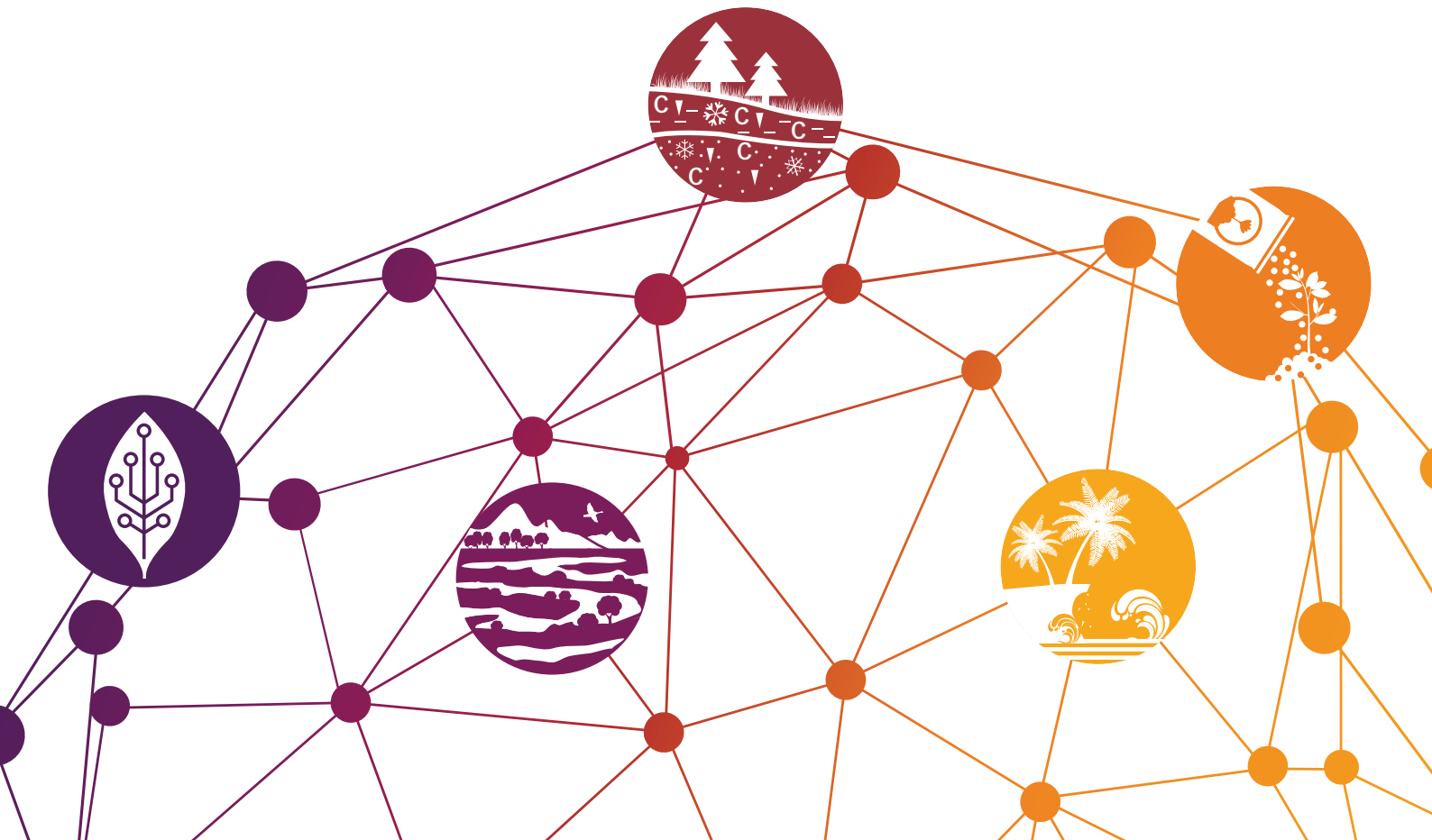


FRONTIERS 2018/19

Emerging Issues of Environmental Concern



© 2019 United Nations Environment Programme
ISBN: 978-92-807-3737-0
Job No: DEW/2221/NA

Disclaimer

This publication may be reproduced in whole or in part and in any form for educational or non-profit services without special permission from the copyright holder, provided acknowledgement of the source is made. UN Environment would appreciate receiving a copy of any publication that uses this publication as a source.

No use of this publication may be made for resale or any other commercial purpose whatsoever without prior permission in writing from UN Environment. Applications for such permission, with a statement of the purpose and extent of the reproduction, should be addressed to the Director, Communication Division, UN Environment, P.O. Box 30552, Nairobi, 00100, Kenya.

The designations employed and the presentation of material in this publication do not imply the expression of any opinion whatsoever on the part of UN Environment concerning the legal status of any country, territory or city or its authorities, or concerning the delimitation of its frontiers or boundaries. For general guidance on matters relating to the use of maps in publications please go to: <http://www.un.org/Depts/Cartographic/english/htmain.htm>

Mention of a commercial company or product in this publication does not imply endorsement by UN Environment. The use of information from this publication concerning proprietary products for publicity or advertising is not permitted.

© Maps, photos, and illustrations as specified.

Suggested citation

UNEP (2019). Frontiers 2018/19 Emerging Issues of Environmental Concern. United Nations Environment Programme, Nairobi.

Production

Science Division
UN Environment
P.O. Box 30552
Nairobi, 00100, Kenya
Tel: (+254) 20 7621234
E-mail: publications@unenvironment.org
Web: www.unenvironment.org



UN Environment
promotes environmentally
sound practices globally
and in its own activities. Our
distribution policy aims to reduce
UN Environment's carbon footprint.

FRONTIERS 2018/19

Emerging Issues of Environmental Concern

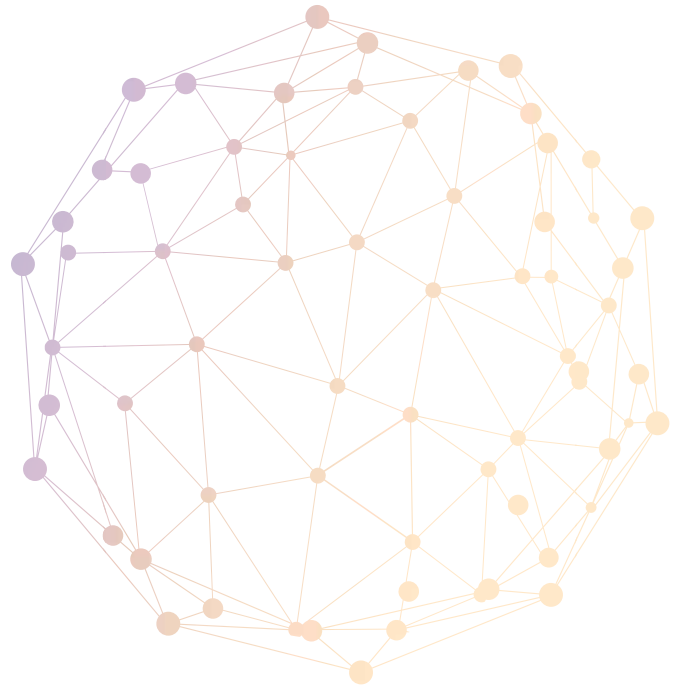
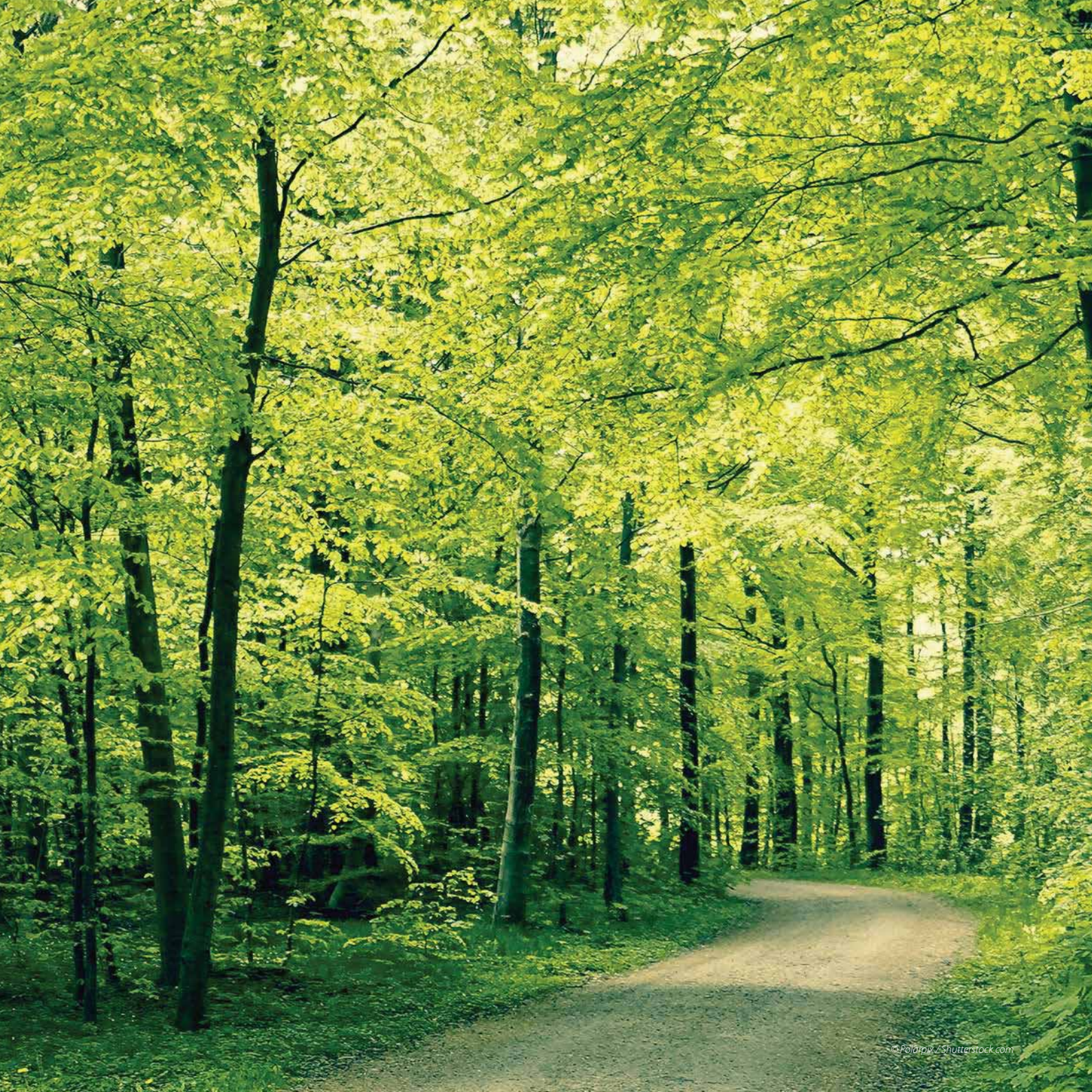




Table of contents

	Foreword	7
	Acknowledgements	8
	Synthetic Biology: Re-engineering the Environment	10
	Opportunities and challenges	10
	Rewriting the code of life	12
	Applications redefined: From laboratory to ecosystem	16
	Innovating with wisdom	18
	References	20
	Ecological Connectivity: A Bridge to Preserving Biodiversity	24
	Reconnecting fragmented ecosystems	24
	The forces of fragmentation	26
	Promoting connectivity solutions	30
	Setting targets for future connectivity	32
	References	34
	Permafrost Peatlands: Losing Ground in a Warming World	38
	Accelerating change in the Arctic	38
	Thawing permafrost, decaying peat and complex interplays	40
	Growing awareness of permafrost peatlands	44
	Knowledge priorities and network expansion	46
	References	48
	The Nitrogen Fix: From Nitrogen Cycle Pollution to Nitrogen Circular Economy	52
	The global nitrogen challenge	52
	The knowns and known-unknowns of nitrogen	54
	Policy fragmentation and circular economy solutions	58
	Towards a holistic international approach for nitrogen	60
	References	62
	Maladaptation to Climate Change: Avoiding Pitfalls on the Evolvability Pathway	66
	Defining adaptation and maladaptation for the climate change context	66
	Maladaptation at scale	68
	Avoiding maladaptation in a 1.5°C constrained future	73
	References	74



Foreword



In the first decade of the 20th century, two German chemists – Fritz Haber and Carl Bosch – developed a way to produce synthetic nitrogen cheaply and on a large scale. Their invention spurred the mass production of nitrogen-based fertilizers, and thus transformed farming around the globe. It also marked the beginning of our long-term interference with the Earth's nitrogen balance. Every year, an estimated US\$200 billion worth of reactive nitrogen is now lost into the environment, where it degrades our soils, pollutes our air and triggers the spread of “dead zones” and toxic algal blooms in our waterways.

It's no wonder that many scientists are arguing that “the Anthropocene” should become the official name of the current geological era. In just a few decades, humankind has caused global temperatures to rise 170 times faster than the natural rate. We have also deliberately modified more than 75 per cent of the planet's land surface, and permanently altered the flow of more than 93 per cent of the world's

rivers. We are not only causing drastic changes to the biosphere, we are also now capable of rewriting – and even creating from scratch – the very building blocks of life.

Every year a network of scientists, experts and institutions across the world work with UN Environment to identify and analyze emerging issues that will have profound effects on our society, economy and environment. Some of these issues are linked to new technologies that have astonishing applications and uncertain risks, while others are perennial issues, such as the fragmentation of wild landscapes and the thawing of long-frozen soil. Another issue, nitrogen pollution, represents an unintended consequence of decades of human activity in the biosphere. While the final issue analyzed here, maladaptation to climate change, highlights our failure to adequately and appropriately adjust to the shifting world around us.

There is some good news to report. As you can read in the pages that follow, a holistic approach to the global challenge of nitrogen management is beginning to emerge. In China, India and the European Union, we are seeing promising new efforts to reduce losses and improve the efficiency of nitrogen fertilizers. Ultimately, the recovery and recycling of nitrogen, as well as other valuable nutrients and materials, can help us to farm cleanly and sustainably, a hallmark of a truly circular economy.

The issues examined in *Frontiers* should serve as a reminder that, whenever we interfere with nature – whether at the global scale or the molecular level – we risk creating long-lasting impacts on our planetary home. But by acting with foresight and by working together, we can stay ahead of these issues and craft solutions that will serve us all, for generations to come.

Joyce Msuya
Acting Executive Director
United Nations Environment Programme

Acknowledgements

Synthetic Biology: Re-engineering the environment

Lead Authors

Bartłomiej Kolodziejczyk, H2SG Energy Pte. Ltd., Singapore
Natalie Kofler, Yale Institute for Biospheric Studies, Yale University, Connecticut, United States

Contributors and Reviewers

Marianela Araya, Convention on Biological Diversity, Montreal, Canada
James Bull, College of Natural Sciences, University of Texas at Austin, Texas, United States
Jackson Chamber, Department of Biological Statistics and Computational Biology, Cornell University, New York, United States
Chen Liu, Department of Biological Statistics and Computational Biology, Cornell University, New York, United States
Yongyuth Yuthavong, National Science and Technology Development Agency of Thailand, Pathumthani, Thailand

Ecological Connectivity: A bridge to preserving Biodiversity

Lead Author

Gary Tabor, Center for Large Landscape Conservation, Montana, United States

Contributors and Reviewers

Maya Bankova-Todorova, The Mohamed bin Zayed Species Conservation Fund, Abu Dhabi, United Arab Emirates
Camilo Andrés Correa Ayram, Alexander von Humboldt Biological Resources Research Institute, Bogotá, Colombia
Letícia Couto Garcia, Federal University of Mato Grosso do Sul, Campo Grande, Brazil
Valerie Kapos, UN Environment – World conservation Monitoring Centre, Cambridge, United Kingdom
Andrew Olds, School of Science and Engineering, University of the Sunshine Coast, Maroochydore, Australia
Ileana Stupariu, Faculty of Geography, University of Bucharest, Romania

Permafrost Peatlands: Losing ground in a warming world

Lead Author

Hans Joosten, Greifswald University/Greifswald Mire Centre, Greifswald, Germany

Contributors and Reviewers

Dianna Kopansky, UN Environment, Nairobi, Kenya
David Olefeldt, Faculty of Agricultural, Life and Environmental Sciences, University of Alberta, Edmonton, Canada
Dmitry Streletskiy, Department of Geography, The George Washington University, Washington DC, United States

The Nitrogen Fix: From nitrogen cycle pollution to nitrogen circular economy

Lead Authors

Mark Sutton, Centre for Ecology & Hydrology, Edinburgh, United Kingdom
Nandula Raghuram, Guru Gobind Singh Indraprastha University, New Delhi, India
Tapan Kumar Adhya, Kalinga Institute of Industrial Technology Bhubaneswar, Odisha, India

Contributors and Reviewers

Jill Baron, U.S. Geological Survey, Colorado, United States
Christopher Cox, UN Environment, Nairobi, Kenya
Wim de Vries, Wageningen University and Research, Wageningen, The Netherlands
Kevin Hicks, Stockholm Environment Institute, York, United Kingdom
Clare Howard, Centre for Ecology & Hydrology, Edinburgh, United Kingdom
Xiaotang Ju, College of Agricultural Resources and Environmental Science, China Agricultural University, Beijing, China
David Kanter, College of Arts and Science, New York University, New York, United States
Cargele Masso, International Institute of Tropical Agriculture, Ibadan, Nigeria

Jean Pierre Ometto, National Institute for Space Research, São José dos Campos, Brazil
Ramesh Ramachandran, National Centre for Sustainable Coastal Management, Ministry of Environment, Forest and Climate Change, Chennai, India
Hans Van Grinsven, PBL Netherlands Environmental Assessment Agency, The Hague, The Netherlands
Wilfried Winiwarter, International Institute of Applied Systems Analysis, Laxenburg, Austria

Maladaptation to Climate Change: Avoiding pitfalls on the evolvability pathway

Lead Author

Catherine McMullen, Stockholm Environment Institute, Bangkok, Thailand

Contributors and Reviewers

Thomas Downing, Global Climate Adaptation Partnership, Oxford, United Kingdom

Anthony Patt, Institute for Environmental Decisions, ETH Zürich, Zürich, Switzerland

Bernadette Resurrección, Stockholm Environment Institute, Bangkok, Thailand

Jessica Troni, UN Environment, Nairobi, Kenya

Special thanks are extended to

Alexandra Barthelmes and Cosima Tegetmeyer, Greifswald Mire Centre, Germany; Marin Klinger, National Snow and Ice Data Center, Colorado, United States; Salome Chamanje, David Cole, Nicolien Delange, Angeline Djampou, Philip Drost, Virginia Gitari, Jian Liu, Ariana Magini, Nada Matta, Pauline Mugo, Susan Mutebi-Richards, Shari Nijman, Andreas Obrecht, Samuel Opiyo, Meses Osani, Roxanna Samii, Rajinder Sian, Nandita Surendran and Josephine Wambua, UN Environment

Production advisers

Maarten Kappelle and Edoardo Zandri, UN Environment

Production team

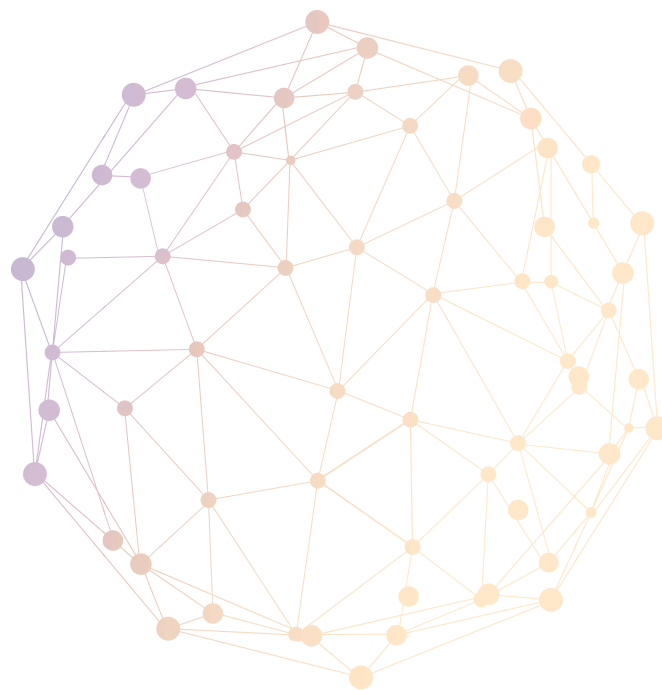
Editor-in-chief: Pinya Sarasas, UN Environment
Technical support: Allan Lelei, UN Environment
Copy editor: Alexandra Horton, United Kingdom

Graphics, design and layout

Graphic designer: Audrey Ringler, UN Environment
Cartographer: Jane Muriithi, UN Environment

Printing

UNON/Publishing Services Section/Nairobi, ISO14001:2004-Certified





*Permafrost peatlands with numerous lake depressions, Cape Bolvansky, Russia
Photo credit: Hans Joosten*

Permafrost Peatlands: Losing ground in a warming world

Accelerating change in the Arctic

Peatlands located in the tropics receive much attention as global hotspots for their critical role in carbon storage and climate change mitigation. They store nearly 120 gigatons of peat carbon, but this is only about 20 per cent of all carbon locked away in global peatlands.¹ The largest volumes are stored in the northernmost areas of our planet, with the northern circumpolar region holding almost half of the world's soil organic carbon, largely in the form of permanently frozen peat.²⁻⁵

Much of the ground in the northern hemisphere freezes and thaws seasonally, and some stays frozen all year round. Underneath roughly 23 million square kilometres of the north lies permafrost – ground that remains at sub-zero

temperatures for at least two consecutive years. Arctic and subarctic peatlands exist within the permafrost zones of Canada, Denmark/Greenland, Finland, Norway, Russia, Sweden and the United States. Permafrost peatlands with a peat layer thicker than 40 centimetres span over 1.4 million square kilometres, and an even larger area has shallower peat.^{3,6-8} Extensive permafrost peat deposits can also be found far outside the Arctic and subarctic regions, for instance in Mongolia and on the Qinghai-Tibetan plateau, where mountain ranges prevent warm oceanic air from moving inland, and winter temperatures are very low.^{9,10}

Permafrost peatlands are undergoing rapid changes. The Arctic is now warming twice as fast as the global average.¹¹ In recent decades, the southern permafrost boundaries have receded northwards by 30 to 80 km, a significant loss in

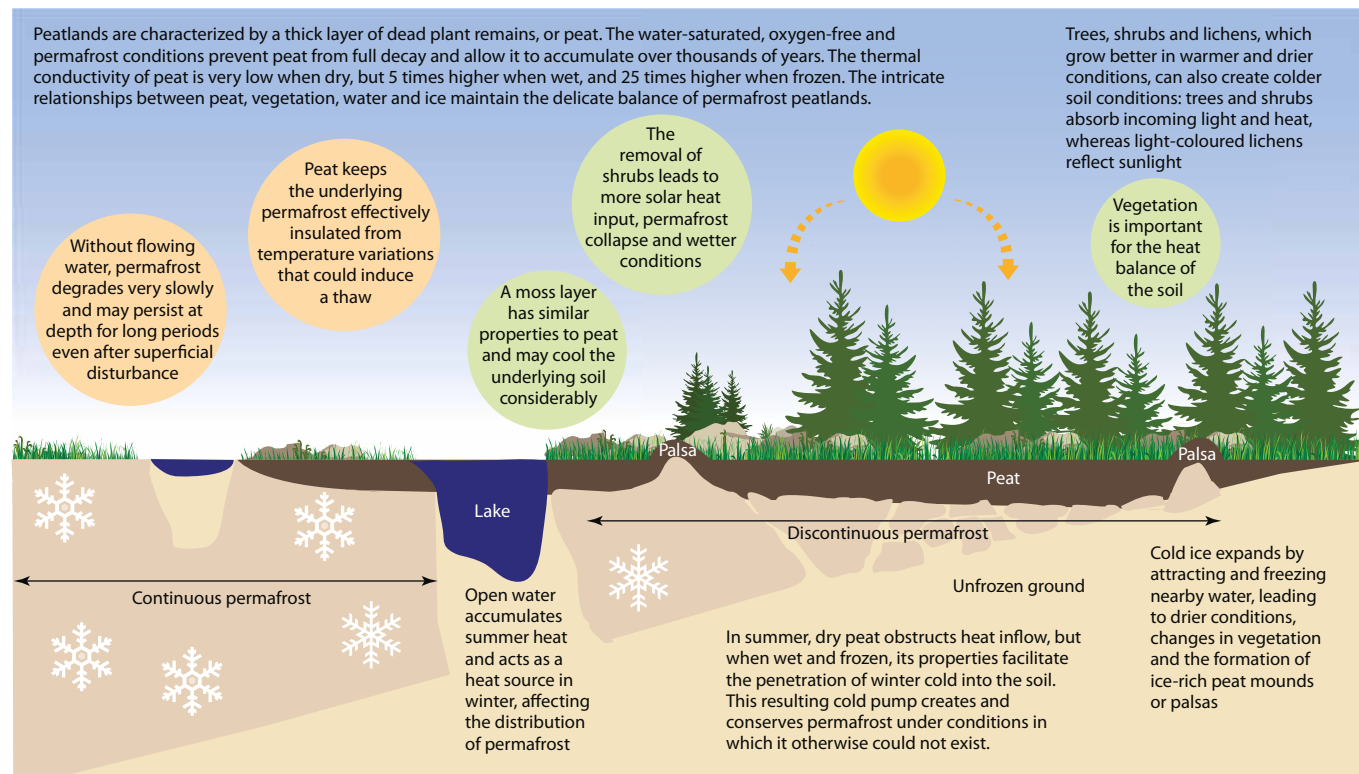
coverage.¹²⁻¹⁵ The risks associated with permafrost degradation are that the mobilization and microbial decomposition of previously buried, frozen organic matter could lead to the release of significant amounts of carbon dioxide and methane, which could, in turn, strongly reinforce global warming.¹⁶⁻¹⁹ Widespread permafrost degradation would also have enormous direct impacts on the regions' ecosystems, hydrology and infrastructure.

Although permafrost has been intensively studied for over a century, more research on its distribution, characteristics and dynamics is critically needed to better understand how it responds to climate change and human disturbance.²⁰ In the case of peatlands with permafrost, knowledge is even more incomplete. The way in which permafrost peatlands respond to a warming climate and their collective role in global climate

change are neither clearly understood nor straightforward, as the interaction of permafrost, ecosystems and climate is extremely complex.²⁰⁻²² For example, although frozen (dry) and thawed (wet) peatland sites may have similar carbon-sequestration rates and act as a carbon sink, they usually have totally different greenhouse-gas flux characteristics and may act as a net source of emissions.²³⁻²⁵ Moreover, frozen and thawed peatland sites could also rapidly alternate over time and space.^{23,26}

Permafrost thaw is seen as one of the most important "tipping elements" that could precipitate a runaway greenhouse effect, or an uncontrollable "Hothouse Earth".²⁷ To avoid such a destructive scenario, it is critical that the world's permafrost and its peatlands stay frozen and retain their carbon deposits.

Peatlands and permafrost: the role of peat, plants and water



Thawing permafrost, decaying peat and complex interplays

Each year of the past decade has been warmer in the Arctic than the warmest year of the 20th century.¹⁵ Globally, permafrost temperatures have continued to rise in recent decades. The greatest increments in annual mean permafrost temperatures have been observed in the coldest parts of the Arctic, whereas the increases have been much less in “warmer” permafrost and in discontinuous permafrost zones. In some locations, permafrost temperatures have dropped marginally because of recent cold winters.^{15,28}

As temperatures rise, the thawing of ice-rich permafrost or the melting of ground ice leads to distinctive depressions in the landscape, known as thermokarst. Over the past decades, thermokarst formation in peatlands seems to have accelerated in the discontinuous permafrost zones.²⁹⁻³¹ However, across the Arctic, long-term observations do not suggest uniform trends in thermokarst development attributable to global warming.¹⁵

When formerly frozen soil collapses due to a thaw, the subsidence allows the formation of small, new bodies of water that can later evolve into lakes. The formation of thermokarst lakes, in turn, accelerates permafrost thaw even faster and deeper.¹⁹ The spread of these lakes, on the other hand, could

 Video: Permafrost – what is it?

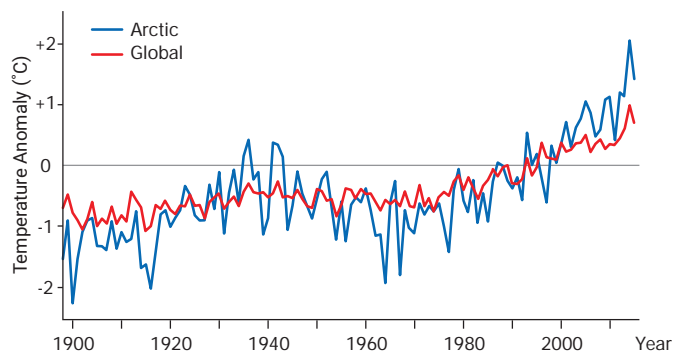


Video link: <https://www.youtube.com/watch?v=lxixy1u8GjY>

Photo: Freshly-drilled core sample of permafrost, Pokhodsk, Russia
Photo credit: Hans Joosten

© Alfred-Wegener-Institut, Helmholtz-Zentrum für Polar und Meeresforschung

Arctic (60–90°N) and global annual surface air temperature relative to the 1981–2010 average value



Source: Adapted from the Arctic Report Card 2018 of the US National Oceanic and Atmospheric Administration¹¹

also increase the connectivity of drainage networks, supporting lake drainage, vegetation regrowth, peat formation and the re-establishment of permafrost.³²⁻³⁷ These contrasting dynamics illustrate the greater need for a better understanding of potential impacts of the warming trend.

Climate change and elevated temperatures have dramatically increased the incidence of wildfires in the Arctic, with blazes spreading into tundra and forest-tundra boundary regions. Fuelled by underlying peat deposits, fires release vast amounts of carbon, destroy vegetation and insulating soil layers, and decrease ground albedo, or light reflectance, leading to increased sensitivity to climate change and widespread thermokarst development.³⁸⁻⁴⁴ Even under the most conservative scenarios, the combined impacts of warmer temperatures and wildfires are predicted to be especially severe in discontinuous permafrost zones, with climate conditions becoming unfavourable to permafrost altogether.³¹ This could cause changes in the types of vegetation and its productivity, which could in turn result in larger and more frequent wildfires.^{45,46}

Another effect of increased warming due to climate change is that permafrost thaw could release significant amounts of methane, a potent greenhouse gas, into the environment. Although there is large variability in Arctic methane-emission estimates, current global climate projection models seem to suggest only slight increases in methane emissions from the northern permafrost region.^{47,48} However, most models do not include an adequate representation of thaw processes.⁸



Thermokarst



Photo credit: Hans Joosten

Thermokarst is a landscape feature that results from the melting of ground ice in regions with underlying permafrost, causing subsidence at the surface. Typical thermokarst formations include thermokarst lakes, sinkholes, pits and troughs in polygonal terrain.^{56,57} Thermokarst is widespread in discontinuous permafrost zones.^{58,59} It is also frequently found in the much colder zones of continuous permafrost, where ice wedges cause permafrost instability.^{60,61}

Water accumulating due to thermokarst initially enhances heat gain and degradation in a positive feedback. Conversely, vegetation growth and the accumulation of organic matter gradually limits further downward thawing. Because of new and rapid peat accumulation in thermokarst depressions, the thawing of permafrost does not necessarily convert the peatland into a carbon source.^{22,23,62} However, wet soil conditions will likely cause the release of methane.

A recent modelling study assessed the long-term climatic consequences of permafrost degradation by considering the abrupt thaw processes relating to recently formed thermokarst lakes. The result suggested that within this century, carbon release in the form of methane (CH₄) may

account for a small fraction of total carbon release from newly thawed permafrost, yet it could cause up to 40 per cent of the additional warming effect attributable to newly thawed permafrost.⁴⁹

Climate change is only one of many factors directly influencing the changes in permafrost peatlands. Any disturbance to the surface soil can lead to permafrost degradation, including natural processes such as forest or tundra fires, and anthropogenic disturbances, such as industrial and urban infrastructure development and construction activity, mining, tourism, and agriculture.^{50,51} These many forms of development in permafrost peatlands often disregard the unique features of the areas, causing landscape fragmentation and disruption of the water cycle.^{14,52} In Russia, 15 per cent of the tundra territory has been destroyed by transport activities, resulting in permafrost thawing, erosion, subsidence and thermokarst development.⁵³ About 45 per cent of the oil and natural gas production fields in the Russian Arctic are located in the most ecologically sensitive areas, often in peatlands, including the Pechora region, Polar Urals and north-west and central Siberia.^{54,55} The rising demand for natural resources and increased accessibility to frozen regions due to warmer conditions may in the future result in more industrial and infrastructural activity, escalating disturbance to peatlands and permafrost. The resulting changes will also impact indigenous peoples who have traditionally depended on the use of land such as peatlands for food, reindeer, game, and fish.¹⁴



Thawing and collapse of permafrost in Mongolia

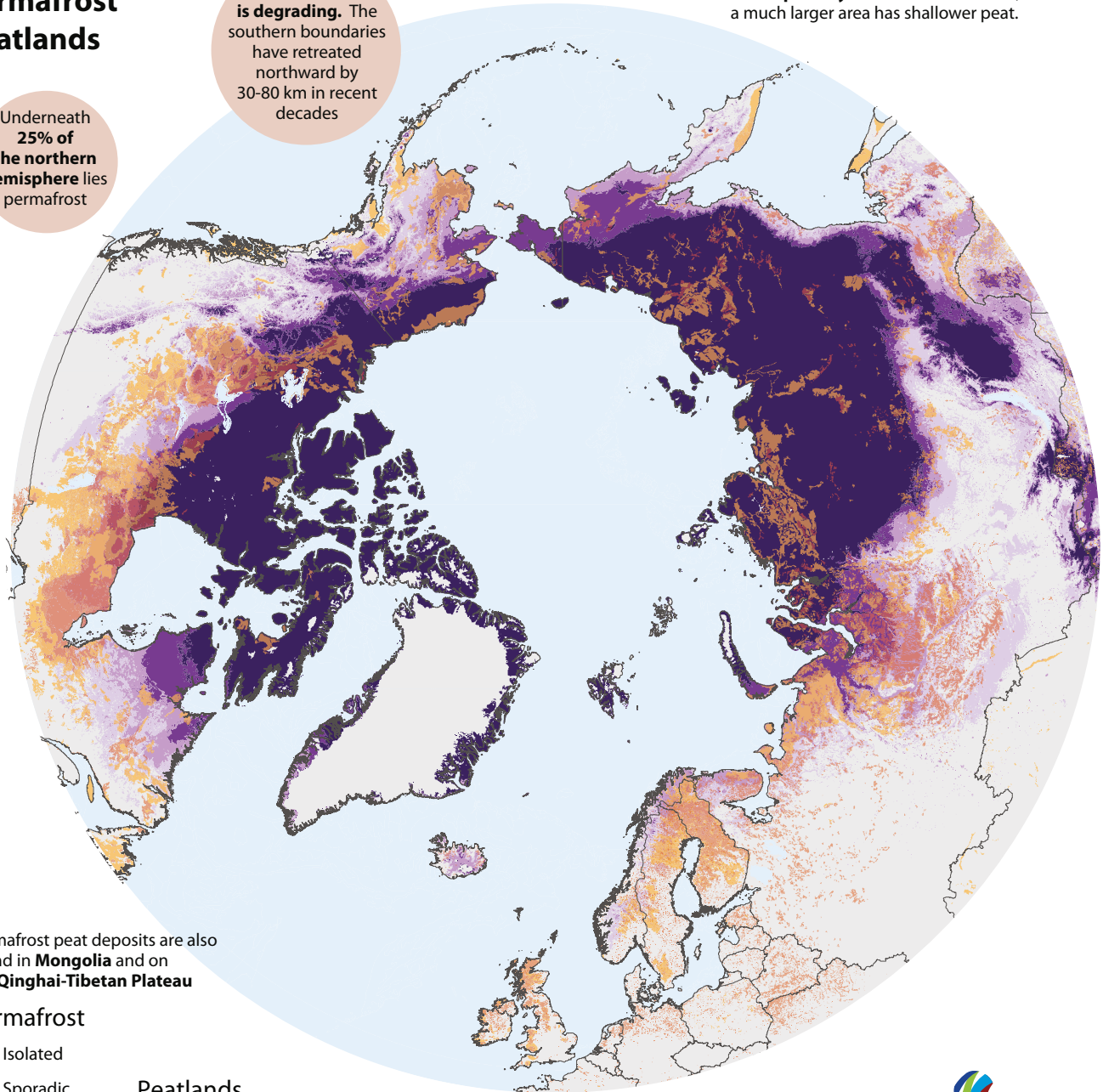
Photo credit: Hans Joosten

Distribution of Permafrost Peatlands

Peatlands span vast areas in the permafrost zones. At least **1.4 million km²** of permafrost peatlands have a **peat layer thicker than 40 cm**, and a much larger area has shallower peat.

Permafrost is degrading. The southern boundaries have retreated northward by 30-80 km in recent decades

Underneath **25% of the northern hemisphere** lies permafrost



Permafrost peat deposits are also found in **Mongolia** and on the **Qinghai-Tibetan Plateau**

Permafrost

- Isolated
- Sporadic
- Discontinuous
- Continuous

Peatlands

- > 50% cover
- 20-50% cover



GREIFSWALD
MIRE
CENTRE

Geospatial data sources:

Peatlands data provided by Greifswald Mire Centre, Greifswald, Germany
Permafrost data provided by Alfred Wegener Institute, Helmholtz Center for Polar and Marine Research (AWI), Bremerhaven, Germany⁹⁰

Arctic temperatures are rising twice as fast as global average

Peatlands are the **largest long-term stores of organic carbon** of all terrestrial ecosystems

Climate models suggest **35% near-surface permafrost loss by 2050**

Shrubs, trees and lichens can keep soil cooler by absorbing or reflecting sunlight. Removal of the protective vegetation can cause rapid degradation of permafrost.

Fire removes insulating vegetation, peat and soil layers, making peatland more vulnerable to climate change

Arctic warming has **increased fire activity** in tundra and forest-tundra regions causing significant reductions in soil carbon

The combined impact of climate warming and **wildfire** is more severe in the zone of discontinuous permafrost

When peat is no longer frozen as a result of permafrost thaw, microbial decomposers become active and breakdown organic materials, causing emissions of CO_2 and CH_4

Deeper water bodies accumulate heat in summer and become a heat source in winter, influencing the local distribution of permafrost

Thermokarst is a distinctive depression in the landscape as a result of permafrost thaw or melting of ground ice

In the absence of moving surface or groundwater, permafrost degrades very slowly and can persist at depth for a long time

Thermokarst is widespread in the zone of discontinuous permafrost

Peatlands are areas with a layer of **dead plant materials** (peat) at the surface. The water-saturated and oxygen-free conditions prevent peat from fully decomposing.

Circumpolar soils hold **50% of the world's soil carbon**, and this carbon is largely stored in peatlands and often conserved as permafrost

Experts expect the permafrost regions to become a **carbon source** by 2100

Permafrost soils including peat deposits contain **twice as much mercury** as the amounts found in the rest of global soils, the atmosphere, and oceans combined

Permafrost thaw could release significant amounts of **mercury** into the environment

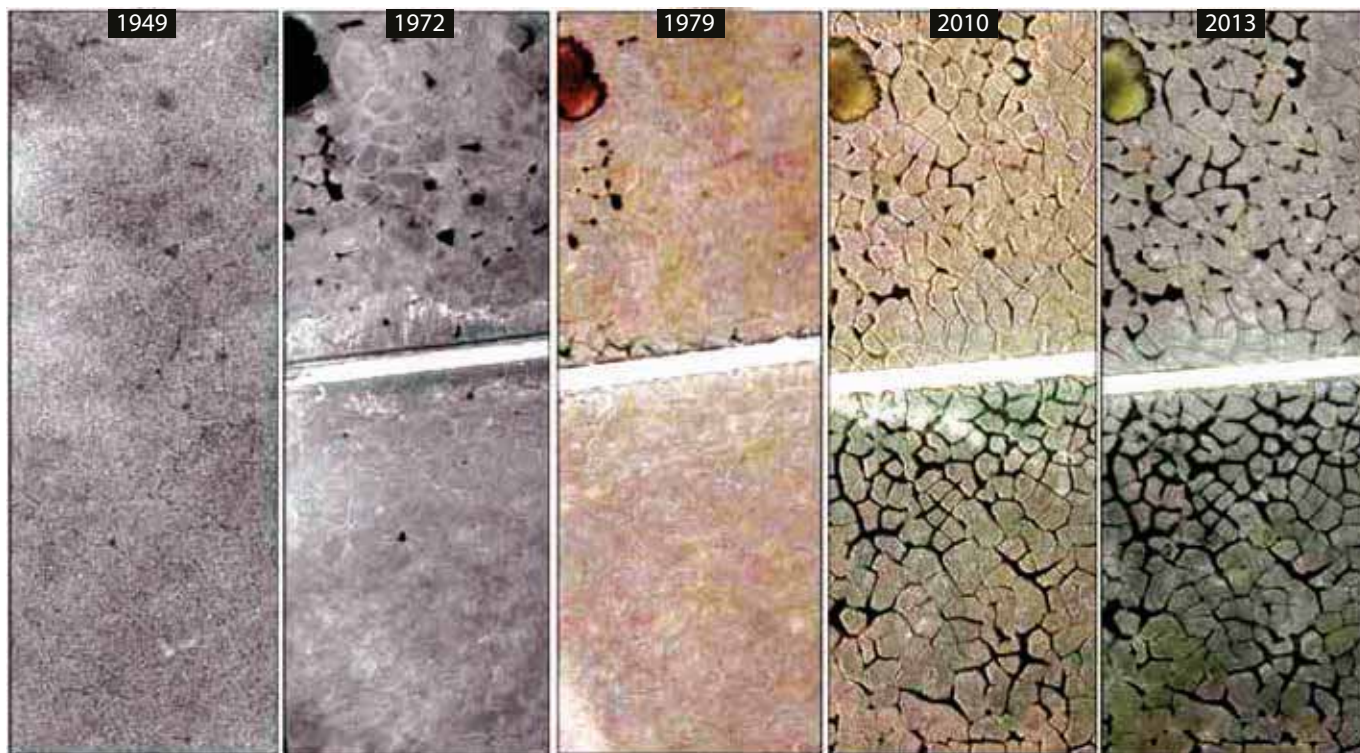
Soil organic carbon may be lost in different forms: as gases – CO_2 or CH_4 – emitted back into the atmosphere, or as dissolved organic carbon or particulate organic carbon transported into rivers

Growing awareness of permafrost peatlands

For more than a century and increasingly over the last decades, permafrost regions have been the subject of research and technology development to address their distinctive scientific and engineering challenges. Despite the efforts of the International Permafrost Association and the Global Terrestrial Network for Permafrost, large gaps in region- and habitat-specific knowledge remain, not least due to extreme climatic conditions, limited accessibility and a complex geopolitical setting. A recent review indicated that 30 per cent of all citations in scientific literature related to field experiments in the Arctic are primarily derived from the direct surroundings of just two research stations: Toolik Lake in Alaska, USA and Abisko in Sweden.⁶³ This could bias scientific consensus and lead to inaccurate predictions of the impacts of climate change in the Arctic.

With the growing awareness of climate change and Arctic ice melt, recent assessments are increasingly trying to encompass aspects such as social-ecological change, regime shifts, and the role of human action in adaptation and transformation.^{64,65} Large-scale research projects are being developed to address the implications of permafrost thaw and degradation. These include the Arctic Development and Adaptation to Permafrost in Transition (ADAPT) initiative, which collaborates with 15 laboratories across Canada and other groups of researchers to develop an integrated Earth systems science framework in the Canadian Arctic. Dedicated laws such as Ontario's 2010 Far North Act are combining with new planning initiatives to open up and protect the Far North through a land-use planning process in consultation with First Nations.⁶⁶

The Arctic Council is an example of strong international cooperation that has been especially instrumental in



Progression of thermokarst development due to permafrost thaw between 1949 and 2013 in a study site located in Prudhoe Bay, Alaska, United States. The white line is the Spine Road constructed in 1969.

Source: Walker et al. (2014)⁵²

generating and increasing knowledge for national and international policymaking, such as with its 2017 report on snow, water, ice and permafrost in the Arctic.^{15,67} While it is recognized that Arctic states play a key role as stewards of the region, efforts by other actors in the protection and awareness of permafrost peatlands are also needed. A number of international organizations, such as the Intergovernmental Panel on Climate Change – through its IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, the World Meteorological Organization, and the International Science Council through the International Arctic Science Committee, have become increasingly engaged, helping to raise awareness and understanding of the implications of changes in the Arctic.



Permafrost thaw has led to thermokarst formation in peatlands near Naryan-Mar, Nenets autonomous region, Russia

Photo credit: Hans Joosten



Ontario's Far North Act and the role of First Nations in protecting permafrost peatlands

Between 50-57 °N and 79-94 °W lies the **Far North of Ontario**, Canada – a dynamic landscape hosting arctic, boreal, and temperate biomes. Here, peatlands dominate the landscape, covering 47 per cent or 21 million hectares of the Far North area, and storing about 36 gigatons of carbon as peat.⁶⁸ This is equivalent to a quarter of the carbon stored in all of Canada's peatlands.

Assented to in October 2010, **Ontario's Far North Act** recognizes the significant role of the Far North in carbon storage and sequestration capacity, and provides for community-based land-use planning as a strategy to fight climate change.^{66,69} The Act centres around the significant role of First Nations – aboriginal peoples in Canada who are not Métis or Inuit – in land-use planning that includes cultural, social, ecological and economic considerations.

As required by the Act, the **Far North land use strategy** sets out to help prepare community-based land-use plans while integrating issues beyond the scope of individual planning areas, such as indigenous knowledge. Four objectives outlined in the strategy include:

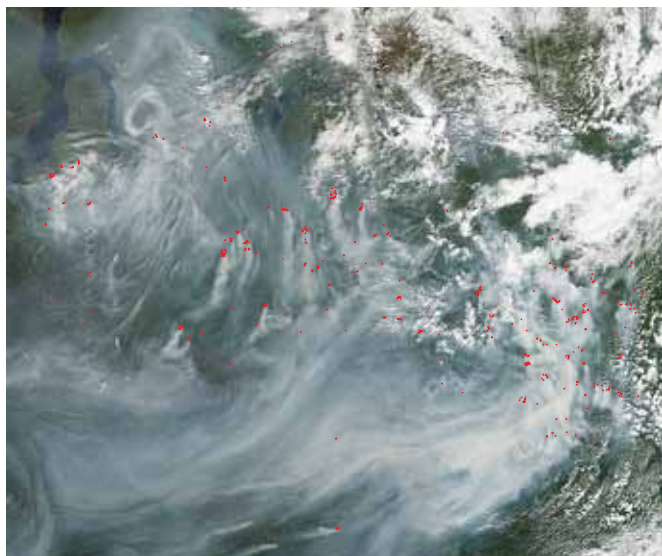
1. A significant role for First Nations in planning.
2. The protection of ecological systems and areas of cultural value in the Far North by including at least 225,000 km² of the region in an interconnected network of protected areas designated in community-based land-use plans.
3. The maintenance of biological diversity, ecological processes and functions, including the storage and sequestration of carbon in the Far North.
4. Enabling sustainable economic development that benefits the First Nations.

The strategy was planned for completion by 2016, but the process is still ongoing, led by interested First Nations working with the Ontario Ministry of Natural Resources and Forestry. Some community-based land-use plans have been approved, some drafted, while others are underway and some have not yet started.⁷⁰ Although progress is being made, uncertainty remains on how to achieve some of the Act's objectives, including in areas of governance, and particularly in scientific knowledge. It is imperative to understand how climate change affects carbon sequestration and storage in the Far North peatlands, as well as the related ecological processes, in order to develop appropriate policy and management responses.

Knowledge priorities and network expansion

There remains a great deal of uncertainty about how fast permafrost peatlands will change and what the impacts of those changes will be, both locally and globally. International cooperation is required to fund further research in the long term and devise workable strategies to reduce vulnerabilities. Nations need to collaborate on a range of implementable measures that acknowledge and apply traditional and local knowledge, facilitate engagement with stakeholders, and develop effective observation networks.¹⁵ At the same time, public outreach and education concerning the risks, likely impacts and potential adaptation options will be key to developing informed governance and policy.

Although there is an existing network of observation stations providing information on general trends in permafrost change, the spatial distribution of sites is very uneven. In particular, there are large gaps in the network across the central Canadian and central Siberian Arctic, Greenland, Russian Far North-East, Tibetan Plateau and subarctic region.^{30,63} The timely assessment of the global status of



Satellite image taken on 19 July 2016 showing dense smoke over permafrost peatlands of north-central Russia. Red demarcations indicate high surface temperatures likely caused by peat fires.

Photo credit: NASA Earth Observatory/Jesse Allen and Joshua Stevens

permafrost requires the expansion of existing research networks to a more comprehensive monitoring network. This extended network would optimally be designed to be user-friendly for all stakeholders, from climate scientists to the general public, and would include the use of standardized measurements and easily accessible databases.^{15,64} Countries with extensive permafrost zones would benefit from preparing adaptation plans that assess the potential risks and include mitigation strategies for the damage and costs of permafrost degradation.⁶⁴

Permafrost peatlands as carbon hotspots represent a special, highly diverse and dynamic environment that encompasses complex relationships between soil carbon, hydrology, permafrost, vegetation, and people. The major knowledge gaps lie in the limited understanding of how the processes interrelate and in the insufficiency of current studies and models. More research is required on the precise location of permafrost peatlands, how they are changing, and what their release potential is. Climate models need to include carbon emissions from the mobilization of permafrost carbon. To better characterize the response and feedback of permafrost peatlands to climate change, it will be critical to advance beyond single-disciplinary investigations. This will require



Video: Restoring peatlands in Russia for fire prevention and climate change mitigation



Video link: https://www.youtube.com/watch?v=QZ5qu_nPHYM
Photo: Fire in dwarf birch tundra in Komi Republic, Russia

© Wetlands International
Photo credit: Hans Joosten

▶ Video: Peatlands – climate regulation and biodiversity



Video link: <https://www.youtube.com/watch?v=ZcxZ9gvNfSU>
Flat palsas in Komi Republic, Russia

© Naturstyrelsen
Photo credit: Hans Joosten

a move towards an integration of field observations and retrospective – or palaeoenvironmental – studies, remote sensing, and dynamic modelling.^{22,30} The physical complexity of permafrost peatlands and the significant potential risks of their degradation and disruption also demand a more holistic approach to land-use planning and management, requiring better integrated knowledge for planners and policymakers.

The Arctic has already begun to change substantially. Even with the full implementation of the Paris Agreement under the United Nations Framework Convention on Climate Change, it is still likely that by the end of this century the Arctic environment would be quite different from that of today.¹⁵ The near inevitability of accelerating impacts reinforces the urgent need for local and regional adaptation strategies targeting these carbon-dense northern ecosystems. The prudent management of permafrost peatlands will be key to limiting greenhouse-gas emissions, reducing human and ecological vulnerabilities, and to building longer-term climate resilience.



Palsa permafrost mire near Noyabrsk, Western Siberia, Russia

Photo credit: Franziska Tanneberger

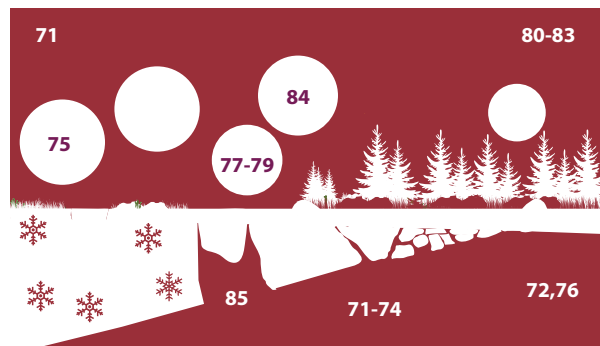
References

1. Leifeld, J. and Menichetti, L. (2018). The underappreciated potential of peatlands in global climate change mitigation strategies. *Nature Communications* 9, 1071. <https://www.nature.com/articles/s41467-018-03406-6>
2. Tarnocai, C., Canadell, J.G., Schuur, E.A.G., Kuhry, P., Mazhitova, G. and Zimov, S. (2009). Soil organic carbon pools in the northern circumpolar permafrost region. *Global Biogeochemical Cycles* 23(2), 1–11. <https://doi.org/10.1029/2008GB003327>
3. Hugelius, G., Strauss, J., Zubrzycki, S., Harden, J.W., Schuur, E.A.G., Ping, C.L. et al. (2014). Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps. *Biogeosciences* 11, 6573–6593. <https://doi.org/10.5194/bg-11-6573-2014>
4. Schuur, E.A.G., McGuire, A.D., Schädel, C., Grosse, G., Harden, J.W., Hayes, D.J. et al. (2015). Climate change and the permafrost carbon feedback. *Nature* 520, 171–179. <https://doi.org/10.1038/nature14338>
5. Strauss, J., Schirmeister, L., Grosse, G., Fortier, D., Hugelius, G., Knoblauch, C. et al. (2017) Deep Yedoma permafrost: a synthesis of depositional characteristics and carbon vulnerability. *Earth-Science Reviews* 172, 75–86. <http://dx.doi.org/10.1016/j.earscirev.2017.07.007>
6. Brown, J., Ferrians, O., Heginbottom, J.A. and Melnikov, E. (2002). *Circum-Arctic map of permafrost and ground-ice conditions, Version 2*. Colorado, USA: National Snow and Ice Data Center. https://nsidc.org/fgdc/maps/ipa_browse.html
7. Ballantyne, C.K. (2018). *Periglacial geomorphology*. Chichester, UK: Wiley-Blackwell.
8. Olefeldt, D., Goswami, S., Grosse, G., Hayes, D., Hugelius, G., Kuhry, P. et al. (2016). Circumpolar distribution and carbon storage of thermokarst landscapes. *Nature Communications* 7, 13043. <http://dx.doi.org/10.1038/ncomms13043>
9. Brown, R.J.E. (1960). The distribution of permafrost and its relation to air temperature in Canada and the USSR. *Arctic* 13(3), 163–177. <http://pubs.ainu.ucalgary.ca/arctic/Arctic13-3-163.pdf>
10. Gravis, G.F., Melnikov, E.S., Guo, D., Li, S., Li, S., Tong, B. et al. (2003). Principles of classification and mapping of permafrost in Central Asia. *8th International Conference on Permafrost 2003*. Arenson, L.U., Springman, S.M. and Phillips, M. (eds.). AA Balkema Publishers. 297–302
11. Overland, J.E., Hanna, E., Hanssen-Bauer, I., Kim, S.J., Walsh, J.E., Wang, M. et al. (2017). Surface Air Temperature. Arctic Report Card: Update for 2017. <https://www.arctic.noaa.gov/Report-Card/Report-Card-2017/ArtMID/7798/ArticleID/700/Surface-Air-Temperature>
12. Intergovernmental Panel on Climate Change (2013). *Climate Change 2013: The Physical Science Basis*. Cambridge, UK: Cambridge University Press. 1535. <https://doi.org/10.1017/CBO9781107415324>
13. Park, H., Kim, Y. and Kimball, J.S. (2016). Widespread permafrost vulnerability and soil active layer increases over the high northern latitudes inferred from satellite remote sensing and process model assessments. *Remote Sensing of Environment* 175, 349–358. <http://dx.doi.org/10.1016%2Fj.rse.2015.12.046>
14. Minayeva, T., Sirin, A., Kershaw, P. and Bragg, O. (2018). Arctic peatlands. In *The Wetland Book II: Distribution, Description, and Conservation*. by Finlayson, C.M., Milton, G.R., Prentice, R.C. and Davidson, N.C. (eds.). Dordrecht, NL: Springer 1–15. https://doi.org/10.1007/978-94-007-4001-3_109
15. Arctic Monitoring and Assessment Programme (2017a). *Snow, water, ice and permafrost in the Arctic (SWIPA) 2017*. Oslo, Norway: AMAP. <https://www.amap.no/documents/doc/Snow-Water-Ice-and-Permafrost-in-the-Arctic-SWIPA-2017/1610>
16. Schuur, E.A.G., Abbott, B.W., Bowden, W.R., Brovkin, V., Camill, P., Canadell, J.G. et al. (2013). Expert assessment of vulnerability of permafrost carbon to climate change. *Climate Change* 119(2), 359–374. <https://doi.org/10.1007/s10584-013-0730-7>
17. Koven, C.D., Schuur, E.A.G., Schädel, C., Bohn, T.J., Burke, E.J., Chen, G. et al. (2015). A simplified, data-constrained approach to estimate the permafrost carbon–climate feedback. *Phil. Trans. R. Soc. A* 373, 20140423. <http://dx.doi.org/10.1098/rsta.2014.0423>
18. Schädel, C., Bader, M.K.F., Schuur, E.A.G., Biasi, C., Bracho, R., Capek, P. et al. (2016). Potential carbon emissions dominated by carbon dioxide from thawed permafrost soils. *Nature Climate Change* 6, 950–953. <https://www.nature.com/articles/nclimate3054>
19. Walter Anthony, K., Schneider von Deimling, T., Nitze, I., Frolking, S., Emond, A., Daanen, R. et al. (2018). 21st-century modeled permafrost carbon emissions accelerated by abrupt thaw beneath lakes. *Nature Communications* 9(1), 3262. <https://doi.org/10.1038/s41467-018-05738-9>
20. Grosse, G., Goetz, S., McGuire, A.D., Romanovsky, V.E. and Schuur, E.A.G. (2016). Changing permafrost in a warming world and feedbacks to the Earth system. *Environmental Research Letters* 11, 040201. <http://dx.doi.org/10.1088/1748-9326/11/4/040201>
21. Shur, Y.L. and Jorgenson, M.T. (2007). Patterns of permafrost formation and degradation in relation to climate and ecosystems. *Permafrost and Periglacial Processes* 18, 7–19. <https://doi.org/10.1002/ppp.582>
22. Swindles, G.T., Morris, P.J., Mullan, D., Watson, E.J., Turner, E., Roland, T.P. et al. (2015). The long-term fate of permafrost peatlands under rapid climate warming. *Nature Scientific Reports* 5, 17951. <https://doi.org/10.1038/srep17951>
23. Gao, Y. and Couwenberg, J. (2015). Carbon accumulation in a permafrost polygon peatland: steady long-term rates in spite of shifts between dry and wet conditions. *Global Change Biology* 21(2), 803–815. <https://doi.org/10.1111/gcb.12742>
24. Ström, L., Ekberg, A., Mastepanov, M. and Christensen, T.R. (2003). The effect of vascular plants on carbon turnover and methane emissions from a tundra wetland. *Global Change Biology* 9(8), 1185–1192. <https://doi.org/10.1046/j.1365-2486.2003.00655.x>
25. Turetsky, M.R., Wieder, R.K., Vitt, D.H., Evans, R.J. and Scott, K.D. (2007). The disappearance of relict permafrost in boreal North America: effects on peatland carbon storage and fluxes. *Global Change Biology* 13(9), 1922–1934. <https://doi.org/10.1111/j.1365-2486.2007.01381.x>
26. De Klerk, P., Donner, N., Karpov, N. S., Minke, M. & Joosten, H. 2011. Short-term dynamics of a low-centred ice-wedge polygon near Chokurdakh (NE Yakutia, NE Siberia) and climate change during the last ca. 1250 years. *Quaternary Science Reviews*, 30, 3013–3031. <https://doi.org/10.1016/j.quascirev.2011.06.016>

27. Steffen, W., Rockström, J., Richardson, K., Lenton, T.M., Folke, C., Liverman, D. et al. (2018). Trajectories of the Earth system in the Anthropocene. *Proceedings of the National Academy of Sciences* 115(33), 8252–8259. <https://doi.org/10.1073/pnas.1810141115>
28. Hartfield, G., Blunden, J. and Arndt, D.S. (eds.) (2018). State of the climate in 2017. *Bull. Amer. Meteor. Soc.* 99(8), Si–S332. <https://doi.org/10.1175/2018BAMSStateoftheClimate.1>
29. Baltzer, J.L., Veness, T., Chasmer, L.E., Sniderhan, A.E. and Quinton, W.L. (2014). Forests on thawing permafrost: fragmentation, edge effects, and net forest loss. *Global Change Biology* 20(3) 824–834. <https://doi.org/10.1111/gcb.12349>
30. Carpino, O.A., Berg, A.A., Quinton, W.L. and Adams, J.R. (2018). Climate change and permafrost thaw-induced boreal forest loss in northwestern Canada. *Environ. Res. Lett.* 13, 084018. <https://doi.org/10.1088/1748-9326/aad74e>
31. Gibson, C.M., Chasmer, L.E., Thompson, D.K., Quinton, W.L., Flannigan, M.D. and Olefeldt, D. (2018). Wildfire as a major driver of recent permafrost thaw in boreal peatlands. *Nature Communications* 9(1), 3041. <https://doi.org/10.1038/s41467-018-05457-1>
32. Jones, B.M., Grosse, G., Arp, M.C., Jones, K.M., Walter, A. and Romanovsky, V.E. (2011). Modern thermokarst lake dynamics in the continuous permafrost zone, northern Seward Peninsula, Alaska. *Journal of Geophysical Research* 116, G00M03. <https://doi.org/10.1029/2011JG001666>
33. Jones, M.C., Grosse, G., Jones, B.M. and Walter Anthony, K.M. (2012). Peat accumulation in drained thermokarst lake basins in continuous, ice-rich permafrost, northern Seward Peninsula, Alaska. *Journal of Geophysical Research Biogeosciences* 117, G00M07. <https://doi.org/10.1029/2011JG001766>
34. Jones, B.M. and Arp, C.D. (2015). Observing a catastrophic thermokarst lake drainage in Northern Alaska. *Permafrost and Periglacial Processes* 26, 119–128. <https://doi.org/10.1002/ppp.1842>
35. Van Huissteden, J., Berrittella, C., Parmentier, F.J.W., Mi, Y., Maximov, T.C. and Dolman, A.J. (2011). Methane emissions from permafrost thaw lakes limited by lake drainage. *Nature Climate Change* 1, 119–123. <https://doi.org/10.1038/NCLIMATE1101>
36. Roach, J., Griffith, B., Verbyla, D. and Jones, J. (2011). Mechanisms influencing changes in lake area in the Alaskan boreal forest. *Global Change Biology* 17, 2567–2583. <https://doi.org/10.1111/j.1365-2486.2011.02446.x>
37. Jepsen, S.M., Voss, C.I., Walvoord, M.A., Minsley, B.J. and Rover, J. (2013). Linkages between lake shrinkage/expansion and sublacustrine permafrost distribution determined from remote sensing of interior Alaska, USA. *Geophysical Research Letters* 40, 882–887. <https://doi.org/10.1002/grl.50187>
38. Flannigan, M., Stocks, B., Turetsky, M. and Wotton, M. (2009). Impacts of climate change on fire activity and fire management in the circumboreal forest. *Global Change Biology* 15(3), 549–560. <https://doi.org/10.1111/j.1365-2486.2008.01660.x>
39. Jones, B.M., Kolden, C.A., Jandt, R., Abatzoglou, J.T., Urban, F. and Arp, C.D. (2009). Fire behavior, weather, and burn severity of the 2007 Anaktuvuk river tundra fire, North Slope, Alaska. *Arctic, Antarctic, and Alpine Research* 41, 309–316. <https://doi.org/10.1657/1938-4246-41.3.309>
40. Hu, F.S., Higuera, P.E., Walsh, J.E., Chapman, W.L., Duffy, P.A., Brubaker, L.B. et al. (2010). Tundra burning in Alaska: Linkages to climatic change and sea ice retreat. *Journal of Geophysical Research: Biogeosciences* 115, G04002. <http://dx.doi.org/10.1029/2009JG001270>
41. Hu, F.S., Higuera, P.E., Duffy, P.A., Chipman, M.L., Rocha, A.V., Young, A.M. et al. (2015). Arctic tundra fires: natural variability and responses to climate change. *Frontiers in Ecology and the Environment* 13(7), 369–377. <https://doi.org/10.1890/150063>
42. Mack, M.C., Bret-Harte, M.S., Hollingsworth, T.N., Jandt, R.R., Schuur, E.A.G., Shaver, G.R. et al. (2011). Carbon loss from an unprecedented Arctic tundra wildfire. *Nature* 475, 489–492. <https://www.nature.com/articles/nature10283>
43. Kelly, R., Chipman, M.L., Higuera, P.E., Stefanova, I., Brubaker, L.B. and Hu, F.S. (2013). Recent burning of boreal forests exceeds fire regime limits of the past 10,000 years. *Proceedings of the National Academy of Sciences USA* 110, 13055–13060. <https://doi.org/10.1073/pnas.1305069110>
44. Rupp, T.S., Duffy, P., Leonawicz, M., Lindgren, M., Breen, A., Kurkowski, T. et al. (2016). Climate scenarios, land cover, and wildland fire. In Zhu, Z. and McGuire, A.D. (eds.), *Baseline and projected future carbon storage and greenhouse-gas fluxes in ecosystems of Alaska*. USGS Professional Paper 1826, 17–52
45. Bret-Harte, M.S., Mack, M.C., Shaver, G.R., Huebner, D.C., Johnston, M., Mojica, C.A. et al. (2013). The response of Arctic vegetation and soils following an unusually severe tundra fire. *Philosophical Transactions of the Royal Society B: Biological Sciences* 368, 20120490. <https://doi.org/10.1098/rstb.2012.0490>
46. Arctic Climate Impact Assessment (2005). *Impacts of a warming Arctic: Arctic climate impact assessment*. Cambridge, UK: Cambridge University Press.
47. Riley, W.J., Subin, Z.M., Lawrence, D.M., Swenson, S.C., Torn, M.S., Meng, L. et al. (2011). Barriers to predicting changes in global terrestrial methane fluxes: analyses using CLM4Me, a methane biogeochemistry model integrated in CESM. *Biogeosciences* 8, 1925–1953. <https://doi.org/10.5194/bg-8-1925-2011>
48. Gao, X., Schlosser, C.A., Sokolov, A., Walter Anthony, K., Zhuang, Q. and Kicklighter, D. (2013). Permafrost degradation and methane: low risk of biogeochemical climate-warming feedback. *Environmental Research Letters* 8(3), 035014. <http://dx.doi.org/10.1088/1748-9326/8/3/035014>
49. Schneider von Deimling, T., Grosse, G., Strauss, J., Schirmermeister, L., Morgenstern, A., Schaphoff, S. et al. (2015). Observation-based modelling of permafrost carbon fluxes with accounting for deep carbon deposits and thermokarst activity. *Biogeosciences* 12(11), 3469–3488. <https://doi.org/10.5194/bg-12-3469-2015>
50. Grosse, G., Harden, J., Turetsky, M., McGuire, A.D., Camilli, P., Tarnocai, C. et al. (2011). Vulnerability of high-latitude soil organic carbon in North America to disturbance. *Journal of Geophysical Research* 116, G00K06. <https://doi.org/10.1029/2010JG001507>
51. Instanes, A., Anisimov, O., Brigham, L., Goering, D., Khrestalev, L.N., Ladanyi, B. et al. (2005). Infrastructure: buildings, support systems, and industrial facilities. In *ACIA: Arctic Climate Impact Assessment*. Cambridge, UK: Cambridge University Press. 908–944.
52. Walker, D.A., Reynolds, M.K., Buchhorn, M. and Peirce, J.L. (eds.) (2014). *Landscape and permafrost changes in the Prudhoe Bay Oilfield, Alaska*. Alaska Geobotany Center Publication AGC 14-01. Fairbanks, AK: University of Alaska Fairbanks. https://www.geobotany.uaf.edu/library/pubs/WalkerDA2014_agc14-01.pdf

53. Vlassova, T. (2002). Human impacts on the tundra-taiga zone dynamics: the case of the Russian lesotundra. *Ambio Special Report*, 12, 30–36.
54. Instanes, A. (2016). Incorporating climate warming scenarios in coastal permafrost engineering design – Case studies from Svalbard and northwest Russia. *Cold Regions Science and Technology* 131, 76–87. <https://doi.org/10.1016/j.coldregions.2016.09.004>
55. Shiklomanov, N.I., Streletskiy, D.A., Swales, T.B. and Kokorev, V.A. (2017). Climate change and stability of urban infrastructure in Russian permafrost regions: Prognostic assessment based on GCM climate projections. *Geographical Review* 107, 125–142. <https://doi.org/10.1111/gere.12214>
56. Jorgenson, T., Shur, Y.L. and Osterkamp, T.E. (2008). Thermokarst in Alaska. *Proceedings of the Ninth International Conference on Permafrost* 1, 869–876. Fairbanks, AK: University of Alaska Fairbanks
57. Kokelj, S.V. and Jorgenson, M.T. (2013). Advances in thermokarst research. *Permafrost and Periglacial Processes* 24, 108–119. <https://doi.org/10.1002/ppp.1779>
58. Jorgenson, M.T., Racine, C.H., Walters, J.C. and Osterkamp, T.E. (2001). Permafrost degradation and ecological changes associated with a warming climate in central Alaska. *Climatic Change* 48, 551–579. <https://doi.org/10.1023/A:100566742>
59. Halsey, L.A., Vitt, D.H. and Zoltai, S.C. (1995). Initiation and expansion of peatlands in Alberta, Canada. *Climate, landscape and vegetation change in the Canadian Prairie Provinces Proceedings* 45–53. Edmonton, Alberta: Canadian Forestry Service. <http://cfs.nrcan.gc.ca/pubwarehouse/pdfs/18992.pdf>
60. Jorgenson, M.T., Shur, Y.L. and Walker, H.J. (1998). Evolution of a permafrost-dominated landscape on the Colville River Delta, northern Alaska. *Proceedings of Seventh International Conference on Permafrost, Collection Nordicana* 57, 523–529.
61. Fortier, D. and Allard, M. (2004). Late Holocene syngenetic ice-wedge polygons development, Bylot Island, Canadian Arctic Archipelago. *Canadian Journal of Earth Sciences* 41(8), 997–1012. <https://doi.org/10.1139/e04-031>
62. Payette, S., Delwaide, A., Caccianiga, M. and Beauchemin, M. (2004). Accelerated thawing of subarctic peatland permafrost over the last 50 years. *Geophysical Research Letters* 31, L18208. <https://doi.org/10.1029/2004GL020358>
63. Metcalfe, D.B., Hermans, T.D.G., Ahlstrand, J., Becker, M., Berggren, M., Björk, R. G. et al. (2018). Patchy field sampling biases understanding of climate change impacts across the Arctic. *Nature Ecology & Evolution* 2, 1443–1448. <https://www.nature.com/articles/s41559-018-0612-5>
64. United Nations Environment Programme (2012). *Policy implications of warming permafrost*. UNEP : Nairobi. <https://wedocs.unep.org/handle/20.500.11822/8533>
65. Arctic Monitoring and Assessment Programme (2017b) *Adaptation actions for a changing Arctic: Perspectives from the Barents area*. Oslo, Norway: AMAP. <https://www.amap.no/documents/doc/Adaptation-Actions-for-a-Changing-Arctic-Perspectives-from-the-Barents-Area/1604>
66. Chetkiewicz, C. and Lintner, A. (2014). *Getting it right in Ontario's Far North: the need for a regional strategic environmental assessment in the Ring of Fire [Wawagajing]*. Canada: Wildlife Conservation Society Canada and Ecojustice Canada. https://www.wcs.canada.org/Portals/96/Documents/RSEA_Report_WCSCanada_Ecojustice_FINAL.pdf
67. Koivuova, T. (2016). Arctic resources: Exploitation of natural resources in the Arctic from the perspective of international law. In *Research Handbooks on International Law and Natural Resources*. Morgera, E. and Kulovesi, K. (eds.) Cheltenham/Northampton: Edward Elgar Publishing. Chapter 17. 349–366. <https://www.elgaronline.com/view/9781783478323.00031.xml>
68. McLaughlin, J.W. and Webster, K. (2013). *Effects of a changing climate on peatlands in permafrost zones: a literature review and application to Ontario's Far North*. Climate Change Research Report CCCR-34. Canada: Ontario Ministry of Natural Resources. <http://www.ontla.on.ca/library/repository/mon/27008/323518.pdf>
69. Legislative Assembly of Ontario (2010). Ontario House Bill 191 2010. An Act with respect to land use planning and protection in the Far North. Ontario. <https://www.ola.org/en/legislative-business/bills/parliament-39/session-2/bill-191>
70. Government of Ontario (2018). Land use planning process in the Far North. Ontario. <https://www.ontario.ca/page/land-use-planning-process-far-north#section-1>

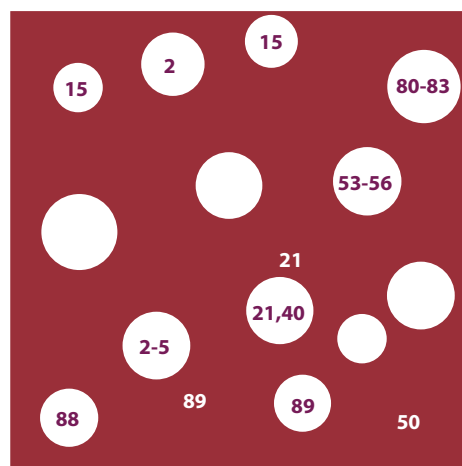
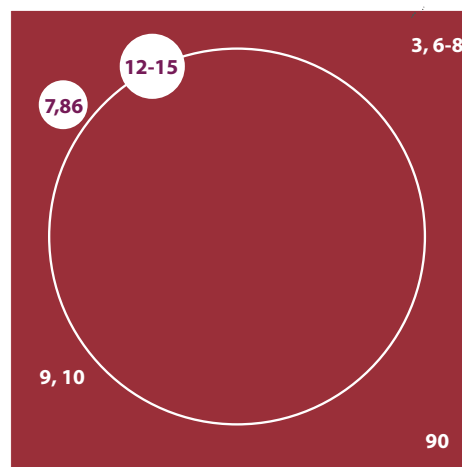
Graphic references



71. Washburn, A.L. (1979). *Geocryology. A survey of periglacial processes and environments*. London: Edward Arnold.
72. Kujala, K., Seppälä, M. and Holappa, T. (2008). Physical properties of peat and palsa formation. *Cold Regions Science and Technology* 52, 408–414. <https://doi.org/10.1016/j.coldregions.2007.08.002>
73. Vasil'chuk, Y.K. (2013). Syngenetic ice wedges: cyclical formation, radiocarbon age and stable-isotope records. *Permafrost and Periglacial Processes* 24(1), 82–93. <https://doi.org/10.1002/ppp.1764>
74. Harris, S.A., Brouchkov, A. and Cheng, G. (2018). *Geocryology: Characteristics and use of frozen ground and permafrost landforms*. Leiden, NL: CRC Press/Balkema.
75. Burn, C.R. (1998). The response (1958–1997) of permafrost and near-surface ground temperatures to forest fire, Takhini River valley, southern Yukon Territory. *Canadian Journal of Earth Sciences*, 35(2), 184–199. <https://doi.org/10.1139/cjes-35-2-184>
76. Routh, J., Hugelius, G., Kuhry, P., Filley, T., Kaislahti, P., Becher, M. et al. (2014). Multi-proxy study of soil organic matter dynamics in permafrost peat deposits reveal vulnerability to climate change in the European

Russian Arctic. *Chemical Geology* 368, 104-117. <https://doi.org/10.1016/j.chemgeo.2013.12.022>

77. Soudzilovskaia, N.A., van Bodegom, P.M. and Cornelissen, H.C. (2013). Dominant bryophyte control over high-latitude soil temperature fluctuations predicted by heat transfer traits, field moisture regime and laws of thermal insulation. *Functional Ecology* 27, 1442–1454. <https://doi.org/10.1111/1365-2435.12127>
78. Porada, P., Ekici, A. and Beer, C. (2016). Effects of bryophyte and lichen cover on permafrost soil temperature at large scale. *Cryosphere* 10, 2291–2315. <https://doi.org/10.5194/tc-10-2291-2016>
79. Park, H., Launiainen, S., Konstantinov, P.Y., Iijima, Y. and Fedorov, A.N. (2018). Modeling the effect of moss cover on soil temperature and carbon fluxes at a tundra site in northeastern Siberia. *Journal of Geophysical Research: Biogeosciences*. <https://doi.org/10.1029/2018JG004491>
80. Chapin III, F., Sturm, M., Serreze, M., McFadden, J., Key, J., Lloyd, A. et al. (2005). Role of land-surface changes in Arctic summer warming. *Science* 310(5748), 657-660. <https://doi.org/10.1126/science.1117368>
81. Blok, D., Heijmans, M.P.D., Schaepman-Strub, G., Kononov, A.V., Maximov, T.C. and Berendse, F. (2010). Shrub expansion may reduce summer permafrost thaw in Siberian tundra. *Global Change Biology* 16(4), 1296-1305. <https://doi.org/10.1111/j.1365-2486.2009.02110.x>
82. Briggs, M.A., Walvoord, M.A., McKenzie, J.M., Voss, C.I., Day-Lewis, F. D. and Lane, J.W. (2014). New permafrost is forming around shrinking Arctic lakes, but will it last? *Geophysical Research Letters* 41(5), 1585–1592. <https://doi.org/10.1002/2014GL059251>
83. Druel, A., Peylin, P., Krinner, G., Ciais, P., Viovy, N., Peregon, A. et al. (2017). Towards a more detailed representation of high-latitude vegetation in the global land surface model ORCHIDEE (ORC-HL-VEGv1.0). *Geoscientific Model Development* 10, 4693–4722. <https://doi.org/10.5194/gmd-10-4693-2017>
84. Nauta, A.L., Heijmans, M.M.P.D., Blok, D., Limpens, J., Elberling, B., Gallagher, A. et al. (2015). Permafrost collapse after shrub removal shifts tundra ecosystem to a methane source. *Nature Climate Change* 5, 67-70. <https://www.nature.com/articles/nclimate2446>
85. Johansson, M., Christensen, T.R., Åkerman, H.J., and Callaghan, T.V. (2006). What determines the current presence or absence of permafrost in the Torneträsk region, a sub-arctic landscape in northern Sweden? *Ambio* 35, 190-197. [https://doi.org/10.1579/0044-7447\(2006\)35\[190:WDTCP0\]2.0.CO;2](https://doi.org/10.1579/0044-7447(2006)35[190:WDTCP0]2.0.CO;2)
86. Zhang, T., Barry, R.G., Knowles, K., Ling, F. and Armstrong, R.L. (2003). Distribution of seasonally and perennially frozen ground in the Northern Hemisphere. In Phillips, M., Springman, S.M. and Arenson, L.U. (eds), *Permafrost, Proceedings of the 8th International Conference on Permafrost*, Zurich, Switzerland, 21-25 July 2003, Volume 2.
87. Joosten, H. and Couwenberg, J. (2008) Peatlands and Carbon. In: Parish, F., Sirin, A., Charman, D., Joosten, H., Minayeva, T., Silvius, M. & Stringer, L. (eds.) *Assessment on Peatlands, Biodiversity and Climate Change: Main Report*, Global Environment Centre, Kuala Lumpur and Wetlands International, Wageningen, 99–117. http://www.imcg.net/media/download_gallery/books/assessment_peatland.pdf



88. Abbott, B.W., Jones, J.B., Schuur, E.A.G., Chapin, F.S. III, Bowden, W.B., Bret-Harte, M.S., Epstein, H.E., et al. (2016) Biomass offsets little or none of permafrost carbon release from soils, streams and wildfire: an expert assessment. *Environmental Research Letters*, 11: 034014. doi: 10.1088/1748-9326/11/3/034014
89. Schuster, P. F., Schaefer, K. M., Aiken, G. R., Antweiler, R. C., Dewild, J. F., Gryziec, J. D., Gusmeroli, A., et al. (2018). Permafrost stores a globally significant amount of mercury. *Geophysical Research Letters*, 45, 1463–1471. <https://doi.org/10.1002/2017GL075571>
90. Brown, J., O. Ferriani, J. A. Heginbottom, and E. Melnikov. 2002. Circum-Arctic Map of Permafrost and Ground-Ice Conditions, Version 2. Boulder, Colorado USA. NSIDC: National Snow and Ice Data Center. <https://doi.org/nsidc.org/data/GGD318/versions/2>