw front. Microbial (enzyme) activity decreased strongest with depth in highly water-saturated plots, which may be explained by the lack of oxygen needed by microbes in those soils.

WHY ARE THE RESULTS IMPORTANT?

This study was, to our knowledge, the first attempt to find out if plant community diversity affects root activity and microbial (enzyme) activity in permafrost soils. By further investigating apparent connections between permafrost thaw and plant community composition, and by revealing underlying soil processes (decomposition and root growth), we can better estimate potential feedbacks on our climate.

THE ADVENTURE

The research station of Abisko is situated beautifully, alongside the 70 km long Torneträsk lake, surrounded by rough tundra terrain and high mountains. The often snow covered Lapporten peaks are a particularly breath-taking land mark. Being at the station from July to October provided the opportunity to observe both the midnight sun and northern lights, which are truly amazing sub-Arctic phenomena. In August/September, the species of birch and willow, which dominate the landscape, shift quite suddenly to autumn colours, which is a remarkable sight. Also, the cloudberries (a typically sub-Arctic berry) that covered the field site gradually ripened, which provided a nice extra to our lunch!

Field location lighting up orange in the autumn sun, with both mixed species communities and communities that were dominated by one species. The species that stands out most in this picture is *Eriophorum vaginatum* (cotton grass) (Esther Dielissen, September 2011).

Further information

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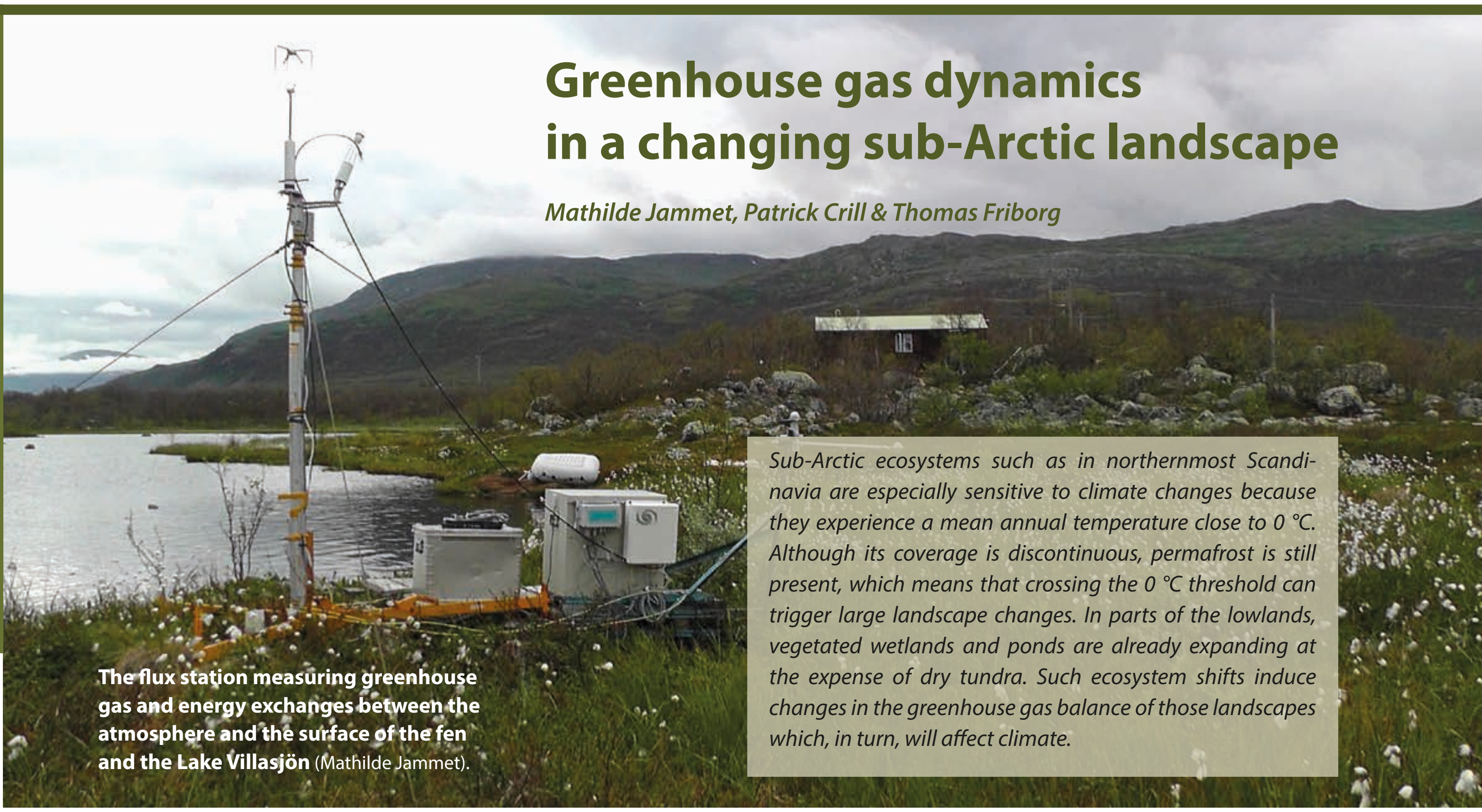
Greenhouse gas dynamics in a changing sub-Arctic landscape

Mathilde Jammet, Patrick Crill & Thomas Friborg



The flux station measuring greenhouse gas and energy exchanges between the atmosphere and the surface of the fen and the Lake Villasjön (Mathilde Jammet).

Sub-Arctic ecosystems such as in northernmost Scandinavia are especially sensitive to climate changes because they experience a mean annual temperature close to 0 °C. Although its coverage is discontinuous, permafrost is still present, which means that crossing the 0 °C threshold can trigger large landscape changes. In parts of the lowlands, vegetated wetlands and ponds are already expanding at the expense of dry tundra. Such ecosystem shifts induce changes in the greenhouse gas balance of those landscapes which, in turn, will affect climate.

AIMS OF THE PROJECT

As part of the Nordic Center of Excellence DEFROST and the EU project PAGE21, our project aims at increasing knowledge on greenhouse gas exchanges in sub-Arctic ecosystems affected by permafrost thaw. Specifically, we want to assess the importance of lake surface emissions within the landscape. We seek to extend knowledge from biologically active summer months to the entire year including winter and the "shoulder seasons" spring and autumn, which represent crucial transition periods for greenhouse gas dynamics.

WHAT DID WE DO?

Within a peatland undergoing permafrost thaw, we mounted a permanent measurement station located between two ecosystems representative of a post-permafrost stage: a *fen*-type wetland and a shallow lake. The station measures surface-atmosphere exchanges of greenhouse gas and energy. Various environmental information such as meteorological conditions, soil and water properties, vegetation development and snow thickness have also been monitored, in order to explain the variability in the fluxes observed at the station.

WHERE DID WE WORK?

The work was conducted in the Stordalen Mire near Abisko in northernmost Sweden. Because the Abisko Scientific Research Station's (•11) activities started in 1913, scientific research in Abisko benefits from extensive background knowledge to build upon as well as great facilities.

While ongoing permafrost thawing is observed in several peat *mires* around Abisko, research in Stordalen already started in the 1950's, which makes it particularly rich in ecological, physical and geomorphological data. From palsa mounds to small ponds, there is a high diversity of land and water surface types in Stordalen depending on different stages of permafrost thaw. This allows us to study several ecosystems and their relationships within one landscape.

WHAT DID WE FIND?

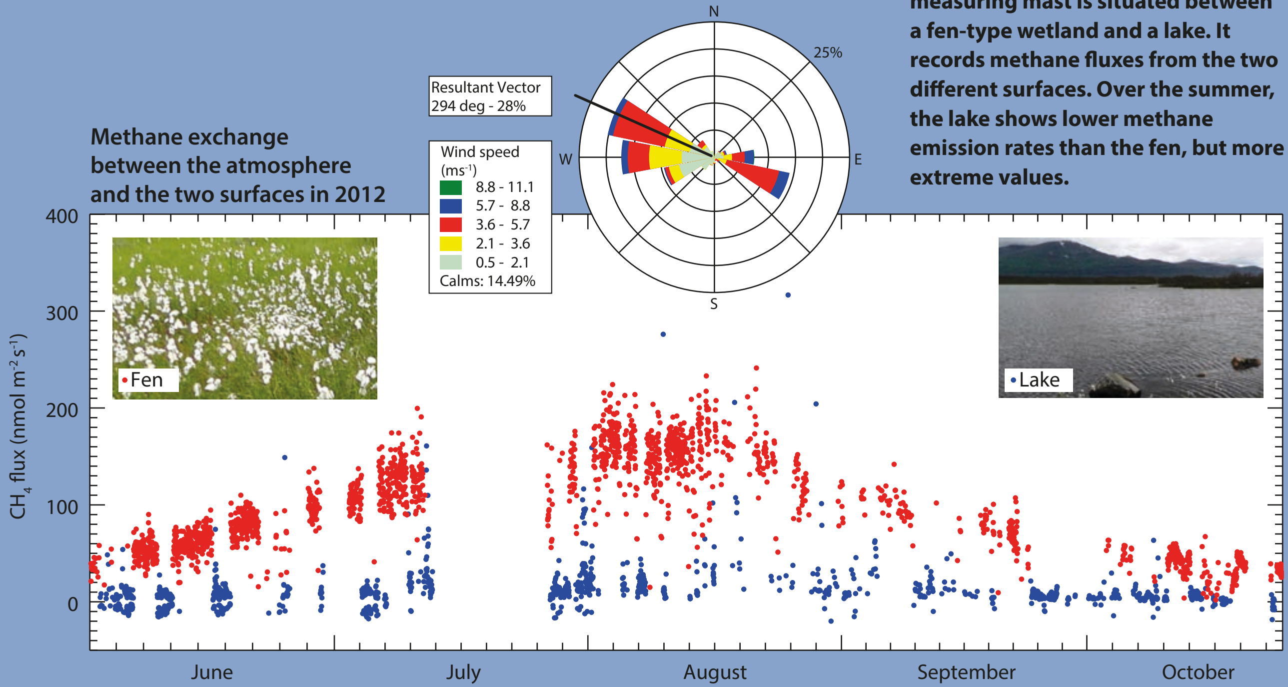
Wind flow in Stordalen is channeled into either a NWN or ESE direction. Due to this wind pattern, our flux station records greenhouse gas exchanges in two different ecosystems: a water-logged fen when wind comes from WNW and a shallow (average depth 0.7 m) lake when wind comes from ESE. In summer the lake emits less methane than the wetland it borders. However, this ratio varies from one season to another; when snow and ice melt in spring, the largest release of gases that were trapped during winter occurs at the lake. We therefore observed that winter is an important season for the production of greenhouse gases such as carbon dioxide and methane. In a wetland ecosystem, some can also be released through snow; 20% of the annual fen methane emissions were observed during the coldest season.

WHY ARE THE RESULTS IMPORTANT?

When trying to understand the full carbon cycling of Arctic landscapes, one realizes that open water bodies have been less studied than vegetated ecosystems. Yet lakes are numerous in northern latitudes (Sections 2 and 6) and can greatly affect the net carbon balance of a landscape (Section 4). Besides, assessing the importance of each season for the annual greenhouse gas budget of those ecosystems is essential to predict their net impact on climate in a future when the lengths of the seasons are very likely to change.

The wind blows alternately from two main directions in Stordalen. The measuring mast is situated between a fen-type wetland and a lake. It records methane fluxes from the two different surfaces. Over the summer, the lake shows lower methane emission rates than the fen, but more extreme values.

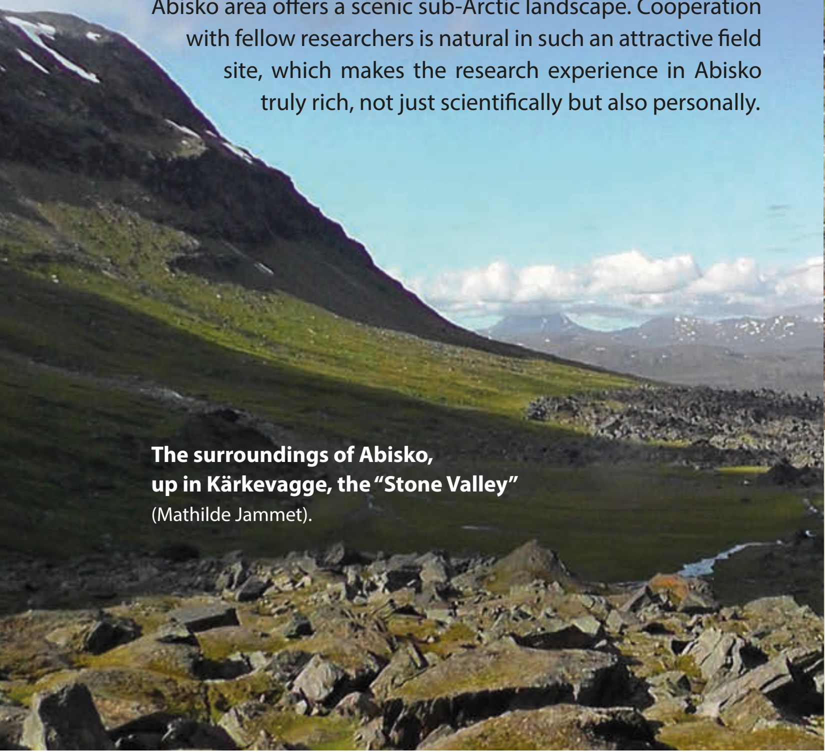
Methane exchange between the atmosphere and the two surfaces in 2012



THE ADVENTURE

Working in a remote environment always involves challenges regarding instrument transportation, power access and, sometimes, even lightning strikes. But it is also an enchantment throughout the year, from the dark cold winter with northern lights to the green summer when the Sun never sets. Located a few kilometres from the Norwegian mountain range and right at the shore of the great Lake Torneträsk, the Abisko area offers a scenic sub-Arctic landscape. Cooperation with fellow researchers is natural in such an attractive field site, which makes the research experience in Abisko truly rich, not just scientifically but also personally.

Palsa edge collapsing as a result of permafrost thaw in the Stordalen mire (Mathilde Jammet).



The surroundings of Abisko, up in Kärkevagge, the "Stone Valley" (Mathilde Jammet).

Further information

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Stable isotopes as indicators of environmental change

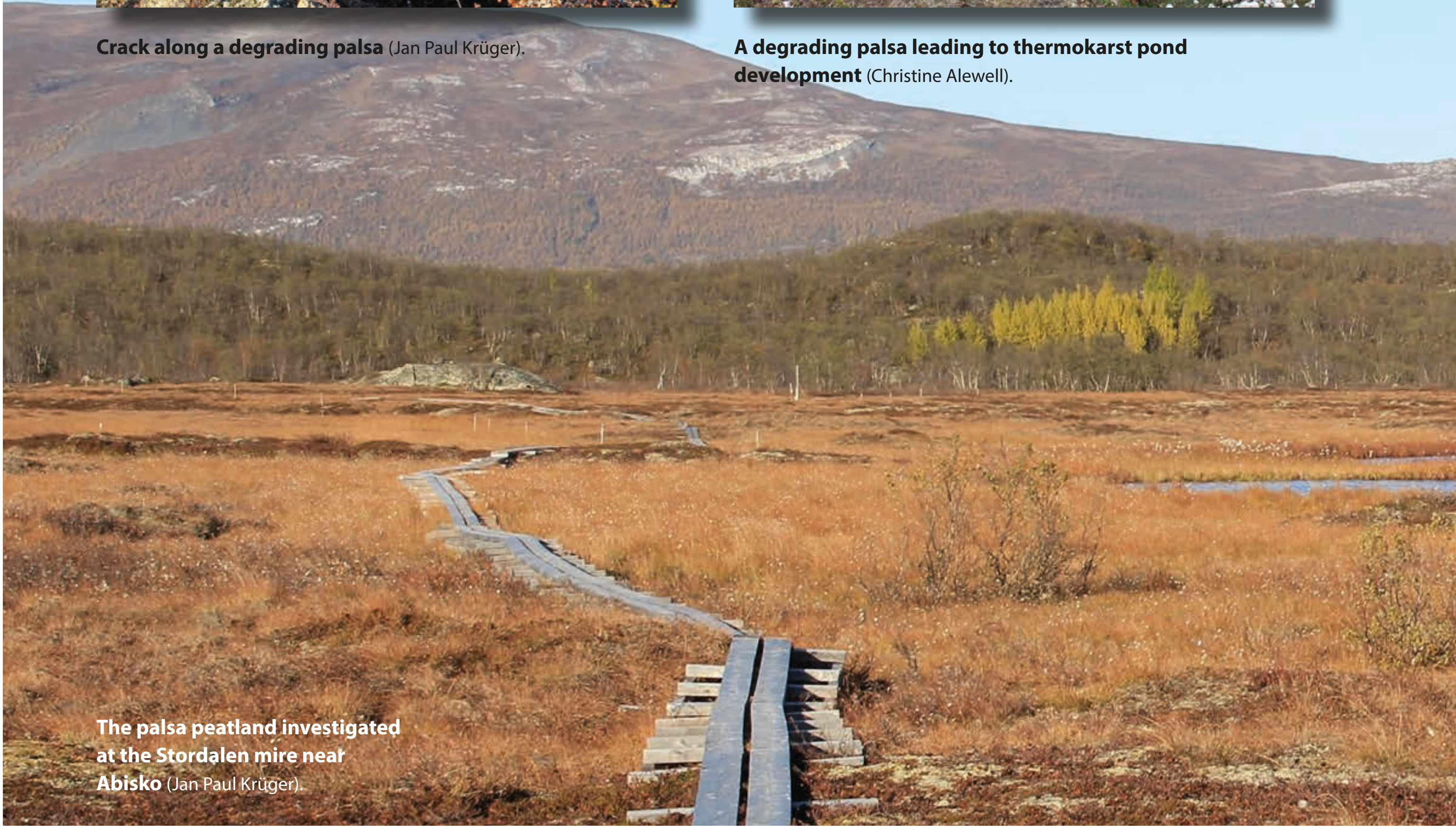
Jan Paul Krüger & Christine Alewell

Peatlands in the northern permafrost zone, where palsa mires are widespread, store a great proportion of the global soil carbon pool and are projected to change by global warming due to accelerated permafrost thaw.

We used the natural abundance of stable carbon isotopes at different depths down profiles of palsa peatlands near Abisko, northern Sweden, to detect historical permafrost aggradation (formation) as well as recent palsa degradation.

Crack along a degrading palsa (Jan Paul Krüger).

A degrading palsa leading to thermokarst pond development (Christine Alewell).



The palsa peatland investigated at the Stordalen mire near Abisko (Jan Paul Krüger).

AIM OF THE PROJECT

We wanted to use stable carbon isotopes in soil profiles as indicators of palsa degradation processes.

WHAT DID WE DO?

Soil cores were sampled from three palsa peatlands down to the permafrost and were analysed for stable carbon isotope abundance. Soil samples were taken in transects (lines constructed to determine sample locations) from hollows and hummocks including degraded sites of hummocks and hollows.

WHERE DID WE WORK?

We worked near the Abisko Scientific Research Station (•11), 200 km north of the Arctic Circle. The research station is in the discontinuous permafrost region where palsa peatlands are widespread. Close to the research station in Abisko there are several palsa peatlands which are degrading due to accelerated permafrost thawing by climate warming in this region.

WHAT DID WE FIND?

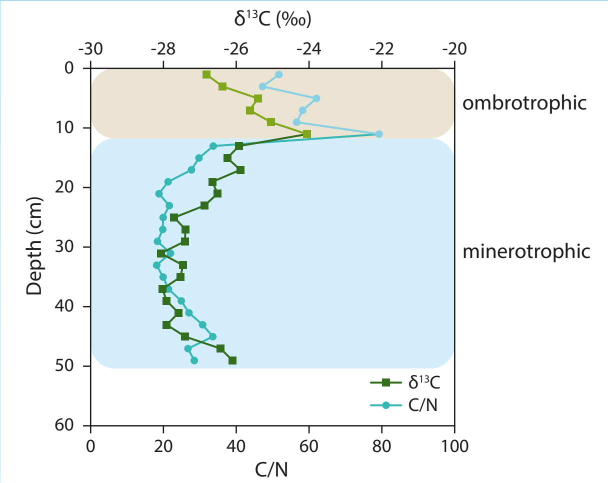
We analysed 36 soil profiles from degraded to non-degraded sites in three palsa peatlands. In transects, we found significant differences between the degraded and non-degraded sites in stable carbon isotope abundance with increasing depth down the profiles. Palsa mires have a complex relief of elevated areas, called hummocks, which are upheaved by permafrost thickening and the wetter depressions in between, called hollows. Differences in the depth patterns of stable isotope abundance indicate the disturbance of hummocks by permafrost thawing as well as disturbance in the hollows due to the input of degrading palsa material. Furthermore, isotopes indicate the uplifting of the peat by permafrost in the intact palsas due to a change in decomposer metabolism (from *anaerobic* to *aerobic*).

WHY ARE THE RESULTS IMPORTANT?

Palsa peatlands are an important carbon pool and the carbon balance of these peatlands is predicted to be changed by the current climate warming in this region. Natural abundance of stable carbon isotopes is a useful tool to detect palsa degradation and palsa development. These analyses help to understand processes related to these changes including peat formation and peat decomposition.

THE ADVENTURE

Reaching the Abisko Scientific Research Station required travel to northernmost Sweden. The station, where we used the good infrastructure including the lab for our research, is situated close to the beautiful lake Torneträsk. All the palsa peatlands investigated can be easily reached from the research station.



Stable carbon isotope depth profile (represented as the change in proportion of the heavier carbon isotope ^{13}C as well as carbon to nitrogen (C/N) ratio) at an intact hummock from a palsa mire in northern Sweden. Increasing $\delta^{13}C$ values with depth as well as high C/N ratios in the upper part indicate *ombrotrophic* conditions (peat formation with low nutrient input). Decreasing $\delta^{13}C$ values with depth as well as low C/N ratios in the lower part indicate *minerotrophic* conditions (peat decomposition which releases nutrients). The change from increasing to decreasing $\delta^{13}C$ values indicates the uplifting of hummocks by permafrost (Modified from Krüger and others 2014).

Soil corer on an intact palsa hummock (Jan Paul Krüger).

Further information

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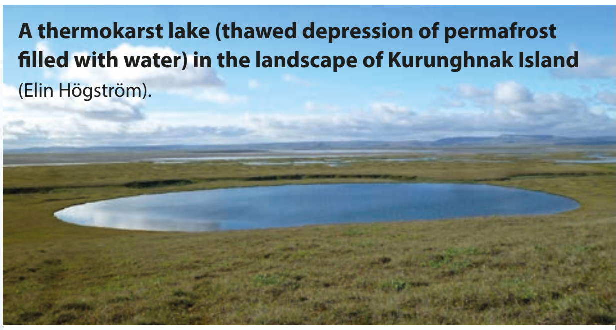
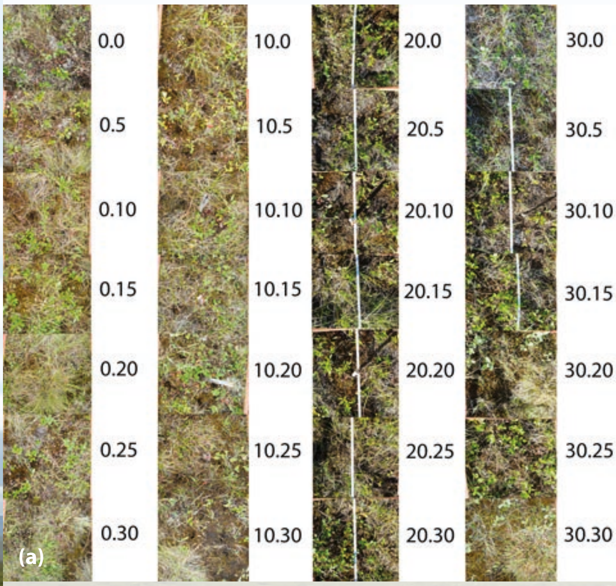
Validation of soil moisture data from the Lena Delta retrieved by satellite

Elin Högström, Birgit Heim & Annett Bartsch



A thermokarst lake (thawed depression of permafrost filled with water) in the landscape of Kurunghnak Island (Elin Högström).



(a) Grid photo documentation and grid point numbering for one of the 5 defined grids at Kurungnakh.
(b) Installation of a shallow soil moisture measurement station.
(c) Instant measurements with a hand held sensor, which were done across the grids (Elin Högström).

Soil moisture is an important factor for modelers working on the global extent of permafrost. Radar satellite data can be used to estimate surface soil moisture (SSM) in remote areas that are difficult and costly to access, such as in the Arctic. Ground based in situ measurements are needed however, to assess the applicability of such estimates. Validation studies from the Arctic are rare particularly as the available in situ networks for soil moisture collect data for various purposes (e.g. process understanding and modelling) with measuring equipment often installed deep below the surface observed by satellites.

AIMS OF THE PROJECT

To validate coarse scale satellite derived SSM in the Arctic, in situ data has already been collected from international measurement networks across the region. For a deeper understanding of how representative such in situ data are for comparison with satellite-derived data, a new set-up of in situ measurements was deployed during an expedition in the Lena Delta in 2013. In this way, we can improve our understanding of the radar signal over the tundra.

The landscape of Samoylov Island (Birgit Heim).

WHAT DID WE DO?

We set up five 30×30 m grids with as consistent/uniform vegetation and topography as possible, as shown in Figure (a) to the left. Instant soil moisture measurements were made at depths of 3 and 5 cm in 28 points across each grid. The vegetation was described for each point. Five shallow automatic soil measurement stations were also installed at Kurungnakh and Samoylov. Each measurement station consists of soil moisture sensors and temperature sensors that are installed at two depths in the uppermost soil layer (Figures (b)-(c) to the left). The depths relate to the satellite sensor signal's theoretical depth penetration of 5-6 cm. The purpose of the grids was to evaluate snapshots of fine resolution satellite data. The purpose of the soil stations is to evaluate coarse-scale satellite soil moisture over time (time series) from the satellite instrument ASCAT.

WHERE DID WE WORK?

The Lena Delta offers a large suite of different permafrost landscape types and tundra vegetation types that can be logistically accessed via boat. The Research Station Samoylov Island (•38) is located on the island of Samoylov. Kurungnakh is another island located only a few kilometres away. There is long-term monitoring on Samoylov, including automatic climate and soil measurement stations (Boike and others 2013), which has been useful for this current project as well.

WHAT DID WE FIND?

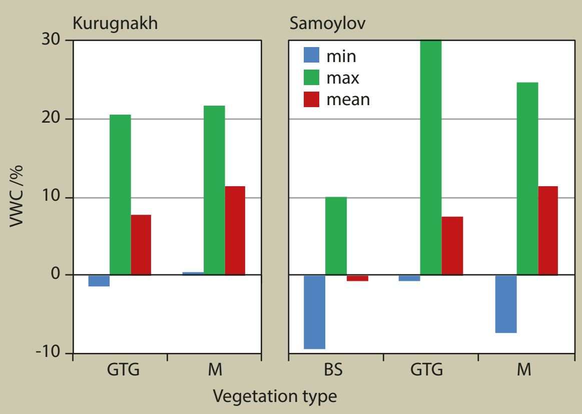
Data from the newly installed measurement stations were collected in August 2014. Comparison of other in situ measurements with satellite data indicates that shallow installation of sensors is an appropriate choice. The uppermost sensors are more directly affected by the atmospheric conditions than the deeper soil layers, where changes in moisture and temperature happen comparatively slowly and to a small extent. The in situ measurements in upper soil layers are expected to correspond well with the satellite data, which represents precisely the uppermost few centimetres where the faster changes occur. Laboratory analyses from moss samples taken from Kurungnakh show the moisture characteristics of the moss layer; water is permanently stored in the *fibric layer* (a layer of decomposing old moss) below the porous living moss layer. We installed one sensor in the living moss layer, and one in the fibric layer. The figure below shows the difference of soil moisture behavior at two depths for various vegetation types across sampling grids on Kurungnakh and Samoylov.

WHY ARE THE RESULTS IMPORTANT?

The results help us to understand the satellite return signal in the tundra which in turn can give us some insights about how improvements can be made to the ASCAT soil moisture product. It contributes to the development of sensor networks for monitoring environmental conditions. By means of collaborations within the EU Project PAGE21 this work contributes to a better understanding of the environmental changes in the Arctic through satellite data improvement, thus facilitating improved large scale assessments.

THE ADVENTURE

On the way back to Europe, the weather conditions did not allow us to fly from Tiksi until several days later than the planned departure, which in turn meant that we missed the connecting flight from Yakutsk to Moscow and Berlin. This gave us time to explore the areas where we were waiting. We were invited by local people for raw frozen meat in the small town of Tiksi and had the opportunity to visit the permafrost museum in Yakutsk – the capital city of the Sakha Republic.



Minimum, maximum and average difference between the *volumetric water content* (VWC) at 5-3 cm depth for various dominating vegetation types, measured across grids at Kurungnakh and Samoylov. GTG = grass and tussuck grass, M = moss, BS = bare/sparsely vegetated ground.

Further information

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3 Snow and ice

SECTION OVERVIEW

Gunhild Rosqvist

The Earth's "*cryosphere*" includes snow, ice sheets, ice caps, glaciers, frozen ground, and ice on rivers, lakes and oceans. Higher air temperatures are resulting in rapid changes in Arctic snow and ice extent and thickness. These changes matter globally because of interactions between the climate and the cryosphere, often leading to accelerated warming through positive *feedback mechanisms*. For example, changes in snow and ice cover influence the reflective character of the Earth's surface through changes in *albedo* (the reflection of heat from the surface). Increased melt of snow and ice results in a freshening of ocean surface waters. This in turn is expected to lead to a change in the ocean circulation, shifts in atmospheric circulation patterns, and regional temperature and precipitation trends and variability. Changes in snow and ice are also highly important for *ecosystems* and people in the Arctic. The effects of the present rapid rate of climate change, together with other pressures on Arctic natural resources, are challenging the traditional land use and livelihood of Arctic communities.

3

PAST CHANGES

Knowledge of the history of climate change comes from reconstructions using so-called natural climate archives. Several well-preserved archives are located in the Arctic, and foremost among them are ice cores. Greenland ice cores provide climate information spanning the last ca. 130,000 years (the *NEEM ice core*). From such records we can derive information on changes in temperature, precipitation, and atmospheric circulation. Moreover, air bubbles in the ice preserve information on the atmospheric concentrations of the *greenhouse gases* carbon dioxide and methane. Such data are extremely valuable because they show that greenhouse gas concentration drives climate changes through the Earth's radiation budget. The ice core data also show that the current rate of change in the Arctic is very rapid.

Environmental reconstructions using ice cores (and also lake sediments and tree rings) have shown that summer temperatures in the Arctic now are the highest for the past 2,000 years. We also know that changes in seasonality of precipitation have had large effects on terrestrial ecosystems and natural resources, and, therefore, also on human society.

The Mittivakkat glacier front nearby the Sermilik Research Station (•68) in Southeast Greenland (Edward Hanna).

CHANGING SNOW CONDITIONS

Arctic snow cover has changed over at least the past 50 years (since recording by satellites began) in response to documented temperature increases and changes in the amount and timing of winter precipitation. Impacts of these changes on hydrological and ecological systems have become obvious in many places.

Several important physical properties of snow influence climate. Snow has a high albedo which means that the snow surface reflects a large proportion of the incoming *short-wave radiation* from the Sun, keeping the surface cool. Snow has a low thermal conductivity, the effect of which is to insulate the ground and soil from the cold Arctic winter air above. Science Story 3.1 shows how large crystals of depth hoar are important to the insulation of the ground in an area of Arctic Russia. Snow cover depth, therefore, influences both temperature and moisture conditions at the base of the snow pack which in turn set the stage for hydrological, ecological and biogeochemical processes in the seasonally frozen ground (to a few metres depth). Snow cover also isolates the ground thereby protecting animals under the snow from predators above and vegetation from herbivores (Figure 3.1).

Variations in snow accumulation influence Arctic hydrology significantly. For example, the seasonal discharge (flow) pattern in Arctic rivers is affected because the thickness of the snow cover, which determines the strength in the seasonality of the hydrological cycle, is changing. Snow stores water during the winter and releases it during spring melt. Hence, at present the highest discharge occurs during spring floods. The expected future shorter snow accumulation season, thinner snow pack, rain events in the winter and stronger and perhaps more frequent rain events during the summer will all affect river discharge patterns. The number of snow-covered days and the water content of the snow pack are therefore important parameters to monitor.

Snow influences Arctic ecosystems as it provides protection from low winter temperatures, large temperature fluctuations, and herbivory. There is a close relationship between snow distribution and vegetation types. Low growing plants that can withstand high wind speeds and summer drought, like *lichens*, often grow on exposed areas where winter snow cover tends to be thin whereas other plants that can withstand very short growing seasons occupy depressions where snow accumulates. Interactions between snow and vegetation/*biodiversity* are complex as vegetation also influences the accumulation (including redistribution) and the *ablation* (melting) of snow.

As winters are getting warmer, mid-winter melt periods and rain-on-snow events occur more frequently. Because the snow packs are cold, the rain water freezes and forms ice crusts underneath (on the ground), within, or on top of the snowpack. These ice layers prevent access to food by herbivores and pose severe challenges for reindeer and small mammals such as lemmings that live in tunnels ("*sub-nivean cavities*") (Figure 3.1) under the snow. An increase in reindeer mortality has been noted after such events and lemming population peaks have disappeared in many Arctic areas (Section 5). Thick snow packs can lengthen the melt-season, delay food availability in the spring, and have drastic effects on the populations of grazing animals. Trampling by large animals such as reindeer hardens the snow pack. This

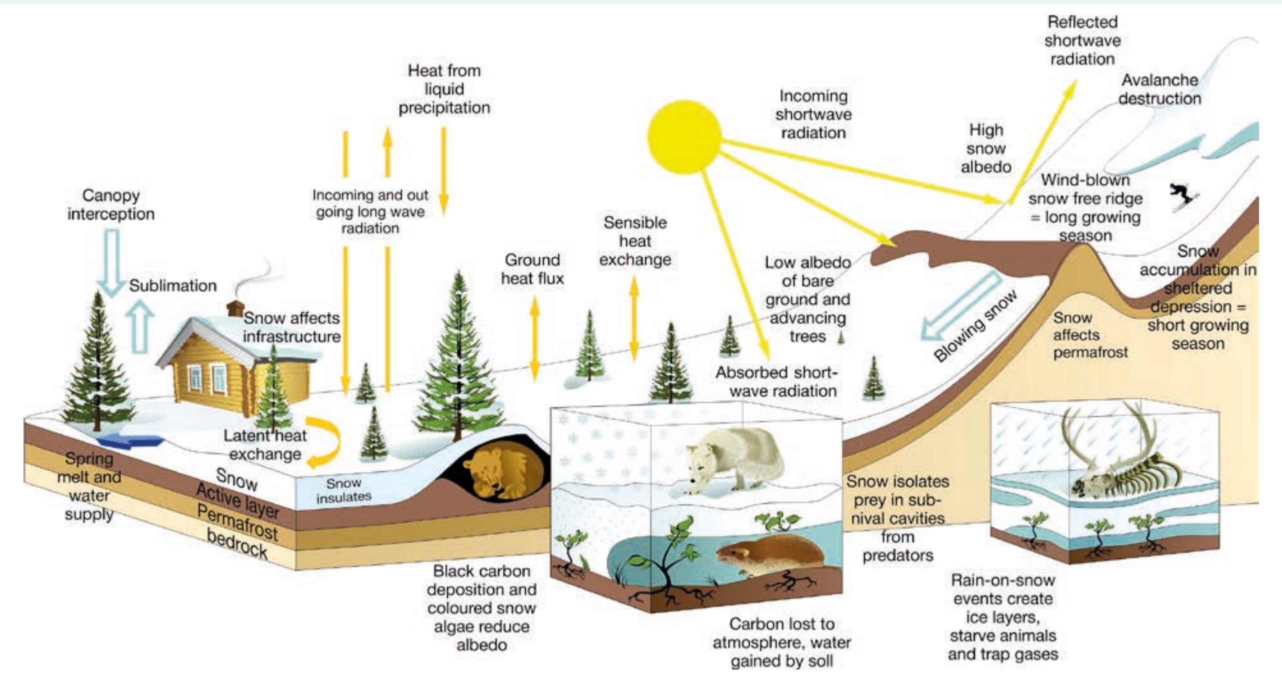


Figure 3.1 Energetic and ecological characteristics of an Arctic snow cover (Terry V. Callaghan modified from Callaghan and others 2011, Callaghan and Johansson 2014, and Seibert and others 2014. Redrawn by Arview, Tomsk).

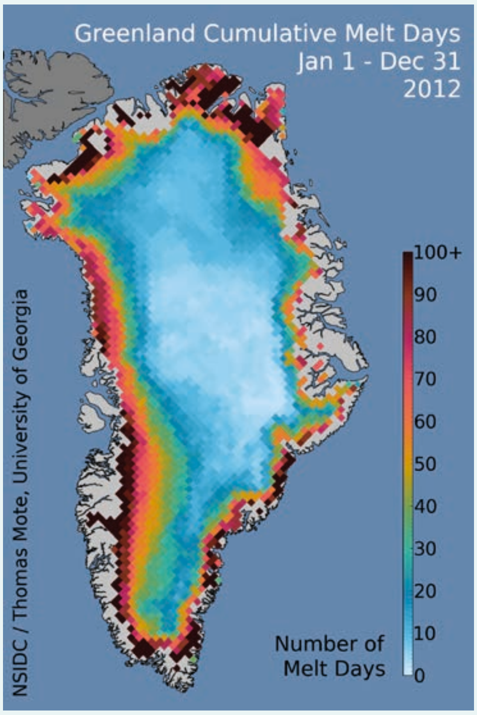
tends to happen when they reside in an area for a longer period of time which is often the case when food is scarce.

Higher summer temperatures will increase the melt rate of snowfields and eventually they may disappear. Successive melting of snowfields and reduction in their area provides fresh soil for vegetation generation throughout the summer season. Summer snowfields are also important environments for the well-being of reindeer as they visit them to avoid insects and cool down. While decrease of the snow season might favor plant growth because of longer growing seasons, the reduced supply of water following melt results in drought in some drier areas during early summer and tree death.

Understanding how the Arctic terrestrial carbon balance will respond to rising temperatures is urgent as the high-latitudes contain nearly half of the global soil carbon (Section 4). Because snow is such a good insulator and increases ground temperatures, snow thickness and extent also influence *permafrost* dynamics (Section 2), and ecosystems in permafrost areas constitute a potential large greenhouse gas emission source. On the other hand, it has recently been demonstrated that even a moderate increase in snow depth may allow Arctic ecosystems to become a source instead of a sink of carbon to the atmosphere (without altering the growing season length or composition of vegetation), and that it can increase plant disease by fungal pathogens.

Pollution through the air, or as local spills of for example hydrocarbons (fossil fuel and oil) in snow and ice, is increasing in the Arctic. This is partly because of increased transport and activity of extractive industries like mining. Atmospheric pollution impacts the snow's energy budget; for example soot particles (elemental carbon), which are produced by burning of fossil fuels and natural forest fires, darkens the snow surface. Forest fires in North America have for example deposited soot on the Greenland Ice Sheet. This in turn decreases the albedo and therefore increases absorption of short wave radiation and the heating and melting of the snow pack. Snow pollutants are released when snow and ice melts. Science Story 3.2 shows how Black Carbon pollution of the Svalbard snow pack has changed over time and to what extent it reduces albedo. Hydrocarbon spills in snow are transported by meltwater downstream where damage to aquatic ecosystems may occur. Alpine glaciers in some settings now represent a secondary source for *persistent organic pollutants* (POPs) while melting rapidly. Heavy metal concentrations are high in snow deposited close to industrial centers. Changes in snow extent and thickness will change the size of the reservoir for contaminants such as heavy metals and POPs.

Ice sheets and glaciers harbor the largest freshwater ecosystem communities in the world! Despite their extreme habitats in glacial ice and snow, several types of organisms thrive here, such as algae, bacteria, fungi, protozoa, rotifers and even larger invertebrates. It is therefore important to study such organisms because they are primary producers in many glacial settings (Science Story 3.3). Understanding how microbes in snow and ice respond to increased warming and increased pollution loads should also be a prioritized task. An improved understanding of how primary colonization of snow and ice occurs can also help us assess the potential of life on other icy planets. In addition, algae and other organisms in snow affect albedo as shown in Science Story 3.3.



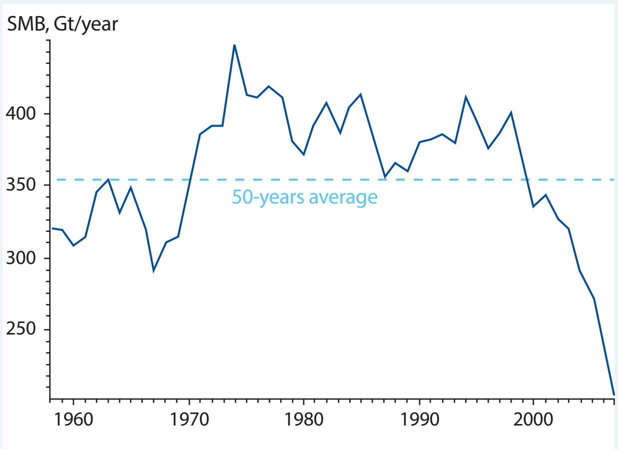


Figure 3.2 More and more of the surface of the Greenland Ice Sheet is melting in summer. The map shows the extensive area of melt in 2012 (National Snow and Ice Data Center/Thomas Mote, University of Georgia, USA).
Over time, the surface mass balance (SMB) of the glacier has declined substantially with a loss of gigatonnes (GT) volume (AMAP 2011).

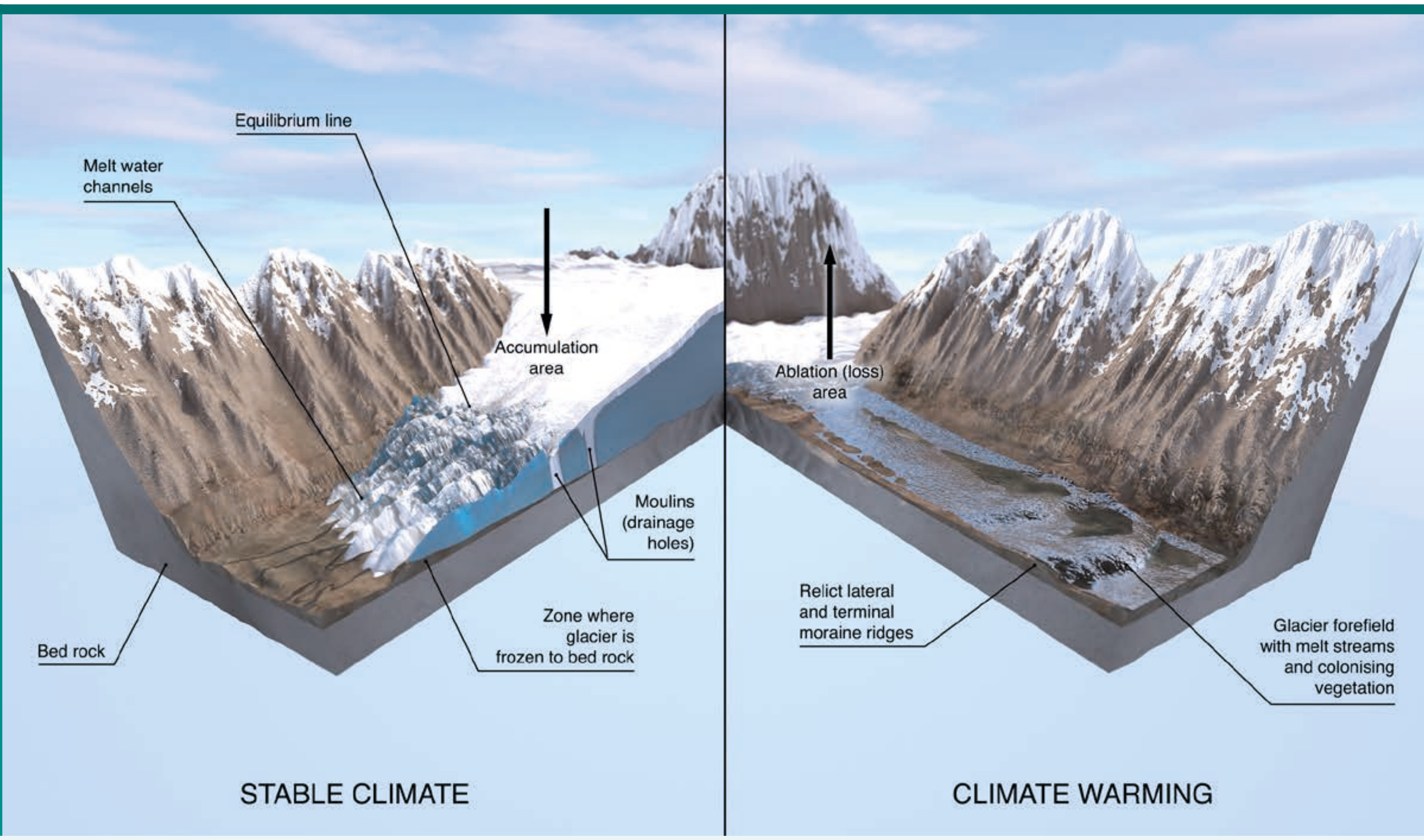


Figure 3.4 The glacier to the left is in balance with climate, snow income (accumulation) balances snow and ice output (ablation) which is indicated by the relatively large accumulation area (ca. 1/3) and a relatively high surface profile. The glacier on the right is losing mass as the accumulation is not high enough to compensate for the high ablation. The glacier is therefore retreating exposing new land in the fore-field which is covered by boulders, smaller rocks and finer particles transported either by the ice or by meltwater. *Moraine* ridges in front (terminal) and on the side (lateral) of the glacier show historical larger extents (Drawn by Arview, Tomsk).

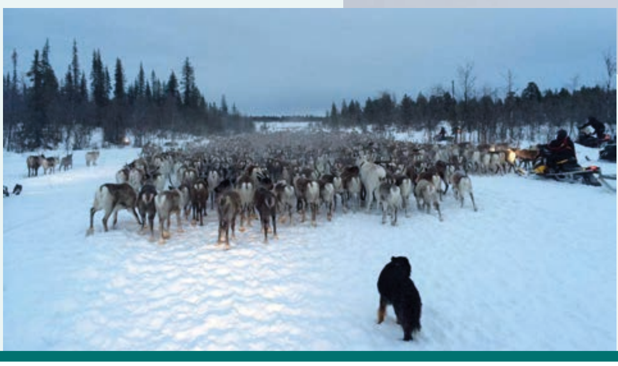


Figure 3.3 Measuring snow depth (accumulation) and drilling ablation stakes (on which summer melt is monitored) on Mårma glacier in northern Sweden (Gunhild Rosqvist).

Figure 3.5 Reindeer being herded to their winter pastures in northern Sweden (Niila Inga).

MELTING ICE

The Antarctic and Greenland ice sheets make up the vast majority of the Earth's cryosphere. If these ice sheets melt entirely, sea level would on average rise more than 70 metres. The observed rise in sea level over the last century of 1-2 mm/year, has been explained by an increased melting of mountain glaciers and the margin of the Greenland Ice Sheet (Figure 3.2), and by a thermal expansion of the oceans (IPCC 2013). It is not yet possible to judge whether melting of the Antarctic ice sheet is contributing to the observed changes in sea level (IPCC 2013). Dramatic thinning rates have been observed at low elevations on the Greenland Ice Sheet and they result from ice flow changes and surface melting. Glacier monitoring (shown in northern Sweden in Figure 3.3) in Southeast Greenland (Science Story 3.4) documented record mass loss for the Mittivakkat glacier in 2011. The processes involved are summarised graphically in Figure 3.4.

The sensitivity of smaller glaciers and ice caps to climate change is determined by their response time (i.e. response to changing climate), which in turn is determined by their volume, temperature regime, and topographic and climatic settings. Science Story 3.5 illustrates how these characteristics were measured for glaciers in the Yukon and Alaska. Most alpine glaciers in the Arctic have response times of a few decades. Hence, the effect of the ongoing warming over the past decades is now becoming striking. Predictions of how glaciers respond to climate change requires knowledge of their ice flow properties. Glacier flow is influenced by internal ice properties (such as temperature) and the composition of the material at the bottom of the ice, where ice, water, bedrock or sediments meet. Such glacier-bed properties can be studied with seismic methods. Science Story 3.6 shows how *ground-penetrating radar* can be used to determine if liquid water is present in an otherwise frozen ice mass. This is important because the presence of water determines how fast the glacier moves and responds to climate change.

The response of alpine glaciers to climate variations on seasonal-to-annual time scales is monitored through glacier mass balance measurements (Figure 3.3). The amount of snow falling during the winter comprises the winter balance (accumulation) and the amount of snow and ice that melts (ablation) during the melt-season, constitutes the summer balance (Figure 3.4). If the net balance is positive, the glacier gains mass. Even if some Arctic glaciers still can attain a positive net balance during individual years, most Arctic glaciers have generally lost mass during the last 50 years, and since 1990 this loss has increased (Figure 3.6 and 3.7).

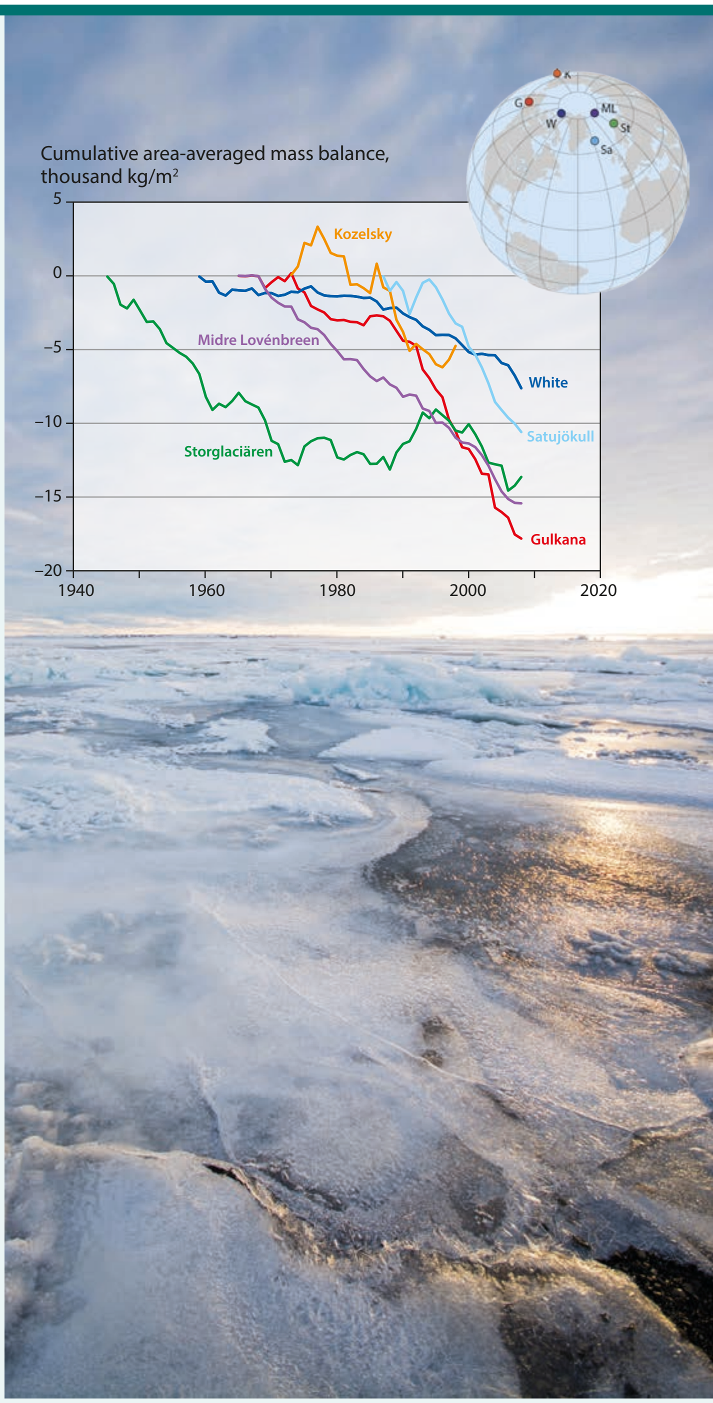


Figure 3.6 Massbalance (cumulative area-averaged) for six Arctic glaciers: White Glacier (dark blue; Axel Heiberg Island, Canada), Gulkana Glacier (red; Alaska, USA), Storglaciären (green; Sweden), Midre Lovénbreen (purple; Svalbard), Satujökull (light blue; Höfsjökull, Iceland), and Kozelsky (yellow; Kamchatka, Russia). All records show net thinning over the period of record and more rapid thinning since ca. 1990 (Stephan Bernberg. Graphics redrawn from M. Sharp, AMAP 2011).

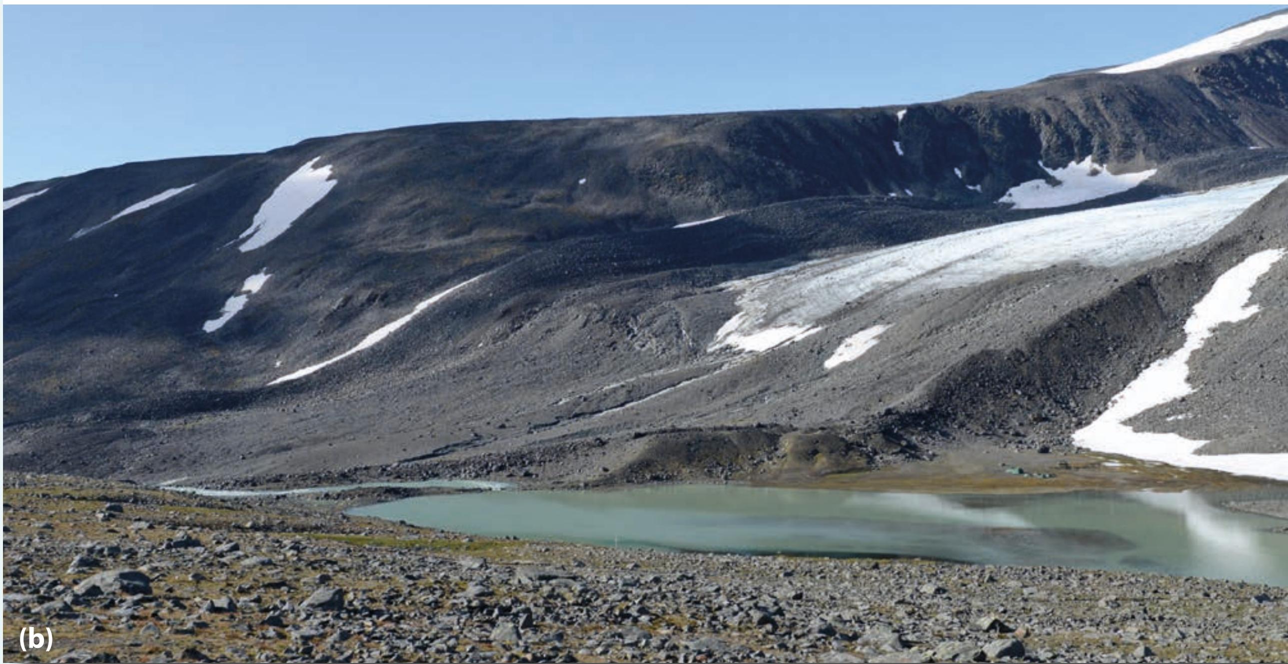


Figure 3.7 A more than 100 year change (from 1990 (a) to 2013 (b) in the extent of Storglaciären, Tarfala, northern Sweden, is clearly marked by moraine ridges (Fredrik Enquist 1910 (a), Per Holmlund 2013 (b)).

Increased melt of glaciers (as well as a shorter snow cover period and changes in the snow water content) affects water supplies in some regions. This is because snow stored on glaciers in the winter melts successively in the spring and summer, together with glacier ice, contributing with meltwater to rivers during the vegetation season. In other areas glacier meltwater is temporarily stored in moraine-dammed lakes. The stability of such dams can degrade, especially if they are ice-cored (contain ice in their centers) and the ice core melts. If these dams break suddenly, meltwater is released catastrophically through *glacial lake outburst floods* (GLOF) (Science Story 1.5), and these floods can potentially destroy downstream settlements and infrastructures causing casualties.

Specific landforms located beyond the presently glaciated area, such as moraine ridges and trim-lines, indicate that glaciers were formerly more extensive. Often the most prominent moraines are those that were deposited up to a few hundred years ago when climate in the Arctic was colder (the so-called *Little Ice Age*; 17th -19th centuries). Mineral particles eroded by the glaciers as they retreated from such moraines became deposited and form "*minerogenic*" layers in downstream lakes.

Such layers also indicate time periods when climate was favorable for glacier growth. This type of landform and sediment evidence can be used to assess the sensitivity of a particular glacier to climate change if independent temperature and precipitation reconstructions are available for the same area. Science Story 3.7 describes how various methods can be used to see how the changes in mass balance of an ice field are reflected in changes in the position of the ice margin and associated deposition of materials carried by glaciers.

EFFECTS ON INDIGENOUS CULTURES

The effects that changes in snow and ice have on Arctic ecosystems require indigenous cultures to change the traditional land use (Figure 3.5). For cultures that are strongly reliant on their natural environment, climate and ecological change will have a significant impact. For example, changes in snow conditions challenge reindeer herding, while activities by extractive industries and associated infrastructure developments are fragmenting the land traditionally used for grazing, thereby further stressing the traditional communities and causing increased pollution. To identify best practices and facilitate adaptation, scientific and traditional knowledge on for example how animal behavior depends on weather and snow conditions need to be collected, shared, and combined.

Key messages and needs for further research

Research projects, such as those at INTERACT research stations, benefit from the availability of monitoring data that provide a long-term context for recent changes. Crucial information which has been lacking concerns details of snow conditions beyond simply depth, duration and water content. Hence, there is a strong requirement for long-term, high-precision and standardized observations of changing snow conditions such as grain size and development, ice layer formation etc. Ice conditions in the Arctic also require careful monitoring. Of special importance will be (a) the influence of ice melting on sea level rise that has many uncertainties yet could affect many millions of people in low lying countries, (b) feedback mechanisms that amplify climate warming, and (c) direct impacts on societies and ecosystems of the Arctic.

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How snow insulates permafrost soils

Martin Proksch & Martin Schneebeli

With the advance of climate change, the permafrost (permanently frozen) soils in large regions of the world are at risk of thawing. This could release immense amounts of greenhouse gases which are currently stored in the permafrost, and thus accelerate climate change. Permafrost is, however, covered by snow for around half of the year, and snow is a very good insulator. The effect of the snow cover on permafrost was the main subject of this expedition.

Infrared photography of a snow profile: the lower 3/4 of the snowpack consists of large depth hoar crystals, which are efficient insulators (Martin Proksch).

AIMS OF THE PROJECT

Our aim was to understand the the complex and largely unknown microstructure of the snow covering permafrost soil.

WHAT DID WE DO?

We collected snow samples in the Samoylov area and brought them back to Switzerland for further analysis in our laboratory. To preserve the very fragile snow samples, we replaced the air in the pores with a liquid freezing slightly below zero degrees. These solid deep-frozen samples could now be transported the long way from northern Siberia to Switzerland. Back in the cold laboratory, we scanned the samples using computed tomography (similar to X-ray tomography in medicine) to reconstruct the 3D microstructure of the snow. We could then calculate the thermal properties of the snow from these images.

WHERE DID WE WORK?

We worked in the area around the Research Station Samoylov Island (•38), northern Siberia, Russia. The Samoylov Research Station is located on a small island in the Lena Delta close to the Laptev Sea and has a long tradition in permafrost monitoring. We joined a research team from the German Alfred Wegener Institute, which has more permanent activities at the Research Station Samoylov Island.

WHAT DID WE FIND?

The surface topography of the *polygonal tundra* in Samoylov is very hummocky (i.e. there were many small mounds about 30 cm high). This results in rapid changes in snow depth and its thermal properties at the scale of a few metres. Typical for this snowpack, we found large amounts of cup-shaped depth hoar crystals, which were extraordinary large with sizes up to 2 cm at the end of the winter. These depth hoar crystals form because of large temperature gradients within the snowpack. Thanks to our special sampling techniques we could, for the first time, preserve and measure the intact snow structure formed by these depth-hoar crystals.

WHY ARE THE RESULTS IMPORTANT?

Depth hoar is known to have a low thermal conductivity which means that the snow cover on Samoylov is an effective insulator which prevents the very low temperatures during the Siberian winter from penetrating deeply into the ground. The permafrost is preserved because of the low temperatures during winter, in order not to thaw in summer. Therefore it is important to determine the exact thermal conductivity of depth hoar.

The new research station at Samoylov Island, Siberia (Michael Grigoriev).

Journey to Samoylov Island on the frozen Lena River (Martin Proksch).

Documenting a snow profile (Thomas Opel).

THE ADVENTURE

Siberia is always an adventure! Reaching the Research Station Samoylov Island requires a trip through northern Siberia by plane, helicopter and tracked vehicle driving on the frozen Lena River. Staying at this kind of remote station and seeing the landscape and how the snow cover evolved was an experience of its own.

Further information

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Taking first measurements on the way to Samoylov Island (Martin Proksch).

Black Carbon and its radiative impact in a Svalbard snowpack

Christina A. Pedersen, Jean-Charles Gallet, Sebastian Gerland, Elisabeth Isaksson, Johan Ström & Terje K. Berntsen

Black Carbon (BC or soot) particles are small particles emitted from incomplete combustion of fossil fuel and biomass. Due to their black color the particles are strong absorbers of solar light. Most of the global BC particles are emitted at lower latitudes, but a fraction can be transported to the Arctic under favorable meteorological conditions, particularly during winter and spring time resulting in the phenomenon of Arctic Haze. The BC particles' lifetime in the atmosphere is short (a week on average), and the particles are deposited on the ground either through wet deposition (with precipitation) or dry deposition (without precipitation). If the ground is snow covered, these dark particles will increase the amount of absorbed energy and therefore decrease the amount of reflected energy by the snow surface, also defined as the snow albedo.

Holtedahlfonna glacier outside Ny-Ålesund. The photo shows a spectral albedo instrument (Trios optical sensors) that measures the reflection at different wavelengths of light. In the foreground we see plastic bags of snow samples (Christina A. Pedersen).

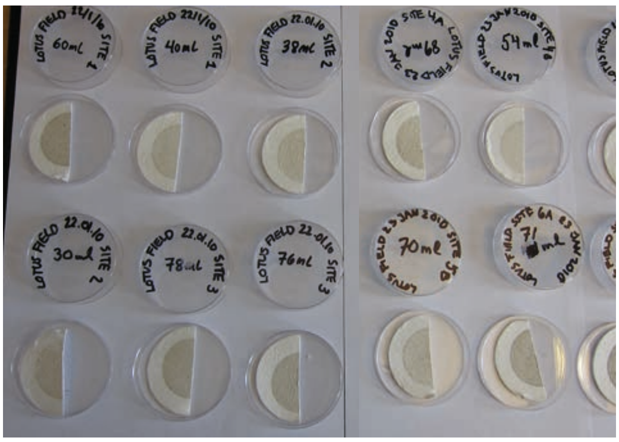
Snow sampling on Svalbard. Clean outer clothing is essential for studies of snow contamination (Jean-Charles Gallet).

AIMS OF THE PROJECT

Even if we know that Black Carbon (BC) particles are very strong absorbers of solar light, there are several processes about how the BC particles interact with the snow particles in the atmosphere and with the snow on the ground that are unknown. The Norwegian Polar Institute (NPI) started working on issues related to BC almost a decade ago, concentrating on issues when the BC particles are deposited and incorporated in the snowpack. When snow is accumulating over time on glaciers, snow becomes ice and we can therefore retrieve past BC concentrations in snow using ice cores collected from glaciers.

WHAT DID WE DO?

We have been collecting snow samples that were melted, filtered and analyzed for BC with a *Thermo/Optical Carbon Aerosol Analyzer*. From some locations we have weekly/biweekly time series of BC in the top 5 cm of the snow for several years. Snow albedo is very dependent on the snow physical prop-



Filters for the Thermo/Optical Carbon Aerosol Analyzer (filters are cut in two). These are samples taken in 2010 from Changbai, Northeast China. You can clearly see the dark half circle where the meltwater including tiny black carbon particles has darkened the filter (Christina A. Pedersen).

erties and the BC content together with the incoming light conditions. So in addition to measuring snow albedo, we have been measuring snow parameters like snow grain size, snow depth, snow density, as well as the amount of clouds and solar zenith angle. This allows us to separate the effect that BC particles have on the absorption from the natural variability caused by changing snow and light conditions. We have also analyzed a 125 m deep ice core for BC, providing BC concentrations and depositions for the past 300 years.

In addition to field measurements, we have used atmospheric transport models to simulate the deposition of BC over snow surfaces. Comparison between ground measurements and models has been done to investigate the BC particle's transport pathways from the source region further south to the Arctic. The more specific radiative (how radiation is distributed) transfer models have taught us how the snow and BC physical properties combine together to affect the snow albedo.

WHERE DID WE WORK?

We have been focussing our work on Svalbard (Sverdrup Research Station (•1)). Our two timeseries on surface BC concentrations are from Ny-Ålesund and Austre-Brøggerbreen. The ice core was from the Holtedahlfonna glacier. In addition we have point measurements from Scandinavia, Fram Strait, Greenland, North Alaska and Northeast China collected by national and international partners (NILU, NORUT, CICERO and the University of Oslo, as well as the University of Washington, the University of Helsinki, the Chinese Academy of Science and the Chinese Meteorological Administration).

Svalbard has been chosen as our main outdoor laboratory because of its pristine environment far away from most local pollution sources. The Alaskan and Chinese sites were chosen to investigate long range transport of BC, and in Greenland the focus was on using a drone to study the variability of snow albedo over a larger spatial scale.

WHAT DID WE FIND?

We found that the amount of BC in the snow in Svalbard was on average 100 times lower than in Northeast China and about 20-30 times lower than on mainland Norway. The concentrations were similar in Svalbard snow and in sea ice in Fram strait and Alaska. Our measurements also confirmed that the amount of BC in the snow increased during snow melting because the particles remained at the surface and did not percolate very easily through the snowpack together with the melt water. We were able to investigate the effect BC particles in the snow had on reducing the snow albedo. The *broadband* (400-900 nm integrating albedo) surface albedo reduction due to surface BC was found to be about 0.5% for 10 ng of BC per gram of snow, while the reduction was doubled for three times larger BC amounts. The effect of BC is enhanced when snow is old because old snow is made of large snow grains and the light penetrates deeper in an old snowpack. Therefore, the contribution of BC particles buried deeper in the snowpack is then not negligible anymore when the snow becomes older.

We noted that the BC concentration started to increase after 1850 and peaked around 1910, similar to ice core records from Greenland. More surprisingly, and in contrast to atmospheric measurements in the Arctic and ice cores from Greenland, the concentration again increased rapidly between 1970 and 2004. Regardless of the cause, the results have implications for the radiative energy at the site.

WHY ARE THE RESULTS IMPORTANT?

The energy balance of every snowpack is mainly driven by the snow albedo. Because the amount of BC in the snow affects the albedo significantly it is crucial to understand the processes behind. BC in the snow causes a positive feedback leading to enhanced light absorption, increased temperature and increased melting. For comparison, a clean snowpack will absorb between 1-5% of the incoming solar radiation in the visible regions (400-780 nm wavelength). This implies that a concentration of 200 ng of BC per gram of snow results in an increase of almost a factor two in absorbed broadband energy.

THE ADVENTURE

When working in the field on Svalbard we are normally a small group of scientists and students. We use snow mobiles to get out from the Ny-Ålesund village to our study site, where we spend the days digging snow pits, collecting snow samples and making albedo measurements. When back in Ny-Ålesund in the afternoon, we melt and filter our snow samples, and back-up data and notes from the day. We normally work long days as the Sun is up 24 hours from April, and the weather is often beautiful with bright white snow (you cannot see the BC particles with your bare eyes), and blue or partly clouded sky. We always have to carry a rifle when leaving the village of Ny-Ålesund as there may be Polar Bears lurking around.

Further information

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SCIENCE STORY

3 • 3

Adaptations and survival of microorganisms on snow and ice

Liane G. Benning

Arctic glacial environments represent the very edge of the Earth's habitable zone. Glaciers are often assumed to be lifeless, yet they are colonized by a plethora of algae, bacteria, fungi, and even invertebrates which do not just survive but thrive on snow and ice surfaces. Among these microorganisms, snow and ice algae (microscopic, single-celled plants) grow and reproduce dramatically (they bloom) during the summer melting season. These algal blooms transform snow and ice surfaces into colourful environments. Algae produce coloured pigments, for various reasons, including as protection against cold or as screens againts the high, Arctic UV radiation. Snow algae are either green because of their production of chlorophyl or various shades of red because of the carotenoid pigments they produce. In contrast, ice algae can turn the surface of glaciers and ice sheets black due to special purple and black pigments. Such colours, together with the dust and black carbon deposited through aeolian (wind) processes (Science Story 3.2) can massively reduce albedo and enhance melting. This is because snow and ice algae are important biological components on glacier surfaces and they regulate a relatively large part of Earth's global carbon cycle. They therefore have a massive impact on the fast changing climate in the Arctic.

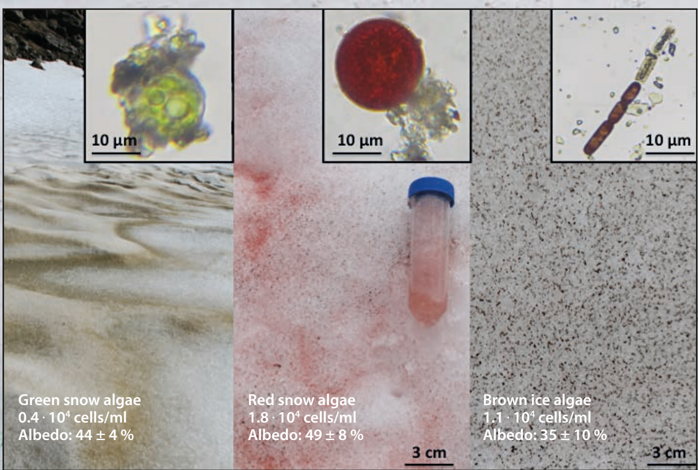
AIMS OF THE PROJECT

Our knowledge about the structure and the relationships between algae and other microorganisms that colonize glaciers in the Arctic is extremely limited. This is primarily because no studies have tried to describe in detail the ecology of snow and ice surfaces. Our aim with two linked INTERACT "CryoLife" projects was to measure as many as possible physical, chemical and biological characteristics of the microbes living in such environments and to evaluate how geographical and latitudinal effects may influence the distribution and abundance of the microbial communities in these environments.

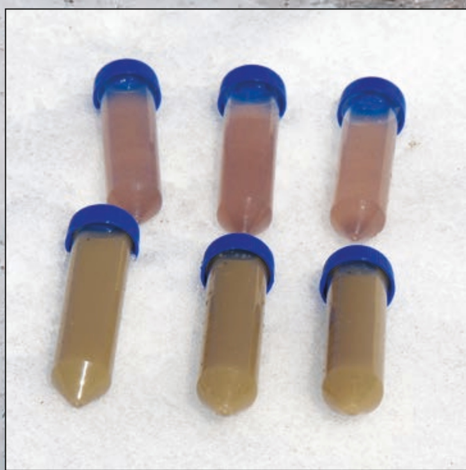
Specifically, we aimed to assess how the fast changing and melt-related ecology of microbes in snow and ice habitats on glaciers affect albedo.

WHAT DID WE DO?

We hypothesised that snow and ice algae are the primary colonizers on a glacier. We tested this both in Southeast Greenland and Arctic Sweden and conducted a detailed and multidisciplinary study on snow and ice communities. We analysed samples with a combination of detailed microbiological, geochemical and mineralogical tools and compared and contrasted the resulting data sets between the two different geographical settings and also with other sites in the European Arctic.



How important is biology for albedo reduction? Green (left) and red (middle) snow and grey ice (right) photos with insets showing their respective main algal inhabitants (Liane G. Benning, inset microscopic images by Lutz. Cell abundance and albedo values at the bottom are from Lutz and others 2014).



Sampling tubes filled with reddish (top) and greenish-reddish (bottom row) snow from Mittivakkat glacier (CryoLife 2012) (Liane G. Benning).

WHERE DID WE WORK?

In 2012 we worked in Southeast Greenland on Mittivakkat glacier to include observations from a maritime, sub-Arctic, low altitude site, i.e., the Sermilik Research Station (•68) within a wider sampling regime. We collected our snow and ice microbial samples during the fastest melting season recorded for Greenland. In 2013 we evaluated the snow and ice environments on and around Storglaciären and Rabots glaciär in Arctic Sweden (alpine, Arctic, high altitude), while being hosted at the Tarfala Research Station (•10). We returned in 2014 to the Tarfala Research Station for another project and again sampled snow and ice on Storglaciären. During our 2012 to 2014 summer field campaigns we also sampled snow and ice from other Arctic but maritime Svalbard and sub-Arctic Iceland glaciers and thus we now have a comprehensive set of microbial habitat samples from about 21 glaciers from across the European Arctic.

WHAT DID WE FIND?

Snow and ice algae dominate the net *primary production* but the algal species are variably distributed on snow and ice. When they grow the algae change their colour and this darkens the snow and ice surfaces. The albedo values measured in green and red snow or grey ice are approximately 30-35 % lower than in clean white snow. Such drastic changes will invariably lead to a positive feedback speeding up melting processes even further.

WHY ARE THE RESULTS IMPORTANT?

We hypothesize that as the climate warms and summer melt seasons become longer, it is likely that the effects seen above will further be intensified and an even stronger positive feedback between increased melting and darkening of the Arctic glacial habitats will develop. Thus, the snow and ice algae will become more important contributors to albedo variations, but these changes have still to be fully measured so that they can be incorporated into global climate change models.

THE ADVENTURE

There were three particular parts of the adventure: being in the Arctic, the greatest and most peaceful place on Earth, studying a problem of massive importance for our Earth's climate, and helping advance our understanding of how our fast changing Arctic environment is affected by things as small as microscopic snow and ice algae. And not to forget, much enjoying getting to know new people and environments through INTERACT.

Sampling snow and ice on Mittivakkat glacier during CryoLife 2012 field work at Sermilik Research Station in Greenland (Liane G. Benning).

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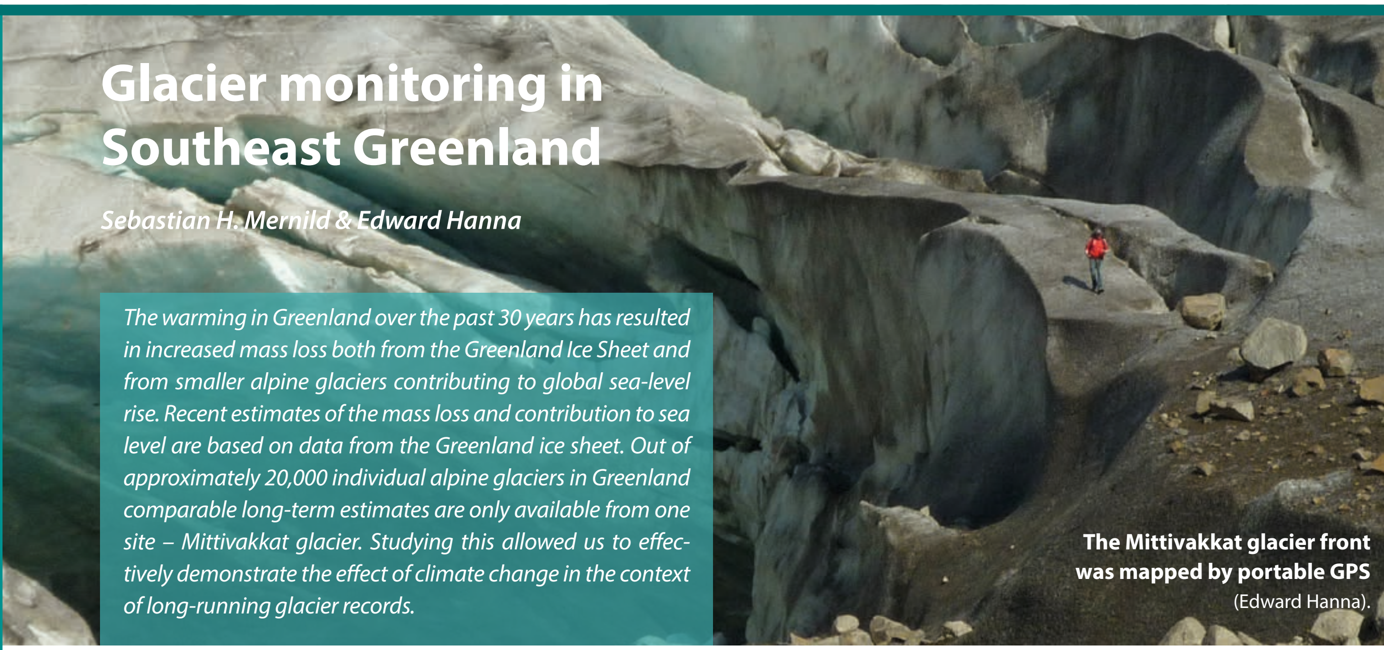


Glacier monitoring in Southeast Greenland

Sebastian H. Mernild & Edward Hanna

The warming in Greenland over the past 30 years has resulted in increased mass loss both from the Greenland Ice Sheet and from smaller alpine glaciers contributing to global sea-level rise. Recent estimates of the mass loss and contribution to sea level are based on data from the Greenland ice sheet. Out of approximately 20,000 individual alpine glaciers in Greenland comparable long-term estimates are only available from one site – Mittivakkat glacier. Studying this allowed us to effectively demonstrate the effect of climate change in the context of long-running glacier records.

The Mittivakkat glacier front was mapped by portable GPS (Edward Hanna).

AIMS OF THE PROJECT

The main aim of the GLAMOSEG-project is to get a better and more detailed understanding of glacier mass-balance conditions in Southeast Greenland, on the Mittivakkat glacier, since glaciers are highly sensitive to changes in climate conditions.

Temperature records from coastal stations in Southeast Greenland suggest that recent Mittivakkat glacier mass losses are not merely a local phenomenon, but indicate glacier changes in the broader region for Southeast Greenland also. Observations for the Mittivakkat glacier therefore provide unique documentation of the recent general retreat of Southeast Greenland's local glaciers under ongoing climate warming.

WHAT DID WE DO?

To assess the present conditions of the glacier we mapped the glacier front position using a portable GPS (Global Positioning System). Results were then related to estimates of previous frontal changes derived from aerial photos and satellite images. Ice-thickness was measured using a portable ground-penetrating radar (GPR); and net surface mass balance observations (accumulation and ablation) were conducted based on stakes drilled in the ice surface. Snow accumulation and snow/ice ablation were measured using cross-glacier stake lines at separations of approximately 500 m. The stakes in each line were 200–250 m apart, and measurements were obtained at a total of 45–50 stakes.

WHERE DID WE WORK?

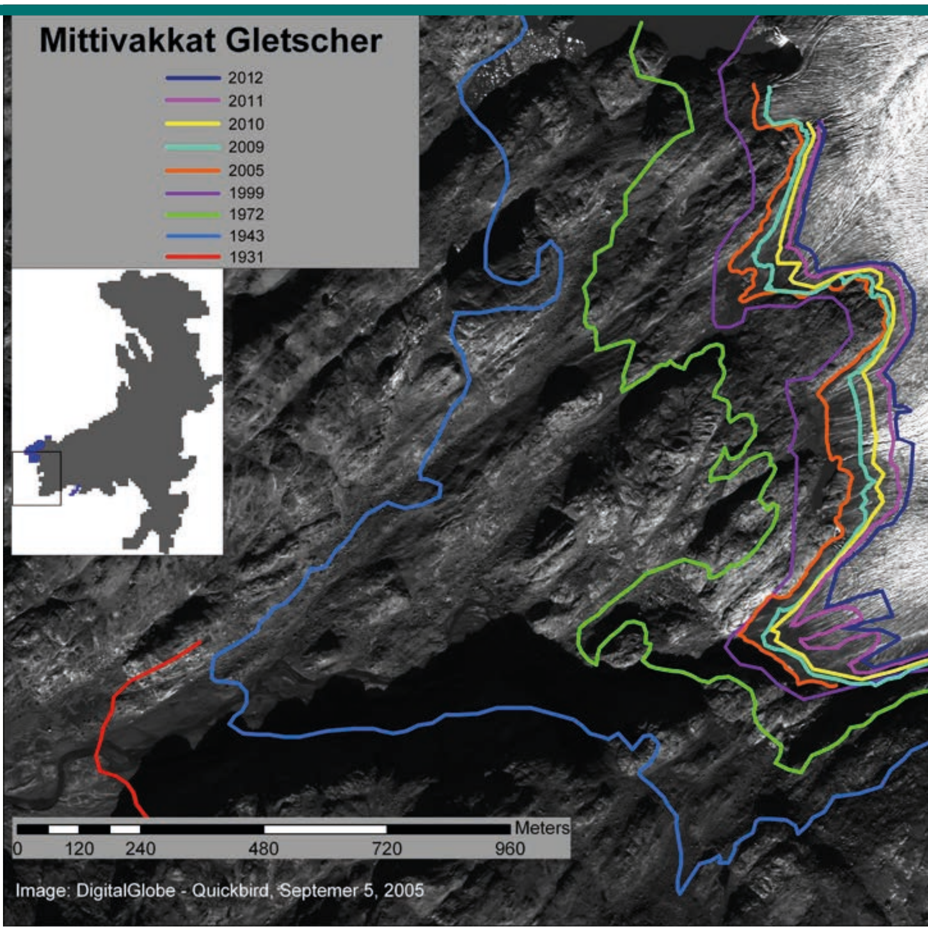
Our research was carried out at the Mittivakkat glacier located on Ammassalik Island at the Sermilik Research Station (•68) between the town Ammassalik (Tasiilaq) and Sermilik Fjord in Southeast Greenland. Mittivakkat is the only glacier in Greenland from where long-term mass-balance observations, glacier surface and volume estimates, and glacier-front fluctuations are kept, allowing us to effectively interpret recent changes in the context of long-running records.

WHAT DID WE FIND?

From our field observations we documented annual record mass loss in 2011 for the Mittivakkat glacier in an archive dating back to 1995 (we attributed this mass loss primarily to record high mean summer (June–August) temperatures in combination with lower than-average winter precipitation); also note that since 1931 the glacier has undergone almost continuous retreat of around 1,300 metres (on average approximately 16 m per year). During 1986–2011, the Mittivakkat glacier declined by 18 % in its area, 15 % in mean ice thickness, and by 30 % in volume. The shrinkage of Mittivakkat follows the overall trend of other glaciers in the Ammassalik region, where glaciers on average shrank 27 % in area during the same period. We used the long-term mass-balance record to estimate present-day glacier equilibrium conditions. We showed that the glacier is significantly out of balance with its present-day climate and is committed to additional losses of at least 70 % of its current area and 80 % of its volume over the next decades before the Mittivakkat glacier reaches equilibrium with the climate of the past decade.

WHY ARE THE RESULTS IMPORTANT?

Mass loss from glaciers is a key component of Earth's changing sea-level and regulates water resources around the globe. Analyses based on direct and geodetic measurements suggest that glacier mass loss is currently rising global mean sea-level by about 1mm yr^{-1}, where glaciers in Greenland contributed with 0.1 mm yr^{-1} and glaciers outside Greenland and Antarctica with 0.76 mm yr^{-1}. This is about one-third of the total rate of sea-level rise inferred from satellite altimetry (surface height measurements), with ocean thermal expansion and ice-sheet mass loss accounting for most of the remainder. Since half of the estimated global glacier surface area and two thirds of its volume are located in the circumpolar Arctic region, this makes glacier observations and the understanding of glacier surface mass-balance trends of northern latitudes, including Greenland, essential.



Mittivakkat glacier front's variability since 1931 estimated from aerial photos, satellite images, and portable GPS measurements (Source: Updated from Mernild and others 2011).

Researchers drill six metre deep holes in the ice surface for ablation (melt) stakes to estimate the annual glacier surface mass balance. Around twenty stakes are annually drilled along and across the glacier following a spatially distributed network to estimate the glacier's annual mass balance (Edward Hanna).

THE ADVENTURE

Going to East Greenland is always an enthralling experience, whether it is the first or tenth visit. East Greenland is one of the last frontiers, where the beauty of Arctic nature is exposed.

Mittivakkat glacier, Southeast Greenland, looking toward ESE (Niels Tvis Knudsen).

Further information

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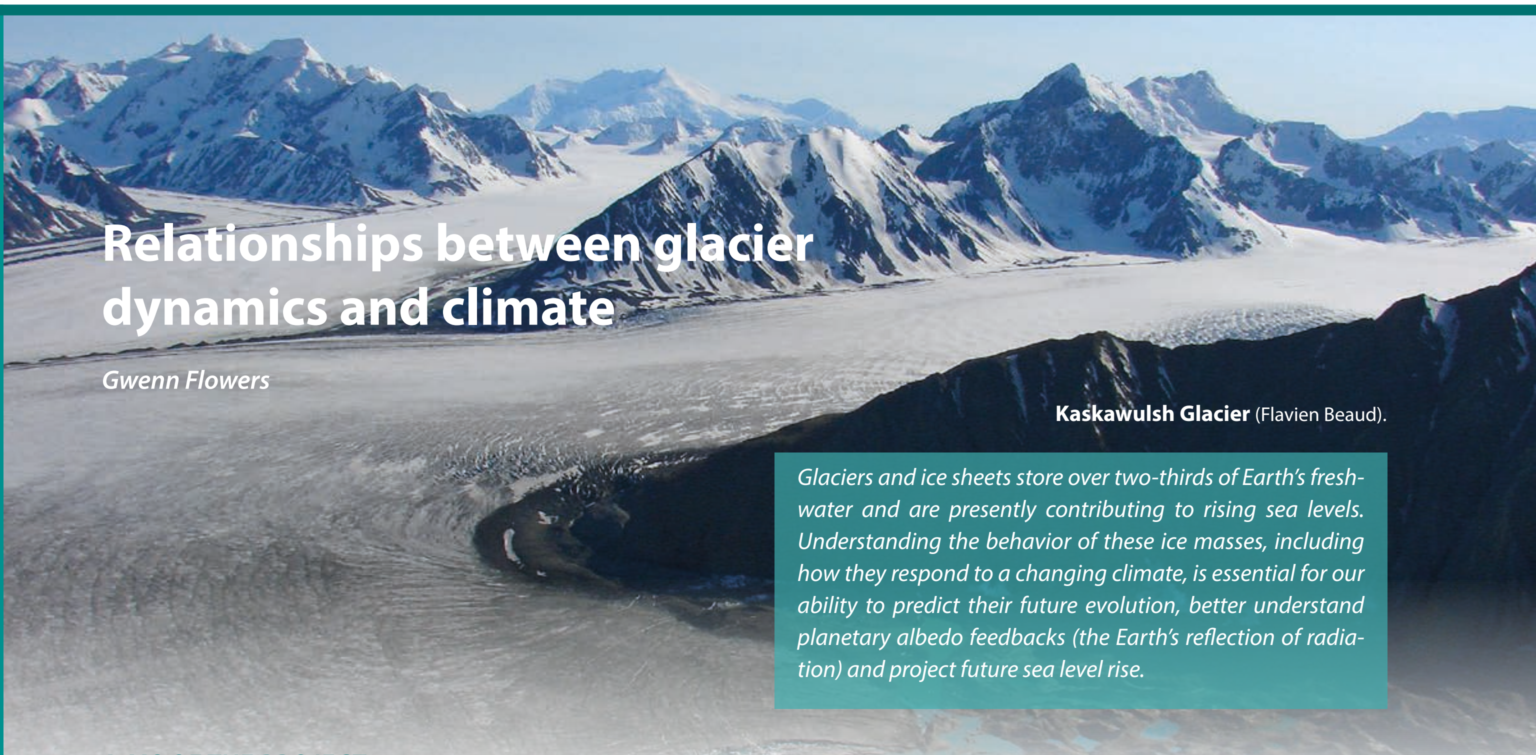


Relationships between glacier dynamics and climate

Gwenn Flowers

Kaskawulsh Glacier (Flavien Beaud).

Glaciers and ice sheets store over two-thirds of Earth's fresh-water and are presently contributing to rising sea levels. Understanding the behavior of these ice masses, including how they respond to a changing climate, is essential for our ability to predict their future evolution, better understand planetary albedo feedbacks (the Earth's reflection of radiation) and project future sea level rise.

AIMS OF THE PROJECT

The goal of the project was to understand the regional variability of glacier response to climate, and assess the role of glacier dynamics (flow) in determining this response. In particular, we set out to (1) measure regional climate variables important for glacier mass changes (e.g. temperature, radiation, precipitation), (2) monitor the glacier mass balance by measuring mass gain (snow accumulation) and losses (ablation), (3) characterize the dynamics of several targeted study glaciers, and (4) model the interaction between climate, glacier mass change and dynamics.

WHAT DID WE DO?

We installed 5 automatic weather stations in our 30 x 30 km study region, and over the course of several years measured the total winter snowfall and total summer melt across two study glaciers. This required the installation and maintenance of a spatially representative network of ablation stakes on each glacier that we measured each year, as well as the establishment of a seasonal stream gauge. Global Positioning System (GPS) measurements of markers drilled into the ice enabled us to calculate glacier flow speeds, while ice-penetrating radar was used to measure glacier depth and map out colder and warmer zones within the ice. Computer models of varying complexity were developed in our laboratory to (a) simulate glacier mass changes in response to measured climate variables, (b) explain the observed glacier flow regimes and (c) predict future changes in glacier thickness, extent, speed and temperature.

WHERE DID WE WORK?

The St. Elias Mountains of Yukon and Alaska are known for their extreme topography, rising from sea level along the Gulf of Alaska up to Mt. Logan (5,959 m), the highest point in Canada. This area also has an abundance of fast-flowing glaciers, making it an ideal setting in which to explore the relationship between climate and glacier dynamics. We worked on a small population of glaciers on the continental side of the St. Elias Mountains, in the traditional territory of the Kluane First Nation. The glaciers here, all subject to the same regional climate, represent a range of thermal and dynamic regimes and are accessible from the Kluane Lake Research Station (•49).

WHAT DID WE FIND?

Glacier mass changes measured in our study area were in broad agreement with independent estimates of glacier mass change in the wider region, with our study glaciers experiencing net losses in all but one year. Despite this broad agreement, there were some significant and systematic differences in winter snow accumulation and summer melt between our targeted glaciers, which were only 10 km apart. The contrasting orientations and positions of these glaciers on opposite sides of the mountain range crest play an important role here.

Our investigation of glacier dynamics through observation and modelling yielded some surprising results. One of the study glaciers, known to have "surged" in the past, i.e. advanced rapidly down the valley, is now undergoing a "slow surge". This phenomenon is characterized by an unsustainably high flow rate, but one that falls short of what has traditionally been identified as a surge. Glaciers in this state have suffered a mass deficit in the period leading up to the surge, and may stop surging altogether if they continue to lose mass. Climate's fingerprints can now be detected in the changing dynamics of glaciers.

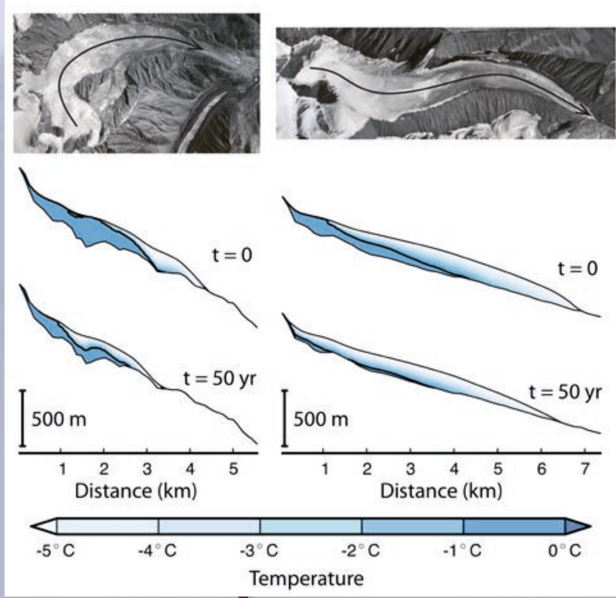
By imaging the ice interior with radar and making direct measurements of glacier temperature with digital borehole sensors, we found that many of the small glaciers on the continental side of the St. Elias Mountains are "*polythermal*". These glaciers have a zone of temperate ice (close to melting point) partially overlain by a thick shell of colder ice. Our models suggest that many of these glaciers will get colder as they retreat and disappear. When meltwater refreezes in a cold snowpack it releases a large amount of heat, which warms the snow that will eventually form glacier ice. The decline of a porous snow-cover on these glaciers inhibits the retention of meltwater and the heat it provides, ultimately producing colder glacier ice. One of our study glaciers is expected to cool significantly in the future, while the other is not, due to differences in their geometries and flow regimes. This cooling may impact the glacier's ongoing response to climate, as colder ice flows more slowly down valley than temperate ice. The same physical processes may produce the opposite effect in other climate settings, including some parts of the Greenland Ice Sheet, where increased meltwater entrapment may warm the ice and produce faster ice flow from the continental interior to the ocean.

WHY ARE THE RESULTS IMPORTANT?

The results of this study tell us that neighboring glaciers can respond differently to climate, and that the details of their geometries, temperatures and flow regimes can combine to produce unexpected behavior. As this new knowledge makes its way into the increasingly sophisticated models used by the scientific community, we will be better able to predict regional to global glacier change and its impact on planetary albedo, freshwater resources and sea-level.

THE ADVENTURE

Working on and around glaciers is fun, but can be dangerous. We do much of our work roped together as a team on skis or snowshoes, navigating crevasses (large cracks in the glacier surface often hidden under snow) with our instruments. A memorable survey was cut short when one of the graduate students fell through a snow bridge and into a crevasse. After 45 minutes of setting up pulley systems and hauling, we finally retrieved a wet and cold but happy student!



Projected changes in geometry and temperature for two different glaciers in the Donjek Range from present day (t=0, middle row) to 50 years into the future (bottom row). Images (top row) show the locations of the modeled profiles on aerial photographs of the study glaciers (left: surging glacier in 1951; right: glacier with no known surge history, 1977). Note the near-complete disappearance of temperate ice (darker blue) in the glacier on the right after 50 years (Figures from Wilson and others 2013).

Snow pit (Laurent Mingo).

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Examining the effect of changes in plateau icefield mass balance on ice margin retreat patterns and depositional processes

Clare M. Boston, Benedict T.I. Reinardy & Danni Pearce

The view from the 1,863 m nunatak (a ice-free peak in an otherwise ice-covered mountain or ice sheet), including ice flowing into Midtdalsbreen in the right of the photograph (Clare Boston).

Small ice masses are important for assessing the impacts of changes in climate due to their shorter response times to these changes compared to large ice sheets. In particular, plateau icefields are acutely sensitive to climatic changes due to the low slope angle of the plateau, meaning that a small rise in temperature could result in a large increase in the size of the ablation (melt) area, leading to rapid retreat.

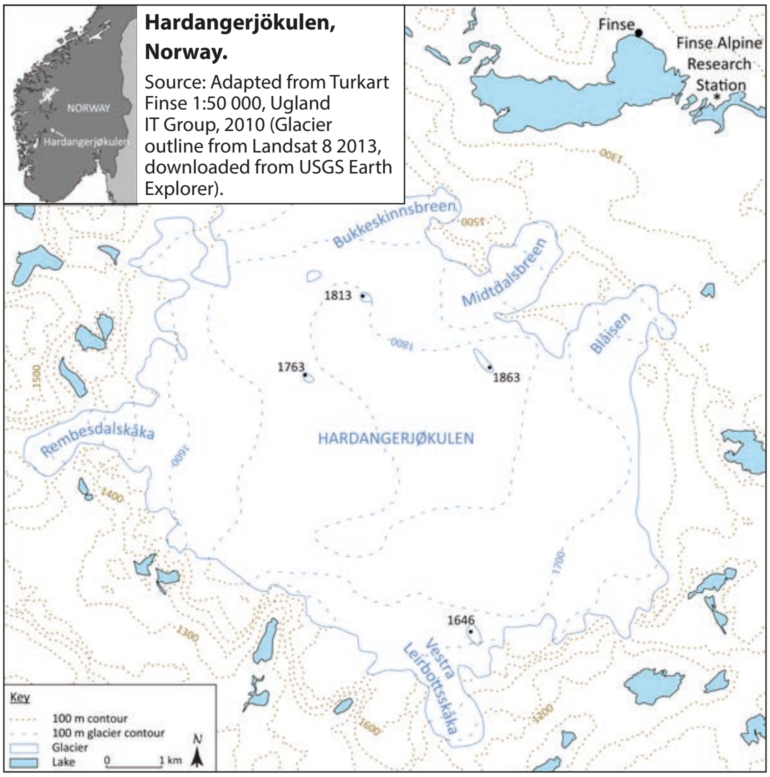
3 • 6

AIMS OF THE PROJECT

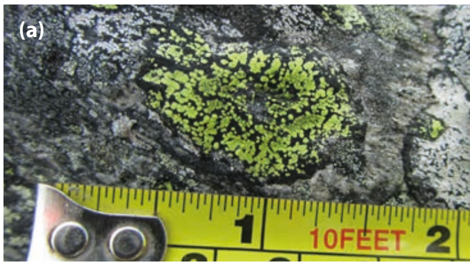
The aim of the project was to examine how changes in the mass balance of a sensitive icefield located in southern Norway, Hardangerjökulen, are reflected in changes in the position of the ice margin at three of its *outlet glaciers*; Midtdalsbreen, Blåisen and Bukkeskinnsbreen. We also studied how such changes influence the processes of sediment deposition at the ice margin that contribute to the formation of glacial landforms such as moraines. The results from this study will help us to further understand the response of this icefield to a warming climate, and to predict its future stability.

WHERE DID WE WORK?

Good access from the Finse Alpine Research Centre (•7) to Hardangerjökulen, the sixth largest icefield in Norway, provided an opportunity to assess patterns of recession at Midtdalsbreen, Blåisen and Bukkeskinnsbreen, both since their Little Ice Age (LIA) maximum extents (around AD 1750) and at present. This is one of the most vulnerable icefields in Norway, and is predicted to have completely disappeared by 2100.



Hardangerjökulen, Norway.
Source: Adapted from Turkart Finse 1:50 000, Ugland IT Group, 2010 (Glacier outline from Landsat 8 2013, downloaded from USGS Earth Explorer).



The lichen *Rhizocarpon geographicum* (a). Cleaning a section before recording it (b) (Clare Boston).

WHAT DID WE DO?

Three key methods were used to assess retreat patterns and ice-marginal processes in August 2013:

- Mapping of the glacial geomorphology, i.e. the landforms left by the glaciers, was carried out to a) record key positions of the margin of each outlet glacier since the LIA, and b) assess differences in the retreat patterns between the three glaciers.
- *Lichenometry* (dating based on lichen size) was used to provide approximate ages of key former glacier positions, marked by moraines, to allow an assessment of differences in the timing of retreat of the three outlet glaciers. This method involved measuring the diameter of the largest lichen growing on boulders on a particular moraine, and using a regional lichen growth rate to estimate when the lichen became established, and thus approximately when the glacier deposited the moraine.
- Sedimentological analysis of ice-marginal landforms, such as moraines (i.e. recording structures within a sediment section, assessing the nature of the sediment (sorted, i.e. clay, *silt*, sand, or unsorted, i.e. a mixture of grain sizes) and measuring the size and roundness of stones within the section), allowed us to assess the processes involved in their formation. These processes can tell us about the glacier dynamics and sediment transport pathways, i.e. where the debris that forms the moraines has come from (*supraglacial*; on the glacier surface, i.e. the debris has fallen off the valley sides; or *subglacial*; at the glacier bed, i.e. the debris has been plucked from the bedrock underneath the glacier and then eroded during transport).

WHAT DID WE FIND?

Our landform (geomorphological) mapping demonstrates that a variety of glacial landforms were produced by the three glaciers during retreat, in part due to differences in the topography over which they were flowing. Midtdalsbreen is particularly interesting since subglacial and ice-marginal processes vary across the margin, also producing different landforms, which we see from differences in the nature of the sediments that they are made up of. Using sedimentological analysis we were able to record sediment transport processes at the southeastern part of the margin, from delivery of sediment to the glacier surface, to transport along the glacier surface by meltwater streams, followed by deposition of this sediment on the glacier surface near the margin. As the ice melts, this leads to concentration of debris at the glacier surface forming a thick blanket of sediment that insulates the ice and slows the rate of melting, eventually leading to a landscape containing buried ice beneath a series of mounds and ridges. Our research also suggests that at its northwestern margin, the glacier is no longer producing annual moraines, compared to two years earlier, when such processes were recorded (Reinardy and others 2013), indicating a recent change in processes relating to moraine formation here.

These findings indicate variations in ice-marginal processes, both across the present glacier foreland and since the LIA, at the three outlet glaciers studied, most likely controlled by changes in topography, sediment supply and the thermal structure of the glacier. Further analysis of these results will help improve our understanding of the different responses of these outlet glaciers to changes in mass balance of Hardangerjökulen.

WHY ARE THE RESULTS IMPORTANT?

This work provides an important basis for future work on the response of small ice masses to changes in climate. Small ice masses are particularly sensitive to climate change and it is important to record processes occurring at the ice margin to help further understand how these glaciers are responding to such climatic changes. This will help us to more confidently predict the future stability of these ice masses and their potential contribution to sea-level rise over the next century. We are grateful for the financial and logistical support of INTERACT *Transnational access* scheme.

THE ADVENTURE

When undertaking fieldwork in a remote, mountainous environment, the weather is an important factor, and can have a large influence on plans for the day. During our three weeks at Finse, we experienced a wide variety of weather, from torrential rain, to freezing winds, and days of beautiful sunshine. This meant fieldwork was never dull, even if it did mean some days were spent identifying good moraines to shelter behind and the quickest route to the nearest hytta (cabin)! A rare sunny and virtually cloudless day gave us the opportunity to hike to the highest point of the icefield and stand on a nunatak (bedrock sticking out of the ice) at an altitude of 1,863 m. From this vantage point we could see ice in all directions, including ice flow into Midtdalsbreen and Blåisen, making all those bad weather days seem irrelevant.

Further information

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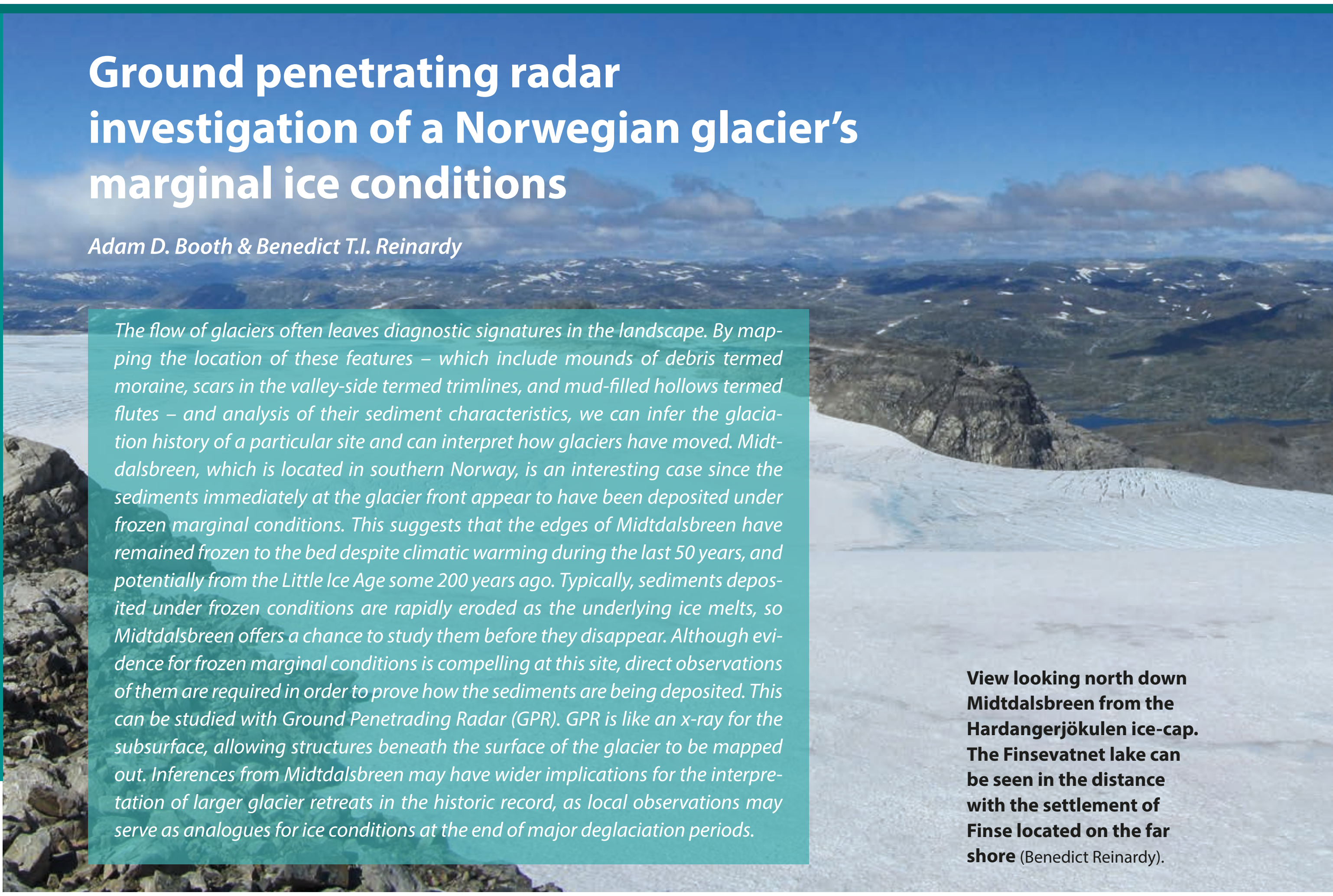
Ground penetrating radar investigation of a Norwegian glacier's marginal ice conditions

Adam D. Booth & Benedict T.I. Reinardy

The flow of glaciers often leaves diagnostic signatures in the landscape. By mapping the location of these features – which include mounds of debris termed moraine, scars in the valley-side termed trimlines, and mud-filled hollows termed flutes – and analysis of their sediment characteristics, we can infer the glaciation history of a particular site and can interpret how glaciers have moved. Midtdalsbreen, which is located in southern Norway, is an interesting case since the sediments immediately at the glacier front appear to have been deposited under frozen marginal conditions. This suggests that the edges of Midtdalsbreen have remained frozen to the bed despite climatic warming during the last 50 years, and potentially from the Little Ice Age some 200 years ago. Typically, sediments deposited under frozen conditions are rapidly eroded as the underlying ice melts, so Midtdalsbreen offers a chance to study them before they disappear. Although evidence for frozen marginal conditions is compelling at this site, direct observations of them are required in order to prove how the sediments are being deposited. This can be studied with Ground Penetrading Radar (GPR). GPR is like an x-ray for the subsurface, allowing structures beneath the surface of the glacier to be mapped out. Inferences from Midtdalsbreen may have wider implications for the interpretation of larger glacier retreats in the historic record, as local observations may serve as analogues for ice conditions at the end of major deglaciation periods.



View looking north down Midtdalsbreen from the Hardangerjökulen ice-cap. The Finsevatnet lake can be seen in the distance with the settlement of Finse located on the far shore (Benedict Reinardy).

AIMS OF THE PROJECT

In the "GIMMIC" project, we conducted GPR measurements over Midtdalsbreen (a land-terminating outlet of the Hardangerjökulen ice-cap, with a detailed focus on the edges of the glacier within 100 m of its terminus.

We were looking specifically for evidence of *liquid-water inclusions* within the otherwise frozen ice. Where the ice is free from such inclusions, the GPR data appear transparent – but where liquid-water is present, the data take on a "fuzzy" character. If the theory of frozen marginal conditions is correct, we expect to be able to map out a corridor of transparent GPR responses towards the glacier front. If we instead see the signature of liquid-water all the way to the front, the assumption of frozen basal conditions cannot be correct.

WHAT DID WE DO?

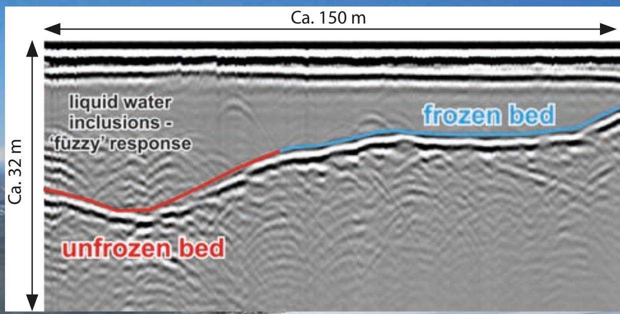
Support from the INTERACT Transnational access scheme enabled a new international collaboration to be initiated, between Dr. Booth from Imperial College London and Dr. Reinardy from Bergen University. During a nine-day stay at Norway's Finse Alpine Research Station, we conducted a series of GPR surveys on Midtdalsbreen. GPR systems use pulses of radio-wave energy to map the structure of a target subsurface. Usually, GPRs have two antennas: a transmitting antenna sends a burst of energy into the ground, which is then recorded at a receiving antenna after being reflected from subsurface structures which may be present. GPR is ideal for mapping water, as water is strongly reflective to the radio-wave pulse. By moving the GPR along many traverses across the glacier, we gradually built up a map of where the glacier bed appears frozen, and where it appears to have liquid-water.

WHERE DID WE WORK?

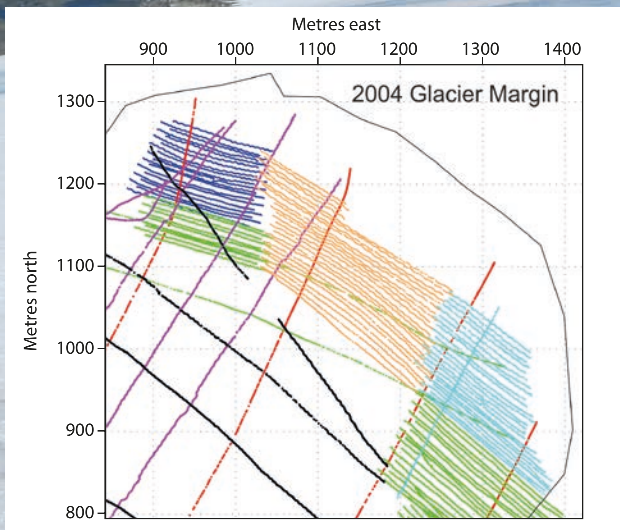
We were based at the Finse Alpine Research Centre (•7), Norway, close to Midtdalsbreen.

WHAT DID WE FIND?

Over 43 km of GPR data were acquired during the 9-day stay, facilitating some very detailed imaging of Midtdalsbreen's marginal ice. The figure on the next page focuses on our traverses across the glacier margin; there are even more lines elsewhere on the glacier! Most often, the antennas of the GPR system (a Mala Geosciences RTA, radiating 50 MHz energy) were towed behind the user although, for our longest lines, the system was attached to a snowmobile. Processing and interpretation of the GPR data is now underway. Preliminary results appear to be supportive of our hypothesis: there is strong evidence that the margins of Midtdalsbreen are frozen at their bed given the transparency of GPR responses at these positions. In general, it appears that the ice is frozen where its depth is less than 10 m, implying that frozen conditions exist in a corridor of up to 50 m from the glacier margin.



Example GPR data, acquired close to the Midtdalsbreen margin. The first 50 m of the profile show "fuzzy" GPR responses which are diagnostic of liquid water; however, transparent ice is observed elsewhere and the glacier is interpreted as being completely frozen at these points.



Location of GPR surveys around Midtdalsbreen glacier; the different colours correspond to data acquired on different days of the field campaign.

WHY ARE THE RESULTS IMPORTANT?

The GIMMIC project will undoubtedly provide interesting and important insights into the conditions of both Midtdalsbreen and, potentially, glaciers beyond this site. GPR surveys of high Arctic glaciers in places such as Svalbard have indicated that in some situations most of the glacier is frozen to its bed and thus interpreting how far these glaciers advanced and retreated in the past is challenging because little evidence remains in the landscape. This study suggests that similar challenges may exist for temperate glaciers that have small areas of ice at the glacier margin that are frozen to the bed. Our project is therefore important because it indicates that, even in temperate glacial environments, restricted or localised areas of the glacier that are frozen to the bed can have a significant impact on the type of landscape features left by the glacier and these conditions may actually be more widespread within both modern and ancient glacial environments than previously thought. Consequently, the project should provide a springboard for further research collaboration. The importance of both the financial and logistical support of the INTERACT Transnational access scheme cannot therefore be understated, and we are grateful for the opportunity it provided to work at Finse station.

THE ADVENTURE

Glacier fieldwork is more than just a scientific challenge; there is the physical challenge of hauling equipment through snow, and it is also an exercise in "planning ahead" – we are always aware of the risk posed by changeable weather conditions or of the appearance of crevasses in the ice. Revisiting the same site gives you a feel for how dynamic an environment a glacier really is. With the melt of the snowpack in spring, meltwater channels begin to show through until the glacier surface is bare ice.

While some areas of the Arctic are extremely remote, Finse is a metropolis by comparison! Our daily snowmobile commute to Midtdalsbreen and the work we then performed was always under the watchful eye of skiers enjoying the best of the Norwegian spring. However, when the Sun is setting and the skiers have gone home, you are quickly reminded of how beautifully bleak a glaciated landscape is.

Further information

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4 Land-atmosphere linkages

SECTION OVERVIEW

Philip A. Wookey & Torben R. Christensen

Biogeochemistry concerns the biological processes and reactions which are involved in the exchange and recycling of key chemical elements and materials, such as aerosols, between and among living things and their *abiotic* (non-biological) environment. Closely linked to this is *biogeophysics*, but here the emphasis is on physical interactions between organisms and the abiotic environment; good examples would be how different vegetation types reflect contrasting amounts of incoming solar energy, cause contrasting soil temperatures and affect snow drifting patterns in the landscape.

Life on Earth (including that of Humankind) is entirely dependent upon element recycling within the Earth System, but this is driven by energy flows largely originating from the Sun; unlike matter, energy cannot be recycled. At high northern latitudes (including the *boreal* forests and Arctic *tundra*) solar energy receipts vary dramatically through the seasons, and this results in correspondingly dramatic responses in the rates of key biological processes, such as photosynthesis and decomposition, due to changes in the availability of thermal energy (which is strongly linked with the rate(s) of chemical reactions) and useful radiant (light) energy which drives photosynthesis. Imbalances between carbon captured by plants and released by soils throughout the dark and light seasons leads to seasonal variability in atmospheric concentrations of carbon dioxide (CO_2) and methane (CH_4). In Figure 4.1, "valleys" represent the dominance of CO_2 uptake in summer whereas "peaks" occur in the dark periods of the year when photosynthesis ceases and release of carbon (also as CO_2) from decomposition dominates. Imbalances also occur on much longer timescales and these have the potential to influence the Earth's climate system through "*feedbacks*". In essence, what this means is that a response in the Earth System to changes (for example, in climate) can accelerate (a "positive feedback") or damp-down (a "negative feedback") the rate of change; in this context, if warming in the Arctic accelerates soil microbial activity (which releases CO_2 and, in waterlogged conditions, CH_4, to the atmosphere) more than photosynthesis (which removes CO_2 from the atmosphere) then the net result would be a release of CO_2 and CH_4 to the atmosphere, which could accelerate warming – a classic "positive feedback" situation. Carbon dioxide and CH_4 are both, of course, "*greenhouse gases (GHGs)*" .

Tundra landscape at Chokurdakh, Yakutia, the Russian Federation
(Matthias Siewert).

4

Due to the strong seasonality in energy receipts at high northern latitudes, as well as the enhanced sensitivity of many biological and chemical reactions to warming when temperatures are low, these regions represent the "front-line" in terms of on-going and potential impacts of climate change on biogeochemistry and the *Earth System*. Related to this is the energy balance of *ecosystems* which in itself will have interactions with climate as the proportions of energy absorbed and reflected by different land surfaces will change with changing vegetation and duration of lake ice and snow cover (Sections 3, 5 and 6). Although northern regions can no longer be considered "remote" from direct Human impacts (Section 7), their populations are low compared with the mid-latitudes of the Northern Hemisphere; in the terrestrial realm (the land surface and freshwaters) we can distinguish the direct and indirect effects of environmental (including climate) change on biogeochemical processes and energy exchange more clearly here than in more densely populated regions further south, where impacts of direct human land-use predominate.

These regions also bear the clear legacy of environmental changes of the past (through the Ice Ages of the last 2.5 million years), and of mismatches in the rates of key biogeochemical processes (e.g. in carbon cycling); a result of the latter is the massive stock of carbon (at least now 1,700 Petagrams; where 1 Pg = 1,000,000,000 tonnes) "stored" in *permafrost* soils. A key question, however (see later), is, for how long? This is particularly important in the context of environments and landscapes undergoing rapid transition (Section 2).

INTERACT-funded projects have tackled some of the key unknowns or uncertainties in the biogeochemistry and biogeophysics of northern high latitudes, and this section presents a selection of these. What each project emphasises is the strong link between the broader Earth System (including the climate) and the *biosphere* in the North. Each project also emphasizes how organisms, communities and ecosystems responding to environmental change have the potential to exert powerful (often reinforcing) feedbacks on those changes. Further-

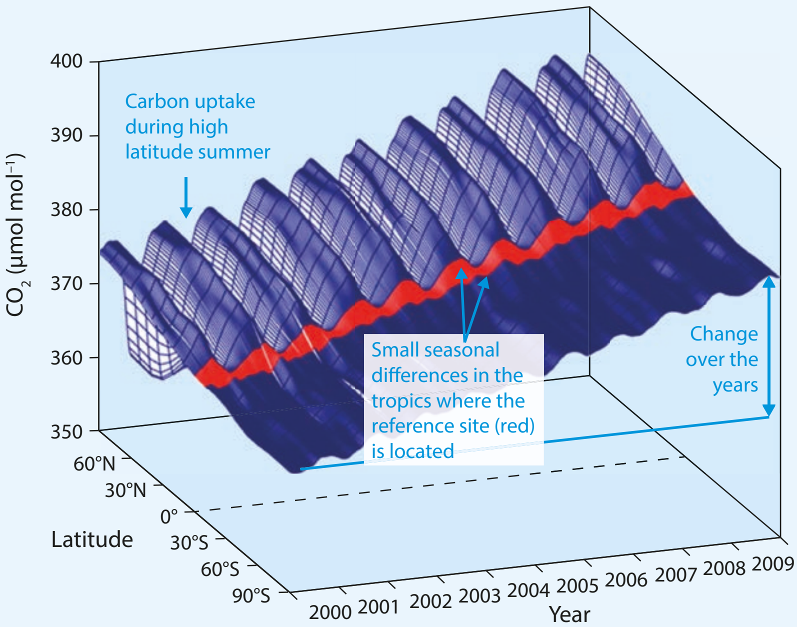

Figure 4.1 Three-dimensional representation of the global distribution of atmospheric CO_2 for 2000-2009 (highlighted in red is the 10-degree latitude band in which Ascension Island resides; a reference site in the tropical Atlantic). This diagram illustrates the direct coupling that exists between the biosphere and the Earth's atmospheric composition, showing the strong within-year variability in concentrations of CO_2 particularly at high northern latitudes. From NOAA's Earth System Research Laboratory.

Figure 4.2 Substantial emissions of CH_4 and CO_2 from surface waters to the atmosphere have been, until recently, a neglected flux in the terrestrial carbon cycle. Making thaw measurements at an Arctic location in Canada (P.A. Wookey).

more, in contrast to the common (but misguided) impression of uniformity of ecosystems and landforms in the North, there are marked variations at a range of contrasting spatial scales (described below) which exert strong influences on biogeochemical and biogeophysical processes. It is of critical importance to understand this variability, and how it might change in the future, in order for us to model and predict how the biogeochemistry and energy exchange of the North will respond to environmental changes, and how this will influence the role of the circumpolar North in Earth's life support systems.

Biogeochemistry and biogeophysics interact to affect ecosystem carbon stocks and greenhouse gas fluxes. Fundamentally, the fact that there is so much carbon in permafrost soils relates to an imbalance, over geological timescales, between the rates of carbon inputs (through photosynthesis) and losses (through decomposition, and release to surface drainage waters (Figure 4.2)). Decomposer organisms in soils and sediments are very sensitive to low temperatures (Karhu and others 2014) and to lack of oxygen, so in cold and often waterlogged, boreal and tundra soils, decomposition is slow. By contrast, photosynthesis in these environments is relatively more responsive to light and nutrient (particularly nitrogen and phosphorus) availability than temperature. Overall, where photosynthesis exceeds decomposition rates, organic matter (and therefore carbon) build up in soils and sediments. As this builds up, year on year, the depth of thaw each melt season cannot keep up with the rate of carbon accumulation, so it gradually freezes-in to permafrost. Figure 4.3 shows the consequences of this for current soil carbon "densities" (amounts expressed per square-metre). We need to know about this carbon at a range of scales, from circumpolar (as shown here) through regional, down to hillslope, or sub-metre scales, because climate warming increases permafrost thaw and makes soil carbon potentially vulnerable to decomposition. If this occurs in situations where soils are waterlogged then this decomposition takes place via *fermentation reactions* (where oxygen is lacking), with both CH_4 and CO_2 as a product (Christensen 2014) (Figure 4.4). If it takes place in a freely-drained part of the landscape then CO_2 will be the main product. Both of these gases are *radiatively forcing ("greenhouse") gases*, and their emissions are very sensitive to increasing temperature, so net emissions to the atmosphere are important contributors to global warming. The amounts of carbon stored are not trivial either; about 1,700 Pg carbon in permafrost soils, compared with less than half of that in the atmosphere, and annual emissions from burning of fossil fuels of about 9 Pg.

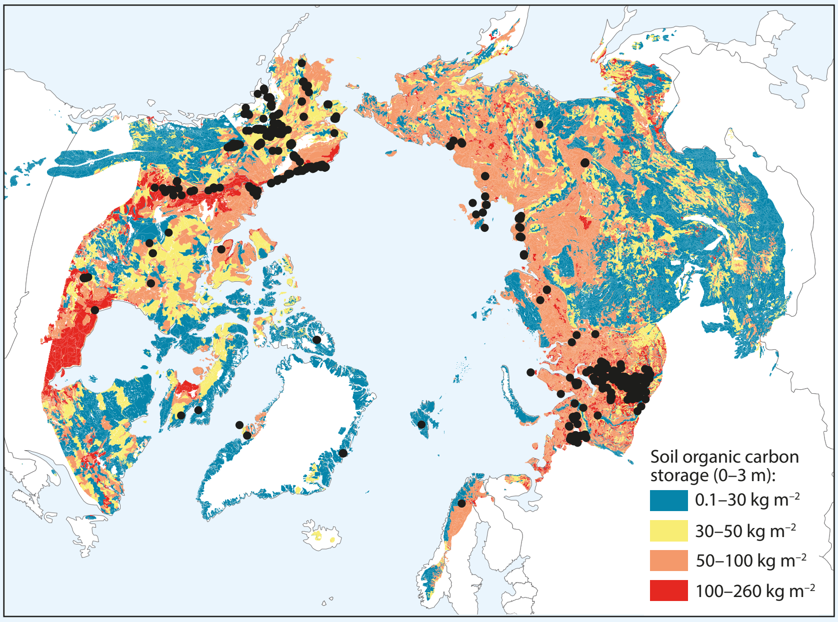

Figure 4.3 Map showing the soil organic carbon pool (kg C per metre squared) contained in the 0-3 m depth interval of the northern circumpolar permafrost zone. Points show field site locations for 0-3 m depth carbon inventory measurements; field sites with 1 m carbon inventory measurements are too numerous to show (Schuur and others 2015).

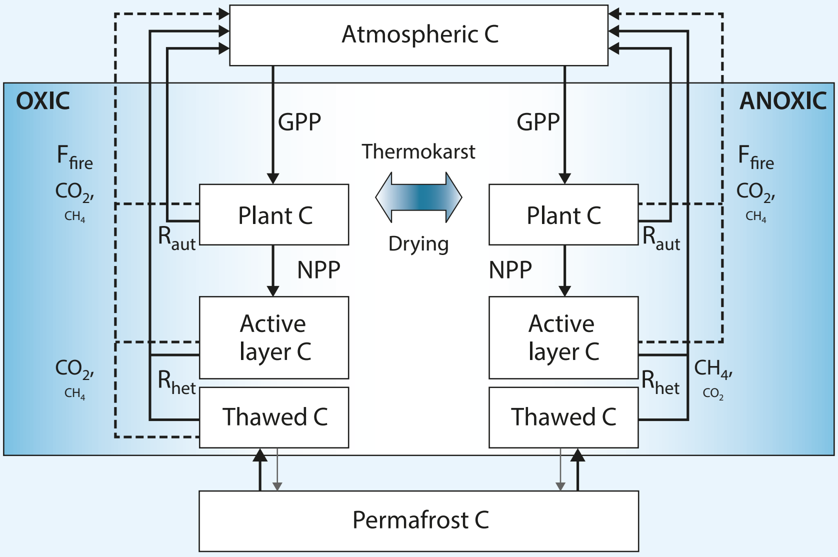

Figure 4.4 Conceptual diagram of the effect of permafrost thawing on climate. Permafrost carbon, once thawed, can enter ecosystems that have either predominantly *oxic* (oxygen present) or predominantly *anoxic* (oxygen limited) soil conditions; this strongly influences the global warming potential (From Schuur and others 2008).

Figure 4.5 Determining soil carbon stocks in permafrost environments is technically challenging as well as back-breaking. There are no short-cuts in collecting this critical information, and many sites across landscapes and regions need to be sampled. This picture shows peat sampling, for the PATTERN project (Science Story 4.2), at Spasskaya Pad, central Siberia, surrounded by mosquitos (Mattias Siewert).

Science Stories 4.1 and 4.2 are tackling questions relating to the spatial variability and controls on soil carbon stocks in the circumpolar North, and the actual and potential effects of climate variability and change on the fluxes of greenhouse gases such as CO_2 and CH_4 as well as the ecosystem energy exchange (Figure 4.5). They highlight, respectively, the role of seasonality (especially snow cover) for energy budgets and GHG fluxes between tundra (at Kobbefjord and Zackenberg, Greenland) and the atmosphere, and the coupling between landscape location and landform ("*geomorphological*") history after recent loss of glaciers (Section 1) for soil and sediment carbon contents in both boreal forests (Spasskaya-Pad, central Siberia) and Arctic tundra (Chokurdakh, northern Siberia).

The general concern about the stocks and vulnerability of organic carbon in Arctic ecosystems ultimately relates to CO_2 and CH_4 as greenhouse gases, and therefore the radiative forcing (the degree to which the gasses warm the Earth) that may be associated with changes in their fluxes between land and atmosphere. Therefore, these carbon exchanges also have to be placed in perspective with other coinciding changes to ecosystem functioning that relate to energy exchanges and, hence, also radiative forcing. These include a range of pivotal processes such as the duration of snow cover and lake, as well as sea-ice, cover. They also relate to external drivers that can affect snow and ice associated processes and feedbacks such as the deposition of black carbon from general pollution or from extensive northern forest fires (Keegan and others 2014) (Science Story 3.2). In a more subtle way, even the change in vegetation composition and "*shrubification*" that is now happening in the Arctic can, in itself, also alter the energy balance of the ecosystems to an extent where it may be as important as the potential effects of changes in the greenhouse gas exchanges mentioned above.

Therefore the feedback mechanisms from these ecosystems in a changing climate are a complex issue that relates both to the biogeochemical and to the biogeophysical processes.

WINTERS ARE LONG UP NORTH (AT LEAST FOR NOW)

A key facet of northern environments, referred to briefly in this book's introduction section, is the dramatic seasonality, especially at locations away from the moderating effect of open (unfrozen) oceans, on land temperatures. In the terrestrial realm there is a growing awareness that biological processes (and therefore biogeochemical and biogeophysical processes), although dictated strongly by the seasons, and most rapid in the thaw period, do not cease entirely through the winter. Although snow-melt is a time of rapid change in surface energy budget and biological activity, as investigated in the following Science Stories 4.1 and 4.3, there is growing evidence of continued microbial activity in soils through the winter (even when soils and sediments are frozen, liquid water is still present in microsites). Snow cover plays a pivotal role in soil and vegetation thermal regimes (patterns of temperature), as well as in *surface energy budget* (balance between energy input and output), and is already undergoing rapid change (Section 3).

CLIMATE CHANGE IS NOT THE ONLY FACET OF CHANGE

Science Story 4.3 explicitly addresses aspects of global environmental change which are not directly "climate"; the ecological effects of increasing atmospheric CO_2 concentrations and increasing fluxes of UV-B radiation to the surface (both a result of human activities). Although, arguably, subtler than warming effects, these facets of global change have the potential to result in cumulative ecological impacts which are superimposed upon, and may interact with, the effects of climate change. In this respect, the experiment upon which Science Story 4.3 was based was running for 20 years prior to the measurements reported here. This kind of long-term, concerted, effort is essential for understanding whole ecosystem and biogeochemical/biogeophysical responses to change.

CARBON DIOXIDE AND METHANE ARE NOT THE ONLY GASES OF INTEREST

Science Stories 4.4 and 4.5 are investigating other *biogenic compounds* emitted to the atmosphere (by plants) which can influence climate. These *biogenic volatile organic compounds* (BVOCs) play a role in climate through influencing the formation of *secondary organic aerosol particles* and *cloud condensation nuclei*, as well as exerting an influence on atmospheric ozone (O_3) concentrations, and CH_4 *oxidation* processes. But they are also important to plants in their defenses against herbivores and also for attracting pollinators. There is growing evidence that both herbivory and warming (Science Story 4.5) may interact to influence BVOC emissions from some plant species. Science Story 4.4 also provides compelling evidence, through the deployment of state-of-the-art techniques (*Proton-Transfer-Reaction Mass Spectrometry*) in Greenland, of the importance of temperature in controlling BVOC emissions from plants.

Key messages and needs for further research

- The spatial heterogeneity in landscapes points to the need for novel approaches and modelling to achieve reliable up-scaled (i.e. small scale measurements made relevant to the larger scale) results relevant for climate feedback studies at the global scale.
- Although we understand the Arctic biogeochemical and biogeophysical processes much better now than a few decades ago, improving our basic process understanding is still a highly prioritized issue.
- Our incredibly low predictive capability in relation to hydrological change at landscape scale remains a serious problem. Much improved understanding on this pivotal driver of changes in ecosystem processes is badly needed.
- Thresholds and non-linear accelerating changes in ecosystem processes are "wild cards" in the climate system and very poorly understood. Nevertheless, the Arctic holds a tremendous potential for such changes to happen and a better understanding of these is necessary.
- The *Arctic Amplification* (warming which is substantially greater than the global average due to several feedback processes; see Serreze and others 2009) and the influence on biogeochemistry and biogeophysical processes, are also issues which need attention to understand future climate changes and impacts.
- Integrating across terrestrial, marine and atmospheric realms is starting to become a pivotal issue as we realise that there is no way we can quantify and understand biogeochemical processes on land in isolation. For example, we cannot understand carbon cycling on land without being able to account for transportation through river systems and the fate of carbon in the coastal environment. Much more holistic approaches are badly needed including links among terrestrial, freshwater, coastal and atmospheric sciences.

Further information and references

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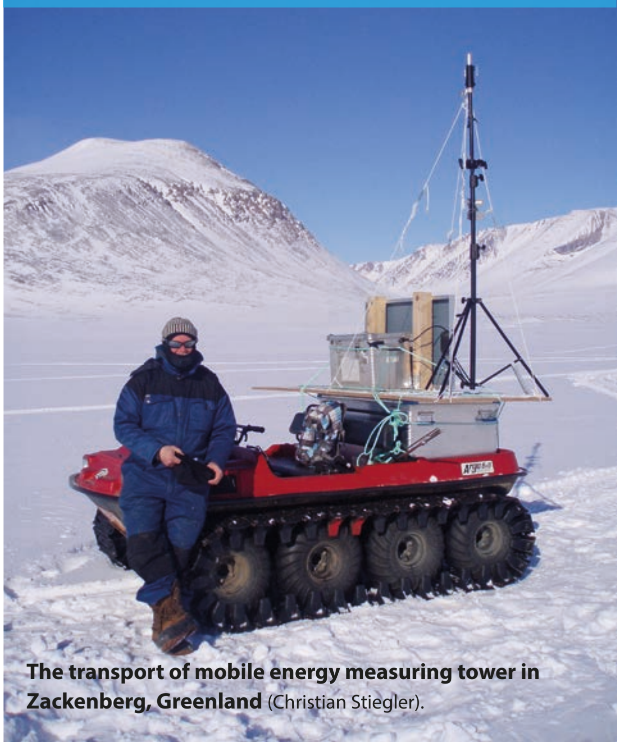
SCIENCE STORY

Energy exchange in the Arctic – a "butterfly effect" for the global climate?

Christian Stiegler, Anders Lindroth & Torben R. Christensen

The Arctic tundra landscape is like the wings of a butterfly: Unique, mystical, majestic and painted in vivid colours. But like the butterfly's wings are sensitive to a single finger touch, the Arctic tundra is sensitive to climate change. A key component in understanding this sensitivity is the exchange of energy and greenhouse gases between the tundra and the atmosphere. Even a small variation in this complex interplay between land and air can cause dramatic changes in snow cover distribution, vegetation cover, permafrost occurrence and atmospheric greenhouse gas concentration. Like any other landscape, the tundra constantly exchanges energy and greenhouse gases with the atmosphere but because the tundra covers large parts of our planet, it is of crucial importance for the global climate system.



The transport of mobile energy measuring tower in Zackenberg, Greenland (Christian Stiegler).

AIMS OF THE PROJECT

The interest in understanding the climate system better has intensified in recent years but the mechanisms of energy and greenhouse gas exchange in the Arctic tundra is still poorly understood. We, a group of researchers from the Nordic Centre of Excellence DEFROST, want to shed more light on the interplay between the Arctic tundra and the atmosphere. The whole idea is to understand the processes of energy and greenhouse gas exchange and to explain how and why changes in this sensitive landscape influence our global climate. In this story we explain our research on energy exchange.

WHAT DID WE DO?

DEFROST has installed a network of measuring stations in Greenland, Svalbard and in northern Scandinavia in the last couple of years. At these stations dozens of instruments constantly monitor the state of the tundra and the atmosphere. Some operate with a striking speed as fast as a blink of the human eye. During the summer months, when sunlight hits the tundra 24 hours a day, we also use a mobile tower system similar to the permanent measuring stations. This system is a valuable tool we can use to study the exchange of energy and greenhouse gases at different locations.

WHERE DID WE WORK?

Most of our study areas like Zackenberg Research Station (•70) and the Kobbefjord area close to the Greenland Institute of Natural Resources (•67) in the capital Nuuk, look like an Arctic storybook: glaciers on the mountain tops, crystal clear lakes, steep slopes, broad vegetated valleys but millions of mosquitoes! The Kobbefjord area is perfectly suited for high-quality research because we benefit from close collaboration with other scientists such as plant biologists, *limnologists*, oceanographers and geologists. This gives us the opportunity to think "outside the box" and to view the situation from different perspectives.

Panoramic view of the Kobbefjord area (Greenland) showing different vegetation types in June 2012 (Christian Stiegler).

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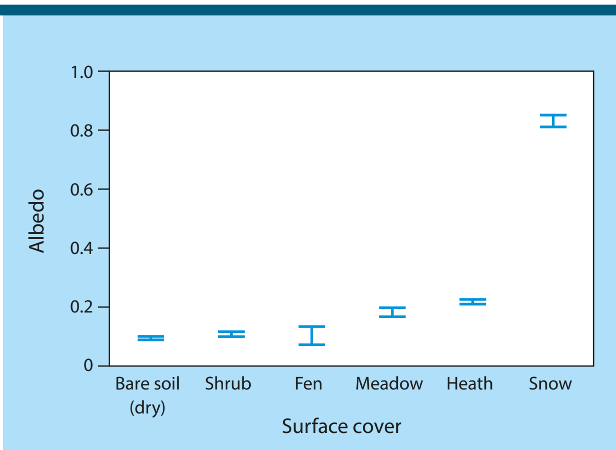

Average values of albedo in relation to various surface conditions at our study sites. The measurements were taken during two weeks in June 2012 in Kobbefjord (bare soil, shrub, *fen*, meadow) and during two weeks in April 2012 (snow) and August 2012 (heath) in Zackenberg.

A measuring station in Zackenberg (Greenland) (Anders Lindroth).

WHAT DID WE FIND?

One parameter we are interested in is albedo. The *albedo* of a surface describes how much of the incoming sunlight is reflected. Dark surfaces, such as wet soil or any water surface, have low albedo whereas white and bright surfaces, such as snow, have a high albedo. We found out that snow cover has an important impact on the energy balance at our study sites. Like a giant white shield the snow blocks off the Sun's energy from warming the tundra surface. When the snow has finally melted we see that soil moisture and the type of plant cover affect albedo. Because of their low albedo, shrub and wet fen areas absorb more incoming sunlight than dry heath vegetation. As taller plants pushing up through the snow are invading many tundra areas, albedo is being further reduced.

WHY ARE THE RESULTS IMPORTANT?

Climate change scenarios show that snow cover duration and snow cover thickness in parts of the tundra will decrease within the next decades. The scenarios predict an even more dramatic temperature increase. An earlier snowmelt allows the Sun's energy to warm the vegetated surface for a longer period. Higher temperatures and changes in soil moisture can boost the expansion of shrubs and wet fen areas. All these changes affect albedo, but more importantly, they change the energy and greenhouse gas exchange between the atmosphere and the tundra. It might be small on a local scale, but like a single flap of a butterfly's wing might cause a storm, shifts in the exchange of energy and greenhouse gases between the tundra and the atmosphere can change our global climate. It is our job to find out how powerful the flap is!

THE ADVENTURE

How do you spend your time when the field work is done for the day: watch snow and ice crystals under the microscope, listen to the breathless silence, play volleyball under the midnight sun, count the mosquito bites on your body, watch the northern lights, warm your cold fingers and toes in the sauna, learn some words in Greenlandic, spot Arctic foxes, seals and muskoxen, ride snowmobiles, use exciting transport systems, fly in the Twin Otter aircraft, listen to sailor's yarns of polar bear encounters …

Further information

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www.zackenberg.dk
www.nuuk-basic.dk

Panoramic view of the Zackenberg area (Greenland) in April 2012 showing the snows surface with high albedo (Christian Stiegler).

Patterns of carbon storage in a Siberian permafrost landscape

Gustaf Hugelius & Matthias B. Siewert

Soils in permafrost landscapes store twice as much carbon as what is currently in the atmosphere in the form of CO_2. These are remote and vast areas, but at the same time the landscapes are incredibly variable with many different permafrost landforms. It is believed that these landforms influence the accumulation and vulnerability of soil carbon to release as a greenhouse gas.

AIMS OF THE PROJECT

We wanted to investigate how the unique landforms that are found in permafrost areas affect the cycling and storage of carbon in Siberian landscapes.

WHAT DID WE DO?

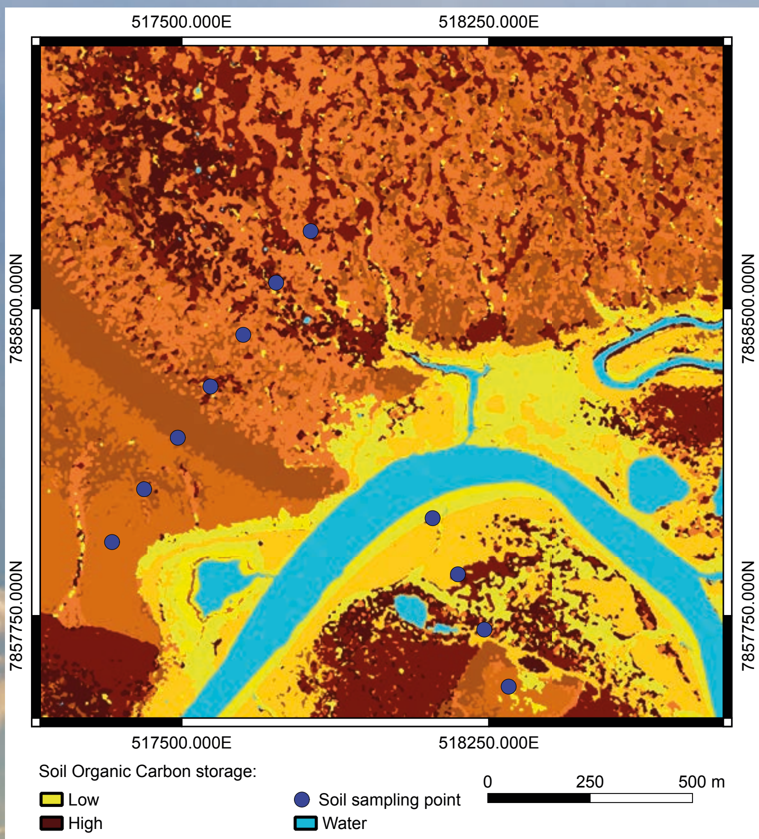
We worked across all different landscape types at our two study sites and described landforms, vegetation and soils. We sampled vegetation and soil and cored into the permanently frozen ground. In some places we collected samples that contain old plant remains that have been locked in permafrost since before the maximum extent of the last *ice age* more than 50,000 years ago. We combined the results from our field work with analyses of very high-resolution satellite images which let us map all the different types of vegetation and permafrost landforms that are found in these areas.

WHERE DID WE WORK?

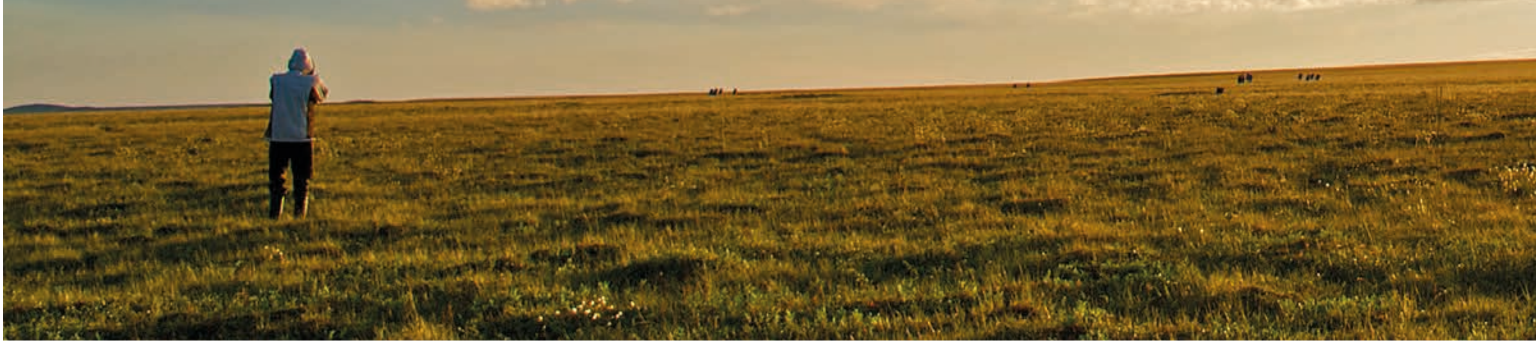
We worked at the Spasskaya Pad Scientific Forest Station (•39) in central Siberia and the Chokurdakh Scientific Tundra Station (•41) in northern Siberia. These stations are located far from each other in *taiga* and tundra, two very different ecosystems. Despite this, they are both situated on cold continuous permafrost with similar permafrost processes and comparisons between the two areas are important. Only in the continental climate of Siberia, with extremely cold winters, can one find permafrost as far south as here. These research stations have long histories of ecological and permafrost research and the station managers know much about the environments and ecosystems.

WHAT DID WE FIND?

We found that the different permafrost landforms in these areas are associated with very distinct soil and vegetation types. Our results show that if you want to understand and model how the carbon cycling of these ecosystems works and will respond to future climate warming, you need to consider which type of permafrost landform you are dealing with. We have also found that the different permafrost and land-forming processes are working at different geographical scales, ranging from metres to kilometres across.



Map of soil organic carbon distribution in Chokurdakh.



Tundra landscape at Chokurdakh
(Matthias B. Siewert).

WHY ARE THE RESULTS IMPORTANT?

Permafrost soils contain twice as much carbon as that currently stored in the Earth's atmosphere. In a warmer climate, thawing permafrost (Section 2) will start releasing this carbon into the atmosphere in the form of greenhouse gases. In order to better understand and model how much may be released we need to understand the permafrost processes that affect carbon storage in permafrost and the landscapes where this carbon is stored.

Trapped in quicksand at Chokurdakh (Niels Weiss).

Sampling peat at Spasskaya Pad protected against mosquitos (Matthias B. Siewert).

THE ADVENTURE

The Spasskaya Pad Research Station is located in Larch dominated forest where fires are frequent. You can see signs of old forest fires everywhere in the landscape. While we were doing our field sampling, forest-fires were raging close to the station. We were often smelling and seeing smoke and there were firefighting aircraft flying overhead. In the end, the winds were favourable and the station was not affected by any fires.

In Chokurdakh, we used a boat to collect samples at sites across the river. At first, the shore seemed like a good boat landing site, but we soon realized that our rubber boots got stuck in the loose mud. We hurried to unload the boat; however, it became harder and harder to reach it. In the end, Matthias was stuck in quicksand up to his knees and after 30 minutes up to his hip. The others covered the ground with shrubs to stabilize the quicksand and finally managed to pull him out.

Further information

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How does increasing CO_2 affect soil microbial diversity and carbon fluxes?

Dylan Gwynn-Jones, Alan Jones, Nick Ostle, Arwyn Edwards, John Scullion, Richard Hill, Dave Comont, Jenny Bussell, Simon Oakley, Kelly Mason & Terry V. Callaghan

The sub-Arctic landscape with the Abisko Village in the foreground and the Abisko Scientific Research Station to the extreme left (Richard Hill).

When we burn fossil fuels and produce CO_2 where does it all go? We should all know about global warming and the increasing levels of CO_2 in our atmosphere. Some of the CO_2 produced by burning fossil fuels is absorbed by plants on land and in the sea. If we did not burn fossil fuels we would expect the planet to be in some kind of balance. However, the global problem we have is that we are burning fossil fuels and our planet does not have the capacity to absorb this extra CO_2 produced, leading to global warming. This project builds on current UK funded research targeting whether sub-Arctic heath communities have the capacity to assimilate and store additional carbon produced in an elevated CO_2 world.

To analyse microbial diversity we used modern DNA fingerprinting and sequencing methods (Alan Jones).

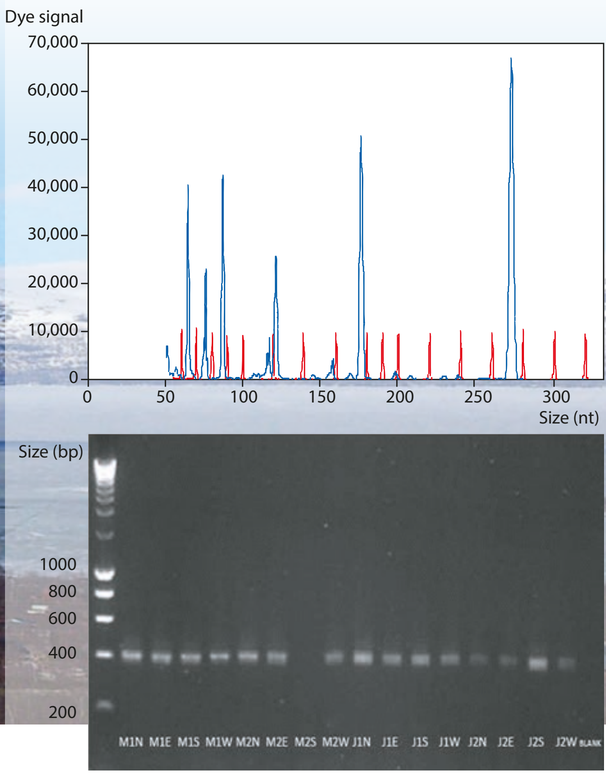
AIMS OF THE PROJECT

Our aim, via an INTERACT *Transnational access* funded project was to investigate seasonal variation in CO_2 fluxes (including winter) and to more closely focus on how CO_2 affects soil microbial diversity using molecular methods.

WHAT DID WE DO?

We measured seasonal variation in carbon fluxes in the winter and summer and looked closely at the microbial populations in the soil. For carbon fluxes we measured the balance of CO_2 produced (from plant and soil respiration) with that assimilated (via photosynthesis), together we can then calculate the carbon balance. For microbial analyses we used modern *DNA fingerprinting and sequencing methods* to understand how diversity varies according to time (season) and space (1 m to 50 m scales) .

We accessed an existing experiment that had exposed a sub-Arctic heath to elevated CO_2 over two decades (Richard Hill).



Example (T-RFLP) DNA fingerprint of the bacterial community in an Arctic heathland soil. Each blue peak is a different group of bacterial species. (Below) Bacterial DNA amplified from the soil for high-throughput DNA sequencing using *IonTorrentTM*. Each glowing band of DNA contains fragments from the *genomes* of thousands of different bacterial species in the soil.

WHERE DID WE WORK?

We worked at the Abisko Scientific Research Station (•11) to access an existing experiment that had exposed a sub-Arctic heath to elevated CO_2 over two decades. The sub-Arctic heath typically has extensive root and soil systems. The project focussed on seasonal effects (including winter) of carbon fluxes and looked at the variation of the microbial population surrounding the experimental site.

WHAT DID WE FIND?

We found large seasonal variation in CO_2 fluxes from the system in terms of photosynthesis and respiration. Community photosynthesis was affected by the CO_2 treatment but this was dependent on the time of year and environmental conditions. Importantly in 2012, the experimental site was at the same time exposed to an insect outbreak by the autumn moth *(Epirrita autumnata)*. Photosynthesis was clearly affected by insect herbivory and associated damage to leaves. Insect *frass* (excrement) introduced to the soil promoted CO_2 production via soil respiration. We therefore had to identify long-term effects of CO_2 in a system that was being exposed to tremendous change via the insect activity. These insects are an important part of this sub-Arctic ecosystem and such outbreaks occur every decade (Section 5).

At the microbial level we observed a community that was most variable in the spring at snow melt when much water entered the soil from snow. In terms of space, diversity was surprisingly consistent.

WHY ARE THE RESULTS IMPORTANT?

Most studies that look at carbon fluxes focus on *peak biomass* – a time in the summer when the plants have fully developed and are green. This study looked at seasonal variation in carbon fluxes and confirms that these systems even lose carbon (to the atmosphere) during the winter months. The insect outbreak was an opportunity to also look at carbon fluxes in an ecosystem exposed to large scale herbivore damage.

The microbial analyses undertaken show that we can now reliably use this research platform to investigate the long-term effects of elevated CO_2 on the soil.

THE ADVENTURE

If we put aside sampling in deep snow and whiteouts in winter. The most exciting part of our adventure was our journey into the unknown and deep into the Arctic soil to explore its most enigmatic *biodiversity*.

Further information

Dylan Gwynn-Jones [1], Alan Jones[1], Nick Ostle[2], Arwyn Edwards[1], John Scullion[1] Richard Hill[1], Dave Comont$_1$, Jenny Bussell[1], Simon Oakley[3], Kelly Mason[3] & Terry V. Callaghan[4]

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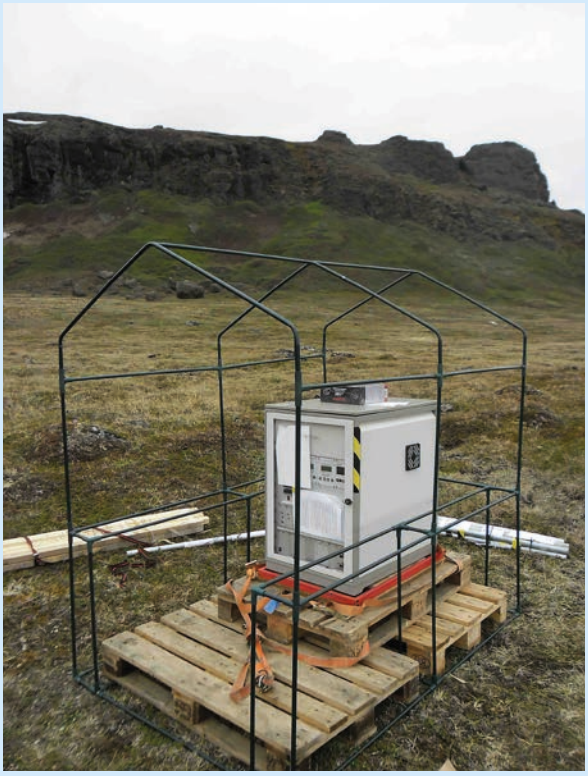
Fluxes of biogenic volatile organic compounds from plants in Greenland

Thomas Holst

Instrument mast with high-resolution wind measurements and air intake for trace gas analyses set up near the Arctic Station (Disko Island, Greenland) (Thomas Holst).



Setting up a specific mass spectrometer to measure trace gas exchange at the Arctic Station on Disko Island, Greenland (Thomas Holst).

Plants emit different amounts of these trace gases mostly dependent on temperature and light conditions, and BVOCs (biogenic volatile organic compounds) can react with greenhouse gases or enhance aerosol production in the atmosphere with significant impact on the climate system. The composition of the specific chemical blend emitted from Arctic ecosystems, as well as its variability with the season is, however, hardly known.

AIMS OF THE PROJECT

The aim of this project was to monitor and quantify the exchange of specific trace gases (BVOCs) between the atmosphere and the vegetation cover at a coastal site in Greenland.

WHAT DID WE DO?

To observe the trace gas emissions for a whole ecosystem continuously over most of the growing season and autumn, a very specific trace gas analyzer, a Proton Transfer Reaction Mass Spectrometer, was set up at the field site. This instrument was combined with high-frequency wind measurements to calculate the exchange (which is turbulent due to rapidly changing wind speed and direction) of a set of trace gases between vegetation and the atmosphere. While this method is often used for gases like water vapor or carbon dioxide, this project was the first to apply this technique in Greenland for BVOCs.

WHERE DID WE WORK?

The project was operating at the Arctic Station (•66) in Qeqertarsuaq (Disko Bay) in central West Greenland. The Arctic Station is located in a low Arctic, coastal climate. The surroundings of the station are dominated by a high number of plant species, with almost half of Greenland's plant species present. Along the coastline, a ca. 300 m wide vegetation belt extends on a transition zone from continuous to discontinuous permafrost. This vegetation belt provided a suitable site for the measurements representing an entire ecosystem.

Additionally, excellent logistics and transport as well as line power supply was available from the Arctic Station: these were essential for using the instrumental set-up.

WHAT DID WE FIND?

We were able to cover a large part of the growing season into late autumn, which was more than expected. The data showed that the ecosystem in Disko Bay emitted about the same amounts of BVOCs as those from other sites at high latitudes, for example in Abisko in sub-Arctic Sweden – even if the vegetation is different. At both sites the emissions increase strongly with temperature, showing that temperature stress for the plants due to climate change might boost emissions of BVOCs from these ecosystems.

WHY ARE THE RESULTS IMPORTANT?

BVOCs are chemically very reactive (react easily with other chemicals) and important for atmospheric chemistry, for example the ozone cycle or the oxidation (breakdown) of methane – an important greenhouse gas. But they are also important as precursors of *secondary organic aerosols* (i.e. indirectly formed organic aerosols), which then influence cloud processes and have impacts on the climate system (clouds can lead to both cooling and warming of the Earth's surface). The climate impacts of these aerosols currently is one of the least understood processes in the climate system – and as the specific trace gases measured during this project are important for forming these aerosols, we need to understand the processes causing their emissions to be able to improve the climate models.

THE ADVENTURE

Taking instruments designed for lab-conditions out to remote field sites and running them under harsh conditions is always a challenge, but there was a lot of support both from the Arctic Station and the Center for Permafrost (CENPERM) in Copenhagen. They provided logistics and line power supply needed to run the instruments, and this project funded by an INTERACT Transnational access award initiated some more collaboration between CENPERM and Lund University.

The site in Qeqertarsuaq on Disko Island of course was most spectacular with flat-topped mountains, icebergs floating by throughout the summer and whales passing by occasionally. However, weather conditions were challenging for operating this specific mass spectrometer in a small instrument shelter. Luckily the tent survived even the first autumn storm, and measurements were made more or less continuously from early summer until early October.

Further information

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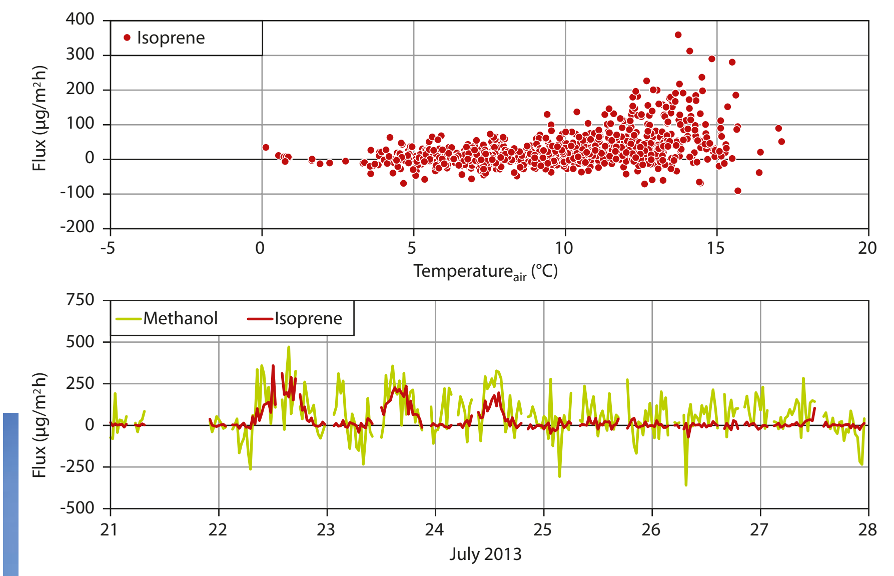
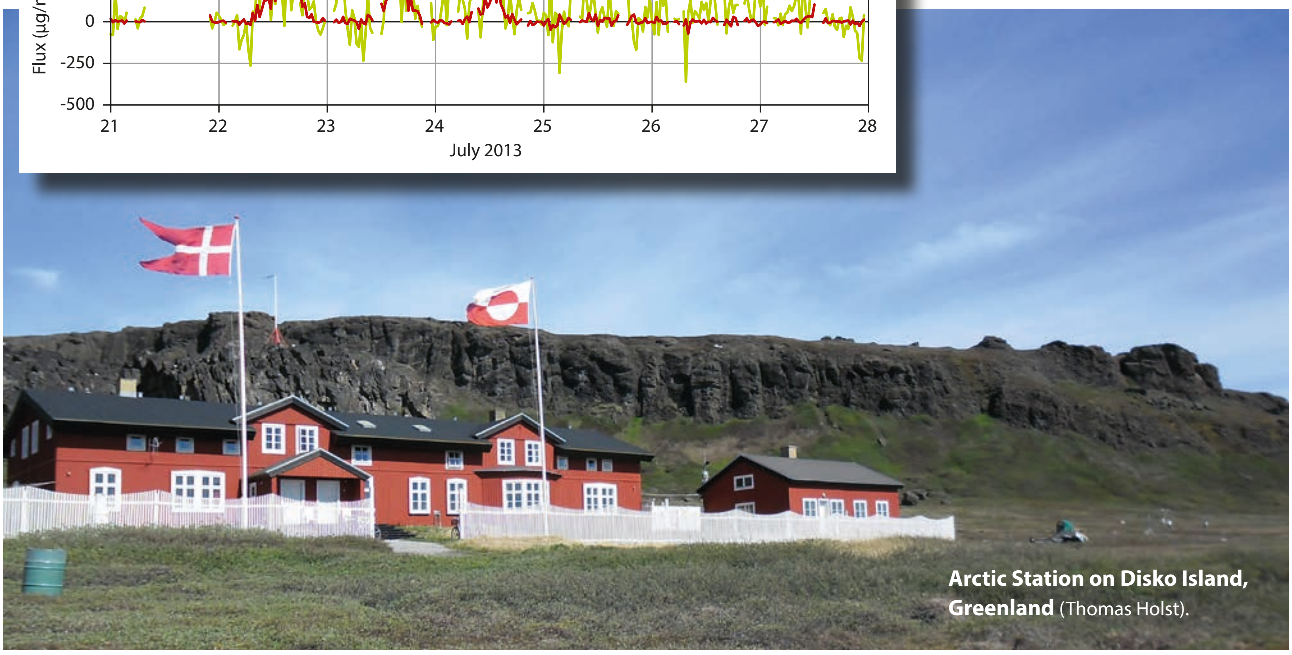


Example of exchange of two biogenic volatile organic compounds (Methanol and Isoprene) observed above an ecosystem in Greenland during a week in July 2013 (lower figure), and the strong increase of Isoprene emissions with temperature (upper figure). Positive numbers are net fluxes from plants to the atmosphere while negative fluxes are absorbtion by the ground.



Arctic Station on Disko Island, Greenland (Thomas Holst).

Controls on volatile organic compound emissions from northern plants

Riikka Rinnan & Hanna Valolahti

Plants release reactive gases (gases that react easily with other chemicals)– some with and some without odour. These gases (so called biogenic volatile organic compounds, BVOCs) have various functions including attracting pollinators to flowers and deterring herbivores from eating leaves.

AIMS OF THE PROJECT

We wanted to see whether herbivory or climate warming would alter the release of reactive gases (BVOCs) from northern plants.

WHAT DID WE DO?

We used bilberry *(Vaccinium myrtillus)* as a model plant, and measured BVOCs emitted from plants growing in experiments mimicking future warmer conditions. These experiments used clear plastic hexagons to warm plots of forest floor and tundra. Herbivory was mimicked by cutting leaves on newly produced plant shoots with scissors.

WHERE DID WE WORK?

We worked at the Kilpisjärvi Biological Station (•12) and Oulanka Research Station (•17) in northern Finland. Both stations have a long-term experiment combining warming and herbivory treatments in their surroundings. The long duration of the experiments (about 20 years) is vital to be able to detect changes that take place slowly.

WHAT DID WE FIND?

The results of our BVOC measurements are still under investigation. We expect that warming by a degree or two increases the BVOC release from bilberry. Herbivory, which is predicted to increase during climate change, normally causes a burst of BVOCs from the plants when they are harmed. We expect that this burst will be larger in the warmed plants. We also expect that after the burst, the herbivory-damaged plants will suffer, so that BVOC release in the long-term will be less than from the undamaged plants.

WHY ARE THE RESULTS IMPORTANT?

BVOCs are not only important for plant-animal interactions. Through complex chemistry in the air they form tiny sub-micron particles (aerosols) that can build clouds and scatter solar rays thereby cooling the climate. While there are huge uncertainties, climate cooling by cloud building may be a way in which plants can mitigate global warming.

THE ADVENTURE

Meeting reindeer and experiencing the vast and barren wilderness of Lapland during the total drive of 10,000 km back and forth between the Oulanka and Kilpisjärvi stations during the summer 2013 was an adventure itself. Misty early mornings, midnight sun, clouds of mosquitoes and a Finnish sauna after a hard day in the field made this a memorable period of field work.

Reindeer are one of the largest herbivore species in northern latitudes. Here they graze on summer pasture in Swedish Lapland (Gunhild Rosqvist).

4 • 5

Studies of plants growing inside a plastic hexagon, which works as an open greenhouse and warms the environment, resulting in increased growth (Hanna Valolahti).

Application of the yearly herbivory treatment on the bilberry plants (Riikka Rinnan).

Measurements of photosynthesis, which indicate the general performance of the plants (Riikka Rinnan).

Further information

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5 Life on Arctic lands

SECTION OVERVIEW

Christian Körner, Brian M. Barnes & Terry V. Callaghan

Over the last 25,000 years of human history, the Arctic, of all places on Earth, has experienced perhaps the most dramatic of changes in geography, plant and animal life, and human occupation. We are now anticipating that changes of near-equal significance and impact to humans will occur in the Arctic over the next 50 years. Just 15,000 years ago, large areas of Arctic Siberia and North America were grasslands and steppe, populated by vast herds of migrating buffalo, wooly rhinoceros and mammoths and their predators of lions, saber-toothed tigers and large wolves and bears.

As the Earth warmed, glaciers melted, sea levels rose and coast lines changed (Section 1). The mega-fauna became extinct and Arctic ecosystems were radically altered by wetter climates and transitioned to an environment that is considered today as one of the world's newest and least varied communities of animals and plants. The Arctic has experienced a relatively limited expansion of human development and environmental exploitation during the post-glacial period when most Arctic Peoples arrived there. However, with the Arctic now experiencing the most rapid rates of warming on the planet over the past few decades (Introduction to the book), and with undeveloped areas becoming accessible for transport, and mineral and oil exploitation, Arctic *ecosystems* are undergoing rapid changes. The life on Arctic lands is therefore facing combined pressures from climate change and direct human activities (Section 7).

Arctic ground squirrel
(Øivind Tøien).

THE ARCTIC LIFE ZONE

The Arctic life zone on land can be defined as the circumpolar area north of the latitudinal *treeline*. This area covers ca. 7 million km^2 (ca. 2 million km^2 of which is Greenland Ice Sheet), separated from the ca. 13 million km^2 coniferous boreal forest zone by the Arctic treeline that marks the seasonal mean temperature isotherm of around 6.4 °C combined with a minimum 3 month growing season length (Paulsen and Körner 2014). While overwhelmingly characterized by a short, cool season and a long cold winter, it would be too simple to view Arctic life as controlled by low temperature only. Conditions are not as cold as weather stations make us believe, and there are many other environmental drivers of Arctic life that can be categorised into four groups, each with various facets: (1) atmospheric drivers, (2) ground related drivers, (3) interactions among plants, animals and microbes, and (4) the human influence (Figure 5.1).

Latitude and elevation interact to limit *biodiversity* moving northward. The upper limit of higher plant life is at 6,300 m a.s.l. in the southern Himalayas, at 4,500 m a.s.l. in the European Alps, at 1,500 m at the Arctic Circle at 500 m a.s.l. in the high Arctic (e.g. on Svalbard) and at sea level at the polar end of higher plant life in northernmost Greenland (Figure 5.2). One flowering plant species, *Saxifraga oppositifolia* represents the cold limit of life, both in the high Arctic as well as at high elevation in the temperate zone (Körner 2011). Increasing elevation affects temperature, the amount and type of precipitation, and snow depth and duration. Elevation plays a key role, not only by co-controlling atmospheric temperatures, but also by creating slopes on which the action of gravity causes topographic diversity, which leads to habitat diversity in terms of warmth, wind exposure, moisture, snow pack, soil depth and nutrient availability. Because of this action of gravity and exposure, mountainous terrain bears far more diversity than flat terrain (Chapin and Körner 1995).

In addition to elevation, topographic diversity (Section 1) also translates into habitat diversity and is the key driver of biological diversity in the Arctic. This driver is not only evident on mountain slopes but also on flat terrain, whenever even minor relief contrasts come into play. As an example, Figure 5.3 illustrates the patterns of thermal conditions in a high Arctic environment at 78° N in Svalbard. In this, by all meteorological standards, very cold world, microhabitats may periodically offer almost tropical life conditions in summer, with temperatures even above 30 °C. The interaction of atmospheric conditions and topography creates a mosaic of life conditions (Figure 5.4).

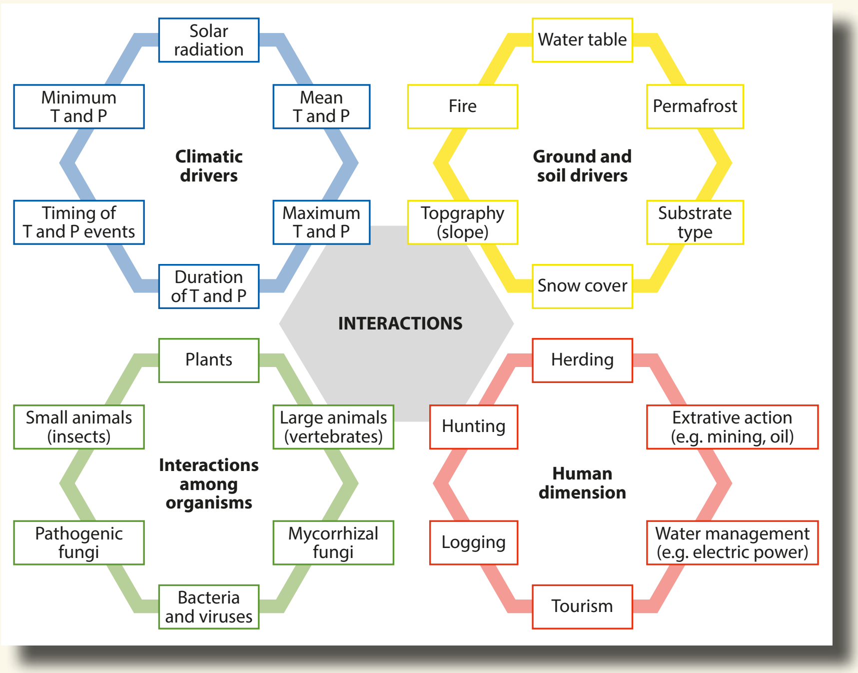

Figure 5.1 Four groups of environmental influences on Arctic wildlife. The examples given for each group are not exhaustive, but they cover the major aspects of action and interaction. Each of these factors can release secondary effects, not listed, and all four groups of drivers interact (T = temperature, P = precipitation).

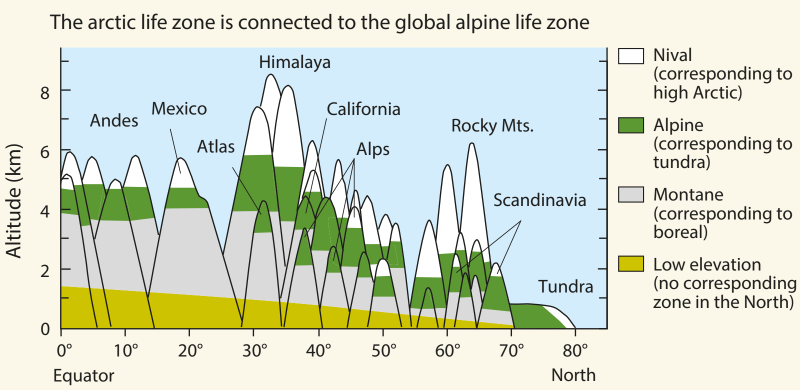

Figure 5.2 The low temperature limits of flowering plants as well as the treeline limit depend on latitude and elevation. Temperatures during the growing season may not differ a lot between equatorial latitudes and the high Artic. The alpine life zone of lower latitudes becomes the Arctic-alpine life zone beyond the Arctic Circle and merges with the Arctic life zone north of the Arctic treeline called *tundra* in the figure. The Arctic looks small in this latitudinal projection, but covers twice the land area than the global total of alpine land area.

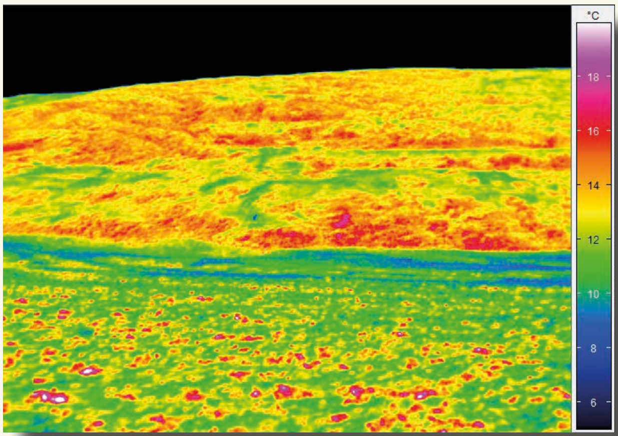

Figure 5.3 A thermal image of an Artic landscape in Svalbard at 78° N. A fixed camera that records 77,000 temperatures at a time "recorded" this terrain over a bright Arctic summer day (07:30-24:00 h, 23 July 2008). Each "pixel" is the mean for that entire period (Scherrer and Körner 2009). Across the vegetated test area, mean temperatures vary from cold to hot spots by about 8 degrees during sunny daytime hours.

Figure 5.4 A high Arctic landscape with a suite of very different life conditions in close proximity: estuarian turf-grass, warm slopes with Arctic heath (note how the green areas follow topography), Arctic desert beyond with a few specialists such as Arctic poppy and saxifrages, mosses and lichens (Svalbard, 78° N) (Christian Körner).

A few centimetres of difference in the level of the water table completely change the *biota* (assemblages of species). Changes may be as dramatic as the presence or absence of trees in the lower Arctic, but even at small scales, the difference of a few cm between a polygon rim and trough (Sections 1 and 2) can affect the diversity of plants. Even slight contrasts in ground elevation also control snow depth, and thus, active soil layer thickness (Section 2) and effective growing season length. Organisms can escape conditions they have difficulties to cope with by selecting suitable microhabitats over often very short distances (Scherrer and Körner 2011).

ARCTIC PLANTS

There are about 2,200 species of Arctic flowering plants, ferns and *fern allies*, 900 species of mosses and 1,750 species of *lichens* in the Arctic (Payer and others 2013). In the low Arctic, most of the *primary production* comes from less than 100 species of flowering plants, largely from sedges, and dwarf willows, *Ericaceae* dwarf shrubs, plus mosses and lichens, with the most abundant genera *Carex*, *Eriophorum*, *Vaccinium*, *Salix*, dwarf *Betula*, (Figure 5.5), and the moss genus *Sphagnum*, all exhibiting milliennia of *clonal* spreading (vegetative propagation (De Witte and others 2012)). Although generally poor in flowering plant species, some high Arctic environments show a quite unexpected plant diversity: there are ca. 100 species at 82° N near the northern edge of Greenland, and the Arctic archipelago of Svalbard hosts 163 species. A very rich moss and lichen flora adds to the overall diversity of primary producers (plants that photosynthesise).

The height and complexity of the canopy of Arctic vegetation decreases from the treeline northwards: fewer species with low canopies cover less and less of the ground surface. Many high Arctic species are small in stature and form aerodynamically dense mats, and thus are modifying their environment, as shown in Figure 5.3. While branches and foliage of trees are exposed to free atmospheric conditions (causing trees to become affected first when it gets cold), the smaller plants such as shrubs, tussock grasses, forbs and particularly "cushion plant" forms of these, create a microenvironment that is sheltered and thus much warmer on sunny days. A second avenue toward "managing" life in the cold, is rapid growth and development. Some of the most cold-tolerant Arctic and alpine plants can mature new shoots and seeds in merely 45 days with some hours above freezing conditions whereas no tree has been found so far to complete growth and tissue maturation in less than 90 days of appropriate conditions.

As a consequence of low ambient temperature, evaporation is limited in Arctic environments, causing high soil moisture in most parts, despite often low precipitation. The combination of low soil temperature and high moisture leads to peaty and acidic soils throughout much of the Arctic. These soils slow nutrient cycling, causing low productivity. However, adding nutrients causes the typical Arctic vegetation to change: productivity increases, but biodiversity decreases as some species such as mosses and lichens disappear while grasses and shrubs become more dominant. In some of the nutrient richest habitats worldwide, under Arctic bird cliffs, lush herbfields exist, often composed of only one or two species (spoonwort, *Cochlearia groenlandica*, and mountain sorrel, *Oxyria digyna*), illustrating the overarching role of nutrients for the appearance of the Arctic's vegetation. These nutrients come from sea food brought back to land by sea birds.

The Arctic life zone underwent significant climatic and thus, vegetation changes during the post-glacial period, with first advances of the boreal forest to current latitudes between 10,000 and 11,000 years before present, and several retreats and advances occuring since then (Barnekow 2000). A mega-trend in response to the warmer climate is that shrubs become more abundant in the Arctic world. Arctic species have been shown to respond very differently to experimental climatic warming, with winners (shrubs and grasses/sedges) and losers (mosses and lichens) (Ims and Ehrich 2013). However, there are variations in this general response (Elmendorf and others 2012, Callaghan and others 2013) because warming is not the only changing driver in the Arctic. Extreme weather situations such as warm spells in autumn and winter can have very negative consequences for plant performance in the following season (e.g. bud development, shoot death and no fruiting (Bokhorst and others 2009)). A big question is how fast "winners" of Arctic climate warming will be able to shift location (e.g. disperse northwards). Elevation gradients over short distances may offer some guidance.

The consequences of current rapid warming, in some parts of the Arctic exeeding 3 degrees (Introduction), include northwards excursions of the Arctic treeline, but these trends are clearly not uniform (Nymand-Larsen and others 2014). The Arctic treeline responds to extreme weather conditions, insect outbreaks, *browsing ungulates* and other herbivores, interactions with *permafrost* level, and melt-water from diminishing winter snow which often prevents climate related shifts. Most surveys revealed faster tree growth near the current tree limit. The sensitivity of annual growth rings can be used to indicate past temperatures and even ocean temperatures when the shrubs grow on islands in the Atlantic Ocean (Science Story 5.1).

Increasing severity and range of insect outbreaks in boreal and Arctic regions are impacting forest health. Birch tree defoliation by moths in northern Sweden (Figure 5.1) have off-set advances in treeline in some areas (Callaghan and others 2013). Also, massive spruce bud worm and birch bark beetle outbreaks accelerated by warm summers that allow multiple generations of insects to occur in one season have damaged millions of hectares of forests in Alaska and Canada leaving standing dead forests, prone to devastating wildfires. Outbreaking insect herbivory is expected to increase with climate warming. In addition, there is constant "background" insect herbivory that over several decades can result in greater loss of plant material than outbreaking insects, and this too, is expected to increase with climate warming (Science Story 5.2).

Figure 5.5 Four major "players" throughout the whole Arctic Circle: (a) mat-forming white dryas *(Dryas octopetala)*, (b) wet-tundra cotton grass *(Eriophorum scheuchzeri)*, (c) the lichen *(Xantoria)* and (d) the dominant dwarf birch of the lower Arctic *(Betula nana)* (Christian Körner).

Among atmospheric drivers other than climatic warming, elevated CO_2 was not found to exert the expected so called "fertilization" effect in both Arctic and high alpine vegetation, and UV-B radiation has been shown to have imperceptible effects on plant species vigour but soil microbes were affected (Gehrke and others 1995, Johnson and others 2002). However, in contrast, even small enhancements of nitrogen deposition (5 kg Nitrogen per hectare per year) exert significant effects (Wookey and others 2009, Bobbink and others 2010).

FUNGI AND MICROBES

Fungi are a major group throughout the Arctic and play major roles in the functioning of ecosystems. Lichens (Figure 5.5c) are composites of fungi and photosynthesising algae that are an important food source for animals throughout the Arctic, especially caribou and reindeer (Callaghan and others 2005). Fungi also develop intimate relationships with plant roots forming "*mycorrhizae*" in which carbon is supplied by the plants and water and nutrients are supplied by the fungi. Even the plants at the coldest place on Earth with a flowering plant were mycorrhizal (Newsham and others 2009). Some fungi also live inside cells of plant seeds. They are called "endophytes" and are a topic of current research as relatively little is known about them (Science Story 5.3).

Microbial diversity is vast and hitherto poorly understood. However, the technology for exploring microbial diversity and function at the molecular level is rapidly expanding (Section 6). Microbial communities are important in all habitats from the "*extremophiles*" that grow inside rocks to carpets in wet seepage areas (Science Story 6.5).

ANIMALS IN THE ARCTIC

Living in the Arctic are about 67 species of mammals, 154 species of birds, but only 6 species of amphibians and reptiles (Payer and others 2013). In contrast, there are at least 3,000 species of insects, mostly flies (CAAF 2013).

Animals are either adapted to Arctic winter conditions as year-round residents or they migrate to warmer regions and avoid the Arctic winter. These migrations may be local, from tundra in summer to boreal forest in winter (e.g. caribou/reindeer) or long distance, for example the Red Knot *(Calididris canutus)*, a shorebird, that breeds in spring on Arctic tundra but overwin-

Figure 5.6 Four iconic animal species: (a) reindeer *(Rangifer tarandus tarandus)*, (b) Arctic fox *(Vulpes lagopus)*, (c) red knot *(Calidris Canutus)*, and (d) red flat bark beetle *(Cucujus clavipes)*.

((a) Mikko Jokinen, (b) William Callaghan, (c) Peter Prokosch/GRID-Arendal and (d) Øivind Tøien).

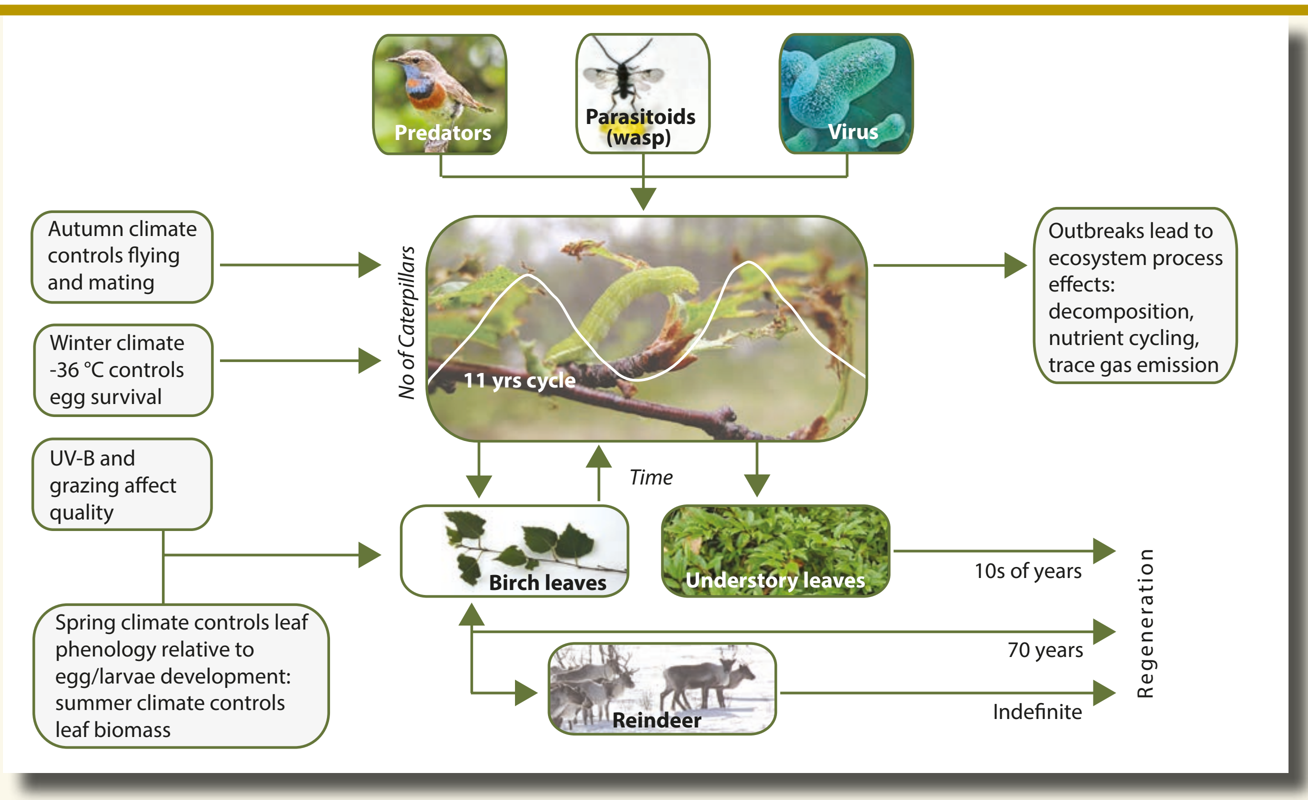

Figure 5.7 Example of how populations of autumn moth, an insect pest of sub-Arctic birch forests, is controlled by many drivers and in-turn, also affects vegetation. In the extreme case, insect outbreaks and high populations of reindeer convert forests to "tundra" (Adapted by Terry V. Callaghan based on numerous sources, graphic design by Hannele Heikkilä-Tuomaala).

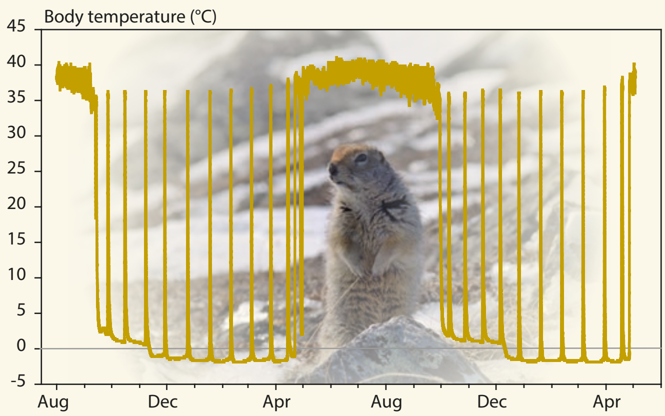

Figure 5.8 Core body temperature of a free-living female Arctic ground squirrel (about 1 kg) near Toolik Lake in Arctic Alaska. Recordings (each 20 minutes) were made by a temperature-sensitive datalogger, implanted within the abdomine. The trace shows two periods of hibernation wherein the animal alternates between prolonged (1-3 weeks) bouts of torpor when body temperature reaches minima of -3 °C and body fluids are supercooled and brief arousal intervals when the animal rewarms briefly (15 hours); arousal intervals may be necessary to allow sleep to occur. The short (4.5 month) summer active period is when reproduction occurs and growth and fattening by young and adults, as they prepare for the next hibernation season.

ters in South America or in Africa (Figure 5.6). Resident animals that over-winter in the Arctic have developed coping mechanisms that lie at the extremes of physiological design, for example the Arctic ground squirrel *(Urocitellus parryii)* hibernates in permafrost soils and allows its body fluids to supercool to -3.0 °C, the lowest body temperature assumed by any mammal (Barnes 1989) (Figure 5.8). Woodfrogs *(Rana sylvaticus)* that range to the Arctic Ocean coast in western Canada overwinter while frozen at body temperatures of -18 °C, then thaw in spring and hop away (Larson and others 2014). Arctic red flat bark beetles *(Cucujus clavipes)* survive temperatures of -100 °C by entering a glass-like state of vitrification in experiments.

Adaptations are also found in behaviour (such as lemmings and voles that live, feed and breed below snow (Figure 5.9)) and morphology (body's form), such as highly insulating fur in reindeer/caribou (these are subspecies of the same species) (Figure 5.6a) and white fur in winter and short ears and legs in the Arctic fox (Figure 5.6b).

However, there are several issues related to changes in Arctic animal populations due to warming climates and altered seasonality that we do not understand yet and that may have major impacts on Arctic systems including humans (Post and others 2009, Ims and

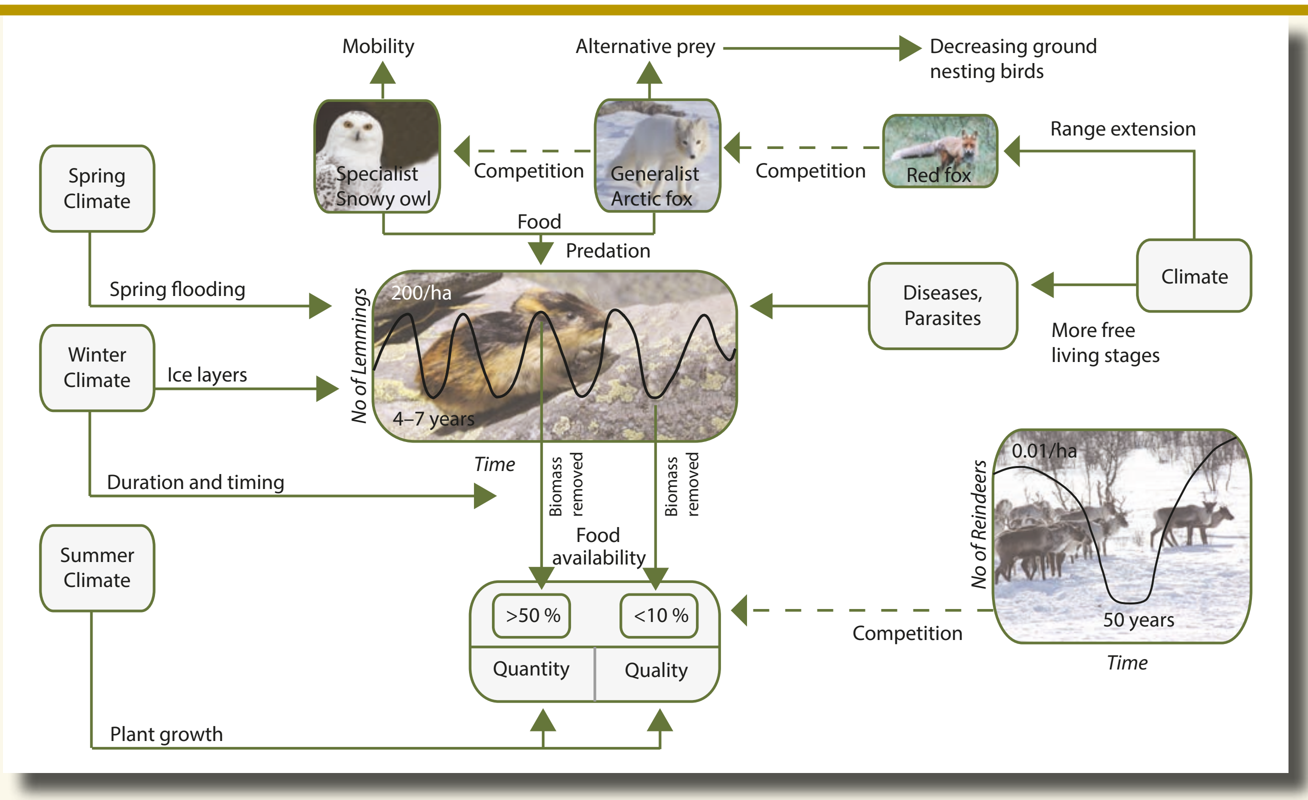

Figure 5.9 Interactions between lemmings, their food plants and their predators – and even species that they do not directly interact with such as alternative prey of lemming predators. The schematic also shows several ways in which various aspects of climate warming affect lemming populations and their cycles (Adapted by Terry V. Callaghan based on numerous sources, graphic design by Hannele Heikkilä-Tuomaala).

Ehrich 2013). Arctic regions are well known for the occurrence of multi-year cycles in population size of small mammals, such as hares, lemmings and voles, and in the number of predators that feed on them (Figure 5.9). These large swings in animal numbers affect the growth and diversity of the plants they feed on, and during population peaks plant production can be reduced by 25-30% (Callaghan and others 2013). Big Arctic mammals, like grazing muskoxen and caribou/reindeer that eat lichens in winter, also experience large, seemingly erratic changes in population size, and during lows their availability as game for subsistence hunters is reduced.

What drives these swings in animal numbers, whether food, predators, or animal stress or disease (Figure 5.9), is a classic debate among ecologists, but the occurrence of regular cycles has been observed to have dampened in some areas of Arctic Fenno-Scandinavia, although resuming in others outside the Arctic (Brommer and others 2010), perhaps as a result of changing snow conditions due to warmer winters (Ims and others 2008). Voles and lemmings depend on deep snow as cover from extreme temperatures and wind and spend winter in *sub-nivian tunnels* (tunnels on the ground surface under the snow) (Section 3) that create conditions that can support breeding and population increases in some species. Caribou/reindeer can dig through soft snow to reach lichens, herbs, and grasses. These opportunities change for the worse with “rain on snow” events that are increasing in frequency in the Arctic (Rennert and others 2009), since melting snow collapses the sub-nivian space and coats food plants in ice when it refreezes, reducing their availability as forage. Also, loss of a winter snow cover can result in flooding and drowning of voles and lemmings, and exposes them to predators (Figure 5.9). A single rain on snow event caused the death of over 20,000 muskoxen on Banks Island in October of 2003 (Putkonen and others 2009).

Range extensions of southern predators into the Arctic are competing with indigenous predators and affecting food webs and prevalence of disease; for example, expansion of red fox populations likely aided by road development and human infrastructure associated with oil exploration and export in northern Alaska have displaced local Arctic fox with the potential of increasing human risk for rabies (Savory and others 2014).

Parasites and insect-borne diseases are invading northward and may soon threaten humans, live-stock and wildlife in Arctic regions. Mosquitoes carrying West Nile disease have entered Canada, and forest regrowth and warmer winters have led to the northern expansions of ticks bearing bacteria causing Lyme disease in the eastern USA. Outbreaks of parasites including winter ticks that are surviving warmer winters have led to a 50% reduction in moose populations due to hair loss and stress in areas of the northern US and Canada, impacting subsistence and hunting-take and local economies while in Arctic Canada, muskox lung worm infection is increasing.

Key messages and needs for further research

- The major questions regarding the future Arctic life and ecosystem processes relate to (1) the consequences of thawing permafrost (Section 2), (2) shorter and less regular snow cover (Section 3), and (3) a change in plant-animal interactions. Since the clonal life form is so dominant in Arctic plants, some persisting over millennia in a given location (de Witte and others 2012), it will need certain extremes or thresholds and competitive exclusion, all to be explored, for significant changes in Arctic vegetation to occur.
- Key questions relate to how much earlier in spring plant growth or the ephemeral (short-term) appearance of insects may occur in the future and whether affected consuming species can respond through *phenotypic flexibility* (non-genetic changes) or rapid evolution to reinstate the match.
- The northward spreading of novel insect species and microbial pathogens bears substantial risks, similar to the loss of ice for some marine biota, especially walrus, seals and polar bears. It is the rapidity of these changes, the loss of Arctic biodiversity and the multiple *feedbacks* to the climate system (Section 4) that makes global change in the Arctic an issue of climate concern.
- It is towards creating a better understanding of the history, current structure and function, and future of the Arctic biome and its feedback on Earth's systems and people that INTERACT hopes to contribute through an expanding network of Arctic field stations and their scientists and managers.

INTERACTIONS AMONG SPECIES

Plants (primary producers), animals (secondary producers) and microbes (often decomposers) are mutually dependent and do not live in isolation. In the past, it was thought that because of low diversity, food webs ("trophic interactions") were simple and competition between individuals was considered the main mechanism for controlling the structure of the communities of species. However Story 5.5 by Roslin and co-workers who used molecular techniques, unravels very complex interactions between invertebrates and plants. Also, whereas competition is the dominant driving force structuring communities of plants in moderate environments, plant-plant help (facilitation) is more important in harsh environments such as those of the Arctic (Carlsson and Callaghan 1991).

The interactions among species, already complex, are becoming even more complicated during climate warming. Effects of climate change are reducing lemming numbers in some areas and their predators are turning to alternative prey (Story 5.6 by Reneerkens) (Figure 5.9). Also, changes in the timing of snow melt during early spring warming that leads to early plant growth or insect development is associated with the potential for "trophic mismatches" between these resources and their migrating or hibernating consumers whose appearance is controlled by changes in photoperiod that are not subject to climate change. Triggered by increasing daylength in spring, Arctic caribou in Greenland, for example, move westward in anticipation of producing calves on calving grounds just as newly emerging plants are available. Early plant growth in West Greenland, however, stimulated by early warmth and snow loss is leading to a mismatch between production of calves and the optimal availability of food that has been associated with a significant increase in mortality of caribou offspring (Post and Forchhammer 2009).

Figure 5.10 One of the first ecosystem warming experiments, Svalbard, 1990 (Terry V. Callaghan).

Further information and references

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Recent influence of climate on shrub growth around the North-Atlantic Region

Allan Buras & Martin Wilmking

Dendrochronology is a scientific discipline analysing annual growth variability of woody plants. In the last decade, dendrochronological analyses have been expanded to ecosystems beyond forests, such as Arctic or alpine tundra. For instance, dendrochronological methods were applied to shrubs growing at their distributional margins. *In this study we were interested in sampling shrubs along a* continentality gradient *to assess whether, and if so, how the differing climate conditions along that gradient alter shrub growth. Such knowledge may be of value when reconstructing past environments using shrubs.*

Willows and the Midtdalsbreen in the sun – one of the many *outlet glaciers* of the Hardangerjökulen icecap at Finse, Norway (Allan Buras).

AIMS OF THE PROJECT

We aimed to investigate if shrubs can be used to learn about past environmental and climatic change.

Working in rainy weather on the Faeroe Islands (Ilka Beil).

WHAT DID WE DO?

We collected many stems and branches of different typical northern shrubs, like heather *(Calluna vulgaris)*, willows *(Salix* spp.*)* and junipers *(Juniperus communis*, an evergreen needle-leaf, prickly shrub). We then analyzed the annual growth rings in the laboratory, after sanding the cross-sections of the stems and branches. The widths of these growth rings tell us something about how good the conditions were for the shrubs to grow in a particular year and what factors influenced the growth.

WHERE DID WE WORK?

We worked on the Faroe Islands Nature Investigation (•75), north of Scotland, to sample a region where the oceanic climate is very important for the vegetation. We also worked at Finse Alpine Research Centre (•7), Norway, close to a large glacier, the Hardangerjökulen, and we went to Kevo Subarctic Research Station (•13) in northern Finland, where the climate is a lot drier, warmer in summer and colder in winter. These three sites represented a climatic gradient from so called hypermaritime Faroe Islands, through maritime-alpine Finse, to continental Kevo.

The weather is often harsh on the Faeroe Islands (Ilka Beil).

Heather *(Calluna vulgaris)* sampled on the Faeroe Islands (Ilka Beil).

WHAT DID WE FIND?

The oldest shrubs were junipers at Kevo with an age of more than 400 years. They had survived a large fire around 1950 and were now reacting with increasing growth to warm summers. In Finse, willows and junipers also grew more in warm summers and therefore could be used as proxies ("approximations") for melt of the Hardangerjökulen, as glaciers melt more in warm summers (see video abstract: http://iopscience.iop.org/1748-9326/7/4/044031/article). In the Faeroe Islands, heather grew especially well when the ocean temperatures around the Islands were warm in summer. Heather annual growth rings were good proxies for sea surface temperatures.

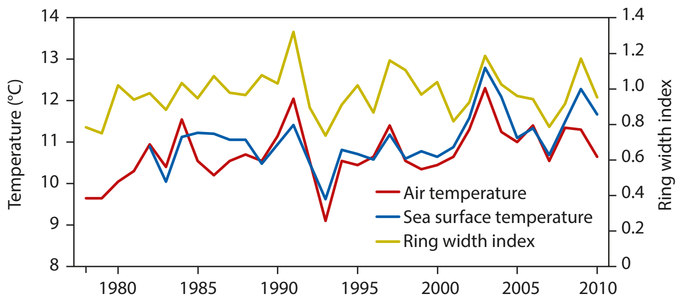
WHY ARE THE RESULTS IMPORTANT?

We could show that scientists can use not only trees to reconstruct past climate and environmental conditions, but also shrubs. The shrubs we analyzed could tell us about past disturbance (fire), they can help to reconstruct how much a glacier has melted in the past, and they can help us to understand the dynamics of ocean currents and ocean heat transfer, such as the "Gulf Stream". This is especially helpful, because shrubs are widespread in Arctic areas, where no trees grow and we therefore hope to extend records of past environmental and climate fluctuations with the help of shrubs. These records are particularly important for assessing past changes before direct measurements were made.

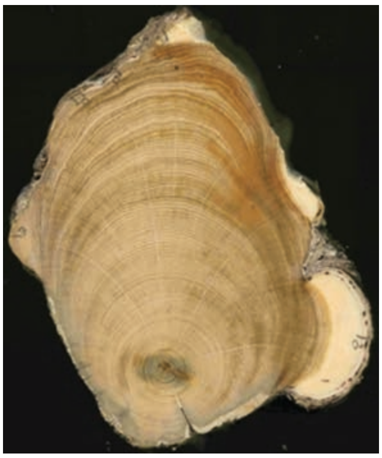
THE ADVENTURE

On the Faeroe Islands, we encountered harsh weather with rain, fog and storm. Working under such conditions was challenging but exciting. To reach our field sites, we had to use a helicopter, and then took a small and bumpy ferry to the island where we collected the shrubs. On other occasions, we had to hitchhike - it was all great fun. In Finse, on the other hand, we could enjoy working in the sun with the fascinating view on the Hardangerjökulen ice cap and slept in a small touristic winter resort, which you could only reach by bike or train.

Heather growth in yellow shows a similar pattern over time as air (red line) and sea (blue line) surface temperature on the Faeroe Islands in the Atlantic Ocean.



Stem of an 180 year old juniper. You can clearly see the annual growth rings which tell us of the past (DendroGreif laboratory).



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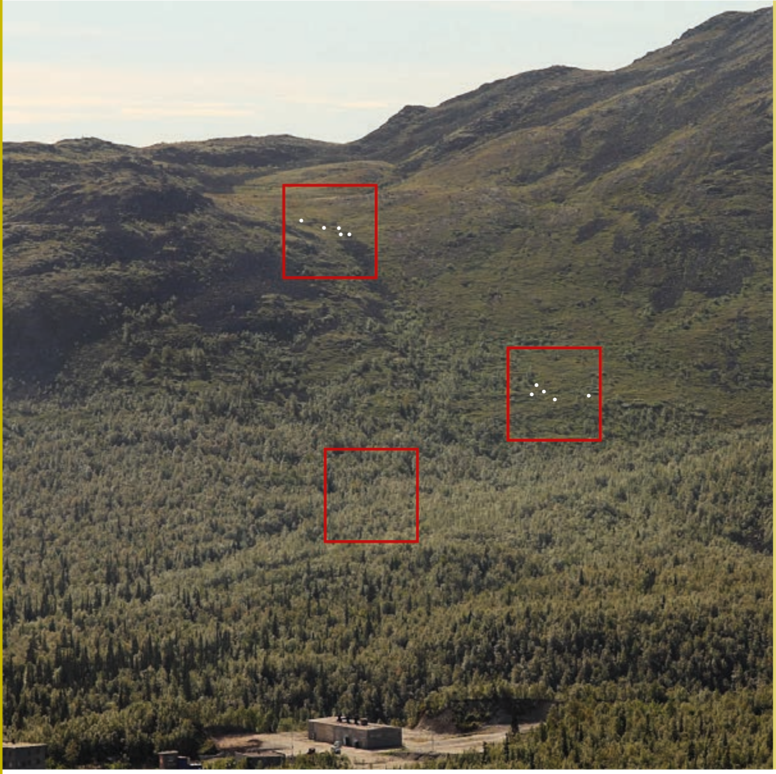
Patterns of insect herbivory along altitudinal gradients in a polar region

Mikhail V. Kozlov & Vitali Zverev



Location of forest, sub-alpine and alpine study sites (showed by red frames) along the "ecological patch" of the Polar-Alpine Botanical Garden in the Khibiny Mountains. White spots seen at sub-alpine and alpine sites are passive greenhouse chambers established in June 2012 (Vitali Zverev).

At the global scale, the larger part of herbivory is attributed to insects – "the little things that run the world". Levels of herbivory can be classified as "background", when insect populations are at their "normal" densities, which are typical for a given ecosystem in a long-term perspective, and "outbreak", when populations of some species occasionally reach very high numbers, dramatically damaging plants. Although background losses of plant foliage to insects in sub-Arctic forests are relatively minor, from 1.5 to 7.5 %, even a small increase in background herbivory due to climate warming can cause severe negative impacts on tree growth. Studies of insect-plant interactions along natural abiotic *(physical environment) gradients are needed to evaluate the impacts of climate on insect herbivory and on this basis to predict effects of climate change on plant damage by insects. The earlier studies of this kind were mostly conducted in temperate ecosystems, and they demonstrated that herbivory usually decreases with both latitude and altitude of the study site. However, the recent research by our team hints that the strength of latitudinal and altitudinal changes in herbivory may well differ between low and high latitudes, and that it may vary with specific climatic conditions of the study year.*

AIMS OF THE PROJECT

The aims of the project were to monitor the background (i.e., non-outbreak) losses of plant *biomass* to defoliating and leaf mining insects (the larvae that live and feed between the surface cell layers of a leaf) in several species of woody plants along altitudinal gradients in sub-Arctic mountains and experimentally assess the effects of temperature increase on these losses.

WHAT DID WE DO?

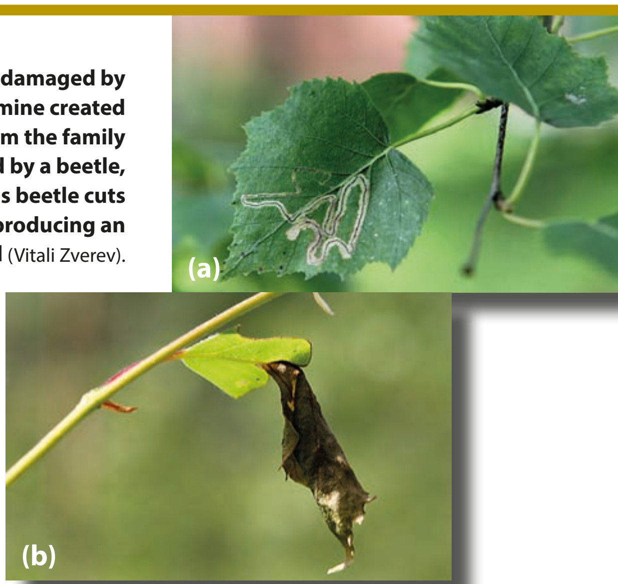
We measured leaf/needle area that was lost to insects in 10 species of woody plants at different altitudes. We also established passive greenhouse chambers (which increase the mean summer air temperature by 1-2 °C) in early summer at different altitudes and compared plant damage inside and outside these chambers at the end of the growing season.

WHERE DID WE WORK?

The unique geographical features of the Kola Peninsula, northwestern Russia, made this region best suited for the establishment of the properly replicated study. Several mountain systems located in the central part of the Kola Peninsula, close to the Khibiny Educational and Scientific Station (•26) of the M.V. Lomonosov Moscow State University, differ from each other in geology and in their floristic composition. Therefore the results of the studies conducted in this region can be generalized over a wide range of environmental conditions. Importantly, the steep slopes of Khibiny, Lovosero and Monche-tundra Mountains are relatively easy to access.

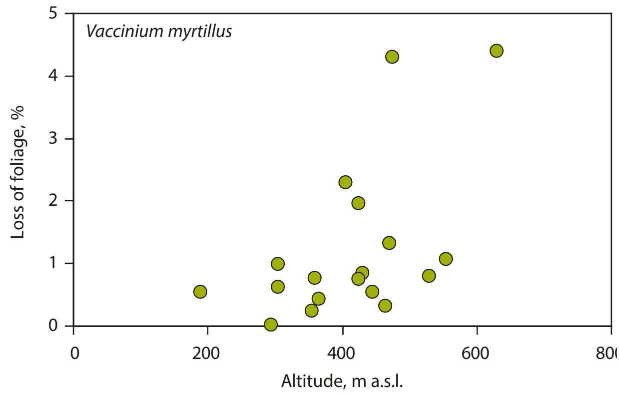
WHAT DID WE FIND?

Our findings were somewhat surprising: we did not discover the expected decrease in foliar damage with altitude in any of the studied species of woody plants. Moreover, some plant species demonstrated paradoxical increase in foliar losses to insects with altitude, while others showed no altitudinal changes or a pattern of herbivory with the highest damage attained at the intermediate altitudes. Meta-analysis demonstrated that, in general, the losses of plant foliage to defoli-



The leaves of a mountain birch are damaged by a number of insects. (a) Serpentine mine created by a larva of a minute moth from the family Nepticulidae. (b) Birch leaf rolled by a beetle, *Deporaus betulae*. The female of this beetle cuts most of the way through a leaf, producing an inverted cone, in which an egg is laid (Vitali Zverev).

A passive greenhouse chamber at a treeline site in the Khibiny Mountains. Mean summer air temperature within these chambers is 1-2 °C above the ambient level, thus mimicking a future warmer climate. However, the current weather conditions in a sub-alpine region can change very rapidly (Vitali Zverev).



The loss of bilberry *(Vaccinium myrtillus)* foliage to defoliating insects increases from 0-1% in forests to 1-5% above the upper tree limit (data from 2012).

ating and leaf mining insects in our study region slightly but significantly increased with altitude. On the other hand, plant losses to insects in passive greenhouse chambers were generally higher than outside the chambers, and this effect was largest at the intermediate altitudes, in sparse sub-alpine birch woodlands.

WHY ARE THE RESULTS IMPORTANT?

This is the first study of the altitudinal pattern in insect herbivory, which was conducted beyond the Polar Circle. Our results demonstrate that in harsh environmental conditions at the upper tree limit some unknown factors may facilitate insect herbivory relative to the more benign environment of low-altitude forests, counterbalancing adverse effects of lower temperatures on insects. The exploration of mechanisms behind the detected altitudinal pattern is likely to advance our knowledge on functioning of sub-alpine ecosystems and improve our predictions on climate change impacts on mountain and polar regions.

THE ADVENTURE

We were extremely surprised by the force of the wind observed one day of June at the upper tree limit in the Monche-tundra Mountains. The wind was so strong that it was impossible to open the doors of the windward side of our car. After leaving the car from the opposite doors, we immediately understood that we needed to change our plans because it was impossible to do any work and even to walk to our study site.

Further information

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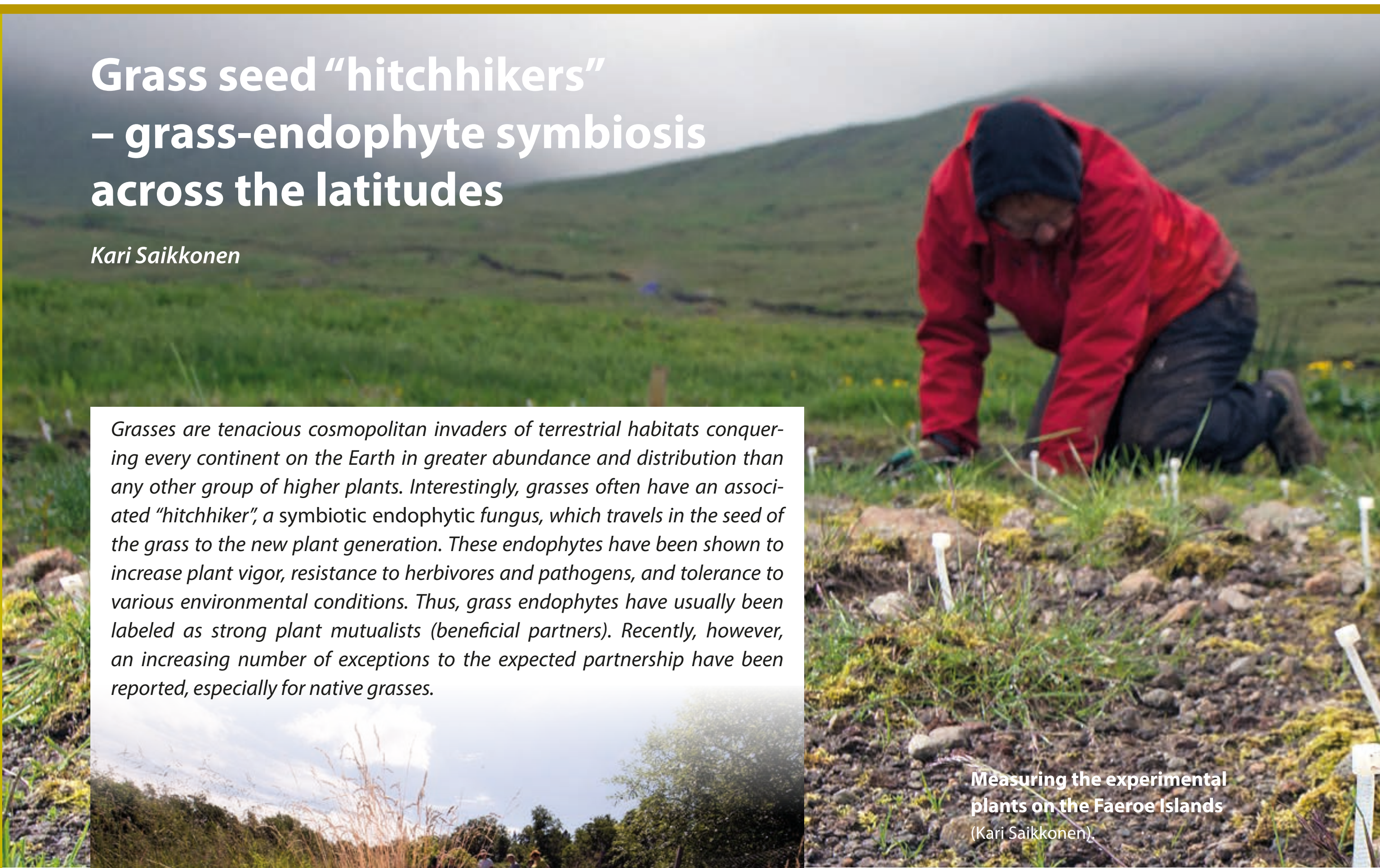

Grass seed "hitchhikers" – grass-endophyte symbiosis across the latitudes

Kari Saikkonen

Grasses are tenacious cosmopolitan invaders of terrestrial habitats conquering every continent on the Earth in greater abundance and distribution than any other group of higher plants. Interestingly, grasses often have an associated "hitchhiker", a symbiotic endophytic *fungus, which travels in the seed of the grass to the new plant generation. These endophytes have been shown to increase plant vigor, resistance to herbivores and pathogens, and tolerance to various environmental conditions. Thus, grass endophytes have usually been labeled as strong plant mutualists (beneficial partners). Recently, however, an increasing number of exceptions to the expected partnership have been reported, especially for native grasses.*

Measuring the experimental plants on the Faeroe Islands (Kari Saikkonen)

Transplantation site at Ruissalo, Turku, Finland (Kari Saikkonen)

AIMS OF THE PROJECT

The project aimed to improve our understanding of the mechanisms underlying phenotypic (non-genetic) variation in red fescue aggregate (a complex grass species) and how grass-endophyte symbiosis affects the distribution ranges of fescue species in changing climate.

We chose red fescue *(Festuca rubra)* and its endophyte *(Epichloë festucae)* as our study objects because red fescue is distributed throughout the Arctic and also has agronomic importance as turf.

WHAT DID WE DO?

First, we explored how common these symbiotic endophytic fungi in grasses are over a wide geographic range from central to Arctic and sub-Arctic Europe. Since 2011, we have collected red fescue plants from southern and northern Finland (Kevo Subarctic Research Station (•13)), southern (Finse Alpine Research Centre (•7)) and northern Norway (Bioforsk Svanhovd Research Station (•8)), Faroe Islands (Faroe Islands Nature Investigation (•75)), Iceland (Litla-Skard (•73)) and Greenland (Arctic Station (•66)). In addition, our colleagues provided us *Festuca rubra* plants from Switzerland and Spain. The individual plants were transported to Finland where they were then grown in greenhouse conditions in the Ruissalo Botanical Garden, University of Turku. The endophyte infection status of the plants, their chromosome numbers (*ploidy levels*), molecular variation of the plant and the fungus as well as the *morphological taxonomical characters* of the grasses have been examined.

Second, we examined whether endophyte symbiosis modulates fescue distribution and responses to changing climatic conditions. For this we established a reciprocal transplant (common garden) experiment with plants of known endophyte status and ploidy levels in Spain, southern- and northernmost Finland and the Faeroe Islands in 2012. In the following two years, these plants have been monitored for their survival, growth and reproduction. In addition to these basic growth measurements, chemical and morphological analyses have been conducted on the experimental plants.

WHERE DID WE WORK?

This project combined site specific observation with experimentation. Because we were interested in the genetic origins of the symbiotic relationships and the consequences of these symbioses under different environmental conditions, we col-

Transplant experiment.

***Festuca rubra* collections, and the endophyte infection and ploidy frequencies of the examined populations. E+ = endophyte infected, E– = endophyte-free.**

On the way from Ilulissat to Disko Island in Greenland (Kari Saikkonen).

lected material from different geographical locations and grew plants at various INTERACT stations as well as at a location in Spain.

WHAT DID WE FIND?

We found that there is no clear geographic gradient in the frequencies of endophyte infected plants. Practically all examined plants collected from southern Finland and Greenland were endophyte-free, and in other geographic locations the frequencies of endophyte infected grasses were highly variable among populations.

Preliminary results from molecular analyses suggest that plants can be categorized in a few clearly distinct morphological groups and most of the genetic variation can be detected within populations. In contrast, geographic location explains 62% of genetic variability in the endophyte. Only 30 % of variation was detected within populations.

WHY ARE THE RESULTS IMPORTANT?

This work allows us to examine statistically the relationships between genetic variation in the fungus and the grass, and phenotypic variation of the grass, and how they mirror the origin of the plants and their growth environment.

THE ADVENTURE

This project has taken us to memorable places, one of the most impressive being the trip from the small town of Ilulissat to Disko Island in Greenland. We were standing on the deck of a small boat navigating between the enormous floating ice sculptures in the midnight sun. This truly gave us a concrete perspective to our research on changing climate.

Further information

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Consequence of climate change on the fate of Arctic-alpine bumblebees

Baptiste Martinet, Nicolas Brasero, Syndonia Bret-Harte & Pierre Rasmont

Wild bees are important pollinators of both domestic and wild plants, and are suffering from a dramatic decline in both diversity and abundance around the world. While much of their decline is likely due to reductions in their habitat caused by human activities, climate warming is likely to pose another challenge to wild bees, especially bees that live in Arctic and alpine regions. The Arctic is warming faster than any place on Earth, and current alpine habitats are decreasing in size as warming moves the environmental envelope up the mountains to higher elevations and into progressively smaller areas. Thus, Arctic and alpine bees may be especially at risk. To better conserve wild bees that live in Arctic and alpine areas, we need to know their current population status, and also how they will respond to climate warming.

At present, bumblebees are the only type of bees that are abundant in Arctic and alpine areas. These robust, hairy, and social bees show adaptations that allow them to regulate their body temperature and thrive in the coldest areas of the world that are inhabited by insects. Also, they are major pollinators in cold regions. The Alpinobombus sub-genus of bumblebees, the focus of our study, is one of the largest and most threatened sub-genera *of Arctic and alpine bumblebees and has members around the circumpolar Arctic. Yet, even within this sub-genus, our prior results in Europe indicate that some Alpinobombus species are very threatened (e.g.* Bombus polaris*), while others are not (e.g.* B. balteatus*). In order to better characterize the* phylogeny *(genetic relationships) of these bees and their need for conservation, and to assess their physiological response to climate warming, we needed to collect bees from around the Arctic. This led us to request a* Transnational access *award through INTERACT, which brought us to the Tarfala and Abisko stations in Sweden, and Toolik Field Station in Alaska, USA.*

AIMS OF THE PROJECT

Our goal was to collect living bumblebees from as many species as possible from different parts of the Arctic to clarify their phylogenetic relationships, and test their responses to climate change over both short and long time horizons.

WHAT DID WE DO?

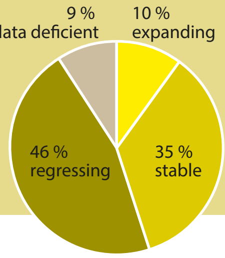
We collected male bumblebees of as many species as possible, and a few females to establish captive breeding colonies, from each Arctic site. We collected mostly males to avoid decreasing the bee populations, because there are more males than needed for breeding. Back in the laboratory in Belgium, genetic and chemical analyses will be run on the males, and morphological features (aspects of body shape) will be measured. These data will help in defining the phylogenetic relationships between the species. Also, experiments to measure bumblebee response to heat stress in the short-term will be run. Correlations between species distribution, density, and climate data over the last 200 years will be used to assess long-term changes in bumblebee species and the need for conservation.

WHERE DID WE WORK?

In our prior work (including support from INTERACT), we had collected samples from several places in the European alpine and Arctic, including the Alps, the Pyrenees, and the Apennine Mountains, and from northern Sweden, northern Finland, and northern Norway. However, we did not have any samples from the North American Arctic. Although bumblebee species are assumed to have

Scenery at Toolik Fiels Station (Nicolas Brasero).

Conservation status of the 68 European bumblebee species
(From Rasmont, Roberts & Michez, 2014).



a pan-Arctic distribution, this had not been verified. Thus, we went to the Toolik Field Station (•48), in the Alaskan Arctic, to collect bumblebees from a part of the Arctic that has not been explored (with respect to bees).

WHAT DID WE FIND?

Of the five Alpinobombus species that are thought to occur in Alaska, we were able to collect multiple individuals of three species at Toolik Field Station (see the table below). We also collected numerous individuals (264) of other sub-genera of bumblebees, for a total of 10 species (see the table below). This is a very high diversity of bees in such a small area. Two species that we collected (*Bombus hyperboreus* and *B. polaris*) have the IUCN (International Union for Conservation of Nature) status of "vulnerable" in Europe. These bees will greatly expand our knowledge of bee diversity and the genetic, chemical and morphological characteristics of these species across the Arctic.

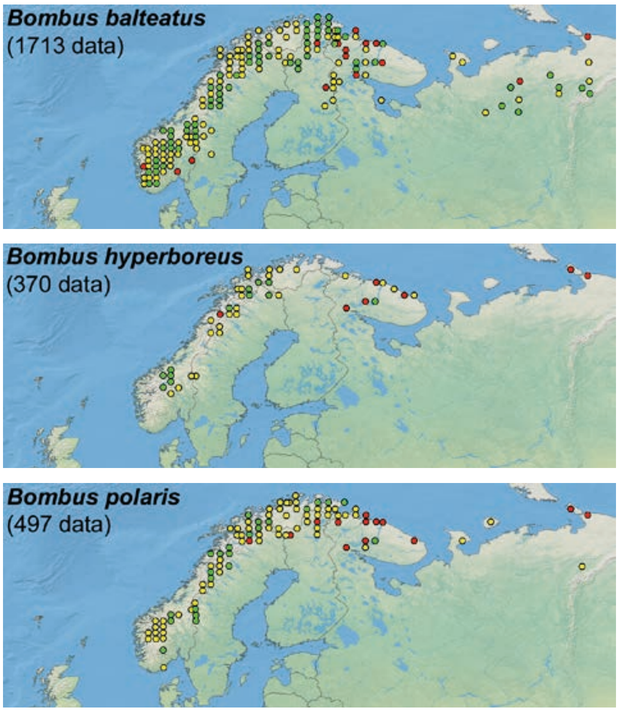
WHY ARE THE RESULTS IMPORTANT?

It is generally assumed that Arctic bumblebee species occur throughout the entire circumpolar Arctic. Thus, a species that is endangered in one part of the Arctic could theoretically find a refuge in another part. However, the distinction between Arctic bumblebee species is presently based largely on morphological characters, and it is possible that there may be a lot of genetic variation between individual local populations in the Arctic. This could change our concepts of what units (species vs. populations) are appropriate for conservation. Our work will allow us to distinguish between these alternatives, and assist in international bee conservation.

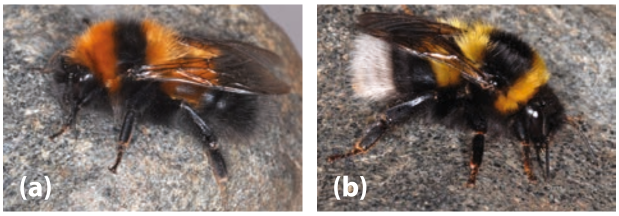
THE ADVENTURE

Two Belgian guys (Nicolas and Baptiste) working on the systematics and ecology of bumblebees in the Zoology Laboratory of the University of Mons in Belgium flew for more than 15 hours from Brussels via Chicago and Anchorage. The cold and windy weather reminded us that we were in Alaska. After few hours, a pickup took us to the Toolik Field Station. The landscape was awesome, nothing on the horizon except the distant mountains and Arctic tundra out of sight. At the Toolik Field Station we were warmly welcomed by Chad Diesinger, the facility supervisor. It was really impressive to see the logistics (accommodation, food, equipment) of this isolated station. The ambiance and work atmosphere of the station were very nice, a well-organized community in the middle of nowhere!

The most annoying and discomforting thing was the presence of lots of mosquitoes everywhere surrounding the station, which was surprising for August. But what would we not do to help science progress!



Distribution map of some European Arctic and Arctic-alpine Alpinobombus (bumblebee) species: Red dots: records before 1950, yellow dots: records from1950 to 1990; green dots: records since 1990 (From Rasmont and others 2015).



(a) *Bombus hyperboreus and* (b) *Bombus jonellus* (Pierre Rasmont).

Taxa	Collecting sites	Males	Females
Bombus hyperboreus	Toolik Field Station	4	0
Bombus neoboreus	Toolik Field Station	13	0
Bombus polaris	Toolik Field Station	27	3
Bombus rufocinctus	Toolik Field Station	1	0
Bombus centralis	Fairbanks	8	1
Bombus flavifrons	Toolik Field Station	5	5
Bombus jonellus	Toolik Field Station	50	35
Bombus melanopygus	Toolik Field Station	5	0
Bombus sylvicola	Toolik Field Station	68	37
Bombus flavidus	Toolik Field Station	2	0
		TOTAL: 264	

Bumblebees collected near Toolik Field Station, Alaska in summer 2014.

Further information

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Rasmont, P., Franzen, M., Lecocq, T. and others 2015. Climatic Risk and Distribution Atlas of European Bumblebees. Sofia: Pensoft, 236p.

Is rodent-borne Ljungan virus responsible for mortality in migrating Norwegian lemmings *(Lemmus lemmus)*?

Heidi C. Hauffe, Cristina Fevola, Chiara Rossi, Annapaola Rizzoli, Jukka Niemimaa & Heikki Henttonen

A Norwegian lemming in a defensive pose. Perhaps unsurprisingly, with nowhere to hide, and cornered in unfamiliar territory, these small mammals can be quite aggressive (Heikki Henttonen).

In 1998, a new virus was isolated in wild populations of bank voles (Myodes glareolus) *in Sweden. The suspected pathogen was named the "Ljungan virus" (LV), after the river near the site of its discovery. Later, it was also detected in voles in the United States and Denmark, and more recently in the UK and Italy.*

Interest in LV stems from reports that this virus may be associated with human fetal death and malformations. Some authors maintain that LV should be considered a potential zoonotic agent *(i.e. a pathogen carried by wild animals that can infect and cause disease in humans), while others are distinctly more skeptical. Recent optimization and testing of a* serological technique *using LV-positive rodent samples show that humans can apparently be infected with LV, or an LV-type virus, but its ability to cause symptoms has not been definitively proven, and species-specificity has not been investigated.*

AIMS OF THE PROJECT

Since the bank vole and other rodents could act as reservoirs of LV, knowledge of LV's geographical and host range is necessary to assess its potential importance as a human pathogen and to identify possible zoonotic reservoirs. On the other hand, because LV is one of the only rodent-borne viruses that causes pathologies in the rodent itself, this virus may also have an effect on rodent ecology. Consequently, knowledge of the presence and effect of LV among wild mammal species is also crucial for estimating its potential role as a rodent pathogen.

Trapping site near the Kilpisjärvi Biological Station. As the snow drifts melt, the lemmings must move quickly to find new cover and sources of food (Heidi C. Hauffe).

As part of the EU FP7 project EDENext (www.edenext.eu), tissue samples are currently being collected by us from rodents across the EU, and ongoing molecular and serological studies suggest that LV has a wide geographical and host distribution, including species that live in close contact with humans (e.g. house mice). However, at the time of the INTERACT Transnational access Call in 2010, the role of LV in lemmings and in lemming cycles had not been examined. Norwegian lemmings (*Lemmus lemmus*) are typical rodents of the alpine mountain regions of Fennoscandia (Norway, Sweden and Finland), and their numbers show extreme fluctuations. When the snow melts in the spring, lemmings must move to find new habitat; these movements become longer distance "migrations" at high densities (Henttonen and Kaikusalo 1993). In contrast, autumn migration is density dependent, and due mainly to social factors. Migrating lemmings can easily be spotted running in all directions, and during particularly high peaks thousands of corpses litter the landscape and roads. At these very high densities, migrating lemmings can be seen for several months.

One factor that may affect the survival of these individuals at such high densities is pathogens. Therefore, since LV was known to have a greater effect on stressed individuals, and migrating lemmings are under considerable stress, this project aimed at studying whether LV is responsible for the high death rate of lemmings during these dispersal events.

WHERE DID WE WORK?

The year 2011 was a particularly fortuitous year to study this phenomenon, since a strong cycle (with a high lemming density) was predicted. Therefore, we visited the Kilpisjärvi Biological Station (•12) in Finnish Lapland to participate in the annual trapping of small mammals during the peak of the

A Norwegian lemming *(Lemmus lemmus)*, intent on finding new habitat (Helena C. Olandi).

A Norwegian lemming *(Lemmus lemmus)* resting among the tangled twigs of the forest floor during his exhausting quest to find food and shelter after the snow melt (Annapaola Rizzoli).

lemming migration in May 2011 in order to collect samples for screening LV. We chose the Kilpisjärvi Biological Station because annual trapping of small mammals has been carried out there for many decades; therefore, we were confident that we would successfully trap enough individuals for our study.

WHAT DID WE DO?

Over the six days of trapping at the station, we trapped over 100 lemmings: 72 of these individuals were dissected, and liver samples were couriered on dry ice to the Fondazione E. Mach in Italy for molecular screening of LV (i.e. we used genetic methods to detect whether LV was present in liver tissue). In addition, lemming samples collected at Kilpisjärvi from June and September 2011 were added to the screening, as well as samples from other small mammal species from another long-term trapping area at Pallasjärvi trapped in the same year.

WHAT DID WE FIND?

Our laboratory analyses showed that only two out of 122 Norwegian lemmings at Kilpisjärvi were positive for LV, both of these trapped after the spring migration in the summer and autumn of 2011. Therefore, it seems unlikely that LV is responsible for the mortality of lemmings at high densities. However, our investigations are ongoing, and we are currently screening lemmings caught before the peak and found dead during the peak to make sure we have the full story. Interestingly, however, we also found that LV infects most vole species in the rodent community, including the bank vole (5 out of 21 LV-positive); the field vole (*Microtus agrestis*: 4 of 29 LV-positive); the northern red-backed vole (*Myodes rutilus*: 2 of 15 LV-positive); and the grey-sided vole (*M. rufocanus*; 1 of 23 LV-positive), as well as another lemming species (wood lemming, *Myopus schistocolor*: 3 of 12 LV-positive), confirming our wider studies that the bank vole is probably the main reservoir of LV. Also, for the first time, we detected LV in the tundra vole (*M. oeconomus*: 1 of 6 LV-positive).

WHY ARE THE RESULTS IMPORTANT?

Although the role of LV in lemming cycles seems improbable, the samples collected during this field trip have added to our knowledge of the geographical and host distribution of LV. The samples will also be used for further studies on the virus, including estimates of genetic variability, which are essential for the future development of a vaccine, should this prove necessary.

THE ADVENTURE

The opportunity to work at the Kilpisjärvi Biological Station could not have come at a better time for consolidating our collaboration with experienced Finnish researchers and ensuring completion of a critical joint project only possible where there are Arctic rodent populations. The Station was exceptionally clean and well-organized, and the efficient and enthusiastic staff made sure we lost no time in settling in, so that we were out trapping on the very first day. On a personal level, to experience first hand the extraordinary beauty and biodiversity at the "top of the world" was a dream of a lifetime.

Further information

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High Arctic food webs

Tomas Roslin

The Zackenberg station offers excellent logistics in Northeast Greenland. The station is located in the biggest national park created to date, in one of the largest uninhabited regions on the Globe (Tomas Roslin).

The Arctic is changing fast. This will affect individual species – but perhaps even more importantly, it may modify how these species interact with each other. A change in one species may result in a change in other organisms (species), and in the overall functioning of the system.

AIMS OF THE PROJECT

Our ambitious aim was to measure and describe a full network of *biotic* (i.e. living) interactions for a high-Arctic area. We started by measuring interactions within tightly-knit groups of closely interacting species, and then worked our way towards the overall structure of the web.

WHAT DID WE DO?

To detect who interacts with whom, we supplemented traditional approaches (like observing what animal visits what flower or who is chewing on whom) by modern molecular tools. Thus, we recorded DNA sequences for almost all visible species of our study area and we can now identify them from nearly any remains, including *scats* (faeces) or gut contents. To achieve this coverage of the local flora and fauna, we crawled on all four through the low vegetation, and used a large variety of traps, nets and other collection methods to get at even the smallest inhabitants of the tundra.

WHERE DID WE WORK?

We worked at the Zackenberg Research Station (•70) in Northeast Greenland. This INTERACT station is situated within the largest national park of the world, providing excellent facilities in a remote and otherwise inaccessible region. The species richness of this area is conveniently low, which allowed us to actually find most species and keep track of their interactions (to do so in more biologically diverse parts of the Globe would be next to impossible).

WHAT DID WE FIND?

When examined in detail, one of the presumed simplest interaction webs on the globe proved far more complex than previously thought. Our findings thus upset the century-old myth of the Arctic as being characterized by simple interactions and simple food webs. Working with the limited species richness of the Arctic also allowed us to renew the methods of food web research. By applying new techniques, we tripled the number of links detected within the mesh, and showed that how you search will have a major impact on what you find. These insights from the Arctic can now be transferred to the more species-rich parts of the Globe.

WHY ARE THE RESULTS IMPORTANT?

What our findings really mean is that even in the far North, organisms affect each other in myriads of ways. Where the traditional view has been “each species on its own under a harsh Arctic climate”, we described an Arctic buzzing with life, where organisms interact intensively with each other. Only by appreciating how species are tied together may we then understand how a change in one species leads to a change in another – and into changes in the overall functioning of the ecosystem.

A trophic interaction of the far North: The female of the Arctic Woollybear (*Gynaephora groenlandica*) is a poor flyer, and frequently mates on the top of its cocoon (Juha Syväranta).

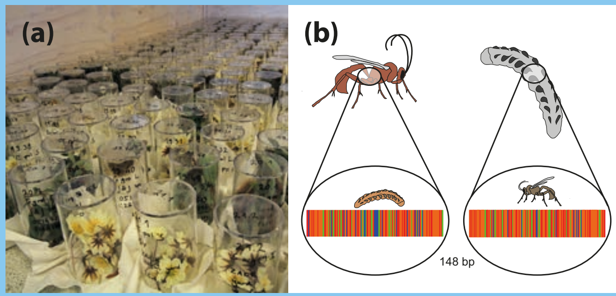
Its offspring then spends nearly a decade as a larva. During this time, many individuals are attacked by parasitic flies (Juha Syväranta).

Parasitism causes the final cocoon to produce not a new moth, but flies (opened cocoon with fly maggots and a fly puparium) (Tomas Roslin).

THE ADVENTURE

Most of our efforts were targeted at the smallest animals (like insects and spiders), as they are both the most species-rich and abundant parts of the local fauna. This did not preclude encounters with larger wildlife. We had muskoxen trampling through our plots, Arctic foxes peeing in our pitfall cups and polar bears wrecking our insect traps – in each case forcing instant replacement.

To create a reference library of DNA sequences for the full flora of Zackenberg, we have collected nearly every plant species of the area. A small piece of leaf tissue will suffice for the job (Riikka Kaartinen).



To understand who eats whom within the food web of Zackenberg, we have used both traditional techniques and modern molecular tools. This picture shows how different methods may be used to resolve one and the same interaction type: To establish what parasitic wasps and flies attack what caterpillars, one may either rear parasitoids from host caterpillars (left), or selectively sequence DNA from the gut contents of adult parasites (revealing whom they ate as larvae; left in graphics) or from laval parasites within larval hosts (revealing who is eating them right now; right in graphics). In the lower part of the picture, the colourful bands represent the DNA sequence recovered (with one colour for each of the four bases of DNA). By working our way through the local flora and fauna, we have established a molecular "barcode" offering unequivocal identification of each species in the area, regardless of its developmental stage

(Gergely Várkonyi (a) and Helena Wirta (b).

To explore the effect of spider predation on other arthropods we have used large corrals to either elevate or reduce local spider densities (Tomas Roslin).

Further information

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How predator-prey interactions impact distribution and breeding systems of high Arctic waders under current climate change

Jeroen Reneerkens

A young lemming peaking out of its burrow in Hochstetter Forland (Jeroen Reneerkens).

Arctic fox at Hochstetter Forland (Jeroen Reneerkens).

Lemmings, Arctic rodents well-known for their impressive cyclical abundance, play an important role in the food web of the tundra. As a consequence of climate change, the high-amplitude cyclic population change of lemmings is increasingly disturbed. This will affect the entire Arctic food web, because predators relying on lemmings are expected to switch to alternative prey.

A sanderling in Zackenberg brooding its chicks (Jeroen Reneerkens).

AIMS OF THE PROJECT

We wanted to describe differences in time and space in survival of clutches of Sanderlings, a common high Arctic migratory bird, and relate this to the local abundance of lemmings and their predators.

WHAT DID WE DO?

We monitored the daily survival of sanderling clutches using small temperature loggers in their nest cups. Also, we measured the growth and survival of Sanderling chicks in relation to their date of hatch within the season; early, during the peak of hatch or late in the season.

WHERE DID WE WORK?

We worked at Zackenberg Research Station (•70) as the main field site and collaborated also with people at Karupelv Valley and Hochstetter Forland in Northeast Greenland. The number of lemmings and their predators differ between these three locations, allowing useful comparisons while the density of bird nests is high.

WHAT DID WE FIND?

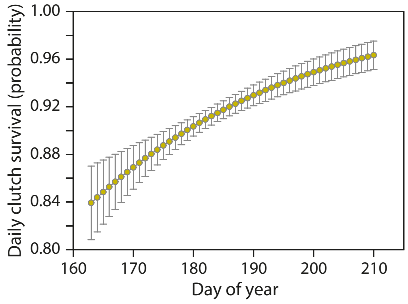
Nest predation is highest early in the season, probably because it is easier for predators to find nests on the small snow-free area in early June compared to July when most snow has melted. The density of lemmings did not differ as much as expected between the three study sites, but predation of clutches differed between sites because of differences in number of predators. The differences between sites were most pronounced in 2013, when there were hardly any lemmings at Karupelv Valley, resulting in Arctic foxes eating many sanderling clutches, while there were a lot of lemmings in Zackenberg and especially Hochstetter Forland, where Sanderlings indeed had good breeding seasons.

WHY ARE THE RESULTS IMPORTANT?

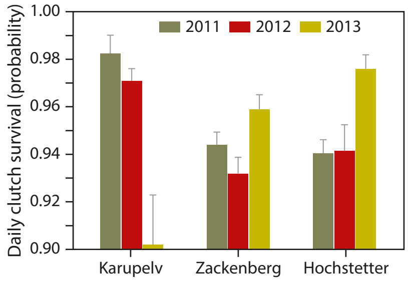
Long-distance migrating birds are declining worldwide due to habitat loss and other human factors. The altered predator-prey interactions in the Arctic food webs come on top of this and will have further consequences for Arctic bird populations.

THE ADVENTURE

We had planned to visit a sanderling nest found earlier, but on our way we found two new nests. It took us some time to catch the breeding birds during which the station manager radioed that a polar bear was close to the station. The bear turned out to be at the location of the nest that we had initially planned to visit. After our work we were able to safely see the bear from a distance, but how close an encounter with this animal would we have had if we had not found those two new nests?



Daily survival probability of sanderling clutches increased with the progressing summer. Day of year 160 = 9 June.



Daily survival of sanderling clutches in nests in three years of study at three locations (Karupelv Valley, Zackenberg and Hochstetter Forland) in Northeast Greenland in the summers 2011-2013.

Locations where sanderlings marked in Northeast Greenland were observed outside the Arctic, indicating that changes in the Arctic can potentially affect bird populations in Europe and Africa.

Further information

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Videos of the fieldwork can be seen at: www.vogelbescherming.nl/actueel/beleef_de_lente_op_groenland

6 Life in cold waters

SECTION OVERVIEW

Warwick F. Vincent & Riku Paavola

Freshwater environments are so abundant in the North that the Arctic is sometimes thought of as a vast circumpolar wetland (Kling 2009), and when seen on maps or from the air, some parts of the Arctic landscape seem like an archipelago of islands in a freshwater sea (Figure 6.1). An analysis of the distribution of the world's lakes by area shows that the vast majority of waterbodies greater than 0.1 km^2 occurs on northern *permafrost* catchments and collectively totals more than 300,000 km^2 (Grosse and others 2013). However, it is not only the abundance of freshwater that has captured the interest and imagination of *limnologists* (scientists who study inland waters), but it is also the diversity of these northern *ecosystems* (Figures 6.2 and 6.3) and their importance as habitats for aquatic life.

Oulanka River, running nearby the Oulanka Research Station (•17), Northeast Finland (Riku Paavola).

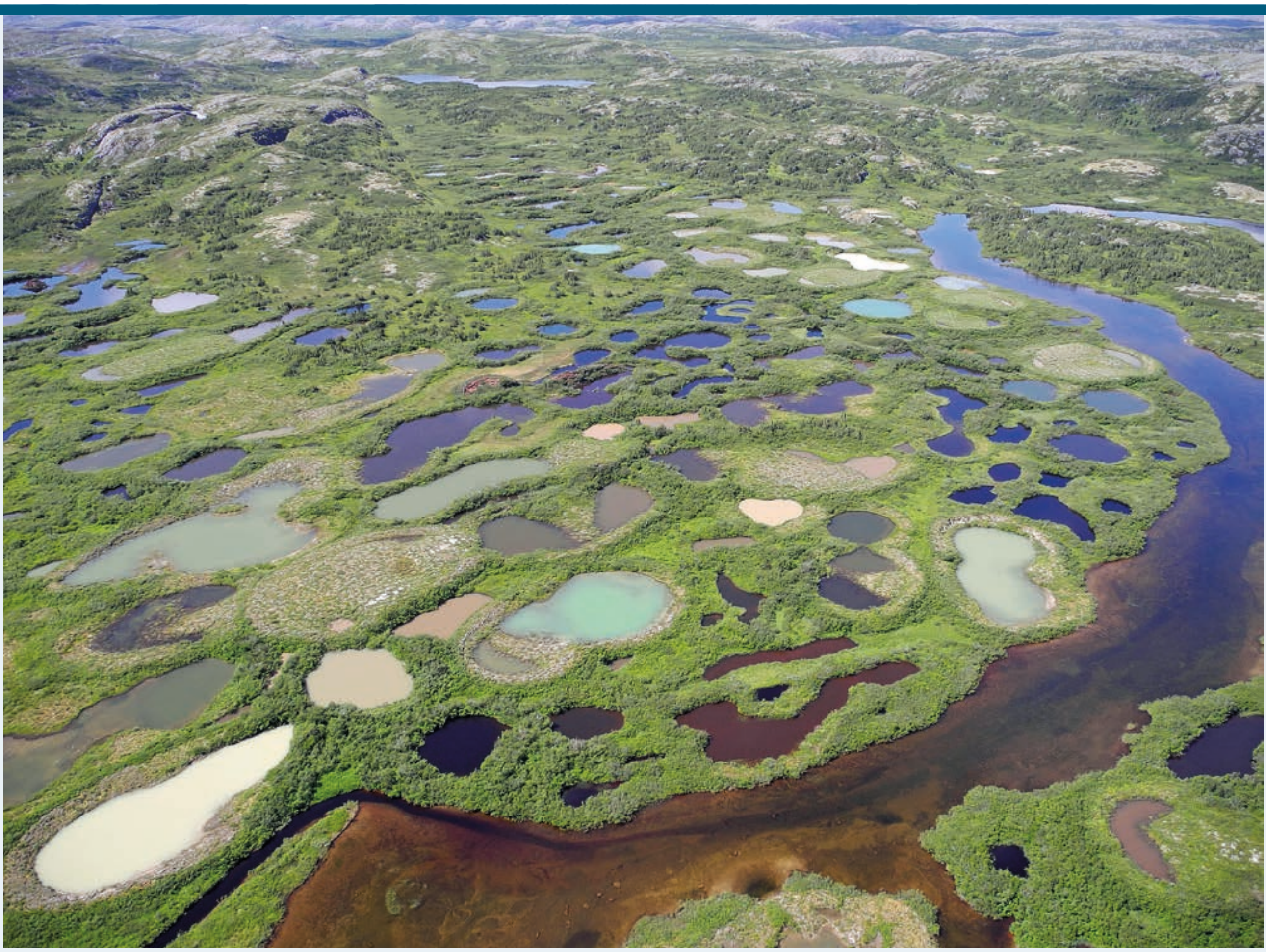


Figure 6.1 Lakes abound in the North and many, such as these near Umiujaq, sub-Arctic Canada, are affected by rapidly thawing permafrost (Warwick F. Vincent).

Figure 6.2 There is a great diversity of freshwater systems in the Arctic. The photo shows a glaciated rock-basin lake in Nunavik, sub-Arctic Canada (Warwick F. Vincent).

Figure 6.3 Lake Hazen, the deepest lake in the Canadian high Arctic (Warwick F. Vincent).

High latitude lakes also have broader global significance as sentinels as well as integrators of environmental change, and for this reason they are important sites for the study of climate fluctuations in the past by analysis of the preserved remains of plants, animals and microbes in their sediments (the study of *palaeolimnology*), as well as for monitoring climate warming and other changes that are taking place in the present at local, regional and planetary scales (Williamson and others 2009). Some northern freshwaters also affect adjacent ecosystems; for example the large Arctic rivers discharge massive quantities of water, solutes, particulate materials and heat into the Arctic Ocean; the large lakes of the North affect the thermal regime of their surrounding watershed; and *thermokarst* lakes (formed when permafrost thaws: see Sections 1 and 3 for lake formation and drainage) and wetlands (areas of seasonally water logged soils) may emit globally significant quantities of *greenhouse gases* into the atmosphere (Vincent and others 2013).

Northern freshwaters are of special significance to the people who live and work in the North, and whose health, cultural well-being and economic prosperity depend on these vital resources. Arctic and sub-Arctic waters provide many essential geosystem and ecosystem services for municipalities, industries and (increasingly) agriculture. These services include drinking water supplies, hydroelectricity, waste disposal and treatment systems, water for mining activities and resource extraction, transport routes (including the extensive networks of river and lake ice-roads in North America and Russia), traditional and recreational fisheries, and habitats for water fowl that are traditionally hunted such as ducks and geese. These economic, societal and cultural values are also setting many of the research priorities in parts of the circumpolar North such as northern Canada.

In this section we introduce some of the current themes and questions in northern freshwater research, including projects taking place through the INTERACT network of terrestrial field stations. We draw upon recent results about the physical, biogeochemical and biological characteristics of high latitude aquatic ecosystems, including reference to a subsample of INTERACT supported projects that are described in more detail below.

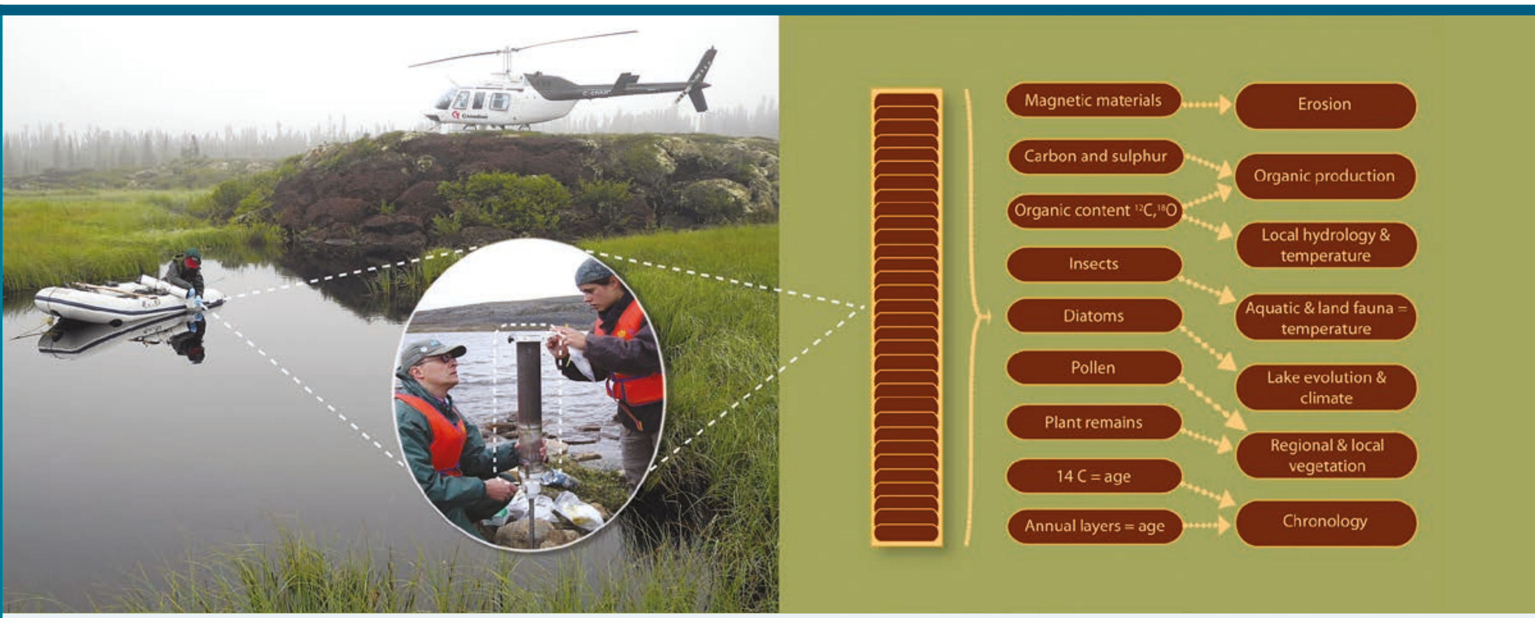
RECONSTRUCTING THE PAST

The bottom sediments of northern lakes provide a rich storehouse of information that can be used to describe and understand past variations in the environment (Hodgson and Smol 2008: see also Section 1). Many types of *sediment corers* are available for sampling lake sediments from a boat or through a hole in the lake ice (Figure 6.4), and the resultant core samples can be split into sections, dated with ^{14}C and ^{210}Pb (*radio-isotopes* of carbon and lead), or other techniques, and the environmental proxies then analysed in each section to reconstruct past conditions (Figure 6.5). Diverse microfossils are routinely measured in northern lake sediments by this palaeolimnological approach, including fossil *diatoms* (algae with silica walls), larval insect remains and pollen. Diatoms

Figure 6.4 Drilling through lake ice on northern Ellesmere Island in the Canadian high Arctic, near the CEN Ward Hunt Island Research Station (•55) (Warwick F. Vincent).

have proven to be especially informative given their enormous species diversity. By establishing relationships between the composition of modern diatom communities and the environment, models can be applied to convert the species composition of a fossil diatom assemblage into quantitative estimates of past conditions such as temperature, pH, phosphorus, dissolved organic carbon or even underwater UV radiation. A wide range of chemical constituents are also often analyzed including stable isotopes of carbon and nitrogen, heavy metals and other pollutants.

The application of these palaeolimnological approaches has provided insights into lake development and ice cover, vegetation dynamics, climate and sea level change, fish and wildlife shifts, and the magnitude of local and long range pollution (Hodgson and Smol 2008). In the INTERACT project of Long and others (Science Story 6.1), sediment cores were taken from lakes at a site near the margin of the Greenland Ice Sheet to analyze variations in temperature over the last 6,000 years. A complementary INTERACT project by McGowan and others (Science Story 6.2) is examining sediment cores from lakes at Disko Bay, Greenland, to reconstruct lake and catchment processes during periods of warming and cooling over the last few thousand years.



Fgure 6.5 Left: paleolimnological analysis of a sediment core, for example from a thaw pond pond formed by a degrading *palsa* **(permafrost mound) near the CEN Whapmagoostui-Kuujjuarapik Research Station (•61), sub-Arctic Canada. The core (middle) is split into sections and each section is then dated based on its radiocarbon (^{14}C) content. The different chemical and biological analyses (right) of these sections then provide information about historical changes in different features of the lake and its surrounding environment.** Modified by Hannele Heikkilä-Tuomaala from Berglund and others 1996 (Warwick F. Vincent and Reinhard Pienitz).

Figure 6.6 Lake A in the Canadian high Arctic near the CEN Ward Hunt Island Research Station (•55). The lake had lost its perennial ice cover after a summer of record warming (August 2008) (Warwick F. Vincent).

Figure 6.7 Thawing permafrost resulting from experimental accumulation of snow (a) creates moist depressions and eventually thermokarst ponds (b) in the Swedish sub-Arctic. In contrast, in other areas ponds are draining and evaporating, for example on Disko Island, West Greenland between 1970 (c) and 2009 (d). (a) Margareta Johansson, (b and d) Torben. R. Christensen, (c) Terry V. Callaghan.

LAKE AND RIVER ICE

Prolonged ice-cover and persistent low temperatures are major features of all high latitude waters, and these properties influence the structure and productivity of their biological communities (Prowse and others 2011). The aquatic *biota* of these habitats must therefore be adapted to cold water conditions for growth and reproduction, and to the highly seasonal availability of solar radiation, from continuous darkness in winter to continuous sunlight in summer. The thick ice-cover greatly affects the availability of light for underwater photosynthesis, and also influences many other important features of the lake such as mixing of water layers and oxygen levels (Section 4). Several projects at INTERACT stations have examined changes in lake ice cover in the past and present, and long-term records are now available at some locations; e.g., >100 years for Lake Torneträsk at Abisko, Sweden. At many locations, ice cover is now decreasing in thickness and duration as a result of climate warming (Figure 6.6). For example, in the River Oulakajjoki near Oulanka Research Station (•17), Finland, there has been a reduction of ice cover by about 3 weeks in recent years (R. Paavola, unpublished data), and at Ward Hunt Lake near INTERACT's most northern station (CEN Ward Hunt Island Research Station (•55) in the Canadian high Arctic, the summer ice cover has thinned from >4 m to complete melt out over the last 60 years (Paquette and others 2015). Many questions remain about how changes in ice cover affect the functioning of Arctic aquatic ecosystems, and these will be an important focus of limnological research.

GREENHOUSE GAS EMISSIONS

Throughout the circumpolar Arctic, there is a major effort to understand the chemicals in northern lake waters, and the biological and mineral (geochemical, geophysical) processes that regulate them. One of the reasons for this intense interest in the chemical nature of northern lakes is their production of greenhouse gases (Section 4). This is especially the case for thermokarst lakes and ponds (small, shallow waterbodies) that form by the thawing and *erosion* of permafrost landscapes (Figure 6.7a) and ponds that drain (Figure 6.7c). Work throughout the North has shown that these waters are *biogeochemical hotspots* on the *tundra*, converting soil organic carbon (Science Story 6.3) to carbon dioxide and methane that are then released to the atmosphere (Vincent and others 2013). Many questions remain, for example about the role of

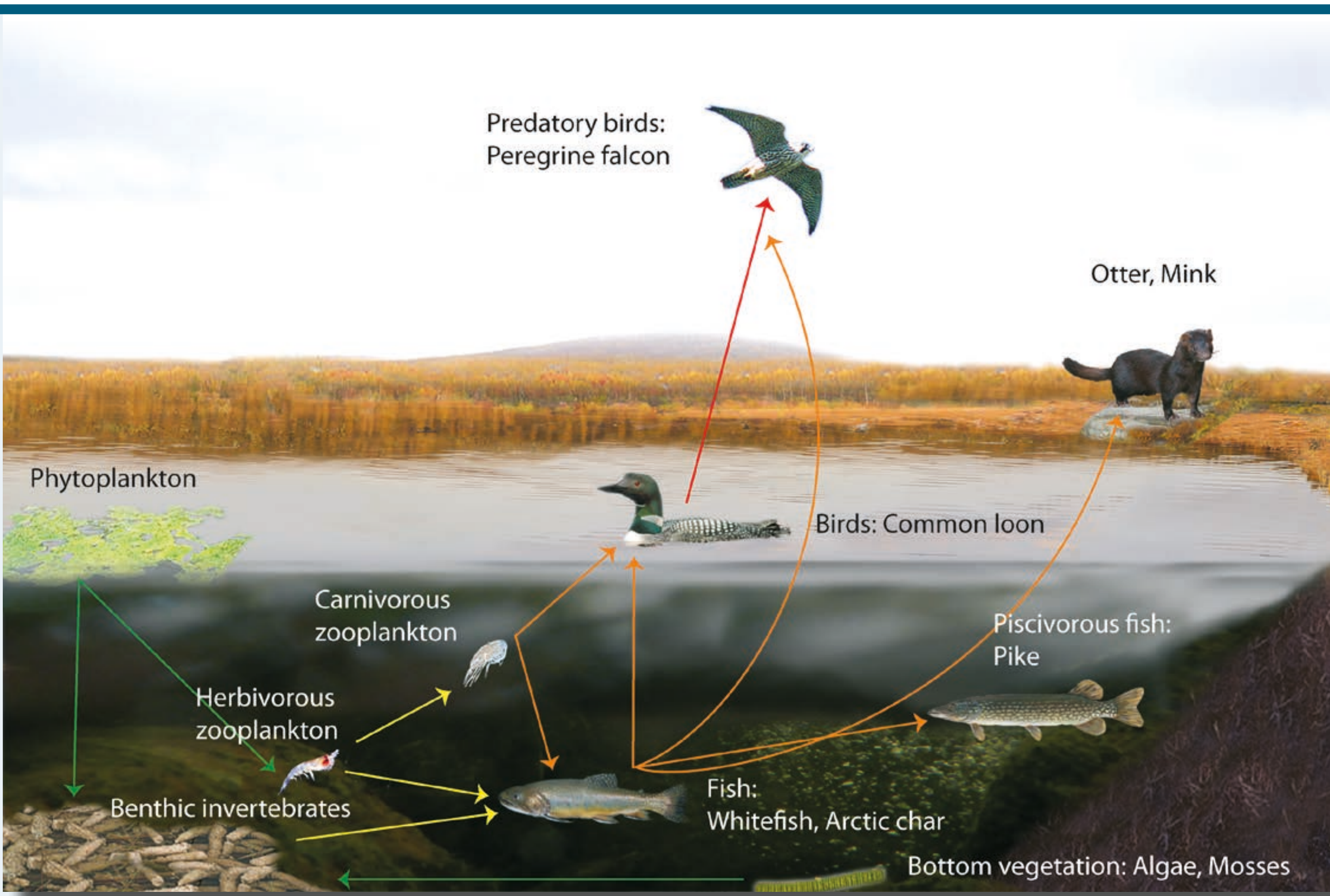


Figure 6.8 There is great inter-connectedness through food webs in Arctic lakes (left) and ponds (right). Deep lakes support fish but shallow ponds that freeze to the bottom in winter cannot. The primary production in the freshwaters even eventually supports wildlife on land (Modified by Hannele Heikkilä-Tuomaala from ACIA, 2005).

oxygen in controlling the net emission of methane, and concerning the seasonal, interannual and long-term variations in the abundance and activity of these microbe-rich ecosystems.

CHARISMATIC MICROFLORA

One of the rapidly emerging frontiers in polar ecology is the *biodiversity* and function of microbial communities. It has long been known that microbes are abundant and play key roles in the ecosystem, including *primary production*, control of gas fluxes and nutrient recycling, but it is only recently that microbiologists have become equipped with the necessary tools to address basic ecological questions such as: what types of microscopic life are present, how are they distributed, what is their function, and how do they respond to environmental change? Many of these questions are being answered by using new tools that are derived from breakthroughs in medical technologies, for example based on DNA analysis, and these approaches are now being applied with enormous success to aquatic environments throughout the world, including northern freshwaters. The result is that we are now entering an exciting new era of deep insights into the life support structures that underpin Arctic aquatic food webs (Figure 6.8) and ecosystems (Lovejoy 2013). Molecular approaches are also generating important insights into how pollutants are broken down and detoxified in natural waters. In the INTERACT study by Michaud and others (Science Story 6.4), microbial DNA techniques were applied to sediments affected by the Pasvik River, the largest river system in northern Fennoscandia. These analyses revealed the presence of bacteria capable of degrading *polychlorinated biphenyls*, a major class of potentially hazardous *persistent organic pollutants*.

Cyanobacteria ("blue-green algae") (Figure 6.9) are a microbial group of special interest in the Polar Regions because they often constitute a large fraction of the total *biomass* in freshwater ecosystems in both the Arctic and Antarctica, and many are *nitrogen (N_2)-fixers*, bringing new nitrogen into the ecosystem. These organisms tolerate a wide range of conditions of water availability, including short-term fluctuations, and they therefore also thrive in semi-aquatic habitats and intermittent flow regimes such as water tracks (Steven and others 2013). In the terrestrial environment, cyanobacteria are found on and even within rocks, and they occur over polar desert soils as biological crusts. The nature of these cyanobacterial communities, their photosynthetic activity and their influence on Arctic soil formation are the subjects of the project by Ventura

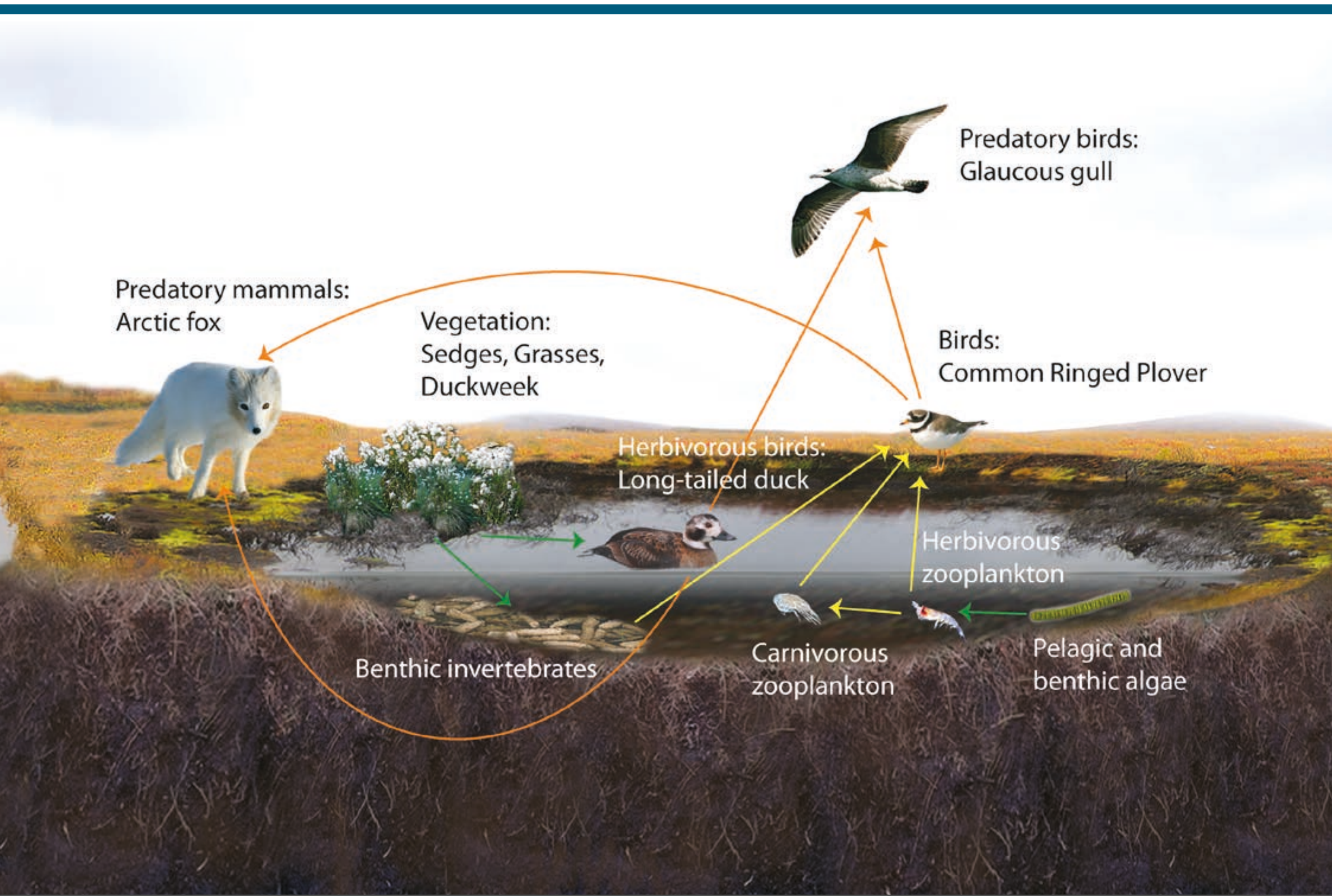


Figure 6.9 Photomicrograph of a nitrogen-fixing cyanobacterium (*Nostoc* colony) from the Canadian high Arctic (Warwick F. Vincent).

and others (Science Story 6.5), and sampling has taken place in a wide range of high latitude environments of different degrees of water availability. Cyanobacteria are also the focus of the project by Sabbe and others (Science Story 6.6), who visited Greenland to sample the prolific cyanobacterial *biofilms* that coat the bottom of Arctic lakes and to compare with similar biofilms from Antarctic lakes.

AQUATIC VEGETATION

When the Swiss natural historian François Forel founded the science of limnology at Lake Geneva in the 19th century, he described the inter-connectedness of all components of the ecosystem (Figure 6.8). One such component that he drew attention to was the underwater plant life distributed across the bottom of lakes, especially in the near-shore zone. He noted that some of these plant communities grew on the lake floor in such great profusion that "they form true underwater forests, as picturesque, mysterious and attractive as the most beautiful forests of our mountains" (Forel 1904). In northern lakes, mosses are often an important component of these "*underwater forests*", ranging from extensive *Sphagnum* bog communities in shallow waters and wetlands in the sub-Arctic, to slow growing but prolific moss stands in the deep cold waters of high Arctic lakes. Semi-aquatic plants such as *Carex* and *Eriophorum* are important elements of the tundra vegetation, and play biogeochemical as well as ecological roles, for example as methane conduits from the sediments to the atmosphere.

Forel (1904) noted with some alarm the arrival of the Canadian water weed *Elodea canadensis* in Lake Geneva, and its "exuberant and frightening expansion" throughout the lake. Unfortunately, this invasive species is now also well established in Finland where its growth has proven difficult to manage (Huotari and others 2011), and the sub-Arctic lakes of Fennoscandia may be increasingly prone to invasion by this species. The ecological impacts of invasive plants and animals will likely be important themes of aquatic research in the future as the lake and river environments continue to warm and temperate species move northward, aided by increased human activity and transport.

COLD-LOVING ANIMALS

Many species of invertebrates and vertebrates thrive within the cold waters of northern aquatic ecosystems, and their vulnerability to warming is a source of increasing concern. Work at INTERACT stations has especially focused on insects, zooplankton and wetland birds (Figure 6.10), but research on freshwater fish (Figure 6.11) and aquatic mammals, including freshwater seals, are also the subjects of ongoing projects. There are large uncertainties about how these animals will respond to increased temperatures in the future, with some species likely to move further northwards, while others may be driven to extinction by physiological stress and competition by invading species from the South. For example, stone flies (Plecoptera) prefer cold water streams and unlike many *taxa*, their species richness increases with latitude (Palma and Figueroa 2008). They may therefore be prone to warming, although this may be offset in part by increased terres-

Figure 6.10 Greater snow goose near the CEN Bylot Island Field Station (•56). The wetlands in this region have the largest breeding colony of this species in the Canadian high Arctic (Nicolas Bradette).

Figure 6.11 Arctic char caught at lac Laflamme in sub-Arctic Canada (Reinhard Pienitz).

trial vegetation and leaf litter as a food source. Arctic Char (*Salvelinus namaycush*) (Figure 6.11), a member of the salmon family, is nutritionally and culturally important to *Inuit* communities, and is a cold-adapted fish species that is restricted to low temperature, highly oxygenated waters. Increased lake production and food availability could stimulate the growth of this species, but changes in temperature, oxygen and migration patterns may counter such effects (Power and others 2008).

Key messages and needs for further research

- From microbes to fish and waterfowl, northern lakes and rivers contain many cold-dwelling species of great biological, ecological and resource use interest.
- These aquatic environments are biogeochemical reactors that convert tundra carbon to greenhouse gases, and they are sentinels and integrators of environmental change in the past and present.
- Arctic freshwaters are also a vitally important resource for northern indigenous communities.
- Given the abundance of these ecosystems, their wide ranging importance, and the many questions that relate to them, freshwater ecology will continue to be a major research focus well into the future, particularly as these northern waters continue to respond to the warming Arctic environment.

Further information and references

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Reconstructing Holocene temperatures

Antony J. Long, Eleanor J. Maddison, P. Helen Ranner & Sarah A. Woodroffe

Members of the field team collecting a core of sediment from the bottom of a lake (Sarah Woodroffe).

Our research reconstructs climatic variations through the Holocene (the last 11,700 years of history) from a site located on the margins of the Greenland Ice Sheet. Our focus is on the South-west sector of the ice sheet which, at low height and with a shallow slope, is potentially very sensitive to small variations in past and future temperature. Our specific attention is on a time period that encompasses a change from warmer (known as the "Holocene thermal maximum") to cooler (the "Neoglacial") conditions approximately 6,000-4,000 years ago.

Outdoor field laboratory for processing collected water samples (Eleanor Maddison).

AIMS OF THE PROJECT

Our aim was to use proxies (indicators) of past climate (pollen and non-biting midges) preserved in the sediment deposited on the bed of lakes to infer how climate changed 6,000-4,000 years ago.

WHAT DID WE DO?

We collected cores of sediment from the bottom of lakes together with present-day samples of lake–bottom surface sediment and water. Once back in Durham University we extracted pollen grains and non-biting midge remains from the sediment, and also analysed the water to study its chemical characteristics. We left ten temperature recorders in our field area that measured air and lake water temperatures for a whole year. Their data meant that we could relate our present-day lake observations to prevailing temperatures in our field site. Combining all of our data we have created a model that we can use to infer past climate change from fossil midge and pollen data extracted from our lake cores. Finally, we have used radiocarbon dating techniques to establish the age of our sediments.

WHERE DID WE WORK?

We used the facilities at the Greenland Institute of Natural Resources (•67) in Nuuk to prepare for our month long fieldwork. Our field area was located approximately 80 km inland of Nuuk, which we accessed using the Institute's boats. We chose our field area because it is mountainous with many small lakes at a range of elevations from close to sea level up to 850 m above sea level. Moreover, the site's proximity to the Greenland Ice Sheet makes it a good location from which to reconstruct past summer temperatures – which are a key control on whether the Greenland Ice Sheet grows or melts.

WHAT DID WE FIND?

Analysis of our cores has provided us with temperature reconstructions that cover the last 7,000 years. Both the pollen and non-biting midge records indicate that there was a change from a relatively warm to a cooler climate about 4,000 years ago. We have associated this transition with some apparent instability in the climate, suggestive of a "flickering" state that may be typical of climate systems that are changing from one state to another.

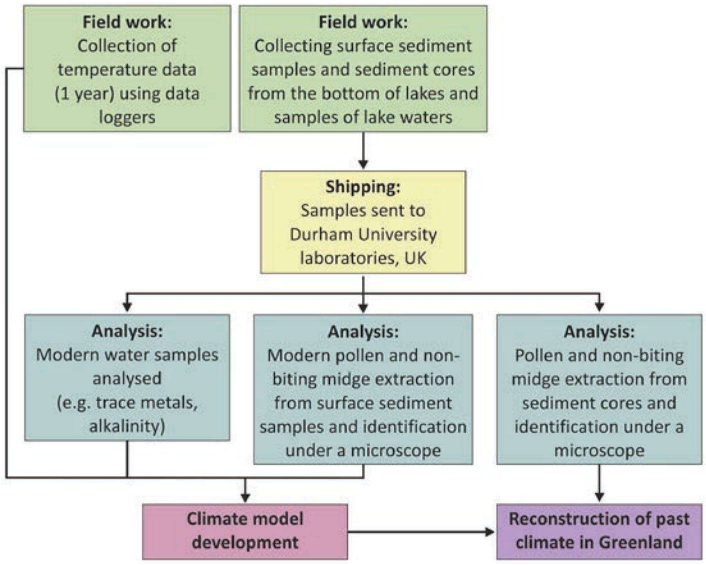
WHY ARE THE RESULTS IMPORTANT?

Reconstructing changes in past climate helps us to better understand the past climate system and the potential for future climate change. We think the switch to cooler conditions is part of a larger re-organisation of the climate in Greenland and the Arctic, most probably initiated by reduced incoming solar radiation. The change to a cooler climate at about 4,000 years ago was associated with a significant expansion of the Greenland Ice Sheet.

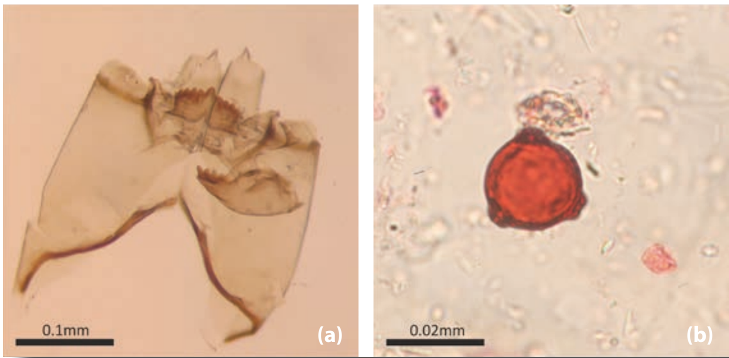
THE ADVENTURE

We used boats to travel up the Nuup Kangerlua fjord in order to reach our remote field area close to the Greenland Ice Sheet. We spent several weeks wild camping in beautiful, uninhabited terrain, with limited communications with the outside world. In order to collect our samples we used small inflatable boats on the lakes. In the field we had numerous sightings of many wild animals and birds such as Arctic foxes, hares, caribou and divers.

Collecting lake sediment from a coring device (Robert Barnett).



Schematic, detailing the pathways used to reconstruct temperature.



Non-biting midge head (a) and birch pollen grain (b) extracted from Greenland lake sediments.

Team members returning to Nuuk on one of the Greenland Institute of Natural Resources' boats at the end of a successful field season (Robert Barnett).

Further information

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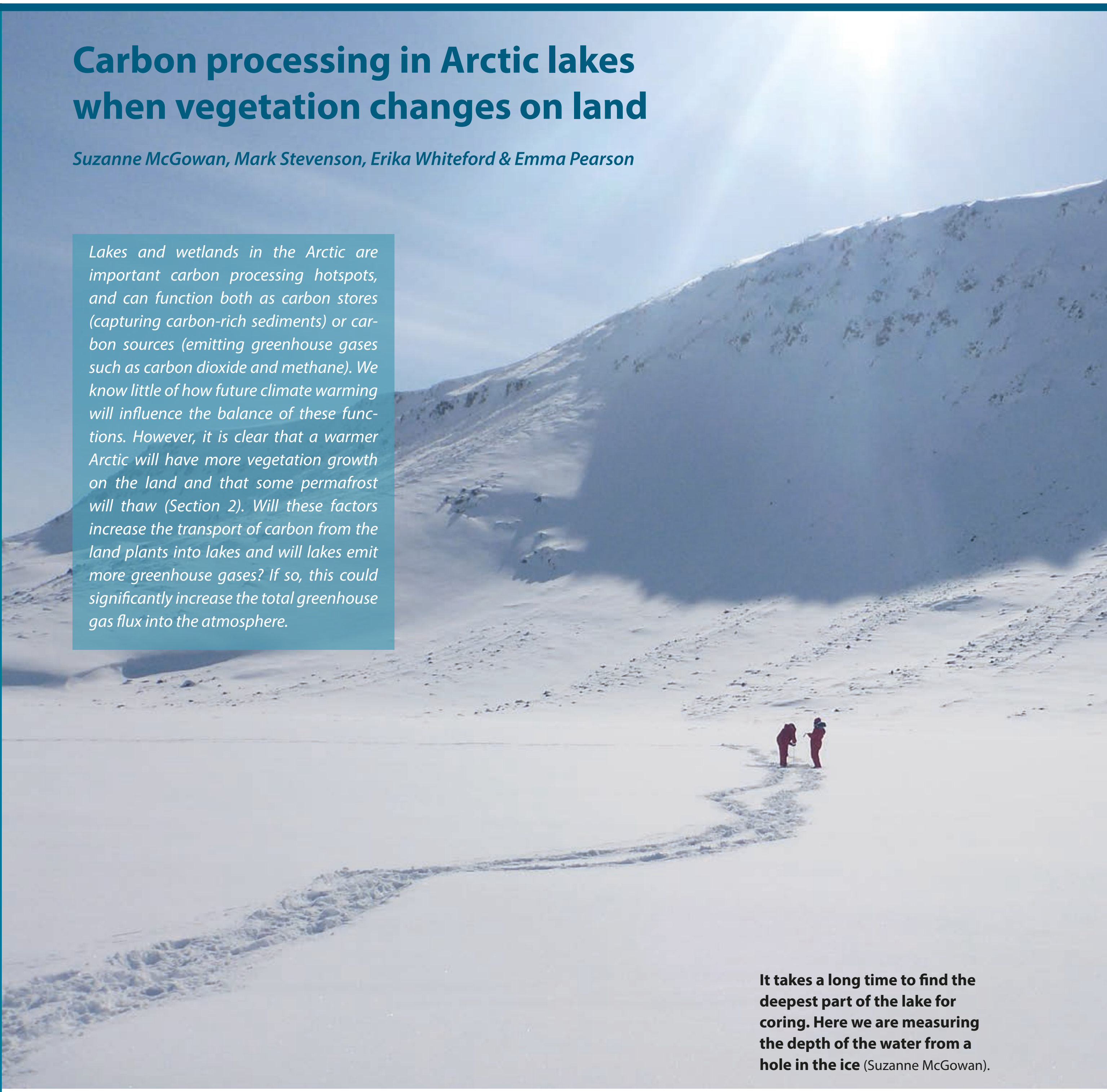
Carbon processing in Arctic lakes when vegetation changes on land

Suzanne McGowan, Mark Stevenson, Erika Whiteford & Emma Pearson

Lakes and wetlands in the Arctic are important carbon processing hotspots, and can function both as carbon stores (capturing carbon-rich sediments) or carbon sources (emitting greenhouse gases such as carbon dioxide and methane). We know little of how future climate warming will influence the balance of these functions. However, it is clear that a warmer Arctic will have more vegetation growth on the land and that some permafrost will thaw (Section 2). Will these factors increase the transport of carbon from the land plants into lakes and will lakes emit more greenhouse gases? If so, this could significantly increase the total greenhouse gas flux into the atmosphere.



It takes a long time to find the deepest part of the lake for coring. Here we are measuring the depth of the water from a hole in the ice (Suzanne McGowan).

AIMS OF THE PROJECT

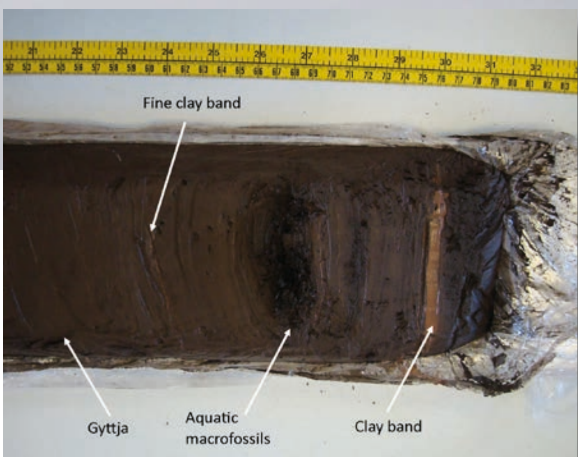
We aimed to use past climatic episodes of known warmer (the "*Medieval Climate Anomaly*, MCA and the "Holocene Thermal Maximum", HTM) and colder (the "*Little Ice Age*"; LIA) periods to test how Arctic lake carbon processing changes under different climatic conditions.

WHAT DID WE DO?

We used lake sediments to record past changes within three lakes and catchments on Disko Island in West Greenland. We used a Russian corer (a particular type of sampler) and made a hole in the lake ice to take sediment cores from the bottom of the lake in April 2013. The challenge for this project is to reconstruct lake and catchment processes by measuring what is preserved in the mud, and we are attempting this by studying a suite of *biochemical remains*. For example, lipids (waxes, fatty acids, carotenoid pigments) can distinguish whether carbon was produced inside the lake (for example from algae) or by catchment vegetation (plants on land). Carbon isotopes and the ratios of carbon relative to nitrogen can also help to identify how the carbon was processed within the lake. To help with interpreting the lipids, we returned to the lakes that summer to assess catchment vegetation cover and take samples from lake and catchment sources.

The equipment being transported by snowmobile to site "Disko 4" overlooking a stunning iceberg-covered bay. We accessed this site by boat in the summer trip (Suzanne McGowan).

We used a Russian corer which is attached to rods (visible in the photo above). A video of the coring can be seen on www.youtube.com/watch?v=Q7Yc-ok2dAs#t=53 (Suzanne McGowan).



The base of a core from a river-fed lake in Blæsedalen (site "Disko 1" at 299 m a.s.l.). The sediment is primarily *gyttja*, with bands of aquatic macrofossils and clay (Mark Stevenson).

WHERE DID WE WORK?

We chose Disko Island because it lies at a latitude of 69° N, and is therefore close to the northern limit of extensive vegetation development. Therefore we hoped that past climatic changes would lead to especially pronounced transitions in vegetation. Given the relatively large climate variability of Disko Bay in time and space, it is important for *paleolimnological* studies to be widespread and cover different time periods. The Arctic Station (•66) is very conveniently located within a few hours snowmobile ride from the sites that we wanted to study.

WHAT DID WE FIND?

Radiocarbon dating suggests that one of the sediment core records (site "Disko 2") is around 7-8,000 years old, but should still encompass the LIA and MCA. There are clear changes in the amount and type of carbon in the sediments, with warmer periods being generally associated with higher carbon content, possibly deriving from catchment vegetation. The summer field visits confirmed what we could not see when there was snow cover – that the lake catchments are sparsely covered with mossy tundra.

WHY ARE THE RESULTS IMPORTANT?

Although we can make predictions about lake carbon processing in a warmer Arctic, we lack evidence to justify these predictions. This work should increase confidence in such forecasts. The retreat of glaciers will form many new lakes and it is even more important therefore to understand lake and wetland processes at high latitudes.

THE ADVENTURE

Approaching the field station in a helicopter looking down at the icebergs in the sea, and squeezed in next to our coring rods and ice drilling equipment was truly exhilarating. The snowmobile rides to access the sites whilst towing the equipment behind us on trailers was a fantastic way to see the stunning basaltic landscapes, but access to our final site up an icy slope proved very challenging, splintering one of the trailers as we slid backwards. Fortunately it was nothing that a bit of skilled driving from our guides could not fix and we managed to take our samples from the legendary "bottomless lake", which turned out to be 7 metres deep! Mark's return to the lakes in the summer made us feel grateful for the snowmobiles – a tough hike on the boulder fields with plenty of mosquitoes for company.

Further information

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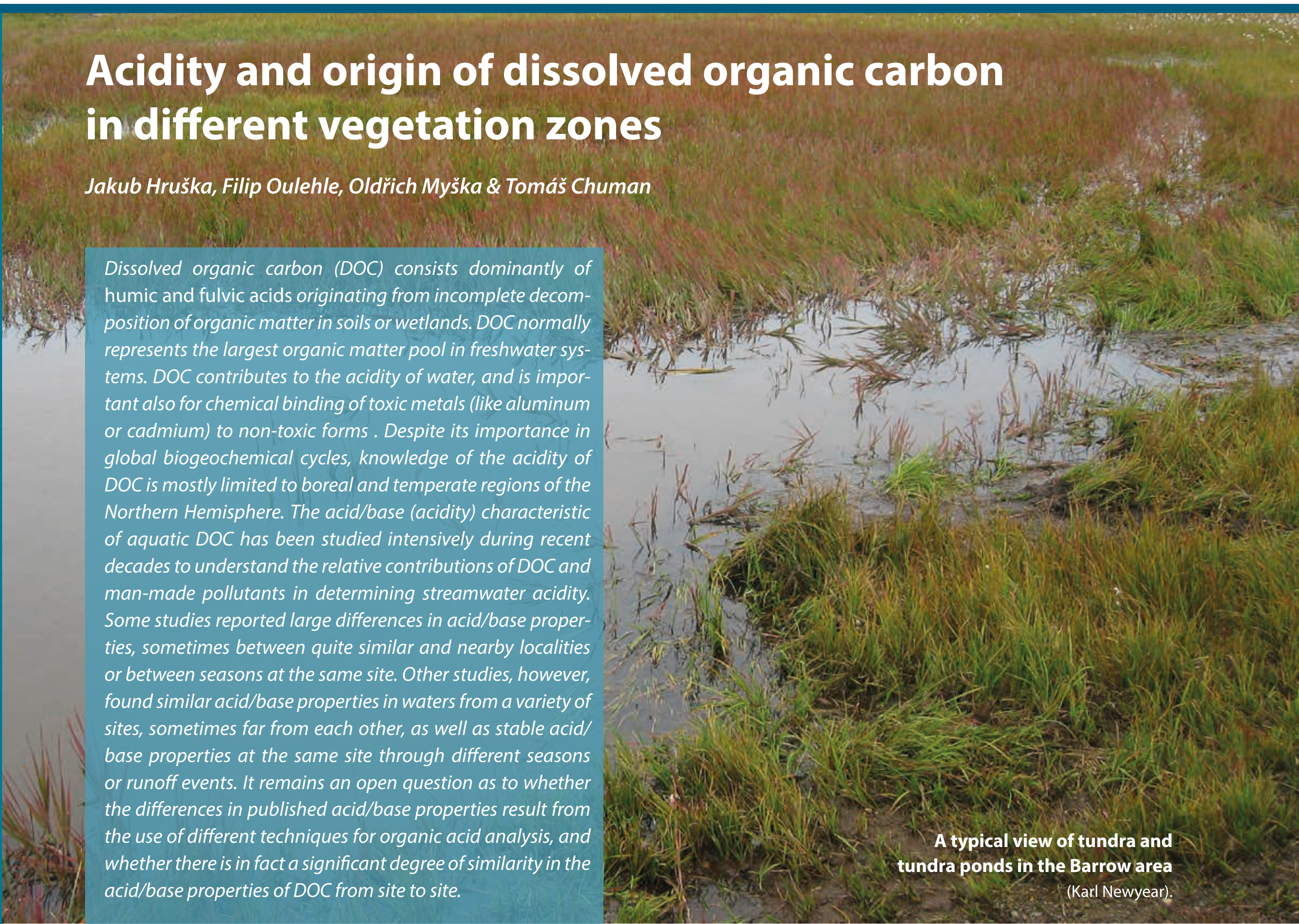


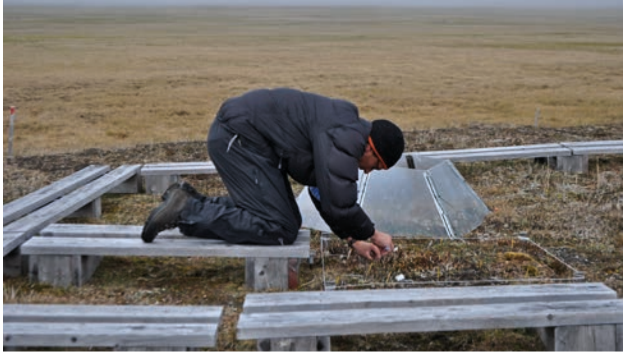
Acidity and origin of dissolved organic carbon in different vegetation zones

Jakub Hruška, Filip Oulehle, Oldřich Myška & Tomáš Chuman

Dissolved organic carbon (DOC) consists dominantly of humic and fulvic acids *originating from incomplete decomposition of organic matter in soils or wetlands. DOC normally represents the largest organic matter pool in freshwater systems. DOC contributes to the acidity of water, and is important also for chemical binding of toxic metals (like aluminum or cadmium) to non-toxic forms . Despite its importance in global biogeochemical cycles, knowledge of the acidity of DOC is mostly limited to boreal and temperate regions of the Northern Hemisphere. The acid/base (acidity) characteristic of aquatic DOC has been studied intensively during recent decades to understand the relative contributions of DOC and man-made pollutants in determining streamwater acidity. Some studies reported large differences in acid/base properties, sometimes between quite similar and nearby localities or between seasons at the same site. Other studies, however, found similar acid/base properties in waters from a variety of sites, sometimes far from each other, as well as stable acid/base properties at the same site through different seasons or runoff events. It remains an open question as to whether the differences in published acid/base properties result from the use of different techniques for organic acid analysis, and whether there is in fact a significant degree of similarity in the acid/base properties of DOC from site to site.*

A typical view of tundra and tundra ponds in the Barrow area (Karl Newyear).

Soil water collection from an ITEX warming experiment at Point Barrow, Alaska (Jakub Hruška).



AIMS OF THE PROJECT

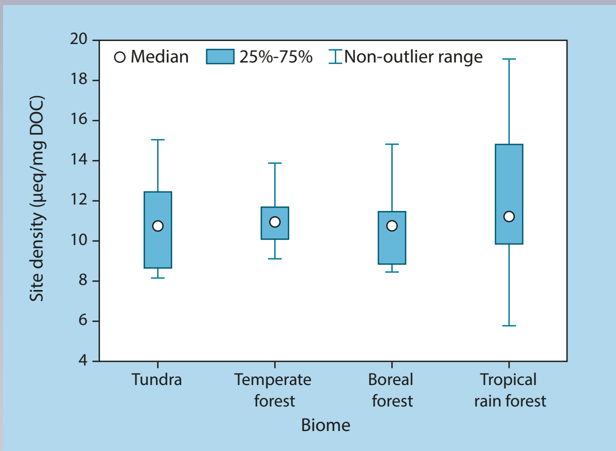
Based on our previous findings and the literature we hypothesized that fundamental properties of natural dissolved organic matter in freshwaters remain stable across a wide range of biomes (vegetation zones), despite large variations in concentration, unless ecosystems are perturbed. Our aim was to investigate DOC acid/base properties from different biomes (tropical, temperate, boreal and Arctic) and compare their site density (amount of acidic carboxylic groups carrying humic and fulvic acids acidity in microequivalent of protons per milligram of organic carbon – units μeq/mg DOC) to resolve if different *biomes* produce different types of organic matter.

WHAT DID WE DO?

We collected surface water from lakes as well as shallow soilwater from climate treatments in tundra ecosystem warming experiments (ITEX – International Tundra Experiment). Surface waters were simply collected by polyethylene bottles but for soilwater sampling we used Rhizon™ samplers. Rhizon consist of a teflon needle and polyethylen syringe. The teflon tip was evacuated by the syringe and water slowly sucked up into the syringe. We sampled each 12 hours during 3 days to have enough water for chemical analyses. Later in the lab, the total DOC acidity (site density) was determined by *titration*.

WHERE DID WE WORK?

We worked at the Barrow Arctic Research Center (•47), located at the northern tip of Alaska (USA) on the Arctic Coastal Plain north of the Brooks Mountain Range, at the junction of the Chukchi and Beaufort Seas. The adjacent Barrow Environmental Observatory comprises 30 km^2 of tundra, lakes and wetlands reserved for scientific research. The northern latitudes are important "end members" of ecological conditions on the Earth and they served as an excellent comparison for more climatically favorable biomes.



Site density (amount of acidic groups of humic and fulvic acids per milligram DOC) in different biomes. The various measures of statistical variability show no differences among biomes.

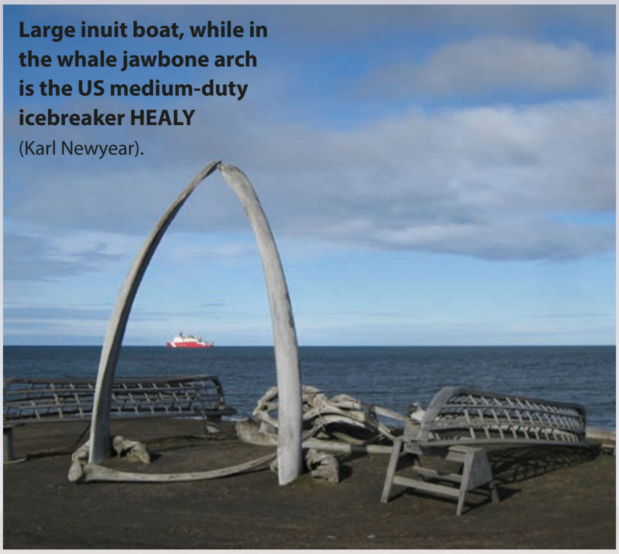
WHAT DID WE FIND?

Site density (µeq/mg DOC) from Barrow's tundra lakes was very similar to those found in surface waters from the very different biomes across the Earth. Site density from northern Alaska did not differ statistically from tropical rain forest in Congo, central Africa as well as from temperate forest in Central Europe or the boreal zone of northern Sweden. Despite observed differences within one site, the median is very similar and varied between 10.4 and 10.7 µeq/mg DOC. This suggests that acid/base properties of surface water DOC can be very similar across large regions with very different environmental conditions.

WHY ARE THE RESULTS IMPORTANT?

Our previous results suggested similarity between boreal and temperate regions of Europe (Hruška and others 2003), but more wide-ranging comparisons had not yet been undertaken. Thus this project significantly extends present knowledge. DOC is an important, but often poorly represented, element of water chemistry simulations using biogeochemical models under different climatic and pollution changes. Providing functional models of acid/base character (general, or for individual ecosystems) and identifying sources of DOC in streams and rivers will improve significantly our ability to predict water chemistry in response to expected climate change, recovery from acidification or potential land-use changes.

Barrow Arctic Research Station in winter (Chris Arends).



Large inuit boat, while in the whale jawbone arch is the US medium-duty icebreaker HEALY (Karl Newyear).

THE ADVENTURE

It was not too hard to reach Barrow as there is an airport and large planes land there easily, a few times per day. But the research area where the cold sea covered by ice meets the tundra just a few metres from the coastline was very impressive. Looking over the sea in the direction of the North Pole one can imagine the hard life of people living here for centuries, hunting whales, snow geese and living in simple cottages during cold and dark winters. That was a real adventure, but we saw little evidence of that life.

Further information

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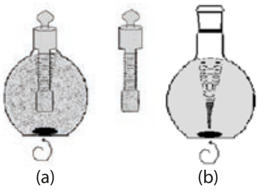
Finding cold-adapted bacteria to combat organic pollutants in the Arctic

Luigi Michaud (posthumous), Stefania Giannarelli, Maurizio Azzaro & Angelina Lo Giudice

Polychlorinated biphenyls (PCBs) are long-lived persistent organic pollutants whose widespread use and chemical stability has led to extensive environmental contamination, even in remote areas such as the Arctic, through accidental releases and inappropriate disposal techniques. Despite their persistent nature, PCBs can be transformed, even at low temperature, into chemical substances by different microbial metabolic pathways, both in the presence or absence of oxygen, facilitating further breakdown.

The late Luigi Michaud during sampling activities in the Arctic. Luigi – the leader of our research project – died in Antarctica during sampling activities in January 2014. His strong enthusiasm and passion for science was fundamental both in the field and laboratory (Angelina Lo Giudice).



Samples (20 Litres) are mixed with a solvent and PCBs are extracted by an innovative method (a) (modified flask-stopper and microextractor), to improve traditional methods (b).

Sampling activities in the Pasvik river (Marco Graziano).

AIMS OF THE PROJECT

We wanted to find a relationship between the amount of PCBs detected in the environment (e.g. water and sediment) and the occurrence of cold-adapted PCB-degrading bacteria.

WHAT DID WE DO?

We collected water and sediment samples for chemical and microbiological analyses, avoiding any external contamination. Samples were pre-treated in the field and then we analyzed them in the laboratory where we extracted PCBs (to be detected by *gas-chromatography* which separates and analyses chemical compounds in a sample) and microbial DNA (to search for genes that are involved in the PCB degradation). In the laboratory, we also isolated PCB-oxidizing bacteria (to be identified, and studied for the ability to degrade PCBs at low temperatures).

WHERE DID WE WORK?

We worked at the Bioforsk Svanhovd Research Station (•8) which is located in the Pasvik area in northern Norway, above the Arctic Circle and in close proximity to Russia and Finland. The Pasvik River, the largest river system in northern Fennoscandia, is contaminated by a wide range of toxic and *bioaccumulative* substances, including PCBs. The river outlet is in the Kirkenes area that therefore appears highly polluted. We argued that the river flow could have a pollutant effect also on the fjord system up to the larger Varanger fjord.

WHAT DID WE FIND?

We determined a moderate PCB contamination in water and sediment samples from the Pasvik area. This was supported by the isolation of a number of PCB-oxidizing bacteria, mainly obtained from sediment, that were able to degrade PCB mixtures at low temperature and harbored genes involved in the PCB degradation process.

WHY ARE THE RESULTS IMPORTANT?

Microorganisms predominate in low-temperature environments in terms of biodiversity and biomass. Cold-adapted bacteria possess high biotechnological potential like the decontamination of polluted cold sites under in situ environmental conditions. Investigations on the ecology and physiology of such bacteria are needed to develop efficient *bioremediation* strategies (methods to biologically clear the pollution).

THE ADVENTURE

Sampling of sediments from the fjord area took several dives during which the majestic – but invasive - king crabs were observed. The use of open boats to reach distant places for diving activities offered us the opportunity to admire the beautiful fjord landscape from the sea. During car trips, we encountered a lot of reindeer and on one occasion a moose.

Sampling sites along the Pasvik River and adjacent fjords.

Preparation to sample underwater (Maria Papale).

Further information

Luigi Michaud (posthumous)[1], Stefania Giannarelli[2], Maurizio Azzaro[3] & Angelina Lo Giudice[1,3]

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A microbial ride around the Arctic

Stefano Ventura

Biological Soil Crusts (BSC), microbial communities living on rock surfaces (lithobiota), *and cyanobacterial mats growing in springs and seepages (temporary puddles generated by the accumulation of water in places where permafrost blocks water drainage through the ground), were selected for this study to describe their diversity, evaluate geographic variations and peculiarities, establish a comparison between patterns of development in high and low Arctic environments, and compare them with corresponding counterparts living in* mesic *(moderate) temperate climates or in hot and cold deserts.*

These communities depend on alternating seasonal cycles of water availability, along with other specific environmental limitations. Prolonged periods of dryness limit the activity and growth of BSC and lithobiota to a part of the Arctic summer, while UV (Ultra Violet) irradiation challenges their survival. Under the long lasting summer sun, temperature can substantially increase due to the low albedo *(reflectivity) of these communities (Science Story 3.3) which form thin, dark pigmented layers on top of the ground, while in winter they are exposed to extreme, low temperature and blasting winds without any protection. Microbial mats dominated by cyanobacteria flourish in seepages. These communities experience cyclic water availability and shortage which determine their structure and biodiversity. In contrast, spring mat communities live continuously underwater but are subjected to seasonal cycles of freezing and thawing. Special cases are the communities of photosynthetic microorganisms living in springs with constantly warm temperatures and "*endoliths*" living inside rocks.*

AIMS OF THE PROJECT

This project aimed to undertake a pan-Arctic survey of microbial communities living in extreme habitats of Arctic landscapes, where plant growth and vegetation coverage of soil is limited or impaired, and microorganisms dominate. Specifically, we aimed to understand the role of BSC in reducing erosion, stabilizing the substrate and increasing its nutrient content, thus favouring the establishment of a more complex and resilient vegetation.

***Stigonema sp*., a filamentous, branching cyanobacterium from a rock wall covered by a wet, black *patina*, that is a thin layer of photosynthetic microorganisms covering the rock surface, Fortune Bay, Disko Island, Greenland. The scale bar is 20 micrometres, the micrometre (µm) being a millionth part of a metre** (Claudio Sili).

Small lake on the *moraine*, at night, in Zackenberg, Greenland (Stefano Ventura).

Spotted BSC in the initial stage of development on the shores of a small lake, Ossiansarsfjellet, Kongsfjorden, Svalbard. This crust represents the kind of less developed, thin, discontinuous crust that can be found in the more extreme habitats on Svalbard (Stefano Ventura).

Cross section of a small rock (sandstone) fragment, with a green layer of cyanobacteria growing immediately below the surface, Ossiansarsfjellet, Kongsfjorden, Svalbard. Microrganisms that live inside rocks are called "endoliths". The sandstone fragment has been put in a sterile plastic bag immediately after having been collected in the environment, for further lab analysis. Scale unit is 1 cm (Stefano Ventura).

WHAT DID WE DO?

We investigated the visible and microscopical structure and the related hydrodynamic properties of BSCs (how BSCs modulate water flow on their surface and through them) and the BSC community composition in the initial stages of development. We also looked into the process of soil formation and development in relationship to the presence of BSC.

Our team identified and characterised the dominating members of fungal and cyanobacterial populations which colonise exposed rock surfaces in different microclimatic conditions in the Arctic (and that recall extra-terrestrial conditions). We also identified community members of mats in seepages and springs and characterised their photosynthetic behaviour.

During the field work, we mostly collected samples and stabilized them for further manipulation in our home laboratories. There, we applied molecular techniques for the identification of the community members, and isolated strains in pure culture to better characterize them. We determined the soil structure and the hydrological properties of the BSC and measured photosynthetic activity.

WHERE DID WE WORK?

Our pan-Arctic survey began in Kongsfjorden, Svalbard at CNR Arctic Station "Dirigibile Italia" (•4), and through INTERACT, it has been extended to Arctic Station (•66), Disko Island in West Greenland, Zackenberg Research Station (•70) in Northeast Greenland and Tarfala Reseach Station (•10) in high alpine northern Sweden. Samples from northernmost Canadian regions will be added to the study through collaborative links with local colleagues.

WHAT DID WE FIND?

Our field work has been concluded only recently, and the lab. work is still ongoing. From the data we already collected and analysed, it seems that BSC growing on Svalbard are more diverse than in the other locations studied, and include a range of BSC morphologies, from very simple, thin, discontinuous crusts, to morphologically complex, structured and thick crusts. We hypothesize that this could be caused by the presence of a range of different habitats on Svalbard, including the most extreme conditions along the forefronts of receding glaciers.

WHY ARE THE RESULTS IMPORTANT?

We hope to understand better how water dynamics influence the development of microbial communities in extreme habitats impacted by climate change. Since strong effects of climate change on water balance are widespread, we aim to supply valuable information to foresee habitat evolution under conditions where water is a main constraint, not only in the Arctic but also in mesic (moderate) temperate climates or in hot and cold deserts.

THE ADVENTURE

Visiting several places we could enjoy so many different beautiful Arctic landscapes, from sailing in front of massive glacier fronts calving big ice chunks into the fjord, to hiking in the silent vastness of Greenland, to meeting birds, seals, foxes, hares and muskoxen. But it was the sudden, close encounter with an old, big muskox, that was the token of our Arctic experience. By the way, the muskox was very peaceful, that time!

A seepage formed by temporary accumulation of water in places where permafrost blocks water drainage. Zackenberg Valley, Greenland (Ondrej Komarek).

Close encounter with a muskox in Zackenberg, Greenland (Stefano Ventura).

Further information

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Microbial biodiversity in polar lake ecosystems: why is it different at the North and South Pole?

Koen Sabbe, Dagmar Obbels, Pieter Vanormelingen, Otakar Strunecky, Bart Van de Vijver, Josef Elster, Annick Wilmotte, Elie Verleyen & Wim Vyverman

Ecosystems in shallow Arctic and Antarctic lakes are largely based on biofilms, complex microbial communities of bacteria and micro-eukaryotes (microalgae and protozoa – small single celled plants and animals), which inhabit the bottom sediments as mats.

Typical sampling lake in the Kobbefjord area, the field site of Greenland Institute of Natural Resources (Koen Sabbe).

AIMS OF THE PROJECT

We wanted to understand what mechanisms shape the biodiversity of biofilms, by making a comparison between Arctic and Antarctic lakes.

WHAT DID WE DO?

During summer 2013, we sampled microbial biofilms in about 80 lakes in Greenland. Bottom sediment samples were taken using a sediment corer from deeper parts of the lakes, but we also sampled the shallower parts and other wetland habitats (seepage areas, bogs, etc.). In addition, we took samples to characterize the environment (nutrients, pH, conductivity, etc.).

WHERE DID WE WORK?

We selected two sampling regions each with an INTERACT station, one in the low Arctic zone (near the Greenland Institute of Natural Resources (•67) in Nuuk and Kapisillit, West Greenland) and one in the high Arctic (Zackenberg Research Station (•70), Northeast Greenland), in order to cover the different Arctic climatic conditions.

WHAT DID WE FIND?

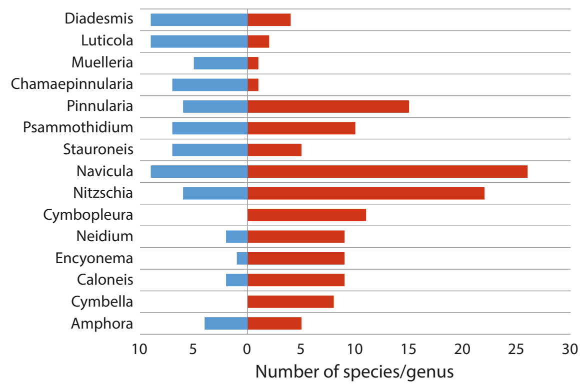
We collected both live biofilm materials, from which cyanobacteria and microalgae were isolated and brought into culture, and frozen biofilm samples, both of which are being used for an in-depth characterization based on DNA molecules using so-called next generation sequencing methods (i.e. methods which "read" the composition of the DNA molecules). While to-date the analyses are still in full progress, preliminary results have uncovered a high microbial diversity in the Greenland lakes, in particular in some groups of silica-shelled microalgae or diatoms. Interestingly, the observed species are different from those in similar habitats in Antarctica, suggesting different evolutionary pathways for biofilm community development in each Polar Region.

WHY ARE THE RESULTS IMPORTANT?

Despite the huge importance of microbial organisms in aquatic ecosystems, both freshwater and marine, their biodiversity remains understudied and hence little understood in comparison with larger animals and plants. It has often been assumed that microbial species, unlike animals and plants, have unlimited dispersal and will therefore be found wherever the environment is suitable for growth. As a result, formation of new species in isolation *(allopatric speciation)* should be negligible and global biodiversity low. The Arctic and Antarctic offer a unique opportunity to test hypotheses regarding

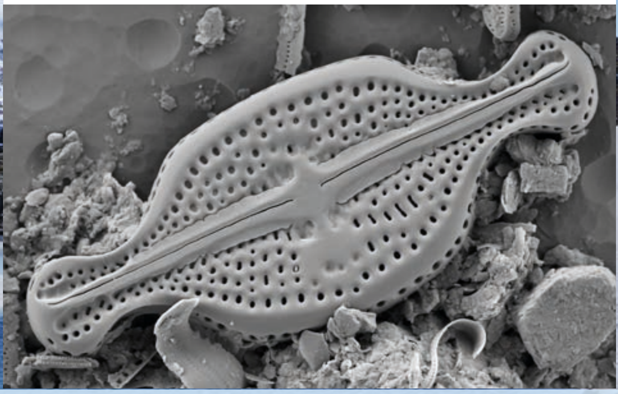
Microbial biofilm (the brownish layer at the top of the sediment core) recovered from the bottom sediment of a lake in the Kobbefjord area (Koen Sabbe).

Bringing a core (taken using a so-called UWITEC corer) from the bottom sediment of a lake in the Kapisillit area to shore (Dagmar Obbels).



Species richness (= the number of species) of diatom genera is not the same in Antarctic (blue) and Arctic (red) lakes. This suggests that the diatom communities in both regions have evolved in isolation of one another.

Diatoms are microalgae which are very common in polar biofilms (here the species *Luticola katkae* is shown in a *scanning electron micrograph*).



the biodiversity and evolution of microbial organisms. While being highly similar from an environmental point of view, the two Polar Regions are separated from one another by the temperate and tropical belts. In addition, the Arctic Region is connected to the Northern Hemisphere land masses, while the Antarctic is isolated by the Southern Ocean. Our project will test the existing hypothesis that because of unlimited dispersal and similar environments, most polar micro-organisms will be present in both Polar Regions. This view needs to be tested as there is growing evidence of dispersal limitation and *endemism* in microbial organisms (endemic species only occur in a specific geographic area). If the latter is true, our data should show that given the higher connectivity of Arctic areas, microbial communities there will be relatively diverse, while the more isolated Antarctic communities will be species-poor and dominated by endemic species.

THE ADVENTURE

Our sampling campaigns took us to two beautiful yet contrasting regions of Greenland: from the sunny late spring tundra full of flowers, birds and, inevitably, mosquitoes in Southwest Greenland to the cold and harsh late summer conditions of Zackenberg. The empty space and silence of the Greenland landscape was overwhelming, especially if you come from a busy country in mainland Europe. Sightings of whales, reindeer and muskoxen made the experience complete.

Further information

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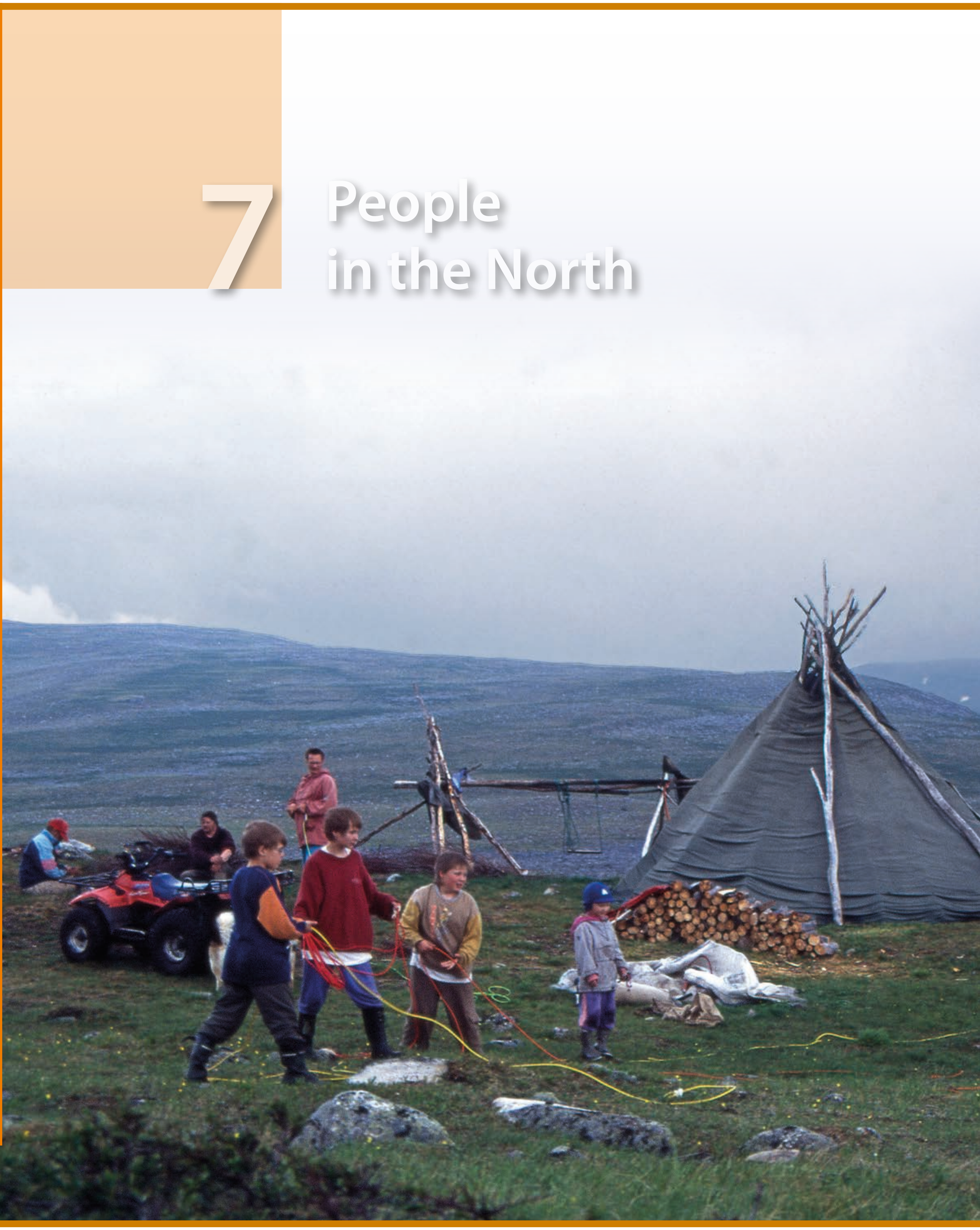
7 People in the North



SECTION OVERVIEW

Jan Dick, Najat Bhiry & Christine Barnard

People have inhabited Arctic and sub-Arctic regions for millennia. Predecessors of the North American native peoples are estimated to have crossed the land bridge about 30,000 years ago while Arctic Russia was inhabited even earlier. Today the northern circumpolar region of our planet is home to approximately 13.1 million people who are spread across a vast territory, some 21.5 million square kilometres. This immense territory is governed by eight countries: Canada, United States, Russia, Finland, Sweden, Norway, Iceland and Denmark/Greenland. Of this population, Indigenous Peoples are estimated to represent about 10 percent of the total population currently living in Arctic areas. In addition to Arctic Indigenous Peoples, the Arctic is inhabited by other peoples such as descendants of Norwegian Vikings and Russians that migrated to the Arctic during the past 1,000 years. As might be expected, Arctic residents are not evenly spread across the vast wilderness, but they group together in cities, towns, hamlets and villages (Figure 7.1). Historically human settlements were often located where a freshwater stream or river joined the ocean, so people could easily obtain their needs from the sea, land and freshwater, i.e. nature's services. The Arctic is no different from other regions of the world in this respect. In the North however, the issue of remoteness was of utmost importance as many northern communities were disconnected from industrial development for centuries due to the great distances and presence of physical barriers (mountains, ocean, wetlands in summer, etc.). Today, many villages are still difficult to access. In Canada for instance, less than half of the northern communities have all-weather road connections with the rest of the country and many villages are only accessible by air (Canadian Polar Commission 2014).

Sámi children practicing the use of lasso in Lapland, Finland
(Mikko Jokinen).

Figure 7.1 Major and minor settlements in the circumpolar Arctic. The small blue dots represent villages and hamlets with less than 20,000 inhabitants (Philippe Rekacewicz/GRID-Arendal).

Figure 7.2 Indigenous peoples of the Arctic. (a) Nenets reindeer herders from the western Russian Arctic (Peter Prokosch/GRID-Arendal). **(b) Sámi reindeer herders from Finland** (Mikko Jokinen). **(c) Canadian *Inuit* fishing at an ice hole** (José Gérin-Lajoie).

Arctic residents, specifically the Aboriginal peoples, are thus resourceful, resilient and adaptive, with an intimate relationship to the land that has been transmitted across generations (Figure 7.2). Their intricate link to the land has provided them with their resources for subsistence and structured their spiritual and cultural identity. Due to this remoteness, traditional ways have dominated life in many northern communities and has historically served to somewhat buffer modernisation and massive resource development.

Today, Arctic residents are faced with unprecedented change in the dual context of climate change and rapid socio-economic development (globalization). This section focuses on the impacts of change specifically relevant to Arctic residents.

A CHANGING NORTH

The circumarctic region has experienced remarkable shifts in climate in the relatively recent past (e.g. the Little Ice Age of the 15th-19th centuries, Section 1). The warming induced by *anthropogenic activities* is unprecedented in both magnitude and scale, and at the same time societal and industrial developments as well as globalization are having an impact in the Arctic Region.

Communities in the Arctic are very diverse ranging from those of larger cities with easy access to the outer world, over communities of smaller remote settlements to migrating nomads. These communities are affected differently by the current and expected changes. Whether these changes are perceived to be good or bad depends on personal opinions and numerous factors like location (e.g. local changes in the natural resource availability, infrastructure underlain by permafrost, access to markets, etc.), local livelihood strategies (e.g. dependency on natural resources for income, food security and health), and societal developments influenced by globalization (e.g. industrial development, school systems, shops, health care, modern equipment, etc.).

Some examples of change impacts relevant to the Arctic Region and its peoples include:

Climate-induced changes:
- *Permafrost* thaw which has impacts on infrastructure and urban planning.
- Rapidly changing weather conditions, increased frequencies of storm events and avalanches, changing freeze/thaw events, reduced ability to predict safety when travelling on the land and ice, changes in snow/ice conditions influencing access to hunting grounds.
- Changes in flora and fauna which influence subsistence hunting, fishing and gathering activities, access to traditional foods, and spiritual/cultural values.
- Easier access to non-renewable and renewable natural resources in the North and new shipping routes.

Globalization-induced changes:
- Increasing levels of resource extraction often conflicting with recognition of rights and perceived environmental concerns.
- Increasing food insecurity for some small, remote settlements, but better food security for the vast majority of Arctic residents through shops, better logistics and hunting equipment that makes hunting more efficient (extended travel and shooting ranges). Improved logistics, safety and communication equipment also make hunting trips safer.
- Changing education needs to adapt to changing conditions in the natural environment and new skills required by a modernised society.
- Some communities may experience increasing health problems with a changing diet (e.g. diabetes and obesity), increasing mental distress, increasing suicide rates, increasing contaminant levels and new diseases from southern regions. On the other side, many communities also benefit from improved access to better health care and access to supplementary nutritious food (some local foods are contaminated due to long-range pollution) etc.
- Increase in inadequate housing due to increasing local populations in some communities, but increasingly improved housing for most Arctic residents through better building materials, insulation, electricity and improved heating systems.
- Better access to knowledge and goods.

It is globalization rather than climate change that has had more impact on Arctic residents in the past century (AHDC 2004). For many Arctic residents who had experienced relatively little contact with other populations prior to this period, the significant improvements in infrastructure, transportation and communications have brought on rapid social change, requiring extensive adaptations and resilience (Allard and Lemay 2012; IPCC 2014). These societal changes occur alongside arctic ecosystems that are undergoing major change in terms of species composition, productivity, timing of reproduction, new infectious diseases and changes in migratory patterns, forcing local communities to adapt to these changes. Unpredictable changes in weather leading to residents' decreased capacity to evaluate safe travel conditions may also make some food items less accessible in some periods, but may also provide easier access to old and new hunting grounds. All of these changes, in turn, affect local food security issues.

Historically, hunting and fishing have significantly reduced local wildlife populations requiring communities to re-settle. The harvest may have been sustainable on a larger scale due to the vast area and low human population, but with increases in human population levels and improved hunting efficiency (boats, rifles, means of communication, etc.) some prey popu-

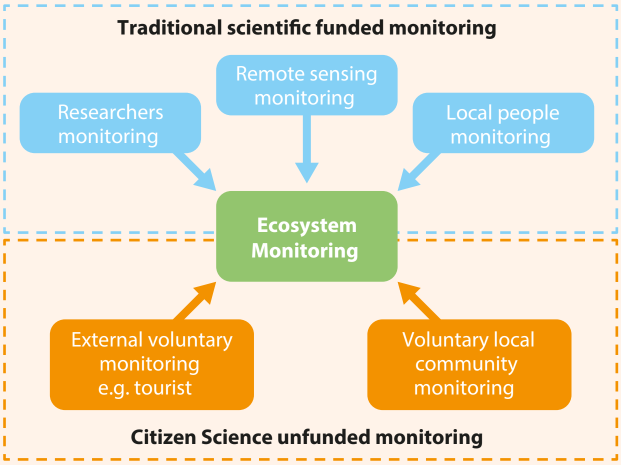


Figure 7.3 Different types of monitoring schemes utilised to monitor change in the Arctic.

lations have been overharvested, thus affecting local food security.

Food security is an issue which eloquently illustrates the complex patterns evolving from both climate change and globalization. Food security exists when "all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (FAO 1996). While food security is less of a problem in the more developed parts of the Arctic, food insecurity is an issue elsewhere due to factors like high food costs (often combined with low incomes), the lack of availability of healthy foods in shops and lifestyle choices that are influenced by the western market for processed foods (Furgal and others 2012). Access to healthy and affordable foods is a major concern for some urban Arctic residents and in remotely located communities nutritious commercial food items may be expensive and difficult to obtain. Traditional country foods of Indigenous Peoples obtained through socially important hunting, fishing, and gathering activities are often considered healthier than less nutritious western food, although concern is also raised over harmful contaminant levels in some predator species that act as "*bioaccumulators*" (concentration of contaminants up through the food web).

The consequences of food insecurity, experienced by some communities, include increased risks of having chronic health conditions (overweight, diabetes, dental cavities etc.), mental health challenges, and a lower learning capacity. In light of these issues, many positive actions have begun to alleviate food insecurity in the North (IPCC 2014). These include better access to nutritious foods through improved infrastructure, reorienting market food subsidies, increasing the availability of country foods (enhancing sustainable harvest and sharing networks, sharing of community freezers, encouraging commercial sale and distribution of country foods, etc.), enhancing hunter support groups, and promoting health and nutrition education (Furgal and others 2012).

Figure 7.4 Diagrammatic representation of the interaction between humans and the planet Earth. Inuit heading out on the ice to hunt seal (José Gérin-Lajoie).

SCIENCE BY THE PEOPLE OF THE NORTH

In order to manage the northern regions of our planet in a sustainable way for both humans and wildlife, we need to better understand the impact of human actions which result in changes in global ecosystems. There is an old saying that "in order to manage you have to measure" (a McKinsey Maxim) and although more challenging than in more southerly regions of our planet due to the harsh conditions, the Arctic has been monitored for many years in innovative ways.

The knowledge generated through conventional science and monitoring is the focus of this book, but other types of non-conventional monitoring are also important. This non-conventional monitoring ranges from local autonomous traditional systems with no or limited formal agreements to formal community-based initiatives embedded in local management systems and to scientist-led Citizen science programmes (CAFF 2013).

Examples of advantages of involving local residents in the assessment of Arctic change:

- Ensures science questions are relevant for the local context.
- Uses existing, often silent, knowledge embedded in the community.
- Builds local capacity.
- Provides more observers with greater geographical and temporal coverage.
- Leads potentially to greater understanding, acceptance and adherence to management needs, and thus more sustainable management. Increases cost-effectiveness compared to conventional monitoring (although it may be relatively expensive to develop and implement).
- Often shortens response time from observation to management action (Danielsen and others 2010).

Examples of disadvantages include:

- Potential conflict of interest leading to flawed observations when resource user and observer is the same person (i.e. letting the fox guard the sheep).
- Development, implementation and training costs depending on applied monitoring / assessment approach.

Two terms have been used to describe the involvement of citizens in monitoring the environment. "Citizen science" is a type of scientific monitoring conducted wholly, or in part, by amateurs or non-professionals but is often centrally designed and analysed by scientists. In contrast, in "community-based monitoring", the community is heavily involved in the design and operation of initiatives, and maintains and retains ownership of the results and uses them freely as they wish within a national legal framework. Knowledge sources like observations, perceptions, experiences and "traditional knowledge" can be used beneficially in the design of both conventional and locally based science and monitoring projects. All types of knowledge have limitations and the current challenge is to bridge the knowledge generated from western science, citizen science, community-based monitoring and traditional knowledge, as all forms of knowledge are invaluable to the overarching mission of ensuring sustainability (Huntington and others 2004).

Figure 7.5 Weighing a reindeer calf to monitor condition of wild reindeer (Joëlle Taillon).

In the context of climate change and the rapidly changing Arctic, it is scientifically and socially important to set up relevant and reliable tools to involve the local populations in learning about research through outreach and educational activities, and also to involve them in community-based monitoring activities. It is one thing to make the data available from a researchers' perspective, but another to make this data comprehensible, interesting, and relevant to northerners. Education and information exchange (traditional and academic) are giant steps towards community empowerment and capacity building for local sustainable management throughout the circumpolar North.

There are many excellent Citizen science initiatives, one being the AVATIVUT: Bridging Environmental Science and Community-based Monitoring Programmes where environmental scientists at the Centre for Northern Studies (CEN) in the eastern Canadian sector of INTERACT have teamed up with a northern school board and education specialists. AVATIVUT (www.cen.ulaval.ca/avativut/) engages high-school students of Nunavik (in the eastern Canadian sub-Arctic) in environmental science, including data collection and archiving. The topics include monitoring of berry productivity, snow and ice cover and permafrost, and the activities are partially supported by the research program ADAPT (www.cen.ulaval.ca/adapt/).

NATURE OR ECOSYSTEM SERVICES – PEOPLE INTERACTING WITH NATURE

The scientists studying the interaction of people and the environment have recently framed their work around the central concept that human needs are delivered by the goods and services they obtain from nature, i.e. nature's services (Figure 7.4). Some scientists use the term "ecosystem services". The concept is focused on humans because scientists argue that in order to manage the land, air and sea in a sustainable way for the benefit of future generations, it is necessary to consider the central role humans play in altering and managing our planet.

The interaction between humans and the environment is often depicted as a series of interconnecting elements where the physical elements provide services which influence human well-being which results in human actions to manage the system to ultimately maximise human well-being. In the past, there has been a focus on monetary valuation but more recently people understand that there is a need to "value" elements of the environment for which there is currently no market. The world is not however neatly partitioned into little boxes as people and services move freely around our planet so actions in one place can have a large impact on another and this is what we see happening in respect to climate change.

The services are commonly considered in three categories. Some of the services are used directly by people and are called "provisioning ecosystem services". There are many examples such as reindeer (Figure 7.5) that are used for food and fur, berries used as food and to flavour drinks and medicinal plants such as *Sedum rosea* famed for its ability to reduce stress and also considered by some an aphrodisiac (http://nature.ca/aaflora/data/www/crsero.htm). These services often have a tradable or market value. There are also important services that are not used directly, but affect our lives. These are called "regulatory ecosystem services". They include, for example, the storage and release of *greenhouse gases* that when released into the atmosphere, accelerate climate warming. These services traditionally were not traded and consequently had no market value. A third category of "cultural ecosystem services" is often recognised such as the aesthetic beauty or spirituality of a location or the space for recreational activities. Many of these services are not tradable and because many are "passive-use" services, everyone can enjoy them but once enjoyed they remain for the next person. These services often only have a tradable value if the area belongs to an individual or group and they control access. In addition some researchers recognize "supporting" (MA, 2005) and "habitat" (TEEB 2010) services from which all the other services flow.

Figure 7.6 Ice fishing in the Canadian North *(José Gérin-Lajoie).*

THE FUTURE FOR PEOPLE OF THE NORTH

Social, environmental and economic change is constantly happening to all the peoples of the world including the people of the North. Science can provide knowledge to help maintain both a healthy environment and to increase people's well-being. In the following pages the science funded by the INTERACT *Transnational access* program and hosted by INTERACT research stations highlights some of these changes and the need for knowledge and tools to aid managers and policy makers.

Climate change is influencing many geophysical aspects (e.g. snow and ice regimes) of northern landscapes. Science Story 7.1 investigated the level of risk for local infrastructure to aid hazard management. Five projects report within the framework of ecosystem services: (a) Science Story 7.2 focused on the biophysical and economic flows, (b) Science Story 7.3 focused on human perceptions of ecosystem services, (c) Science Story 7.4 focused on forests, (d) Science Story 7.5 which combined elements presented in the projects mentioned using a statistical tool called a Bayesian Belief network, and (e) Science Story 7.6 which brought together permafrost specialists, engineers, architects, local authorities, and community members to develop detailed maps and a sustainable urban planning strategy to adapt to changing permafrost conditions.

Key messages and needs for further research

- Actions of human's today have wide ranging (often global) and long term influences on the environment. Consequently long-term monitoring of the environment is vital for society to ensure the knowledge needed to sustainably manage the planet is available for future generations.
- Involving a wide range of citizens in the monitoring of the environment has societal advantages yet challenges scientists to ensure robust knowledge is generated.
- Knowledge about the Arctic environment through single disciplinary research has advanced our understanding of specific aspects but there is a need for future research to focus on a holistic analysis that will require new tools, statistical techniques and societal involvement.

Further information and references

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Dynamic risk management for an Artic region

Sven Fuchs

Snow avalanche risk is dynamic due to the variability of avalanche hazard and people exposed. During our stay we accessed Russian literature not available in Central Europe. Moreover, data was collected in order to quantify the risk for individuals using the road network as well as for the railroad in the region.

City of Kirovsk, Kola Peninsula, Russia (Sven Fuchs).

AIMS OF THE PROJECT

The project was targeted at the development of a computer model for the development of avalanche risk at different scales of space and time. The risk is defined as the probability of occurrence of snow avalanches multiplied by the expected damage for elements at risk.

Avalanche mitigation team in Khibiny (Yuri Zuzin).

A mountain pass near the Khibiny Research Station (Sven Fuchs).

WHAT DID WE DO?

The objectives of the field season included accessing Russian literature which is not easily accessible from outside the country, and accessing local meteorological data, as well as information related to the avalanche activity in recent decades. Moreover, we collected data related to the elements at risk (with a particular focus on roads and railroads). Hence, the focus was on gathering available information which is needed for the calculation of risk to individuals and communities. As a result of our field campaign, we were able to quantify the risk factor for people using the road connection when commuting to their workplace as well as estimate the risk factor for the main railroad connections among the industrial establishments in the region.

WHERE DID WE WORK?

The city of Kirovsk, located adjacent to the Khibiny Educational and Scientific Station (•26), in the heart of the Khibiny Mountains on the Kola Peninsula (Northwest Russia), was chosen as a test site because of (1) the almost unique situation of a mountain area prone to avalanche hazards with regional construction activities from time to time consisting of mainly maintenance and development of roads and railroads which are (2) heavily dependent on and influenced by industrial activities, including land development for industrial and residential construction, and the construction of infrastructure lines, e.g. power lines and pipelines.

Daily catering at the Khibiny Research Station (Sven Fuchs).

Variability of the hourly traffic on a diurnal basis in 2012 for a major road connection in the Khibiny Mountains, Russian Federation (Fuchs and others 2013).

WHAT DID WE FIND?

We found clear variations in the level of risk which infrastructure is exposed to both on a short-term and long-term time frame. While the short-term variations in snow avalanche risk are highly dependent on the traffic density on the road and railroad sections studied, the long-term variability of risk is more influenced by the overall dynamics of economic activities in the region.

WHY ARE THE RESULTS IMPORTANT?

Knowledge of the dynamics of avalanche risk provides information on economically efficient and technically effective risk mitigation measures, such as permanent measures (snow supporting structures in avalanche starting zones) and temporary measures (road closure, evacuation). The identification of dynamics in natural risk hazards, as well as the underlying processes, contributes to an improved understanding of present-day risk levels while allowing local managers to consider the different aspects of risk evolution for the future safety of local people and property.

THE ADVENTURE

Khibiny Research Station is easily accessible by public transport – the challenge is to organize daily life there. Working and living in northern Russia is demanding in daily adjustments, and requires the challenge of improvisation. The support of the local station manager as well as of the Moscow State University crew was great and we thank all of them for the stylish hospitality and all the efforts that had to be undertaken prior to our arrival.

Further information

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Assessing and valuing ecosystem services in the Abisko area

Pier Paolo Franzese, Natasha Nikodinoska, Tiina Häyhä, Silvio Viglia & Alessandro Paletto

Ecosystem services are the benefits humans gain from ecosystem structure and functions. Nature supports human economy and well-being with a wide range of ecosystem services. This research work focused on the assessment and valuation of ecosystem services in the area of the Abisko National Park (Sweden).

The Abisko area hosts many ecosystem services such as tourism, fishing and carbon sequestration by the forest (Pier Paolo Franzese).

AIMS OF THE PROJECT

We wanted to identify and determine the value of ecosystem services in the area of the Abisko National Park (Sweden) in order to aid management decisions.

WHAT DID WE DO?

First we collected data on physical, social and economic aspects. Then we made a model to illustrate the interplay between natural ecosystems and human activities in the study area. The data collected were used to evaluate the main ecosystem services as well as to account for environmental costs and impacts due to tourism and research activities. Finally, we estimated the economic value of the ecosystem services based on tourists' perceptions and willingness to pay for supporting nature conservation activities.

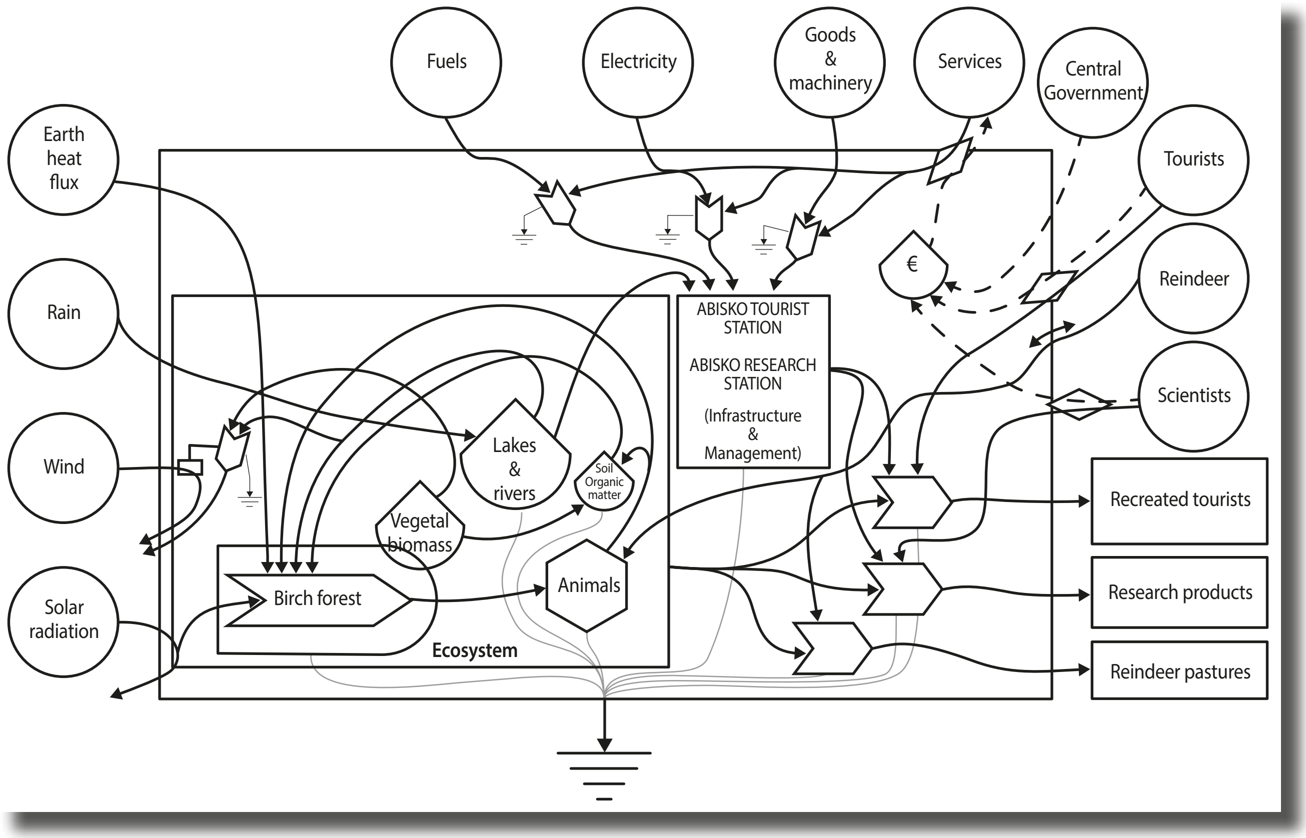
WHERE DID WE WORK?

We worked at the Abisko Scientific Research Station (•11) located in Swedish sub-Arctic Lapland. The station is open throughout the year and has modern and well-equipped research facilities. In addition, the station is located in a strategic position and has long-term databases and a wide collection of scientific literature most useful for setting up scientific studies in the area.

WHAT DID WE FIND?

We found that the presence of the Abisko National Park ensures the generation of a valuable set of ecosystem services, which include: regulating (e.g., carbon sequestration, water regulation), provisioning (e.g., game, wood, water), and cultural services (e.g., recreation and research activities). Human-managed activities in the area entailing the main environmental costs and impacts were tourism and reindeer husbandry. Results also showed that 61% of the interviewed tourists were willing to pay for the implementation of adaptation strategies coping with climate change impacts. The willingness to pay ranged from 2€ to 376€, with an individual mean value of 20.6€. These results are in line with those obtained from previous studies on protected areas located in boreal and temperate forest ecosystems.

Lapporten near Abisko Scientific Research Station, Sweden (Pier Paolo Franzese).



Symbolic model showing the main input and output flows, and the interactions between natural ecosystems and human managed activities in the Abisko area. Snow and soil nutrients were not included in the model.

WHY ARE THE RESULTS IMPORTANT?

The Abisko National Park represents one of Europe's last remaining wilderness areas, showing major environmental, climatic and vegetation gradients and changes. Although the Arctic landscape seems to be pristine and untouched, there has been an impact of human activities which is becoming more and more evident at Arctic latitudes, where global change manifests itself first and fastest.

THE ADVENTURE

The field activities gave us the opportunity to experience the beauty of Nordic flora and fauna. Particularly exciting was the moment when we found a big moose right outside the door of the research station. Another unforgettable experience was a night when suddenly the sky got enlightened by the marvelous *aurora borealis* (northern lights).

Moose outside the Abisko Station buildings
(Pier Paolo Franzese).

Further information

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Ecosystem service social assessments in extreme environments

Daniel Orenstein & Roy Zaidenberg

The project is a social-based inquiry into cultural ecosystem services. The ecosystem services (ES) concept has become a prominent framework for ecosystem assessment and research relevant to people. ES are ecological processes that give rise to benefits to humans that make life possible and worth living. These include the fundamental processes that assure livable climate, fertile soils, and clean air and water, processes that allow humans to derive food and materials from the Earth, and processes that create cultural landscapes that provide recreation and social meaning. We study the last of these – cultural ecosystem services.

Nature: majestic pines of the Cairngorms (Daniel Orenstein).

AIMS OF THE PROJECT

We aimed to understand what characteristics of ecosystems humans appreciate for non-material well-being, what aspects of the landscape they most appreciate, what is the connection between their activities and their values vis-à-vis the landscape, and how do they perceive tradeoffs between economic development and provision of cultural and other services. In order to answer these questions, we apply social research methods, including public surveys, in-depth interviews, and focus-group discussions.

WHAT DID WE DO?

We completed over 400 questionnaires querying the opinions, perceptions and behaviours of the local and tourist populations and we returned a year later to complete 20 in-depth interviews with diverse stakeholders.

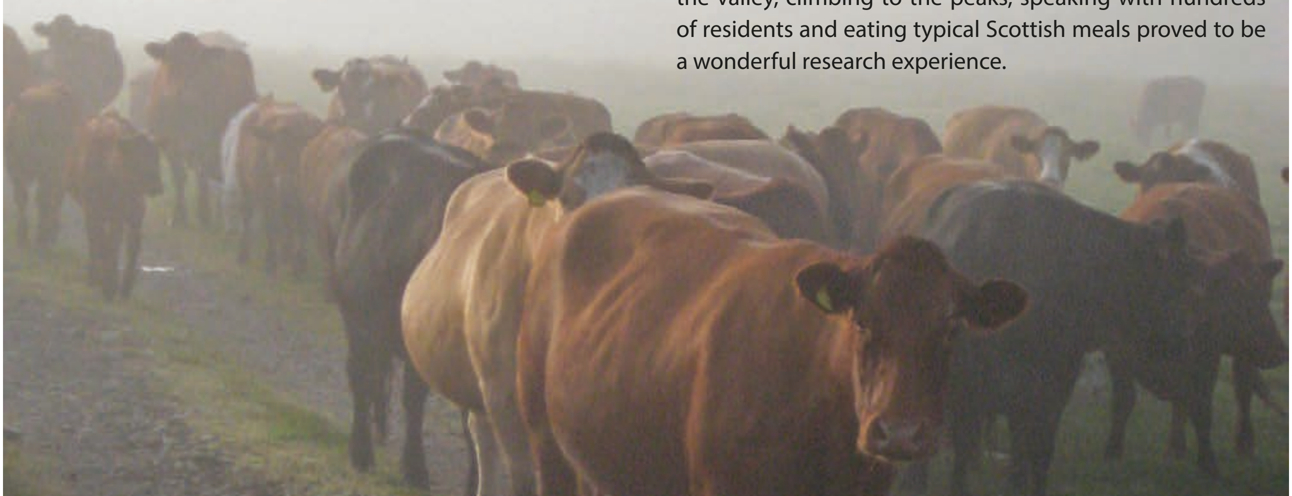
WHERE DID WE WORK?

We worked in Scotland's Cairngorms National Park (ECN Cairngorms (•76)) and compared our data with data obtained in the Dead Sea Basin in Israel; both the Cairngorms and the Dead Sea Basin are considered extreme environments (sub-alpine and hyper-arid, respectively) and are geographical/demographical peripheral areas relative to their respective countries.

WHAT DID WE FIND?

A sample of the survey results reveals that local residents have a strong affinity for both geography (landscape, mountains, openness) and biodiversity (trees, flowers, animals), while characteristics of the extreme environments (wind, precipitation, winter day-length) along with biting insects are among the least favored environmental characteristics. These results correlate closely with the Dead Sea data and previous research conducted in extreme environments in Israel and Jordan. The population expresses high commitment to environmental and ecological values in both surveys and interviews, but also believes that economic development and environmental protection can, and should, occur together (i.e. "sustainable" development). Both the Dead Sea and the Cairngorms respondents see tourism and agriculture as the basis of their economies. In the Cairngorms, most respondents did not want to see more population growth in the region, while in the Dead Sea, population growth was seen as essential to long-term socio-economic sustainability. In the Cairngorms, respondents involved in farming/fishing and forestry recognized the natural environment as crucial to their economic livelihood. Despite the role of the natural wild landscape in attracting tourists to the region, those who reported working in tourism-related businesses did not judge that their economic well-being was dependent on the natural resources of the area.

Agriculture: The cattle of Balliefurth Farm, Scotland (Daniel Orenstein).



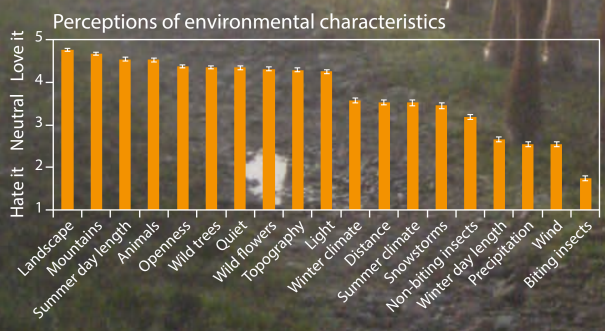
WHY ARE THE RESULTS IMPORTANT?

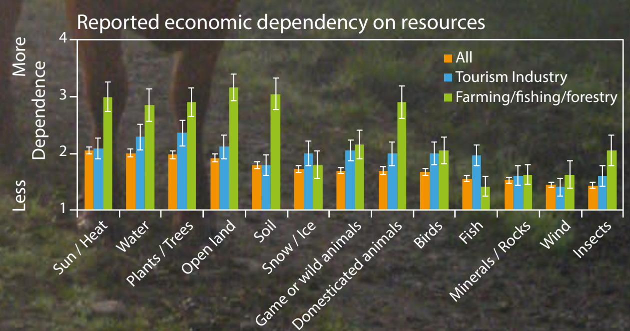
The ecosystem services concept is becoming integrated into environmental policy and planning, and cultural services should play a central role in shaping policy alongside provisioning (e.g. natural foods) and regulating (e.g. carbon capture) services. The research conducted here allows us to begin to characterise and quantify cultural services in the ecosystem. Further, it is a way in which the public can express its desires and preferences vis-à-vis their natural environment.

THE ADVENTURE

Coming from the hot, arid Middle East and experiencing the rainy, green Cairngorms was an adventure in itself. Hiking the valley, climbing to the peaks, speaking with hundreds of residents and eating typical Scottish meals proved to be a wonderful research experience.

Sample of research results from public surveys in the Cairngorms.





Tourism: Cairngorm Hotel in Aviemore (Daniel Orenstein).

Further information

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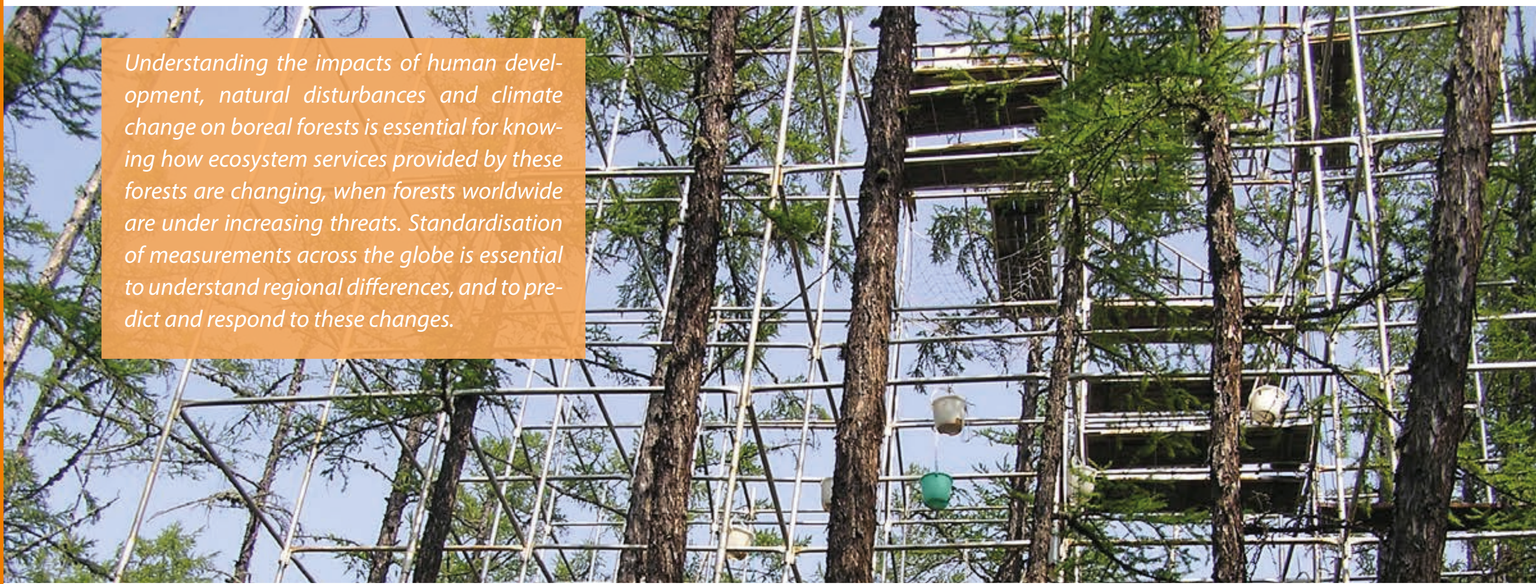
Assessment of boreal forest ecosystem services at two Russian sites

Jill Thompson & Mike Smith

Understanding the impacts of human development, natural disturbances and climate change on boreal forests is essential for knowing how ecosystem services provided by these forests are changing, when forests worldwide are under increasing threats. Standardisation of measurements across the globe is essential to understand regional differences, and to predict and respond to these changes.



Scaffold allows access to trees for tree physiology measurements near Spasskaya Pad Scientific Forest Station (Jill Thompson).

AIMS OF THE PROJECT

We aimed to establish new scientific collaborations and to exchange knowledge and information about boreal forest ecosystems and human interactions with the forests. To this end we used questionnaires with local people to determine the ecosystem services provided by boreal forests and also assessed the feasibility of establishing large, long-term forest plots. The questionnaires were adapted from those used by the project described in Science Story 7.3 to give information on the full range of ecosystem services that forests deliver and included questions such as what amount of timber and food is collected and how much time is spent visiting and enjoying the forest. The large forest plots will help us to understand the amount of carbon that is stored in the forests and the ecological processes that maintain them. The forest plot methods which were discussed during our visit, followed those developed by the international Center for Tropical Forests that has expanded to include all other forests by joining with the Smithsonian Institution "Global Earth Observatory Network" (CTFS-SIGEO, www.sigeo.si.edu). This global forest network now acts as a platform for a wide range of studies including ecosystem services, ecosystem processes, carbon dynamics and plant and animal interactions. The methods describe how the data on trees and tree size is collected and enables the information about the forests to be shared.

WHERE DID WE WORK?

The journey inside Russia started in Khanty-Mansiysk at the University of Yugra and the first forest site at the Mukhrino Field Station (•29) was on the eastern bank of the Irtysh River in the central *taiga* (the Russian boreal forest) area of western Siberia. The research site is representative of the western Siberian pristine peatland ecosystems with pine and dwarf shrub bogs. The forest is characterised by the following species: *Pinus sylvestris, P. sibirica,* (evergreen pine trees) *Larix sibirica,* (deciduous larch trees) *Populus tremula* and *Betula platyphylla* (deciduous poplar and birch trees).

The team then flew east to the city of Yakutsk in the Central Yakutia region and visited the Spasskaya Pad Scientific Forest Station (•39), located on a Pleistocene terrace on the western bank of the Lena River. The forest ecosystem surrounding the station is characterized by sparse taiga and also by pine and larch forests (*Pinus sylvestris* and *Larix sibirica*).

These sites, which are each typical of their regions, are not currently included in the CTFS-SIGEO network (mentioned above).

WHAT DID WE DO?

Along with our hosts we visited forest sites and identified suitable areas for the establishment of large 50 ha forest plots, and discussed CTFS methods for plot establishment and how to measure the trees.

We also visited education establishments, local administrators and scientists interested in participating in the projects in Khanty-Mansiysk and Yakutsk to discuss the needs and opportunities for long-term forest plot monitoring.

We distributed the questionnaires about forest ecosystem services and collated verbal feedback at both sites from students, staff and scientists, and also local people in three small villages near to Yakutsk.

WHAT DID WE FIND?

We found great enthusiasm for the potential to join the CTFS-SIGEO network both at the political administrative level and from the local forest managers.

The Department of Natural Resources in Khanty-Mansiysk, the University of Yugra and staff at the Institute of Biological Problems of Cryolithozone agreed to engage in collaborative research and to support the establishment of large forest plots, research projects and student exchange. We obtained a total (for both sites) of 118 completed questionnaires about forest ecosystem services. The ecosystem service concept was new to the local people and the questionnaires proved to be a useful medium to exchange knowledge about the interaction of local people with the forests and surrounding areas.

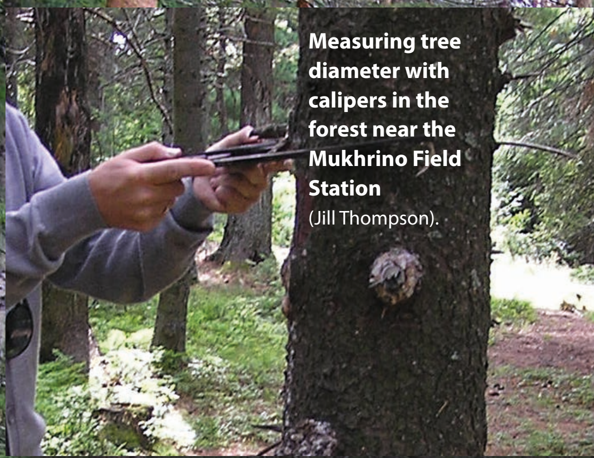
WHY ARE THE RESULTS IMPORTANT?

Worldwide, forests are under increasing threat from human development, changing intensity and frequency of natural disturbance, and climate change. The impact of these threats on forests and their plant, animal and microorganism dynamics, ecosystem functions and resistance and resilience to change is not fully understood. Scientists are therefore establishing long-term forest plots across the Globe to learn more about forests and human interactions. There are currently no large forest plots (16 -50 ha) that we know of in boreal Russian forests.

THE ADVENTURE

We had a wonderful time at both sites and very much appreciated the opportunity to meet knowledgeable and interesting people with an enthusiasm for studying natural science and understanding the links to human well-being. We tasted new foods, saw new forests, and learnt a great deal about a completely different part of the world that we had not previously experienced. We were made to feel very welcome by everyone at both sites and were very grateful that our hosts spoke English!

Edge of forest near Khanty-Mansiysk field station (Jill Thompson).



Measuring tree diameter with calipers in the forest near the Mukhrino Field Station (Jill Thompson).

Forest with board walk over wet areas near the Mukhrino Field Station (Jill Thompson).

Further information

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Working with local communities to quantify Arctic ecosystem services

Ron Smith

Representatives of local communities explained how their lives are linked to the ecosystems in northern Sweden. A decision tool helped construct a snapshot of the current situation and probe potential pressures, providing a way to evaluate trade-offs and empower communities.

AIMS OF THE PROJECT

We aimed to collate information from local stakeholders and to test the usefulness of a *decision tool*, a Bayesian Belief Network (BBN), in helping to quantify the ecosystem services of the Arctic.

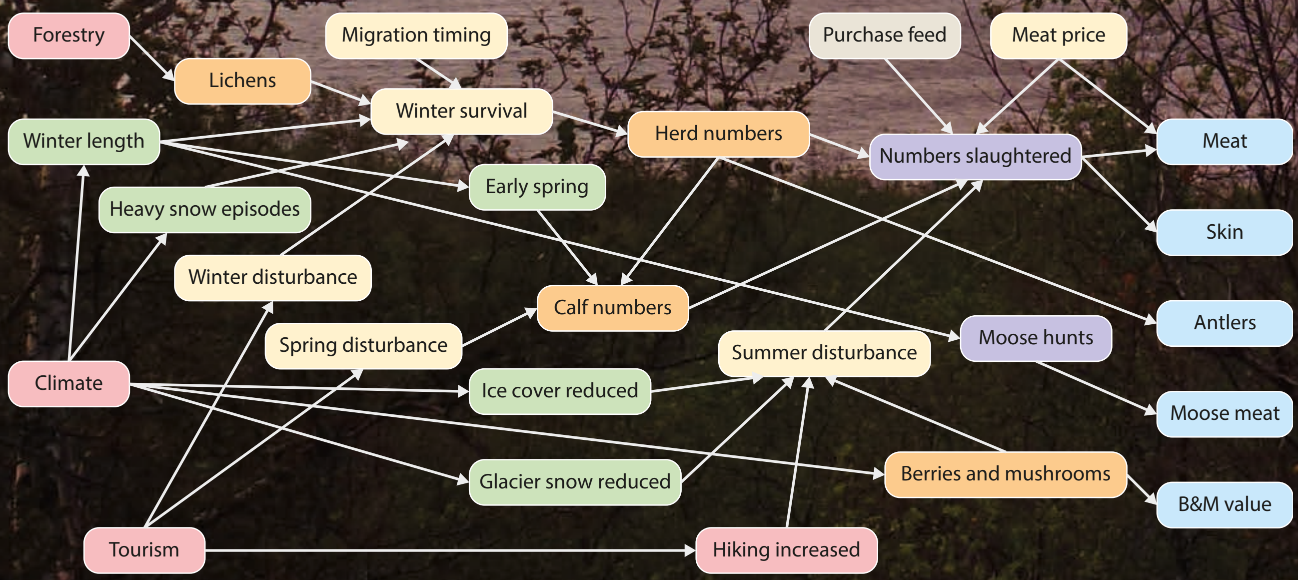
WHERE DID WE WORK?

Having developed ecosystem services ideas around the Scottish INTERACT site in the Cairngorms National Park (ECN Cairngorms (•76)), the sub-Arctic area in Norrbotten Province (the northernmost province of Sweden) provided a contrasting landscape with very different challenges – a good place to develop the work further. Abisko (•11) and Tarfala (•10) research stations, with their links both to the ecology and the social structures in the area, were ideal bases.

WHAT DID WE DO?

Having established the background history of the area, local experts informed us about current environmental issues from different stakeholder perspectives, i.e. the Swedish Tourist Board and the Naturum ("Nature Room" visitor centre). Both institutions at Abisko provided the main inputs on tourism, conservation and the National Park. Other stakeholders included the Kiruna Community Environment Office on regulation and planning and the Sámi community on traditional lifestyles. This knowledge was supplemented by very helpful exchanges with

Example Bayesian Belief Network of reindeer herding.



staff at the two INTERACT stations. We constructed separate storylines around the environmental issues of conservation, tourism, development regulation and reindeer herding. Interactions of different groups of people with the environment were translated into BBNs, a graphical representation of the dependencies from environmental pressures to human benefits (see example BBN of reindeer herding) which can then be quantified to aid management decisions. A second visit allowed us to work with Sámi from other reindeer herding districts, to gain more information about mining activities, and to review the storylines and BBNs with stakeholders – giving us an informal assessment of both the usefulness of the tools and the availability of data to quantify the processes.

WHAT DID WE FIND?

Stakeholders are using the underlying ideas of the ecosystem services concepts already, though the jargon tends to be a barrier to communication. The BBN diagrams were easy to understand and helped stakeholders probe for information about the processes being described. We had comments that the whole exercise had enabled them to stand back to consider the entire context of their environmental issues, providing them with a valuable snapshot of the current situation and potential pressures. Data were readily available for some ecosystem services and their responses to pressures, but not for all parts of the diagrams we developed.

WHY ARE THE RESULTS IMPORTANT?

There are trade-offs in any activity which exploits the environment, from the opening of an area for hiking to the development of mineral extraction (promoted as providing substantial income to the local community). However, in the fragile Arctic environment with very slow recovery rates, ecological damage may be long-lasting and potentially irreversible, so care of the environment is particularly important. BBNs set within an ecosystem services framework clearly helped to identify environmental issues in Norrbotten Province by using a formal and transparent process. This could provide the people of the North with a useful tool to take stock of their environment and also empower communities to discuss their different interests and establish compromises.

THE ADVENTURE

The two visits to the area were very contrasting experiences. Balmy summer days with long evenings and pleasant walks changed into struggling with ice and slush on a winter's day, but also walking in snowshoes through magnificent sunny snow-bound mountain landscapes with breathtakingly low temperatures. The team's Arctic journeys brought home the challenges of the landscape and climate, the attraction of the peaceful isolation contrasting with the hard graft and persistence needed to work in these areas. The warm welcome and help from all the people we met enhanced the experience.

Evening over Torneträsk lake from Abisko (Ron Smith).

Further information

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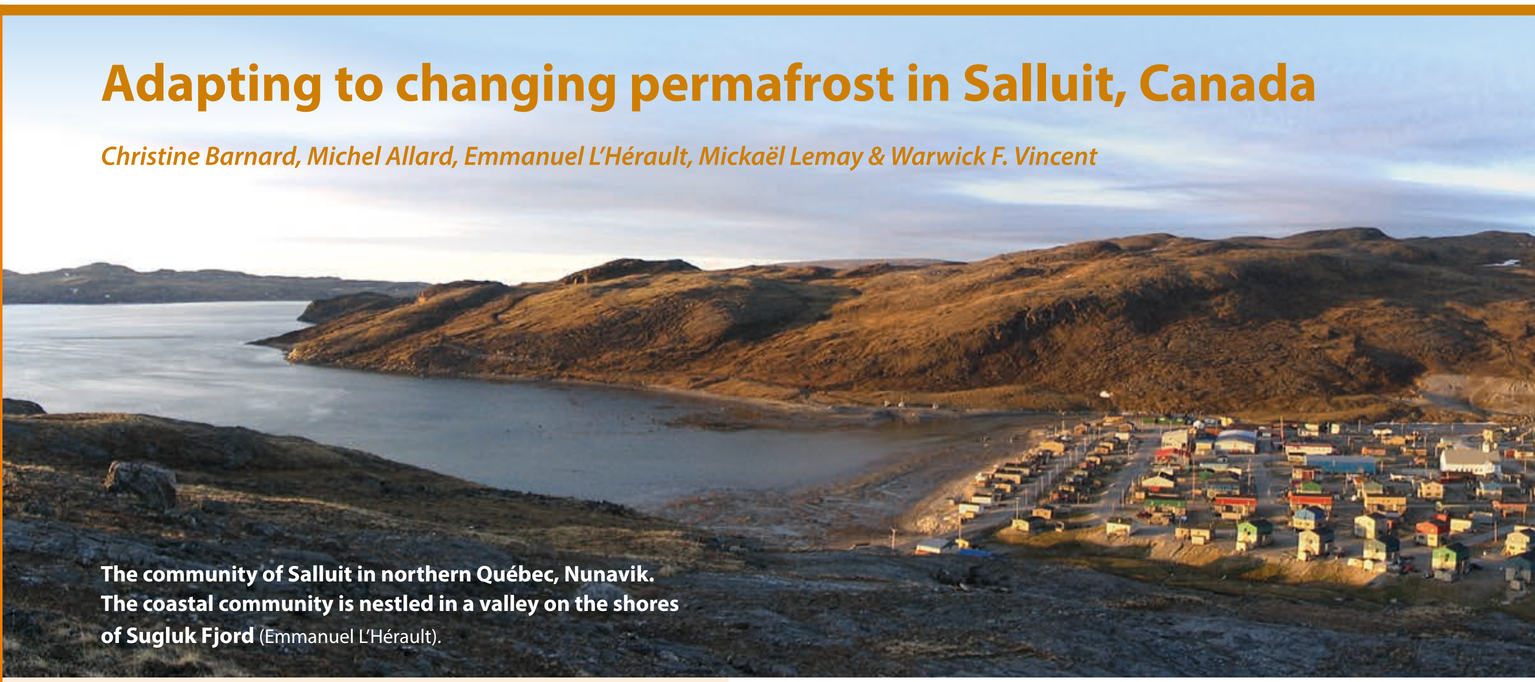
Train taking tourists back to Stockholm (Ron Smith).

Kiruna with mine workings in the background (Ron Smith).

Path damage (Ron Smith).

Adapting to changing permafrost in Salluit, Canada

Christine Barnard, Michel Allard, Emmanuel L'Hérault, Mickaël Lemay & Warwick F. Vincent



The community of Salluit in northern Québec, Nunavik. The coastal community is nestled in a valley on the shores of Sugluk Fjord (Emmanuel L'Hérault).

Permafrost is the key factor that makes Arctic lands particularly sensitive to climate change. This solid land provides the physical support for terrestrial ecosystems and it is also the base on which infrastructure such as roads, runways and houses are built. Permafrost is currently thawing (Section 2) and this now threatens the integrity of northern municipal, transportation and industrial infrastructure. This requires new engineering designs to either preserve permafrost or to adapt infrastructures to loss of frozen ground, and these have to be applied with increased care and meticulous planning. Climate change comes at a time when intense industrial development and fast growing northern populations call for new facilities such as roads, airstrips, seaports, railways, and housing units. From a sustainable development perspective, it is critical that northern communities adopt specific adaptation techniques and strategies to deal with warming permafrost in order to preserve or expand their infrastructure.

*The Canadian coastal village of Salluit, situated in northern Québec (Inuit territory of Nunavik), has a population of approximately 1,350 inhabitants with an expected increase in population of up to 2,000 inhabitants by 2025 (Institut de la statistique du Québec). Accommodating this increase in population is a complex issue to resolve as Salluit lies in the base of the valley underlain by ice-rich permafrost (*saline marine clays or tills*) which are sensitive to thaw and make even gentle slopes unstable for construction due to the potential risk of landslides. Formulated in the double context of rapid population growth and increasing vulnerability of infrastructure to thawing permafrost, this project was carried out at the request of the Government of Québec and funded by several ministries (Transports, Municipal Affairs, and Public Safety). The Kativik Regional Government was involved as the indigenous government responsible for community development. Permafrost and climate specialists, land use planners, economists, engineers, architects, local authorities and community members were brought together to develop detailed maps of permafrost conditions and sensitivity maps, and subsequently, a sustainable urban planning strategy.*

AIMS OF THE PROJECT

This project focused specifically on: (a) extensively characterizing permafrost in Salluit to determine safer areas for building; (b) determining how thawing permafrost is affecting man-made infrastructure; and (c) developing adaptation strategies to address population growth in a changing environment.

WHAT DID WE DO?

Representatives from the community, local government and scientists were first brought together to determine the community development needs and gather local knowledge on permafrost to identify instability issues observed in the village and its surroundings. The next steps involved several months of field work to collect the diverse types of data required to create multi-layer maps to ultimately determine the areas of Salluit that are safer for building. The variables collected during the field work included topographic data, geological characteristics, ground-ice conditions, snow cover and permafrost landforms. Over 100 boreholes were drilled to map Quaternary deposits over the solid bedrock. Several of the boreholes were used to install thermistor

One of the many community consultations held with local Inuit (Valérie Gratton).

cables to monitor ground temperature and *active layer depths*. Frozen cores were extracted from a series of sites to analyze the subsurface characteristics. This technique was coupled with *ground–penetrating radar, electrical resistivity surveys* and seismic surveys to complement data. All of these data were then integrated and collated in a *Geographic Information System* (GIS) application to produce detailed map layers of permafrost conditions. These map various layers were superimposed over a high resolution "hillshade" to create visual representation of topographic relief and also visualize the town's current infrastructures within their environmental context. Modelling active layer thickness variations and the permafrost thermal regime was also done using climate projections of the Canadian Regional Climate Model produced by Ouranos. Risk management maps were then generated and were based on a risk index integrating three layers of information: slopes, permafrost conditions and zones with severe constraints for construction (such as wetlands, actively moving ground and zones particularly sensitive to thaw). The final step was organizing several multidisciplinary meetings with community representatives, stakeholders and scientists to communicate results, to re-evaluate needs and potential risks and to make decisions for adaptation and urban development. The meeting also planned the community's future under the known terrain conditions.

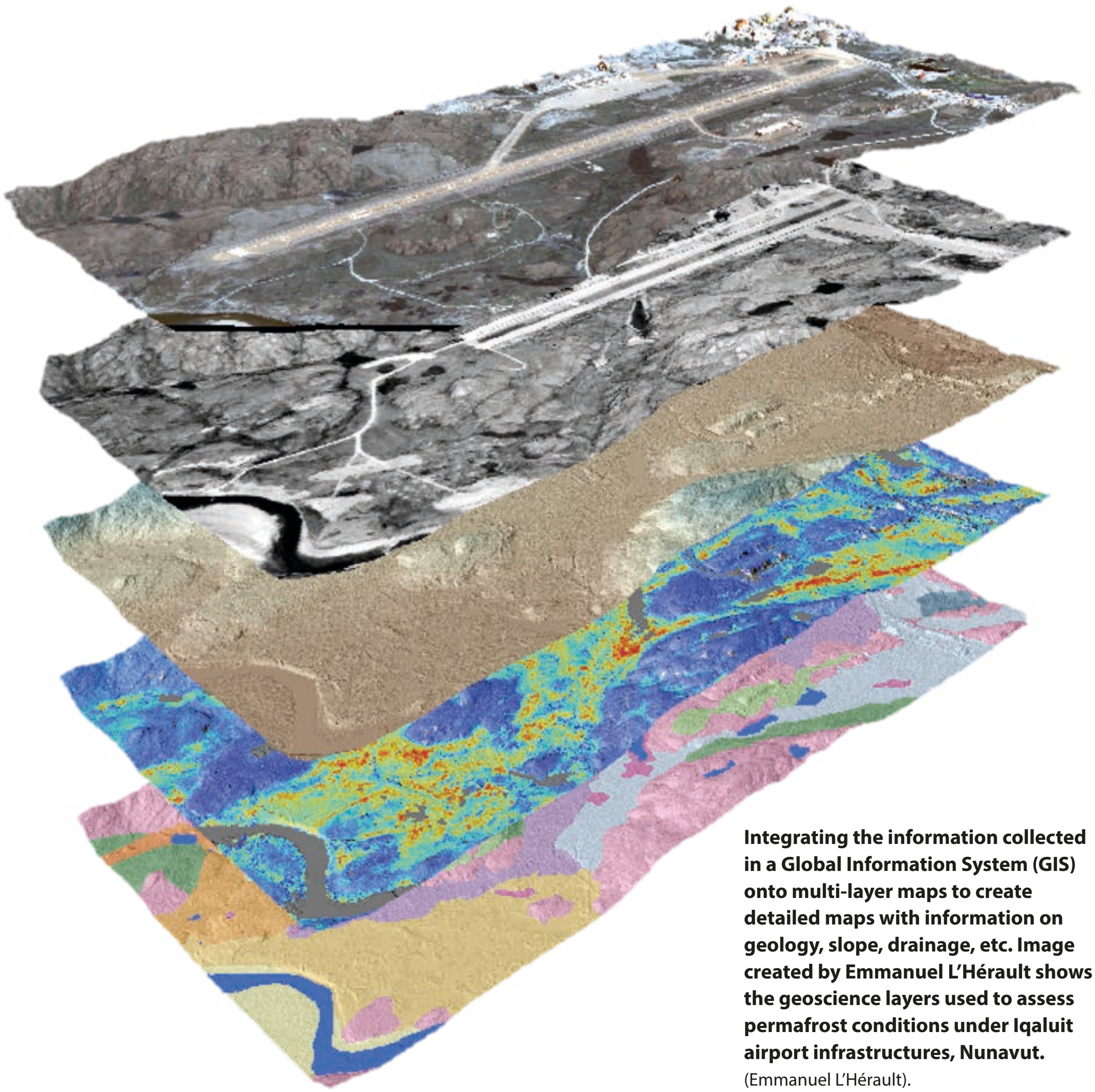
Thawing permafrost has major impacts on municipal and residential infrastructure (Emmanuel L'Hérault).

WHERE DID WE WORK?

In 1998, a massive landslide took place in Salluit prompting the abandonment of a new housing development project and the removal of 20 newly constructed houses. Since then, Salluit has been extensively surveyed and monitored to determine its actively changing permafrost characteristics. In 2011, Centre d'études nordiques (CEN) inaugurated a new INTERACT field station (CEN Salluit Research Station, (•58)) that serves as a base for permafrost research and community consultations. Using a site-optimized foundation design and solar panels, the CEN station is promoting sustainable land use and development over thaw-sensitive permafrost. The construction was funded by a federal infrastructure project.

WHAT DID WE FIND?

We presented our findings in maps. These maps of construction potential in areas with thawing permafrost are a powerful tool for policy-makers and managers. They contribute greatly to the generation of careful urban management plans to ensure the quality and sustainability of northern infrastructure. Furthermore, these maps aid engineers in developing new approaches for building infrastructure by providing tools that aid in visualizing the impacts of current methods used to control the effects of snow and water accumulation due to changing permafrost conditions in the vicinity of transportation and municipal infrastructure.



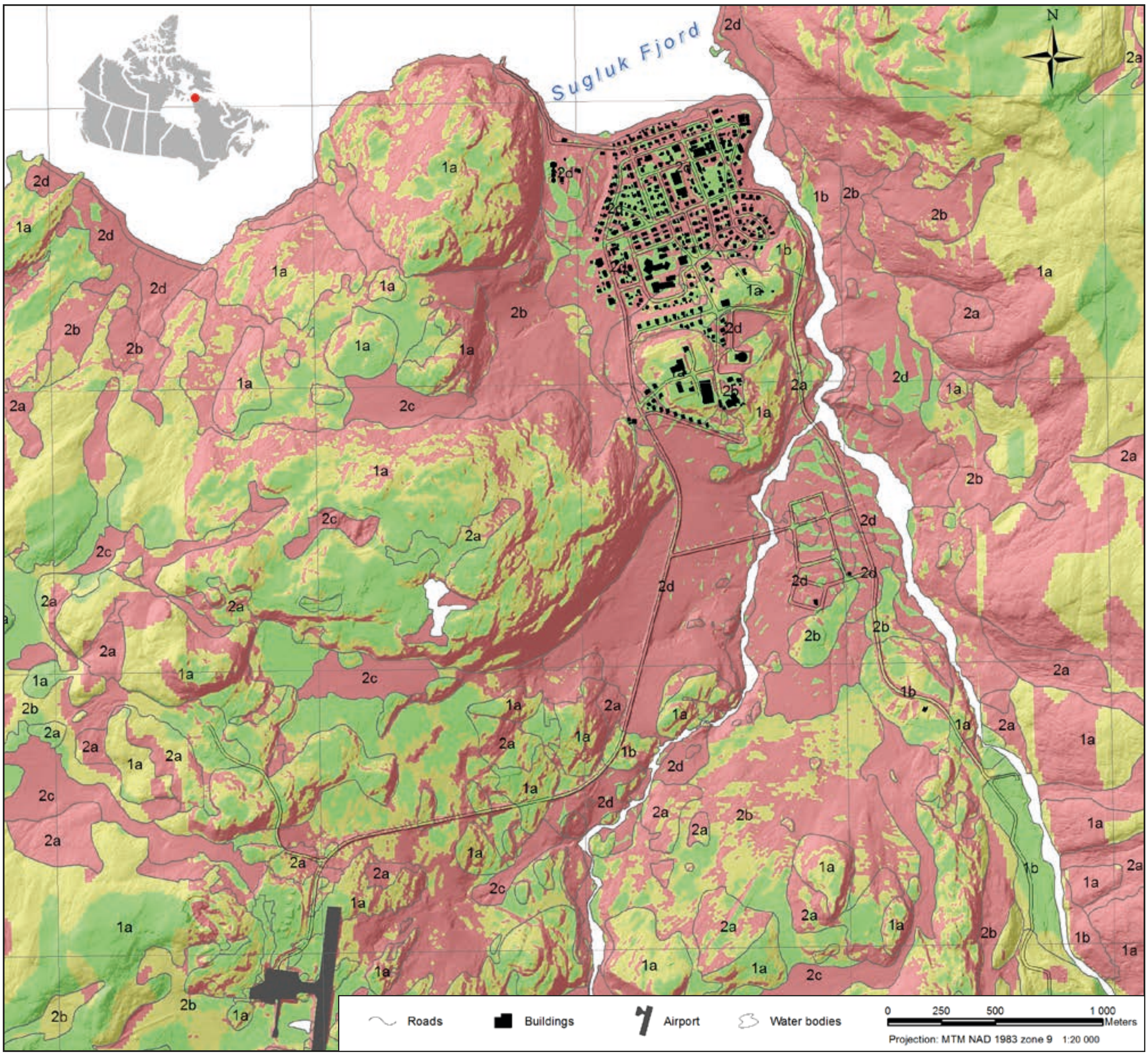
Integrating the information collected in a Global Information System (GIS) onto multi-layer maps to create detailed maps with information on geology, slope, drainage, etc. Image created by Emmanuel L'Hérault shows the geoscience layers used to assess permafrost conditions under Iqaluit airport infrastructures, Nunavut. (Emmanuel L'Hérault).

WHY ARE THE RESULTS IMPORTANT?

This project showcases how research has helped a community adapt to change brought about by permafrost in transition. It is ongoing and has been expanded in other Inuit communities in Nunavik and in Nunavut. Building on the long history of work in this village, research has continued within the ADAPT project (Arctic Development and Adaptation to Permafrost in Transition; www.cen.ulaval.ca/adapt) which focuses on how changing permafrost and snowfall affect landscapes, water and wildlife, and the implications for northern communities and industries who depend on these resources. ADAPT brings together laboratories from across Canada and abroad to examine diverse aspects related to thawing permafrost conditions in the Arctic. Here we have focused specifically on how thawing permafrost is affecting man-made infrastructure, but the ADAPT project also studies the links between changing permafrost and ecosystems (wildlife and vegetation), microbiological processes and greenhouse gas fluxes, and the development of permafrost monitoring protocols. The long-term data from Salluit are available via the online data series Nordicana D (www.cen.ulaval.ca/nordicanad).

THE ADVENTURE

All the persons involved, be they local residents, community executives, employees of governments and academia, lived a special personal experience, mainly through listening and sharing concerns not just about the permafrost issues at the origin of the problems, but mostly about how to build better living conditions and a more promising environment for people. A series of exchanges with the community, including conversations on the local FM radio, field outings on snowmobiles and camping on the land, and extensive workshops with elders and school kids took place. The project presented several fantastic opportunities for the researchers to stay in camps on the land and share country food with the community. At one point, the tragic loss out on the sea ice of three hunters, who were our friends in-the-making and actively involved in the community improvement project, was a reminder of the harsh traditional living conditions of the Inuit and the increased dangers resulting from climate warming. Permafrost research with people who are truly engaged is a lifetime human experience for a scientist.



Risk management map for potential construction development in Salluit. The various colours identify the different risk categories for building: green = terrain manageable for construction; yellow = terrain manageable for construction but may require significant earthwork; dark pink = terrain unsuitable for construction due to slope or problematic terrain type. 1) Bedrock and superficial deposits with no or little ice content; 2) Ice-rich permafrost in superficial deposits. 1) and 2) are further subdivided into their geomorphological characteristiscs in the full version (Derived from Allard and L'Hérault 2010).

Further information

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Appendix

Projects supported by INTERACT Transnational Access 2011-2015

Section 1 Landscapes and land-forming processes

Project	First author/ Project leader	Affiliation	Station numbers	Stations visited	Reference
Evaluating radar remote sensing data for Arctic tundra landscapes	Jennifer Sobiech-Wolf	Alfred-Wegener Institute, Helmholtz Center for Polar and Marine Research, Germany	70	ZAC	SS 1.1
The impact of glacial erosion on the bedrock plains of northern Fennoscandia	Karin Ebert	Stockholm University, Sweden	12, 13, 16	KILPIS, KEVO, KOLARI	SS 1.2
Past climate of the Faroe Islands during the Late glacial period	Brice R. Rea	University of Aberdeen, Scotland, UK	75	FINI	SS 1.3
Moraine internal structure and form	Toby N. Tonkin	Nottingham Trent University, UK	10	TRS	SS 1.4
Outburst flood characteristics of a glacier-dammed lake in N-E Greenland	Daniel Binder/ Wolfgang Schöner	ZAMG, Vienna, Austria	70	ZAC	SS 1.5
The effects of climate change on air and soil microclimates in areas of complex topography	Nick Pepin	University of Portsmouth, UK	11, 13	ANS, KEVO	www.eu-interact.org
A sedimentological investigation of palaeoglacier dynamics from Midtdalsbreen, south central Norway	Benedict Reinardy	Swansea University, UK	7	FINSE	www.eu-interact.org
Investigating palaeoenvironments and palaeoseismicity in the Abisko area, N-Sweden using sedimentary records from Torneträsk	Bernd Wagner	Institute for Geology and Mineralogy, Cologne, Germany	11	ANS	www.eu-interact.org
The Arctic-alpine parallels in a changing climate: permafrost, glaciers, soils and biota	Oleg Pokrovsky	Georesources and Environment, Toulouse, France	10, 11, 12	TRS, ANS, KILPIS	www.eu-interact.org
Torneträsk isotope dendroclimatology	Neil Loader	Swansea University, UK	11	ANS	www.eu-interact.org
Peatland ecological and hydrological dynamics in the Arctic	Lee Brown	University of Leeds, UK	11	ANS	www.eu-interact.org
Impact of the microbial diversity on phosphorus mobilisation and soil organic matter stability in biological soil crusts in alpine and Arctic conditions	Christel Baum	University of Rostock, Germany	7, 13, 73	FINSE, KEVO, LBHI	www.eu-interact.org
Mapping periglacial landforms in the Faroe Islands	Ole Humlum	University of Oslo, Norway	75	FINI	www.eu-interact.org
Effect of vegetation cover on dissolved organic carbon in peatlands	Luca Bragazza	University of Ferrara, Italy	29	MFS	www.eu-interact.org
Viral and bacterial communities and interactions in western Siberian Sphagnum-peatlands	André-Jean Francez	University of Rennes, France	29	MFS	www.eu-interact.org
Changing flow characteristics and their impacts to river systems in the Arctic: a combined approach of earth observation data and simulations	Petteri Alho	University of Turku, Finland	49	KLRS	www.eu-interact.org

Section 2 Permafrost

Project	First author/ Project leader	Affiliation	Station numbers	Stations visited	Reference
The influence of permafrost on glacial meltwater and sediment transfer	Kathryn Adamson	Manchester Metropolitan University, UK	66	ARCST	SS 2.1
Plant community controls on thawing permafrost soils	Esther Dielissen/ Bjorn Robroek	Utrecht University, The Netherlands	11	ANS	SS 2.2
Greenhouse gas dynamics in a changing subarctic landscape	Mathilde Jammet/ Thomas Friborg	University of Copenhagen, Denmark	11	ANS	SS 2.3
Stable isotopes as indicators of environmental change	Jan Paul Krüger/ Christine Alewell	University of Basel, Switzerland	11	ANS	SS 2.4
Validation of soil moisture data from the Lena Delta retrieved from satellite	Elin Högström	Vienna Technical University, Austrian Polar Research Institute, Austria	38	SAM	SS 2.5
Permafrost thermal and geocryological state in Zackenberg	Hanne Christiansen	University of Svalbard, Longyearbyen	70	ZAC	www.eu-interact.org
Thaw-induced mobilization of soil organic carbon pools in permafrozen landforms and quaternary deposits	Christian Juncher Jørgensen	University of Copenhagen, Denmark	38	SAM	www.eu-interact.org
Combining field studies and remote sensing for analyses of permafrost landscape development	Annett Bartsch	University of Salzburg, Austria	38	SAM	www.eu-interact.org
Changing permafrost in the high latitude areas and its global effects	Trofim Maximov	Institute for Biological Problems of Cryolithozone of Siberian Branch of the Russian Academy of Sciences, Russian Federation	61	WKRS	www.eu-interact.org

Section 3 Snow and ice

Project	First author/ Project leader	Affiliation	Station numbers	Stations visited	Reference
How snow insulates permafrost soils	Martin Proksch/ Martin Schneebeli	WSL Institute for Snow and Avalanche Research, Davos, Switzerland	38	SAM	SS 3.1
Black carbon and its radiative impact in a Svalbard snowpack	Christina A. Pedersen	Norwegian Polar Institute, Norway	1	SVERDRUP	SS 3.2
Adaptations and survival of microorganisms on snow and ice	Liane G. Benning	University of Leeds, UK	10, 68	TRS, SER	SS 3.3
Glacier monitoring in South-East Greenland	Sebastian H. Mernild/Edward Hanna	Centre for Scientific Studies, Chile	68	SER	SS 3.4
Relationships between glacier dynamics and climate	Gwenn Flowers	Simon Fraser University, Burnaby, Canada	49	KLRS	SS 3.5
Examining the effect of changes in plateau icefield mass balance on ice margin retreat patterns and depositional processes	Clare M. Boston	University of Exeter, UK	7	FINSE	SS 3.6
GPR investigation of a Norwegian glacier's marginal ice conditions	Adam D. Booth	Imperial College London, UK	7	FINSE	SS 3.7
Testing hypotheses on the responses of small Arctic glaciers to climate change	David M. Rippin	University of York, UK	11	ANS	www.eu-interact.org
Mapping of glacial trimlines from multi-spectral satellite imagery, South-East Greenland	Anna Hughes	Swansea University, UK	68	SER	www.eu-interact.org
Quantifying the influence of refreezing melt water on the mass balance and runoff of Freya Glacier	Wolfgang Schöner	University of Graz, Austria	70	ZAC	www.eu-interact.org
Structural glaciology and debris transfer of Storglaciären	Simon Cook	Aberystwyth University, UK	10	TRS	www.eu-interact.org
Investigating the maximum Weichselian ice extent and deglacial history around Mittivakkat Glacier, Sermilik Fjord, South-East Greenland	Laurence Dyke	Swansea University, UK	68	SER	www.eu-interact.org
Dating techniques cross calibrating using lichenometry, radiocarbon dating, and surface exposure dating	Vincent Rinterknecht	University of St. Andrews, UK	66, 68, 70	ARCST, SER, ZAC	www.eu-interact.org
Glacsweb reconnaissance study	Jane K. Hart	University of Southampton, UK	7	FINSE	www.eu-interact.org
Measuring englacial liquid-water using borehole geophysics at Storglaciären	Charlotte Axtell	Swansea University, UK	10	TRS	www.eu-interact.org
Examining the effect of changes in plateau ice field mass balance on ice margin retreat patterns and depositional processes	Robert Bingham	University of Aberdeen, UK	11	ANS	www.eu-interact.org
Glacial anthropogenic nutrients in SE Greenland	Andrew J. Hodson	Sheffield University, UK	68	SER	www.eu-interact.org
Holocene glacial evolution in East Greenland determined from pro-glacial sediment proxies	Craig Frew	University of Aberdeen, UK	68	SER	www.eu-interact.org
Nitrogen fertilization of oceans by the melting Greenland Ice Sheet	Jon Telling	University of Bristol, UK	68	SER	www.eu-interact.org
Transitional glaciation in the central Khibiny Mountains, Arctic Russia	Lorna Linch	University of Brighton, UK	26	KHIBINY	www.eu-interact.org
Laser scanning Tarfala for geomorphological characterization and activity analysis	Jonathan Carrivick	University of Leeds, UK	10	TRS	www.eu-interact.org
Flute morphometry from photogrammetry	Jeremy Ely	University of Sheffield, UK	10	TRS	www.eu-interact.org
Structural controls and runoff forcing Arctic cryospheric ecosystems	Tristram Irvine-Fynn	Aberystwyth University, UK	10	TRS	www.eu-interact.org
Spatial impact of outburst floods on the A.P. Olsen Ice Cap dynamics (North-East Greenland)	Andreas Wieser	Institute of Geodesy and Photogrammetry, Swizerland	70	ZAC	www.eu-interact.org

Section 4 Land-atmosphere linkages

Project	First author/ Project leader	Affiliation	Station numbers	Stations visited	Reference
An energy exchange in the Arctic –A "butterfly effect" for the global climate?	Christian Stiegler/ Anders Lindroth	Lund University, Sweden	67	GINR	SS 4.1
Patterns of carbon storage in a Siberian permafrost landscape	Gustaf Hugelius	Stockholm University, Sweden	39, 41	SPA, CHO	SS 4.2
How does increasing CO_2 affect soil microbial diversity and carbon fluxes	Dylan Gwynn-Jones	Aberystwyth University, UK	11	ANS	SS 4.3
Fluxes of volatile organic compounds from plants on Greenland	Thomas Holst	Lund University, Sweden	66	ARCST	SS 4.4
Controls on volatile organic compound emissions from northern plants	Riikka Rinnan	University of Copenhagen, Denmark	12, 17	KILPIS, OULANKA	SS 4.5
Effects of long-term environmental change on carbon fluxes and mycorrhizal diversity in subarctic heath ecosystems	Anders Michelsen	University of Copenhagen, Denmark	11	ANS	www.eu-interact.org
The effect of temperature on the subsurface microbial production of greenhouse gases in the Arctic	Will Manning	Newcastle University, UK	66	ARCST	www.eu-interact.org
Plants in a low CO_2 world: development and validation of botanical and organic geochemical proxies for the Pleistocene plant record and reconstructed feedbacks on the carbon cycle	Alexandra Hincke	University of Utrecht, The Netherlands	13	KEVO	www.eu-interact.org
Impact of Arctic zone on the chemical and biochemical processes, conversions and transformation in peat layers	Lech Szajdak	Polish Academy of Sciences, Poznán, Poland	29	MFS	www.eu-interact.org
Functioning of Siberian mire ecosystems and their response to climate change	Fatima Laggoun-Defarge	University of Orléans, France	29	MFS	www.eu-interact.org
Plant-soil-herbivore interactions in the Arctic -feedbacks to the carbon cycle	Lena Ström	Lund University, Sweden	70	ZAC	www.eu-interact.org
Plant-soil interactions in a greening Arctic: Effects of shrub expansion on carbon cycling	Thomas Parker	University of Stirling, UK	11	ANS	www.eu-interact.org
The effect of forest type and microbial characteristics on soil thermal sensitivity	Beata Klimek	Jagiellonian University, Krakow, Poland	17	OULANKA	www.eu-interact.org
Forecasting Arctic soil microbial communities in 2050	Arwyn Edwards	Aberystwyth University, UK	11	ANS	www.eu-interact.org
Photodegradation in peat decomposition	Bente Foereid	University of Abertay Dundee, UK	29	MFS	www.eu-interact.org
Changes in soil organic matter and decomposition due to defoliation of subarctic birch stands by insect outbreaks	Hans Göransson	BOKU, Austria	8, 11	BIOFORSK, ANS	www.eu-interact.org
Are free amino-acids in soils BIO-indicators of climate change effects in ecosystems?	Louise C. Andresen	University of Gothenburg, Sweden	7	FINSE	www.eu-interact.org
Greenhouse gas exchange in boreal wetland and freshwater ecosystems: a multi-scale approach	Ivan Mammarella	University of Helsinki, Finland	29	MFS	www.eu-interact.org
How climate change may affect the composition of Dissolved And Volatile Organic Carbon Compounds generated by Arctic Peatlands: the DAVOCCAP project	Roxane Andersen	University of the Highlands and Islands, UK	29	MFS	www.eu-interact.org

Section 5 Life on cold lands

Project	First author/ Project leader	Affiliation	Station numbers	Stations visited	Reference
Recent influence of climate on shrub growth around the North-Atlantic region	Allan Buras/ Marting Wilmking	University Greifswald, Germany	7, 13, 75	FINSE, KEVO, FINI	SS 5.1
Patterns of insect herbivory along altitudinal gradients in a polar region	Mikhail Kozlov	University of Turku, Finland	26	KHIBINY	SS 5.2
Grass seed "hitchhikers" –grass-endophyte symbiosis across the latitudes	Kari Saikkonen	National Resources Institute, Finland	8, 13, 66, 73, 75	BIOFORSK, KEVO, ARCST, LBHI, FINI	SS 5.3
Consequence of the climate change on the fate of the Arctic-alpine bumblebees	Baptiste Martinet/ Pierre Rasmont	University of Mons, Belgium	10, 11, 48	TRS, ANS, TOOLIK	SS 5.4
Is rodent-borne Ljungan virus responsible for mortality in migrating Norwegian lemmings (Lemmus lemmus)	Heidi Hauffe	Research and Innovation Centre, Fondazione Edmund Mach, Italy	12	KILPIS	SS 5.5
High Arctic food webs	Tomas Roslin	University of Helsinki, Finland	70	ZAC	SS 5.6
How predator-prey interactions impact distribution and breeding systems of high Arctic waders under current Climate Change	Jeroen Reneerkens	University of Groningen, The Netherlands	70	ZAC	SS 5.7
Sex ratio variation in northern Common frogs	Cécile Patrelle	University of Angers, France	12	KILPIS	www.eu-interact.org
Effects of changes in climate and reindeer management during a century on the vegetation composition in a Fennoscandian tundra ecosystem	Åsa Lindgren	The Swedish Agricultural University, Umeå, Sweden	12	KILPIS	www.eu-interact.org
Betula nana leaf growth response to changing CO_2 and growing season length	Friederike Wagner-Cremer	University of Utrecht, The Netherlands	13	KEVO	www.eu-interact.org
Screening cell features of Scots pine on extreme dry and moist sites in northern Scandinavia for their climatic signals and their qualification to reconstruct palaeoclimate	Dieter Eckstein	University of Hamburg, Germany	11	ANS	www.eu-interact.org
Geographic variation in functional traits of Arctic plants: predicting responses to climate change	Pawel Olejniczak	Institute of Nature Conservation, Polish Academy of Sciences, Poland	7, 11, 12, 13, 17, 68, 75	FINSE, ANS, KILPIS, KEVO, OULANKA, SER, FINI	www.eu-interact.org
Effects of species interactions on the co-occurrence, diversity and performance of Arctic plant species along abiotic stress gradient	Josep Ninot	University of Barcelona, Spain	68, 70	SER, ZAC	www.eu-interact.org
Possible range expansion of Plasmodium in bird populations of the Northern Europe	Indrikis Krams	Daugavpils University, Latvia	12, 13, 17	KILPIS, KEVO, OULANKA	www.eu-interact.org
Spatial variability of winter canopy structure across Arctic forests	Tim Reid	University of Edinburgh, UK	11	ANS	www.eu-interact.org
Genomics of adaptive variation in Pines	Stephen Cavers	Centre for Ecology and Hydrology, UK	29	MFS	www.eu-interact.org
Diurnal changes in leaf physiological activity during polar day in natural environments	Lea Hallik	Estonian University of Life Sciences, Tartu, Estonia	11, 12, 70	ANS, KILPIS, ZAC	www.eu-interact.org
Competition, adaptation and parasitoids of invasive species in northern communities.	Tea Ammunét	Swedish University of Agricultural Sciences, Uppsala, Sweden	8, 12, 13, 16	BIOFORSK, KILPIS, KEVO, KOLARI	www.eu-interact.org
Functional relationships between Carex species in subarctic and Arctic environments	Jan Dick	Centre for Ecology and Hydrology, UK	67, 73	GINR, LBHI	www.eu-interact.org
A functional analysis of microbial diversity in subarctic soils	Rien Aerts	VU University Amsterdam, The Netherlands	7, 11	FINSE, ANS	www.eu-interact.org
Spatial gradients in physiological adaptations and life history variation in Arctic wolf spiders	Philippe Vernon	University of Rennes, France	67, 70, 73, 75	GINR, ZAC, LBHI, FINI	www.eu-interact.org
Changes in the invertebrate community along natural and anthropogenic gradients in mires	Gert-Jan van Duinen	Bergerveen Foundation, Nijmegen, The Netherlands	29	MFS	www.eu-interact.org

Pollination biology of Calypso bulbosa and Epipactis atrorubens in Northern Europe	Tiiu Kull	Estonian University of Life Sciences, Tartu, Estonia	17	OULANKA	www.eu-interact.org
Spider-driven foodwebs in the high Arctic	Peter Hambäck	Stockholm University, Sweden	70	ZAC	www.eu-interact.org
Population dynamics driven by natural selection: do changes in frequencies of leaf beetle phenotypes contribute to density fluctuations?	Elena L. Zvereva	University of Turku, Finland	26	KHIBINY	www.eu-interact.org
Impact of grazing on biodiversity	Dan Cogalniceanu	University Ovidius, Constanta, Romania	16, 17	KOLARI, OULANKA	www.eu-interact.org
Decadal time-scale vegetation changes in the North: climate and land-use effects	Jutta Kapfer	Norwegian Forest and Landscape Institute, Norway	13, 16	KEVO, KOLARI	www.eu-interact.org
East-Greenland bryophytes – Biodiversity and importance as herbivore diet	Michael Stech	Naturalis Biodiversity Center, Leiden, The Netherlands	70	ZAC	www.eu-interact.org
Birch genetics in Finland and Scotland	James Borrell	Queen Mary University of London, UK	13	KEVO	www.eu-interact.org
Development of brown bear scrub tree hair snares	Anja Rudolph	Senckenberg Museum, Görlitz, Germany	8	BIOFORSK	www.eu-interact.org
Aspen genetic patterns	Berthold Heinze	Federal Research Centre for Forests, Switzerland	29	MFS	www.eu-interact.org
Parasites explain parthenogenesis in extreme environments	Matthew Tinsley	University of Stirling, UK	66	ARCST	www.eu-interact.org
Will high-altitude plants go extinct in a changing climate? Long-term changes of European mountain flora	Sonja Wipf	WSL Institute of Snow and Avalanche Research SLF, Davos, Switzerland	7, 10	FINSE, TRS	www.eu-interact.org
Grasses and their endophytes in subarctic environment	Marjo Helander	University of Turku, Finland	7, 75	FINSE, FINI	www.eu-interact.org
Research on alpine plant traits and functionality in the context of climate change	Harald Pauli	Austrian Academy of Sciences, Institute of Mountain Research, Austria	76	CEH	www.eu-interact.org
Testing of using lichenicolous fungi as indicators of long term ecological continuity in arctic-alpine ecosystems	Jana Kocourková	Czech University of Life Sciences, Prague, Czech Republic	75	FINI	www.eu-interact.org
Serial-sectioning applied to tundra shrubs for dendrochronological analyses in the high Arctic	Agata Buchwal	Adam Mickiewicz University, Poznan, Poland	48, 66, 67, 70	TOOLIK, ARCST, GINR, ZAC	www.eu-interact.org
Plant invasions at high altitudes and latitudes: what drives them	Ivan Nijs	University of Antwerp, Belgium	11	ANS	www.eu-interact.org
Vulnerability of arctic soil microbial communities to different kinds of stress	Marcin Chodak	AGH University of Science and Technology, Poland	8, 11	BIOFORSK, ANS	www.eu-interact.org
Comparison of related pollen depositions of tundra in central-European mountains and in subarctic region	Helena Svitavska Svobodova	Institute of Botany, Czech Academy of Sciences, Czech Republic	11	ANS	www.eu-interact.org
Local adaptation and gene flow in Empetrum hermaphroditum, a keystone species of boreal-arctic ecosystems, along an altitudinal stress gradient	Miriam Bienau	Institute of Landscape Ecology and Resource Management, Germany	11	ANS	www.eu-interact.org
Uptake of insect-derived nitrogen by Pinguicula vulgaris assessed using $\delta^{15}N$ stable isotopes	Francis Q. Brearley	Manchester Metropolitan University, UK	13, 17	KEVO, OULANKA	www.eu-interact.org
Understanding self-reinforcing feedbacks of woody invasion under contrasting permafrost conditions in boreal ecosystems	Juul Limpens	Wageningen University, The Netherlands	13	KEVO	www.eu-interact.org
Shrub expansion in the Arctic: An experimental and dendroecological analysis on community level	Stef Weijers	University of Bonn, Germany	66	ARCST	www.eu-interact.org
The forested-to-open bog ecotone in naturally and artificially forested peatlands	Richard Payne	University of Stirling, UK	29	MFS	www.eu-interact.org

Has synchronicity in tree performance increased during the last century in arctic biomes? Testing for continent-wide dendroecological imprints under global warming	Jordi Voltas	University of Lleida, Spain	29	MFS	www.eu-interact.org
Postglacial palaeoclimatic and -botanical dynamics at the tundra-taiga border-zone of West Siberia, Russia	Leeli Amon-Veskimeister	Tallinn University of Technology, Estonia	29	MFS	www.eu-interact.org
Spectral library of Arctic plants	Gareth Rees	University of Cambridge, UK	26	KHIBINY	www.eu-interact.org
Physiological and molecular adaptations to extreme climatic conditions in Pieris rapae	Jesper Givskov Sørensen	Aarhus University, Denmark	39	SPA	www.eu-interact.org
Vegetation - permafrost interactions in a lowland tundra ecosystem: shrub or graminoid expansion?	Monique Heijmans	Wageningen University, The Netherlands	41	CHO	www.eu-interact.org
Succession of biota after glacier retreats in subarctic-alpine climate zones	Alena Lukešová	Institute of Soil Biology, Biology Centre ASCR, Czech Republic	7, 10	FINSE, TRS	www.eu-interact.org
Effect of roads on species composition of forests in north-south gradient	Małgorzata Jaźwa	Jagiellonian University, Poland	8, 17	BIOFORSK, OULANKA	www.eu-interact.org
Constraints in spring advancement of High Arctic nesting birds	Theunis Piersma	University of Groningen, The Netherlands	70	ZAC	www.eu-interact.org
Climate change and ecosystem functioning – a pan-Arctic perspective	Helena Wirta	University of Helsinki, Finland	70	ZAC	www.eu-interact.org
Linking plant phenology to plant success in a warmer future	Janet Prevéy	WSL Institute for Snow and Avalanche Research SLF, Davos Dorf, Switzerland	47	BEO	www.eu-interact.org

Section 6 Life in cold waters

Project	First author/ Project leader	Affiliation	Station numbers	Stations visited	Reference
Reconstructing Holocene temperatures	Antony J. Long	Durham University, UK	67	GINR	SS 6.1
Carbon processing in Arctic lakes when vegetation changes on land	Suzanne McGowan	University of Nottingham, UK	66	ARCST	SS 6.2
Acidity and origin of dissolved organic carbon in different vegetation zones	Jakub Hruška	Czech Geological Survey, Prague, Czech Republic	47	BEO	SS 6.3
Finding cold-adapted to combat organic pollutants in the Arctic	Luigi Michaud (post-humous)	University of Messina, Italy	8	BIOFORSK	SS 6.4
A microbial ride around the Arctic	Stefano Ventura	National Research Council of Italy	10, 66, 70	TRS, ARCST, ZAC	SS 6.5
Microbial biodiversity in polar lake ecosystems: why is it different at the North and South Pole?	Koen Sabbe/Wim Vyverman	Ghent University, Belgium	67, 70	GINR, ZAC	SS 6.6
Survival strategies of freshwater zooplankton in Arctic and Subarctic ponds	Martin Kainz	Danube University Krems, Austria	12, 13	KILPIS, KEVO	www.eu-interact.org
Investigating the spatial expression of millennial-scale Holocene climate changes: a multi-proxy lake sediment approach, Finnish Lapland	Daniel Fower	University of Portsmouth, UK	12, 13, 16, 17	KILPIS, KEVO, KOLARI, OULANKA	www.eu-interact.org
Winter survival strategies of freshwater zooplankton in subarctic ponds and plankton diversity and stability in aquatic food webs	Maren Striebel	Wasser Cluster Lunz, Austria	12	KILPIS	www.eu-interact.org
Understanding the natural environmental and climatic controls on baseline fluxes of suspended particulate matter in freshwater ecosystems	Gary Bilotta	University of Brighton, UK	13, 73	KEVO, LBHI	www.eu-interact.org
Comparing late Holocene climate changes in low and high Arctic regions using lake sediments and annual rings of dwarf tundra shrubs records	Daniel Nývlt	Czech Geological Survey, Brno, Czech Republic	8, 67	BIOFORSK, GINR	www.eu-interact.org
Solar convection and lateral currents under lake ice cover	Georgiy Kirillin	Leibniz-Institute of Freshwater Ecology and Inland Fisheries, Berlin, Germany	12	KILPIS	www.eu-interact.org
Nutrient fluxes and biotic communities in Arctic rivers with different water source contributions	Alexander Milner	University of Birmingham, UK	49, 70	KLRS, ZAC	www.eu-interact.org
Hydrological niches on a Siberian floodplain	David Gowing	Open University, Milton Keynes, UK	29	MFS	www.eu-interact.org
Trophic interactions, temperature and greening in a changing climate	Anders G. Finstad	Norwegian Institute for Nature Research, Norway	70	ZAC	www.eu-interact.org
Microbial and geochemical insights into Lake Torneträsks sediment archive	Jorien Vonk	Utrecht University, The Netherlands	11	ANS	www.eu-interact.org
The influence of rainfall and soil runoff events on freshwater bacterial composition during polar days vs. day/night cycles	Carina Rofner	University of Innsbruck, Austria	12	KILPIS	www.eu-interact.org
Sponge associated culturable microbiome able to degrade persistent organic pollutant along the Pasvik River and the Bokfjorden (Norway)	Maurizio Azzaro	Institute for Coastal Marine Environment, Italy	8	BIOFORSK	www.eu-interact.org
Arctic ostracods and copepods of the hyporheic zone in Swedish Lapland – assemblages' resilience and shell chemistry	Sanda Iepure	IMDEA Water, Madrid, Spain	10	TRS	www.eu-interact.org
Microbes in the carbon cycle of subarctic thermokarst ponds	Sari Peura	Evolutionary Biology Centre, Uppsala, Sweden	61	WKRS	www.eu-interact.org
Biocomplexity of microbial mats. A bipolar perspective	Antonio Quesada	Universidad Autonóma de Madrid, Spain	61	WKRS	www.eu-interact.org

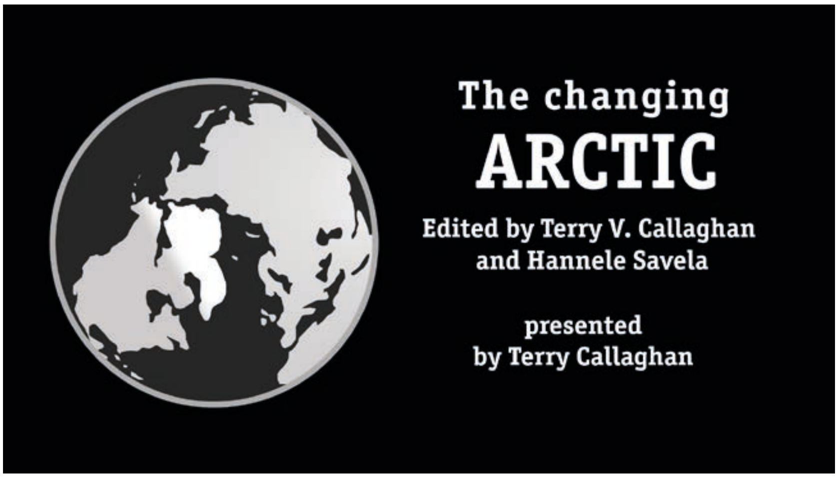
Section 7 People in the North

Project	First author/ Project leader	Affiliation	Station numbers	Stations visited	Reference
Dynamic risk management for Arctic mountain regions	Sven Fuchs	University of Natural Resources and Life Sciences, Vienna, Austria	26	KHIBINY	SS 7.1
Mapping and valuing ecosystem services in the Abisko area	Pierpaolo Franzese	Partnenope University of Naples, Italy	11	ANS	SS 7.2
Ecosystem service social assessments in extreme environments	Daniel Orenstein	Technion –Israel Institute of Technology, Israel	76	CEH	SS 7.3
Assessment of boreal forest ecosystem services at two Russian sites	Jill Thompson/ Mike Smith	Centre for Ecology & Hydrology, Scotland, UK	29, 39	MFS, SPA	SS 7.4
Working with local communities to quantify Arctic ecosystem services	Ron Smith	Centre for Ecology & Hydrology, Scotland, UK	10, 11	TRS, ANS	SS 7.5
Adapting to changing permafrost in Salluit, Canada	Christine Barnard	Centre d' études Nordiques, Université Laval, Québec, Canada	58	SALLUIT	SS 7.6
Dividing up Greenland?	Kees Bastmeijer	Tilburg University, The Netherlands	67	GINR	www.eu-interact.org
Soil biota community and diversity as bioindicators to the impact of ecotourism in a subarctic ecosystem	Yosef Steinberger	Bar-Ilan University, Israel	17	OULANKA	www.eu-interact.org

1	SVERDRUP	Sverdrup Research Station	Svalbard
7	FINSE	Finse Alpine Research Centre	Norway
8	BIOFORSK	Bioforsk Svanhovd Research Station	Norway
10	TRS	Tarfala Research Station	Sweden
11	ANS	Abisko Scientific Research Station	Sweden
12	KILPIS	Kilpisjärvi Biological Station	Finland
13	KEVO	Kevo Subarctic Research Station	Finland
16	KOLARI	Kolari Research Unit	Finland
17	OULANKA	Oulanka Research Station	Finland
26	KHIBINY	Khibiny Educational and Scientific Station	Russian Federation
29	MFS	Mukhrino Field Station	Russian Federation
38	SAM	Research Station Samoylov Island	Russian Federation
39	SPA	Spasskaya Pad Scientific Forest Station	Russian Federation
41	CHO	Chokurdakh Scientific Tundra Station	Russian Federation
47	BEO	Barrow Arctic Research Center/ Barrow Environmental Observatory	US
48	TOOLIK	Toolik Field Station	US
49	KLRS	Kluane Lake Research Station	Canada
58	SALLUIT	CEN Salluit Research Station	Canada
61	WKRS	CEN Whapmagoostui-Kuujjuarapik Research Station	Canada
66	ARCST	Arctic Station	Greenland
67	GINR	Greenland Institute of Natural Resources	Greenland
68	SER	Sermilik Research Station	Greenland
70	ZAC	Zackenberg Research Station	Greenland
73	LBHI	Litla-Skard	Iceland
75	FINI	Faroe Islands Nature Investigation	Faroe Islands
76	CEN	ECN Cairngorms	Scotland, UK

INTERACT Products

On-line course and video lectures: The Changing Arctic



This book, "INTERACT Stories of Arctic Science", forms the basis of an on-line course with a series of video lectures arranged by Lektorium of St. Petersburg and Tomsk State University, Russia, together with the University of the Arctic.

The course "The Changing Arctic" presents a range of topics from the forefront of Arctic science including landscape formation, permafrost dynamics, glaciology, land-atmosphere links, and ecology on land and in freshwaters. The final lectures discuss the implications of change for the People of the North and the global community and summarise INTERACT's contributions to studying these issues.

No prior knowledge is needed for taking the course or for viewing the lectures; all that is required is natural curiosity and willingness to invest time in understanding these environmental issues of global concern.

The course is edited by Terry V. Callaghan and Hannele Savela, and presented by Terry V. Callaghan. The course material can be used either as a resource for education to gain a course certificate, or for viewing out of general interest.

Register for the course or view the on-line video lectures and other material at:

Coursera on-line learning platform, **www.coursera.org/learn/the-changing-arctic**

National research Tomsk state university

Lektorium: www.lektorium.tv

Tomsk State University: http://tsu.ru/english/

UArctic

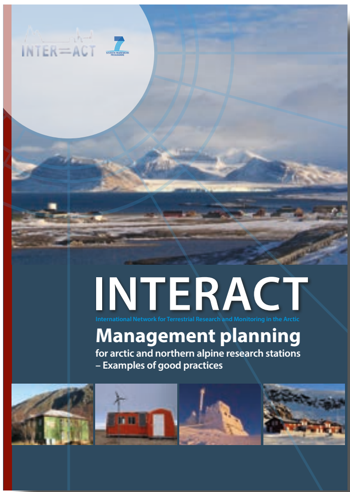
INTERACT: www.eu-interact.org

University of the Arctic: www.uarctic.org

Other INTERACT Products

INTERACT Management planning for Arctic and northern alpine research stations

Many scientists studying the Arctic and alpine areas of the Northern Hemisphere rely on research stations for conducting their research and monitoring projects. These stations should provide an efficient and safe platform allowing scientists to focus on their field of interest.



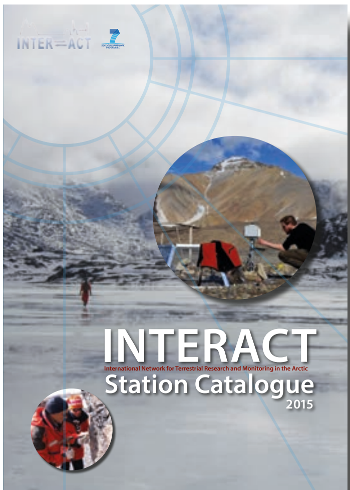
In this highly illustrated book, INTERACT station managers share their combined knowledge and experiences gained from managing a set of very different research stations located in very different environmental and climatic settings. The book describes and identifies key aspects of station management in chapters on management planning, policies, staff, visitors, permit issues, health and safety, environmental impact, outreach and marketing, research and monitoring, training and education, and knowledge capture and data management.

The target audience for the book is mainly managers of research stations in Arctic and alpine areas, but it may also be a useful tool for all others involved in science coordination and logistics.

The book can be downloaded freely at www.eu-interact.org

INTERACT Station Catalogue – 2015

The INTERACT research stations provide a circumarctic platform for research and monitoring in Arctic and alpine areas, and adjacent forest environments. INTERACT stations are located in all major environmental envelopes of the Arctic providing an ideal platform for studying climate change and its impact on the environment and local communities.



To help guide scientists to their ideal platform, INTERACT has produced a catalogue of research stations that can help researchers and other stakeholders to identify research stations that suit their specific needs. In this highly illustrated "travel guide" for researchers, station managers describe their station and share facts about the local climate and surrounding environment.

The target audiences for this catalogue are scientists, scientific networks, organisations, managers of research and monitoring programmes, and others who are looking for relevant field sites for implementation of their research and monitoring agendas.

The catalogue can be downloaded freely at www.eu.interact.org

ORGANISATIONS WORKING WITH INTERACT

The International Arctic Science Committee (IASC) is a non-governmental, international scientific organization. The IASC mission is to encourage and facilitate cooperation in all aspects of Arctic research, in all countries engaged in Arctic research and in all areas of the Arctic region.
www.iasc.org

Arctic Monitoring and Assessment Programme (AMAP) is an Arctic Council initiative with the objective of providing reliable and sufficient information on the status of, and threats to, the Arctic environment, and providing scientific advice on actions to be taken in order to support Arctic governments in their efforts to take remedial and preventive actions relating to contaminants.
www.amap.no

The Circumpolar Biodiversity Monitoring Program (CBMP) is an Arctic Council initiative supporting an international network of scientists, governments, indigenous organizations and conservation groups working to harmonize and integrate efforts to monitor the Arctic's living resources.
www.caff.is/monitoring

Sustaining Arctic Observing Networks (SAON) is an Arctic Council initiative that supports and strengthens the development of multinational engagement for sustained and coordinated pan-Arctic observing and data sharing systems that serve societal needs, particularly related to environmental, social, economic and cultural issues.
www.arcticobserving.org

International Study of Arctic Change (ISAC) is a program that provides a scientific and organizational framework focused around its key science questions for pan-Arctic research including long-term planning and priority setting. ISAC establishes new and enhances existing synergies among scientists and stakeholders engaged in Arctic environmental research and governance.
www.arcticchange.org

The WWF Global Arctic Programme has coordinated WWF's work in the Arctic since 1992. WWF works through offices in six Arctic countries, with experts in circumpolar issues like governance, climate change, resilience, fisheries, oil and gas, and polar bears.
www.wwf.org

INTERACT TRANSNATIONAL ACCESS

The editors of this book, Terry V. Callaghan and Hannele Savela (Photo: Morten Rasch).

Transnational Access is a way to support international research conducted at research stations and other research infrastructures. Researchers are selected to receive Transnational Access through scientific evaluation to ensure high quality. The researchers then have free access to conduct research at the site, including travel and accommodation costs, and the use of research facilities and instruments. To facilitate international scientific collaboration and more efficient use of research infrastructures, support is only provided to stations and facilities located in another country than where the researcher lives.

INTERACT's Transnational Access program has been funded by the EU, Canada and the US. By autumn 2015, 500 scientists from 19 countries have received awards from INTERACT to work at 24 research stations located throughout the Arctic.

www.eu-interact.org

INTERACT

International Network for Terrestrial Research and Monitoring in the Arctic

INTERACT is a circumarctic network of more than 75 terrestrial field bases in Arctic, alpine and neighbouring forest areas.

The main objective of INTERACT is to provide a circumarctic platform for identifying, understanding, predicting and responding to current environmental changes that take place in the Arctic and neighbouring areas. The INTERACT stations host over 5,000 researchers annually, facilitating top-level research and monitoring programmes within a wide range of scientific disciplines from natural sciences to the human dimension.

The book takes the reader on a journey through the Arctic and neighbouring alpine and forest areas, and reveals the excitement and adventure that the researchers both enjoy and endure. The book consists of seven highly illustrated sections focusing on landscape-forming processes, glaciers and permafrost environments, ground processes that store and release greenhouse gases, the ecology of land and freshwater, and the Peoples of the Arctic. These topics are all interconnected and together contribute to the "Arctic System" – a system of great importance to the global community but one that is changing dramatically.

Let's INTERACT !

www.eu-interact.org

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