Arctic Office
NATURAL ENVIRONMENT RESEARCH COUNCIL

UK Arctic Terrestrial Research: Towards International Polar Year 2032/33 and Beyond

Research Strengths, Priorities and Implementation

This document arises from three online workshops, held on the 2nd, 4th and 9th December 2025, attended by 39 UK-based researchers from 22 institutions covering the breadth and depth of expertise in UK Arctic terrestrial science. The workshops were organised by the workshop lead, **Gareth Phoenix** (University of Sheffield) and an organising committee of **Millicent Harding** (Durham University), **Iain Hartley** (University of Exeter), **Lena Lancastle** (University of Sheffield), **Julian Murton** (University of Sussex), **Thomas Parker** (James Hutton Institute), **Nick Rutter** (Northumbria University) and **Lorna Street** (University of Edinburgh). During the workshops, discussion summaries were produced by subject-themed breakout groups comprised of subject area experts (see list of workshop participants). These summaries were combined into an initial draft of this document, edited by the workshop lead and organising committee. The document went through two rounds of editing by the workshop participants prior to final production.

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Front page photo credit: Marc Macias-Fauria

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EXECUTIVE SUMMARY

The terrestrial Arctic: a place of rapid change

The Arctic is warming nearly four times faster than the global average. On land and in freshwaters, this warming is having rapid and substantial impacts that threaten its ecosystems and change the way the Arctic stores carbon and releases greenhouse gases. These changes have direct consequences for the people that populate this special region of our planet, and for the rest of the world, because a warming Arctic amplifies global warming. It is especially concerning that the changes seen across the terrestrial Arctic are some of the clearest, largest and most widespread of changes caused by global warming seen in any region worldwide. Arctic scientists in the UK have long been at the forefront of understanding these changes, and that expertise is ready and organised to address the substantial challenges that lie ahead as the Arctic continues to warm and change at pace.

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Urgent challenges at the intersection of science, policy and society

The sheer scale and pace of change in the terrestrial Arctic means that research to understand current and future change, and the consequences for local people and nations worldwide, is pressing and urgent.

The Arctic's frozen ground (permafrost) contains at least twice as much carbon as the atmosphere, and carbon dioxide (CO_2) and methane (CH_4) released from thawing ground could rival deforestation or land-use change to become the greatest biospheric source of greenhouse gases. Ground subsidence from thawing permafrost threatens Arctic communities, businesses and infrastructure. Arctic wildlife and ecosystems are threatened by climate change and extreme events such as wildfires. These place the Arctic's biodiversity at risk and impact the livelihoods of people that depend on it.

The Arctic's freshwater systems provide key ecosystem services, from biodiversity hotspots, food and domestic water supplies, to river systems which are key to the flow of the Atlantic Meridional Overturning Circulation (the global heat-and-nutrient engine that includes the Gulf Stream). These same rivers also deliver nutrients essential for marine food webs and fisheries. As the Arctic warms, however, these freshwater systems are changing.

The Arctic is a place of great geopolitical change and importance. Here terrestrial scientists can play a key role in science diplomacy, helping to build or strengthen relationships between nations, as well as advising on the management and consequences of an increasingly accessible Arctic, including increasing terrestrial habitation, infrastructure, and resource extraction.

The importance of a changing Arctic to the world is well recognised, with the United Nations Intergovernmental Panel on Climate Change's (IPCC) 6th Assessment Report highlighting that several of the most serious global consequences of climate change are linked to the rapid and substantial changes in the polar regions. In light of this, the 5th International Polar Year (IPY5 2032/33) is being organised to address urgent global challenges by advancing polar research.

Early action is crucial for both local and global understanding, adaptation and resilience. Research therefore needs to focus on priority science questions with clear and robust approaches that draw on the diverse strengths of the research community.

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Photo credit: Roseanna Mayfield

UK Arctic terrestrial science: strengths in people, institutions and infrastructure

UK Arctic terrestrial research strengths arise from world-class expertise spread across a diversity of universities, and government and non-government research institutes, supported by multiple funding opportunities and funding models. It benefits from strong logistical support, including field stations, research aircraft and ships, as well as cutting-edge technology. Extensive international partnerships, advanced observational and modelling capabilities, and a vibrant early career researcher community ensure globally integrated, interdisciplinary research that plays an internationally important role in understanding Arctic change.

In this document, the UK Arctic terrestrial science community details the expertise and capacity it has to meet the challenges ahead, describes the most pressing science questions in the terrestrial Arctic, and outlines how that expertise can best be deployed to address these challenges.

Photo credit: Nick Rutter

Research strengths towards IPY5 and beyond

(1) Changing ecosystems and biodiversity

UK researchers have a long track record of excellence in understanding ecosystem change through long-term monitoring and experiments, application of remote sensing, modelling and palaeoecology. This expertise is supported by strong infrastructure as well as extensive historical collections and curated environmental datasets.

(2) Ecosystem biogeochemical cycling through plants, soils and microbes

UK research advances understanding of Arctic environmental and biogeochemical change through whole-ecosystem approaches, advanced carbon cycle science, long-term experiments, and integration of field data, ground-based and satellite remote sensing, modelling and machine learning. These contributions are enhanced by the development and application of emerging technologies to assess climate impacts and feedbacks across multiple scales.

(3) A warming terrestrial cryosphere

The UK has played a leading role in understanding the processes and consequences of permafrost thaw by integrating interdisciplinary process science, advanced isotopic and spectroscopic techniques, and multi-platform remote sensing with machine learning. These approaches have enabled the tracking, mapping and upscaling of carbon dioxide and methane release across Arctic landscapes, and their feedback to climate change.

(4) Freshwater systems under change

UK research has advanced Arctic freshwater science through expertise that integrates ecology, biogeochemistry and palaeoecology. This research includes working at different scales across lakes, rivers and wetlands to capture the Arctic's diverse freshwater environments. Using biological, geochemical and sedimentary understanding combined with long-term monitoring and experiments, the UK research community is able to assess climate and human impacts on nutrient, carbon and pollutant pathways.

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Research Priorities for UK Arctic Terrestrial Science

(1) Changing ecosystems and biodiversity

The accelerated environmental change in the Arctic is impacting ecosystems, altering species distributions, community composition and ecosystem function, with consequences for biodiversity, human societies and global climate feedbacks. To understand these changes, UK research should prioritise understanding native and invasive species dynamics and identify the causal drivers of these. Terrestrial changes should link to broader Earth system processes, and integrate data across ecological gradients at different spatial and temporal scales. Improved monitoring and modelling are essential to predict and understand Arctic ecosystem change.

(2) Ecosystem biogeochemical cycling through plants, soils and microbes

Rapid warming is altering the biophysical environment of the Arctic and its ecosystem properties, including snow, albedo, soil insulation and evapotranspiration which, in turn, have substantial consequences for greenhouse gas emissions and biogeochemical cycles. To understand these changes and their consequences, multi-scale research is needed to investigate heterogeneous landscape processes, hydrology, and trophic interactions, contrasting the impacts of gradual climate change with the impacts of disturbances and extreme events. Work related to these is also needed to understand the impacts on carbon and nutrient cycles, and therefore to quantify how these changes feedback to global warming.

(3) A warming terrestrial cryosphere

Thawing permafrost poses major uncertainties for Arctic greenhouse gas release and global warming projections. To address this, UK research priorities include monitoring and modelling gradual and abrupt permafrost thaw across scales in boreal and tundra regions, integrating in situ and remote sensing data with machine learning, and assessing impacts on water quality and nutrient release to oceans. Multidisciplinary approaches, including collaboration with Indigenous communities, will be essential to understand environmental, societal, and land-to-ocean consequences of permafrost thaw, and improve Earth system projections.

(4) Freshwater systems under change

The warming Arctic is transforming freshwater systems, altering ice cover, nutrient fluxes and carbon cycling, with major impacts on biodiversity, ecosystem function and greenhouse gas emissions. To understand these rapid changes, UK research priorities include advancing understanding of freshwater responses to environmental change across multiple scales from microbes to whole catchments, as well as quantifying nutrient, carbon and trace metal fluxes. Better understanding and quantification of the changing biogeochemistry will help advance understanding of changing freshwater systems and how these will feed back to climate change and influence Arctic Ocean productivity and biodiversity.

Ways forward and opportunities towards IPY5 and beyond

(1) Changing ecosystems and biodiversity

The priorities in Arctic terrestrial ecology will require robust, spatially and temporally representative biodiversity monitoring, combining ground truthing, advanced sensors, molecular tools and AI-driven data analysis. Standardised, high-resolution datasets on vegetation, soils and microclimate across Arctic ecosystems are essential to improve modelling, understand ecosystem dynamics and predict responses to climate and biogeochemical changes.

(2) Ecosystem biogeochemical cycling through plants, soils and microbes

To address pressing questions in biogeochemical cycling, work is needed to sustain long-term experiments and improve integration of remote sensing and sensor networks for pan-Arctic coverage. Necessary field work will be facilitated by enhanced infrastructure and logistics. Combining rapid-response and next-generation experiments will provide mechanistic understanding of disturbances, multi-trophic interactions and biogeochemical fluxes, supporting upscaling, modelling and improved prediction of climate feedbacks.

(3) A warming terrestrial cryosphere

Terrestrial cryosphere research will need to enhance simulation and projections of changes in permafrost temperature and the distribution of seasonal snow, and their consequences for greenhouse gas emissions and climate impacts across varied Arctic landscapes. This work requires multi-scale remote sensing and ground-based monitoring, along with improved subsurface and landform mapping to complement long-term experiments and understanding of abrupt permafrost thaw dynamics. This will facilitate improved integration of soil carbon, microbial processes and greenhouse gas emissions into models to predict future climate change.

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(4) Freshwater systems under change

Advances in freshwater research should include a focus on high-resolution, multi-year monitoring of hydrology, biodiversity, biogeochemistry, greenhouse gas fluxes, water quality, and pollution. This work should utilise autonomous sensors, satellites and field experimentation, with a particular need for river gauging and sustained long-term measurements to capture extreme events and episodic nutrient fluxes. Lake sedimentary records can provide valuable baseline conditions to contextualise recent changes in biodiversity, biogeochemistry, and greenhouse gas and nutrient fluxes over time-scales longer than recent observations.

(5) Interdisciplinarity, partnerships and co-design

UK research should continue to champion co-designed science and co-creation of datasets, engaging with local and Indigenous communities to integrate knowledge and build scientific capacity. This should be facilitated by longer-term, flexible funding models that foster relationship building. Multi- and trans-disciplinary collaboration is also needed across terrestrial, marine, cryospheric, atmospheric and social sciences. Enhanced international engagement, centralised data infrastructure and strategic partnerships will strengthen UK contributions, avoid unnecessary duplication of research activity and help to address urgent Arctic environmental and societal challenges effectively.

UK STRENGTHS IN ARCTIC TERRESTRIAL RESEARCH

The UK's strengths are rooted in a long history of individual and collaborative interdisciplinary research that has been undertaken in all parts of the Arctic. Methodological innovation and advancement across multiple spatial and temporal scales linked to remote sensing and modelling drives advancement in terrestrial ecology, biogeochemistry, the terrestrial cryosphere and freshwater systems. UK Arctic terrestrial research also benefits from strong international collaboration, including with local and Indigenous communities, thus driving innovation and building capacity.

Photo credit: Marc Macias-Fauria

UK Arctic terrestrial expertise is held across multiple UK universities, research institutes and government organisations, complemented by support in logistics, networking and capacity building from national and international funding bodies, as well as the Natural Environment Research Council (NERC) Arctic Office and the United Kingdom Arctic and Antarctic Partnership. UK investment in UK-managed or partner Arctic field stations, such as Ny-Ålesund (Svalbard), provides accommodation, laboratories and on-the-ground field support, whilst UK marine research vessels like the RRS Sir David Attenborough facilitate terrestrial research by providing logistical support and transport for scientists and equipment to remote Arctic locations and the marine-terrestrial interface.

This strong financial and logistical support ensures the UK maintains a high level of activity within national and international programmes across the Arctic. This activity helps drive the UK's strong engagement with international partnerships, both through major funding programmes and national opportunities such as the NERC Arctic Office Bursaries, as well as bilateral funding frameworks with other nations. Recent collaborations include those arising from the Canada-Inuit Nunangat-United Kingdom Arctic Research Programme (CINUK), with emphasis on collaboration and co-production with Indigenous partners.

The UK therefore has a strong research community that is well integrated into global networks. This integration enables internationally recognised work on the terrestrial Arctic with a collaborative focus that has promoted an interdisciplinary approach spanning spatial scales from microns to the pan-Arctic, and timescales from seconds to millennia. Across scales, ground observations and experiments are well linked to UK satellite and ground-based remote sensing expertise where UK researchers are skilled in upscaling field observations to track year-to-year changes in greenhouse gas fluxes, hydrology, phenology, landscape disturbances and impacts on land surface properties. These empirical insights inform UK-developed models predicting future Arctic change, including Earth system models that contribute to IPCC assessments.

A further strength of UK Arctic terrestrial research is the size and importance of its vibrant early career researcher (ECR) community that is supported by the highly active UK Polar Network (UKPN). This dynamic ECR community is key to meeting the UK's long-term goals, by driving innovation, building capacity and maintaining a legacy of expertise.

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Photo credit: Roseanna Mayfield

Changing ecosystems and biodiversity

The UK excels in multi-scale remote sensing (satellite, airborne, drone, spectroscopy) of Arctic vegetation change, supported by national facilities such as the NERC Airborne Research Facility and Field Spectroscopy Facility. This is complemented by strong modelling of past and future Arctic vegetation dynamics (greening and browning), extensive palaeoecological expertise (including a/eDNA, dendroecology and paleolimnology), and involvement with long-term distributed experiments such as the International Tundra Experiment (ITEX).

UK groups contribute to microclimate and snow monitoring, disturbance ecology, research on herbivores as ecosystem engineers, and biotic–abiotic linkages including sea ice–terrestrial interactions. The UK's research strengths are supported by substantial historical collections—including maps, images, expedition archives and herbaria at the British Antarctic Survey (BAS) and the Scott Polar Research Institute (SPRI), alongside curated datasets at the UK Centre for Environmental Data Analysis, NERC Polar Data Centre and the British Atmospheric Data Centre. Together, these collections provide important resources for understanding long-term ecological change.

Ecosystem biogeochemical cycling through plants, soils and microbes

The UK has long-standing expertise on the impacts of Arctic environmental change, spanning from global warming to impacts of human infrastructure, and how these impact the release of greenhouse gases and feedback to climate. The UK community's whole-ecosystem focus highlights the importance of landscape dynamics and plant-soil interactions. This multiscale approach allows UK research to answer critical questions about the impacts of future climate on Arctic vegetation biodiversity and productivity, including biomass increases and decreases (greening and browning). It also facilitates quantification of the effects of extreme climatic events and permafrost collapse, as well as understanding the consequences for biogeochemical fluxes from terrestrial to freshwater to coastal ecosystems.

Key research strengths include terrestrial carbon (C) cycling in terms of both process understanding and modelling, with terrestrial scientists closely linked to the UK and International Earth system modelling communities. To understand continuing change in Arctic terrestrial ecosystems, UK scientists place emphasis on long-term field studies and experimental manipulations both in situ and in the laboratory. Methodologically, the UK excels in developing and deploying cutting-edge techniques and subsequently upscaling

that understanding. Such advances include the development of natural abundance radiocarbon (^{14}C) methodologies to identify old permafrost-derived carbon contributions to contemporary gaseous and dissolved fluxes of carbon, crucial for identifying drivers of greenhouse gas release. A long-standing strength is combining field data with remote sensing data from satellites and airborne platforms such as Landsat, Copernicus and drones. By using novel machine learning methods, the community integrates long-term monitoring with remotely sensed data to generate spatially and temporally resolved understanding of landscape changes across catchment, regional and pan-Arctic scales. Other technological strengths include palaeoenvironmental analysis, eDNA in soils, omics, and the use of supercomputing and AI for addressing complex, interdisciplinary problems.

Photo credit: Roseanna Mayfield

A warming terrestrial cryosphere

UK research plays a major role in reducing uncertainties about how climate warming and precipitation change will impact permafrost thaw, and the consequences of this for the vast carbon stocks held in Arctic terrestrial permafrost and their release as greenhouse gases. The UK excels in interdisciplinary hydrology, biogeochemistry and terrestrial biology, enabling the tracking of carbon and nutrient flows. Cutting-edge techniques have been developed to fingerprint greenhouse gas sources using mass spectrometry, stable isotope analysis, radiocarbon (at NERC Isotope Facilities), and Diamond Light Source Synchrotron facilities.

UK strengths lie in the integration of ground, airborne and satellite observations to understand active-layer deepening, permafrost degradation and methane emissions across scales. To detect thaw patterns and drivers, researchers have combined multi-sensor datasets from drones and uncrewed aerial vehicles (UAVs) with data from Sentinel-2 and Sentinel-5, interferometric radar (for example, APSIS/ISBAS), digital elevation models (DEMs) and long-term orthophotography. Ultra-high-resolution UAV data and DEMs have enabled detailed assessments of topography, vegetation structure and thermokarst development, while APSIS has proven highly effective at detecting ground subsidence as an early proxy of permafrost thaw. Further distinctive strengths in permafrost research are spatial, statistical and machine learning modelling. UK researchers have reduced uncertainties on the spatial patterns of active layer and permafrost conditions through machine learning, ground thermal regime analysis and environmental variables including land surface temperature, snow cover, vegetation indices and soil moisture.

A further emerging strength is in upscaling methane fluxes from local measurements to regional and Arctic-wide maps using remote sensing datasets and land cover characterisation. UK researchers are linking vegetation types, surface moisture and thaw indicators to greenhouse gas fluxes, and are exploring the potential of drone-based methane observations for calibration of Earth Observation-based products. The UK also benefits from research on its domestic peatland and alpine systems that provide process-understanding applicable to Arctic systems, while its Quaternary landscapes impacted by past permafrost provide a valuable analogue for newly-thawed Arctic regions, allowing UK researchers to predict Arctic environmental changes.

Freshwater systems under change

The UK has strengths in advancing understanding of freshwater systems in how they act as dynamic pathways that transport and store nutrients, carbon, sediments and pollutants, and how they act in integrating signals of environmental change from terrestrial landscapes (including biosphere, cryosphere, mountains) and the atmosphere. Research advances are of further importance because freshwaters provide important habitats for a diverse range of organisms, from microbial communities to invertebrates, fish and local and migratory birds. Research on freshwater systems varies from single lakes, ponds and rivers, to catchment-wide systems and nearshore environments.

Arctic freshwater researchers in the UK cover a wide range of subject areas and landscapes. Research environments include Arctic tundra, boreal forests, perennially and seasonally ice-covered lakes and river systems, supraglacial cryoconite holes, thermokarst, terrestrial ice formations and the marine–freshwater interface. Across these areas, the UK has expertise in lake and river systems, water–landscape interactions, greenhouse gases, nutrient and biogeochemical cycling, ecology and palaeoecology. Proxies used to infer environmental conditions and ecosystem processes range from biological (for example microbes, a/eDNA, pollen, diatoms, algae, and freshwater invertebrates such as chironomids), to biogeochemical (such as nutrient stoichiometry, carbon cycling, dissolved/particulate concentrations) and geochemical proxies (for example, isotopes, biomarkers, pigments) and sedimentology (such as grain size, mineral composition).

The UK has strengths in the study of changes to freshwater systems caused by both natural and anthropogenic stressors, including climate, nutrients, human activities such as building infrastructure, changing land use and input of nutrients and pollutants (from both in-wash and atmospheric deposition). UK researchers are experienced in empirical data collection ranging from seasonal field campaigns to intense short-term sampling campaigns, long-term monitoring and deployment of in situ experiments at sites both close to and remote from human habitation. In addition, UK researchers are skilled at the integration of these data with remote sensing and model based findings. Time periods studied span the late glacial to modern day, on time scales such as millennial, centennial, decadal and modern-day measurements.

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PRIORITIES FOR UK ARCTIC TERRESTRIAL RESEARCH

Research priorities centre on uncovering the fast-moving ecological and biogeochemical shifts transforming terrestrial, freshwater and permafrost systems that arise from the particularly rapid pace of climate change in the Arctic. Key needs include revealing how species and ecosystems change on land and in freshwater systems, scaling local and regional understanding to pan-Arctic change, and reducing uncertainty in the powerful feedbacks among climate, carbon cycling, and ecosystem function. These include understanding the consequences of land and freshwater ecosystem change, and thawing permafrost, for release of greenhouse gases and nutrient export to oceans, as well as understanding the consequences for local and Indigenous communities. Uniting remote sensing with in situ networks is also needed.

Photo credit: Georgia Hole

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Changing ecosystems and biodiversity

Understanding ecosystem change and novel communities. This priority arises from rapid environmental change and new ecological interactions that are becoming apparent across the Arctic. These changes are happening at pace, with major implications for Arctic biodiversity, trophic interactions, human society, conservation and policy, as well as feedback to climate, in turn magnifying global impacts. Research gaps include understanding the establishment of non-native invasive species as well as changes in the abundance, distribution and performance of native species, communities and ecosystems. Identifying in situ changes in community composition and performance, and their causal agents (such as ecosystem engineers, or abiotic drivers such as climate change), is also needed to identify vulnerable ecosystems and species and to facilitate the prediction and mitigation of local or global extinctions.

Connecting terrestrial dynamics to broader Earth system processes. What happens in the Arctic does not stay in the Arctic, so research is needed on system-level feedbacks to the Earth system, including climate change feedbacks, with a focus on linkages across atmospheric, cryospheric, geological, terrestrial, freshwater and marine systems. This research need includes the study of the biological and biogeochemical impacts of ecosystems and communities on components of the Arctic system, such as vegetation, albedo, climate, permafrost stability, the carbon cycle, nutrient flows and hydrological regimes. Such research requires explicit definition of the appropriate temporal and physical scales.

Connecting scales to understand rapid and long-term Arctic change. Arctic ecosystems are often highly heterogeneous, exhibiting variation that occurs at small, sub-metre, scales within ecosystems to variation across the pan-Arctic. Work is therefore needed to explicitly connect across spatial, and temporal scales incorporating macroclimate, microclimate and biological responses. This work also needs to include trends and changes resulting from extreme events and disturbances, especially where data scarcity currently limits work on extreme events. More broadly, the measurement evidence base is currently biased towards easier-to-access Arctic areas, but these sites are not necessarily representative of the wider Arctic, and conclusions about environmental trends may not always be valid when upscaled. Because of data gaps and biases, more research and data are needed to better constrain models and provide a holistic baseline across the Arctic at appropriate scales. Improved reconstructions of past ecosystems, species distributions and extreme events are also needed, for instance on the increasing frequency and severity of fires and rain-on-snow events.

Ecosystem biogeochemical cycling through plants, soils and microbes

Changing energy balance and biophysical environments. Work is needed to understand how and why the energy balance and biophysical environments of the terrestrial Arctic are changing. This is urgent because rapid warming is associated with changes in the timing of spring and autumn, the frequency and severity of extreme events, and shifts towards increasingly rain-dominated (as opposed to snow-dominated) and fire-prone ecosystems. Impacts of these changes on the biophysical environment will affect local, regional and global climate, and play a key role in controlling future rates of permafrost thaw and greenhouse gas emissions. Therefore, more work is needed to help understand how key ecosystem properties control ground and air temperatures through influences on snow, albedo, evapotranspiration, shading and soil insulation. Furthermore, because ecosystems can cool soils and protect permafrost from thaw, work is required to understand how these ecosystem properties are themselves vulnerable to the impacts of climate change.

Multiscale research to understand Arctic landscape change. This research is needed because the terrestrial Arctic spans large climatic gradients. Also, the physical geography of Arctic landscapes, including variability in geology, post-glacial processes and landforms, and soil physics, results in considerable spatial heterogeneity that strongly influences the overall impacts of environmental change. Furthermore, connectivity through hydrological systems, and associations with large-scale animal movements, means that a landscape-level focus is required for understanding Arctic change. A challenge that needs to be addressed is that contrasting responses are often occurring in different parts of the landscape, so it is crucial to determine pan-Arctic variability and the overall net effect. Research is therefore needed to understand how the impacts of global change are experienced at the landscape scale where a myriad of effects combine.

Understanding changing carbon and nutrient cycles, and implications for greenhouse gas emissions and feedbacks to climate change. Vast stores of carbon are held in Arctic ecosystems in areas experiencing rapid climate change, therefore research is needed to detect and understand losses of carbon from soil active layers and the release of previously-frozen carbon. Such work requires whole ecosystem approaches that recognise the importance of multi-trophic interactions as well as plant–soil interactions, both above and below ground. This is essential because these interactions control potentially enormous greenhouse gas emissions, as well as vertical and lateral movements of carbon and nutrients that can impact marine ecosystems and feedback to climate change.

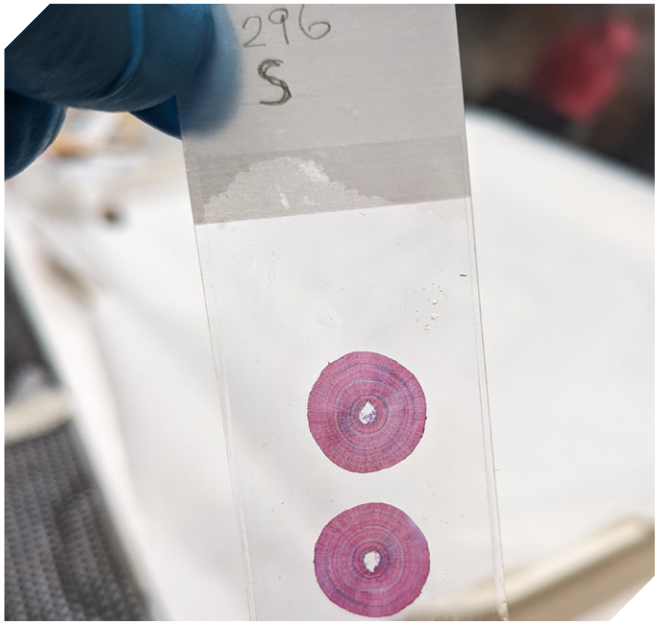

Photo credit: Georgia Hole

Photo credit: Marc Macias-Fauria

A warming terrestrial cryosphere

Release of greenhouse gases from thawing permafrost. This topic is a priority because understanding future carbon budgets and climate forcing from Arctic change is pressing, especially regarding responses to different global warming scenarios and the potential for crossing irreversible tipping points. Research is needed because large uncertainties remain about carbon release from permafrost thaw (estimated 30–200 PgC). Work is especially needed on gradual versus abrupt thaw mechanisms, and to quantify the amount of carbon released. New satellite technologies and machine learning techniques now enable spatial integration beyond traditional methods, facilitating this work and offering unprecedented analytical capabilities.

Permafrost thaw impacts and climate feedbacks: integration across scales. As the Arctic climate warms more quickly than lower latitudes, permafrost and environmental conditions are changing at different rates. Therefore it remains a priority to monitor and model recent decadal changes at different temporal and spatial scales across the Arctic, and to project these changes through to the end of the 21st century. For this, multidisciplinary approaches are needed to integrate research across the natural sciences. Until now permafrost maps have tended to be either very broad scale or site-specific, therefore increasing their spatial and temporal resolution presents opportunities to systematically monitor changes. This will facilitate upscaling understanding of permafrost thaw from site-specific to regional scales, and ultimately to the pan-Arctic. Quantification of climate–permafrost feedbacks resulting from release of greenhouse gases is urgently needed for realistic global climate predictions, including the impacts of abrupt thaw in Earth system modelling.

Integrating in situ and remote sensing networks. To constrain uncertainties in permafrost thaw impacts, harmonisation of measurement networks is needed to create improved data products, reduce data redundancy and enable machine learning to link datasets across spatial scales and temporal resolutions. New technologies and machine learning can integrate observational data across scales, combining new and legacy datasets to improve Arctic change projections. This aligns with UK strategic objectives for global scientific presence and maintains UK expertise in ground-truth campaigns for future Earth systems missions.

Consequences of change for Arctic people. Thawing permafrost releases nutrients, minerals and contaminants with consequences for water quality. Research is needed to better understand how permafrost thaw affects water quality and quantity for local and Indigenous communities as well as the impact of the release of nutrients to oceans. Working with Indigenous and local communities is essential to ensure co-design of research that best meets the needs of these communities, to gain understanding

Photo credit: Kirsi Keskitalo

from Indigenous and local knowledge regarding thaw impacts on water supplies and food security, and for building research capacity in these communities. Additionally, nutrients released from thawing permafrost could fertilise oceans, with cross-disciplinary work needed here in collaboration with ocean and coastal researchers.

Freshwater systems under change

Understanding rapid environmental change in freshwater systems. Because of rapid Arctic climate change, work is needed to understand the fast-paced changes in freshwater systems and assess their wider impacts. Baseline datasets are urgently needed to connect past, present and future conditions. For freshwater systems, this is particularly important as many of the biological processes that are affected by the cold are disrupted by the transition from liquid water to solid ice and vice versa, rather than the low temperatures. As global temperatures warm, increasing areas of ice and snow are transitioning into freshwater ecosystems with concurrent nutrient inflows. These changes are already having a profound effect on ecosystem function, in particular on productivity and community stability. They are evident at both the small scale (for instance, change from seasonal ice cover to ice-free) to large scale (for example, increased presence of pollutants and 'forever chemicals' in rivers, highlighting catchment increases).

Climate change consequences for freshwater biodiversity and ecology. Arctic freshwater environments consist of a range of inter-connected habitats, from freshwater flowing from glacier tops, through rivers and streams, to seasonally or perennially ice-covered lakes. Understanding how climate and environmental changes in these systems affect the biodiversity of organisms and their ability to respond to change, particularly microbes driving nutrient cycling, is needed since current understanding is poor to non-existent. As Arctic freshwater systems warm, more frozen environments turn to liquid and stay liquid for longer during the year. These changes have consequences for people, ecosystems, biogeochemistry, and climate feedback. There are pressing needs, therefore, to understand freshwater biodiversity from ice-bound pools to raging rivers, in its ecology, functionality and feedback roles, before it is transformed forever.

Nutrient and carbon cycling in freshwater systems. Many Arctic biological systems are nutrient limited, so as the climate and environments change, the quantity and type of nutrients delivered to freshwater systems also change, such as through melting glaciers, atmospheric deposition, vegetation greening and browning, and landscape development. As the Arctic undergoes rapid change, it is critical to understand, quantify, and predict the changes in nutrient and carbon cycling. This is a priority because warmer temperatures and increased nutrient availability stimulate greater vegetation growth and soil development, both within freshwater systems and their catchments. Better understanding is needed of how increased carbon availability within freshwater environments, along with changes in hydrological systems (for instance, stratification), can increase carbon dioxide and methane production and emissions from lakes and, hence, directly contribute to global greenhouse gas emissions. Additionally, more knowledge is needed on how Arctic freshwater systems supply and regulate nutrient and carbon input into the Arctic Ocean, impacting local and global productivity, biodiversity, food security and carbon uptake. It is vital for cross disciplinary work that bridges the marine-fresh water interface to fully quantify and understand these changes in nutrient supply and biogeochemical cycling.

Photo credit: Georgia Hole

WAYS FORWARD: INTERDISCIPLINARITY, PARTNERSHIPS, CO-DESIGN AND DATA

Addressing UK terrestrial Arctic research priorities should embrace interdisciplinarity across the terrestrial, marine, atmospheric and social sciences, along with co-design of partnerships with local communities and Indigenous people, supported by flexible, long-term funding that facilitate meaningful collaboration. Integrated cross-system science, stronger international collaboration, and centralised FAIR/CARE-compliant data infrastructures are essential to address Arctic terrestrial research priorities responsibly and effectively.

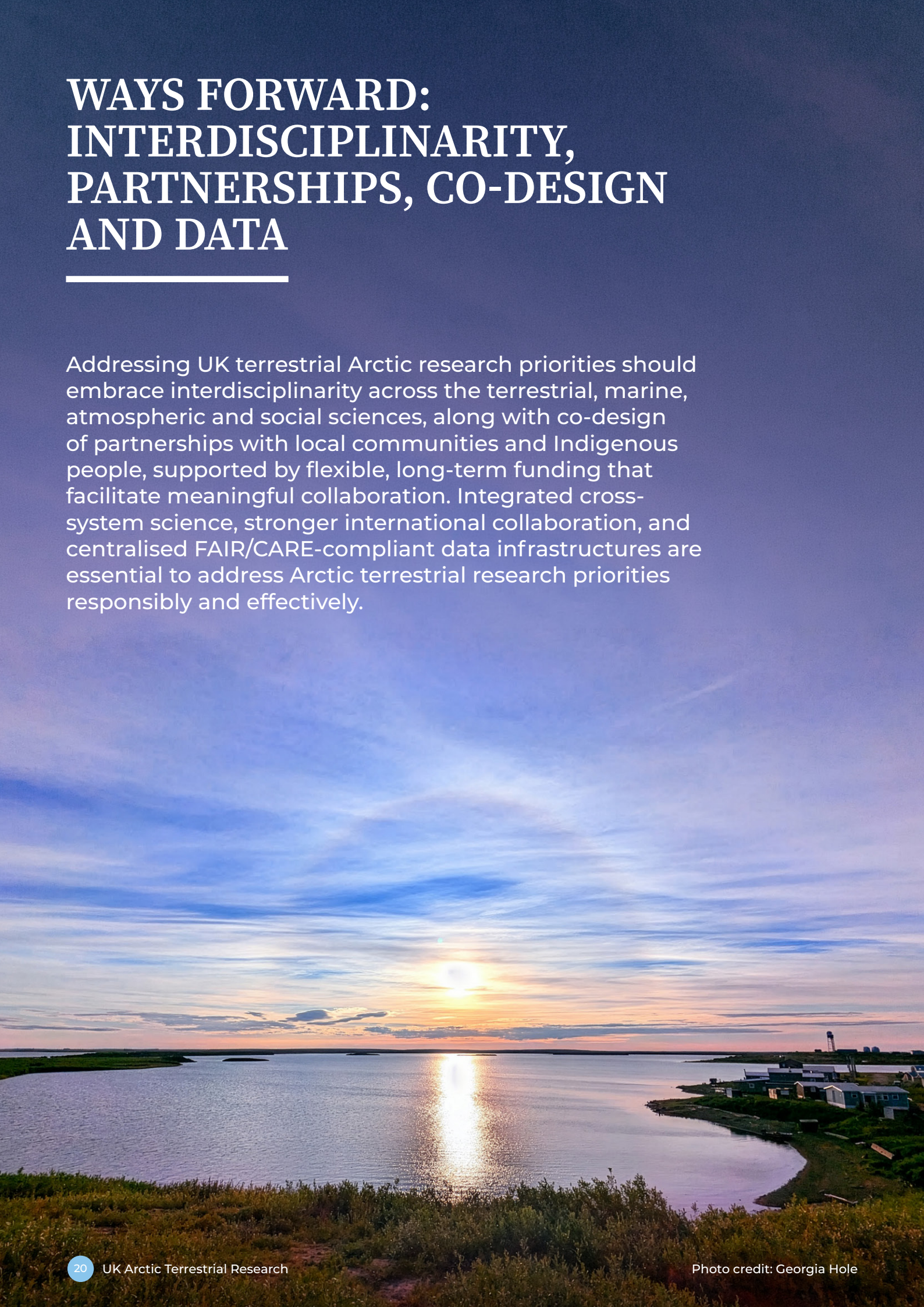

Photo credit: Georgia Hole

UK terrestrial research should champion collaboration with local and Indigenous communities from the early stages of idea development through to project completion, thus incorporating Indigenous and local knowledge and expertise into research, and ensuring initiatives deliver on the needs of those communities. By working with local and Indigenous partners, UK terrestrial science can help build a legacy of expertise and local research capacity. To facilitate this, UK science would benefit from funding structures that enable local engagement and allow time to build relationships with Indigenous communities and local stakeholders, and further help maintain long-term collaborations. The CINUK programme (2021-25) provides a good example when considering how to achieve such a funding model, as do small grants from the UK NERC Arctic Office that have allowed collaborations to be built and thrive between UK and overseas Arctic scientists. None-the-less, larger grants are needed based around slower funding models, with built-in time for relationship building to promote better and more responsible science and enhance meaningful engagement.

Photo credit: Richard Streeter

UK terrestrial Arctic science benefits from a range of grant opportunities, including national and international funding. However, new funding models would help address the UK's research priorities including those that promote inter- and trans-disciplinary interaction, incorporating cross-system integration (i.e. working across atmosphere, geosphere, cryosphere, terrestrial and marine systems). The Arctic terrestrial science research priorities detailed in this document recognise the need to collaborate across terrestrial disciplines (including across biodiversity and ecosystem science on land and freshwater, biogeochemical cycling, permafrost and snow science, remote sensing and modelling) to address the major knowledge needs going forward. Furthermore, Arctic terrestrial and freshwater environments are tightly connected to, influenced by, and influence the surrounding coastal, ocean and atmospheric realms, as well as being home to millions of people. If we are to properly address the challenges of understanding a rapidly changing Arctic, future research needs more genuine multi- and trans-disciplinary collaboration between terrestrial, marine, atmospheric and social sciences.

A clear home for Arctic data, operated under FAIR and CARE principles, is also important to facilitate future Arctic research and prevent data redundancy. The UK can further benefit from improved engagement with international Arctic research and consortia. Membership of Svalbard Integrated Arctic Earth Observing System (SIOS), for example, would give the UK a seat at the table and greater insight into a key Arctic research hub. Greater awareness and communication of UK and international Arctic science plans allows for the creation of complementary, not competing, approaches to key research questions.

WAYS FORWARD: ADDRESSING RESEARCH PRIORITIES IN ARCTIC TERRESTRIAL SCIENCE

To address UK Arctic terrestrial research priorities, there is a need for robust, spatially and temporally representative biodiversity monitoring, integrating ground observations, advanced technologies, molecular methods and AI-driven data science. Standardised pan-Arctic datasets are needed to improve modelling of biogeochemical cycling, permafrost dynamics and ecosystem change. Long-term field presence, rapid-response capacity to extreme events, and next-generation experiments will strengthen understanding of climate-driven phase shifts and carbon feedbacks. Advances in remote sensing, modelling and subsurface mapping are critical for research on permafrost and other parts of the cryosphere. Freshwater science requires high-resolution, year-round monitoring. All research fields will benefit from integration of satellite and ground observations and shared data infrastructure.

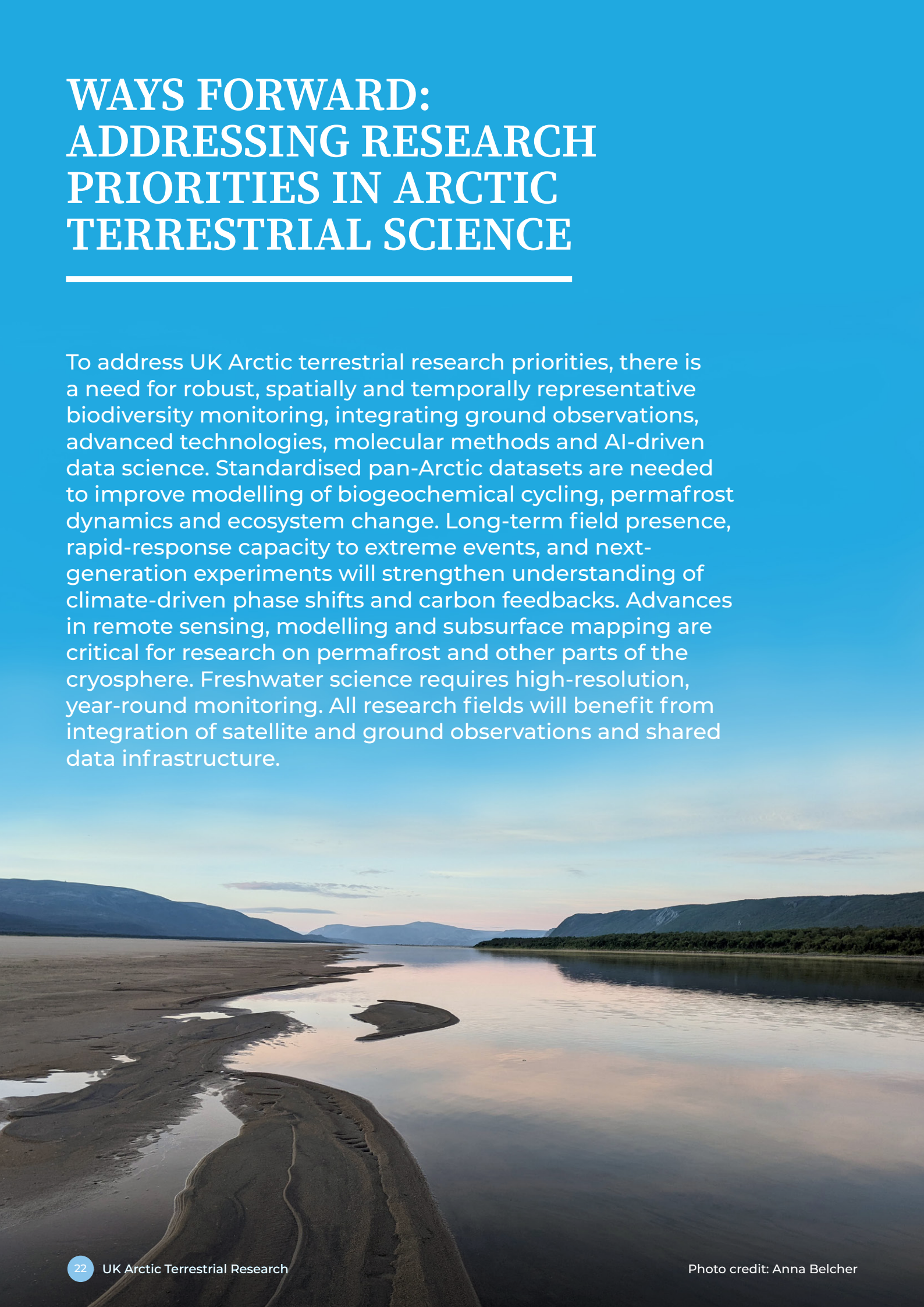

Photo credit: Anna Belcher

Changing ecosystems and biodiversity

To address priorities in terrestrial ecology and biodiversity there is a need for robust biodiversity monitoring and ground truth data that are i) spatially balanced and representative of the wider landscape (including addressing interpretation limitations from remote sensing derived products) and ii) temporally relevant to the dynamics of the systems studied. This research will need observational and experimental data that capture a range of ecological niches across a large spatial area employing compatible methodologies. There is also a requirement to 'bridge the gap' between macroclimate and biological microclimate descriptions and modelling. A multi-layered sampling approach can be used to address multiple priorities within one protocol.

Addressing priorities will also require enhanced use of ground surveys and biodiversity monitoring technologies, including sensors on UAVs, time-lapse cameras, animal-borne sensors and other technologies for in situ environmental monitoring. Work should also prioritise advanced molecular approaches, with an emphasis on microbial biodiversity (for example, soil microbiomes).

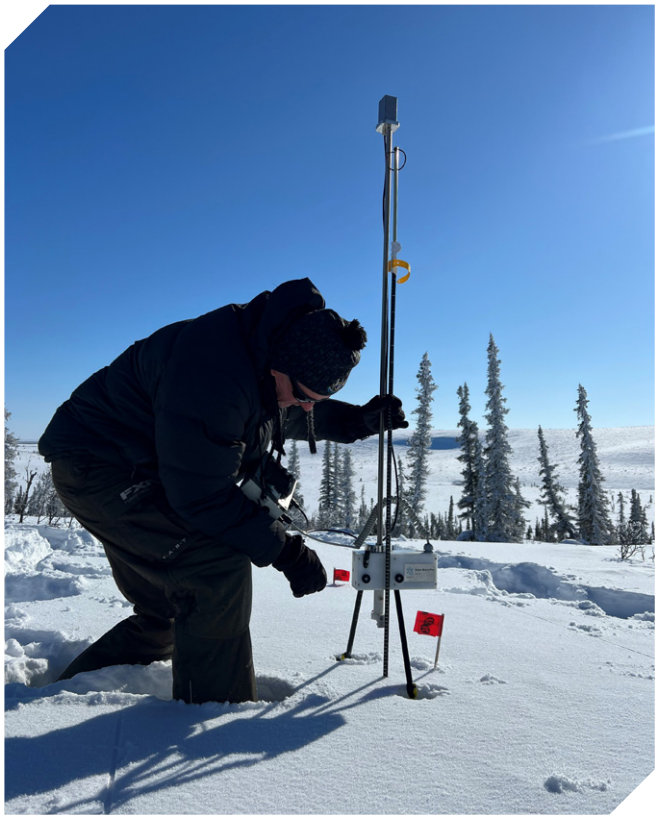

Photo credit: Nick Rutter

AI and data-science approaches offer integrative tools to investigate complex, high-dimensional datasets and to understand and predict ecosystem change. These tools can be used to identify relationships between multi-modal datasets (such as soil characteristics, eDNA and citizen science data) and can improve data modelling and prediction to generate insights into patterns within complex systems. Such work must be underpinned by robust ground truthing.

For work on biogeochemical cycling, geophysical processes such as permafrost thaw, and snow–ecosystem interactions, there is a need for standardised Arctic-specific vegetation data, metadata formats and nomenclature across countries and disciplines to ensure comparability and reproducibility. Significant benefit will be gained from shared pan-Arctic datasets for training and validation linked to vegetation types, soils, hydrology and permafrost thaw indicators for model improvement and understanding. Very high resolution mapping and microtopography datasets are needed to calibrate and upscale with satellites. There should be emphasis on seasonal changes in vegetation, moisture, surface stability and freeze–thaw transitions. Also needed is improved translation of observations linked to plant functional types, as these are relevant for climate and gas flux modelling. Better representation of mosses and lichens in models, and the field data to support that, are also required.

Ecosystem biogeochemical cycling through plants, soils and microbes

To address key priorities in Arctic terrestrial ecosystem biogeochemical cycling, the UK must enhance our field campaigns to sustain long-term experiments and international collaborations, including partnerships with Indigenous and local communities. Existing infrastructure should be strengthened, alongside the deployment of new technologies such as remote sensing and distributed sensor networks, to enable pan-Arctic coverage. International collaborations are essential to this effort and should be supported through targeted funding. Equally important is the capacity for rapid research responses to extreme events and disturbance, including tundra fires, weather extremes and abrupt permafrost collapse. Research should focus on regions most vulnerable to change, with priorities identified through

collaboration with local and Indigenous communities and international partners. By combining long-term continuity with rapid-response capabilities, we can better assess Arctic change across multiple timescales and spatial extents.

Experiments are needed to investigate key climate drivers and their interactions that may trigger ecosystem phase shifts. These include disturbances such as fire, insect outbreaks, vegetation change, thermokarst development, rain-on-snow events, extreme rainfall and heatwaves. Developing mechanistic understanding is essential to enable upscaling, including quantifying the role of thawed organic matter and soil microbial communities in ecosystem fluxes: radiocarbon tracing and DNA-based methods will be critical. A whole-ecosystem perspective is required, integrating multi-trophic interactions and recognising both top-down and bottom-up controls on carbon and nutrient cycling.

Advancements in upscaling and downscaling remain a priority: understanding climate feedbacks requires linking small scale biophysical and biogeochemical processes with large scale regional observation, modelling, and impacts. The UK's strengths in remote sensing and Earth system modelling provide a strong foundation, but a key challenge lies in connecting remotely observable ecosystem properties, such as vegetation change, with belowground processes that drive climate feedbacks.

Progress will depend on developing standardised, accessible databases that integrate above- and below-ground indicators, supporting modelling and experimental upscaling. Models should be underpinned by appropriately scaled data, linking monitoring and nested experimental sites within catchment-scale observations, capturing and integrating Arctic heterogeneity without excessive complexity.

A warming terrestrial cryosphere

Addressing priorities in permafrost monitoring requires advances in remote sensing, including frameworks of monitoring for thaw detection on different scales from plot to drone, satellite, to pan-Arctic, along with radar data to map vertical land movement. To address priorities around permafrost extent and active-layer thickness, their mapping should focus more on ground surface thermal regime relationships with climate warming, ecosystem change and inclusion of rain events so they can be better represented in models. Benefits will be gained from improved subsurface mapping and its association with geology, hydrology, warming and surface vegetation, as these have important links with soil biogeochemistry and microbial communities.

Advances in abrupt permafrost thaw research will need more observations of the landforms most vulnerable to abrupt thaw. This requires knowledge of the subsurface characteristics (sediment properties, ground-

Photo credit: Philip Wookey

Photo credit: Georgia Hole

ice stratigraphy) and assessments of the rates of changes across different permafrost zones. New models are required to characterise abrupt thaw, for example through blending physical models with statistical AI models. To gain a better understanding of the relationship between loss of glacial ice and impacts on permafrost, more information is needed on the geophysical, hydrological and biogeochemical relationships between these two cryospheric systems. Key information needed include how fast retreating permafrost and talik expansion is happening, and how this can be modelled to understand future rates of permafrost thaw and glacial forefield expansion.

Improved quantification of carbon feedbacks to the atmosphere will need greater representation in models of soil organic matter decomposition processes (including microbial models) which will require observations of, for example, carbon lability, depth at which decomposition occurs, forms of carbon released and its transport mechanisms. Manipulation experiments will help, but should be carried out over the long-term to properly determine how soils respond. Further mapping of the amount and distribution of soil carbon is also needed to elucidate relationships between different landforms and soil carbon. To better constrain methane emissions, flux measurements from freshwater bodies are needed combined with measurements of changing in-lake conditions, with these subsequently linked to large-scale modelling and related uncertainties, along with improved upscaling over heterogeneous landscapes. Advances here can be gained also through downscaling from satellite to the ground scale for better wetland mapping, which will require the inclusion of more ground truthing to capture spatial heterogeneity. Work will benefit from sharing inventory maps internationally, and including wider temporal data for validating models to hindcast and forecast emissions over decadal to millennial timescales.

Freshwater systems under change

Freshwater science will be transformed through increasing high-resolution monitoring across seasonal, full-year and decadal time periods. Parameters to be monitored include water quality, productivity, pollutants, thermokarst development, sediment fluxes and river discharge. This will be enabled through expansion of autonomous sensors, camera networks, gauging stations and experimental setups. Improved taxonomic and multi-omic biodiversity assessments are needed, especially for under-represented groups (for example, microbial eukaryotes). Quantifying and understanding changes to freshwater driven fluxes of carbon and nutrients requires robust baseline data, combined with process studies and long term monitoring of concentrations of key nutrients and river discharge. High-frequency measurements of greenhouse gas fluxes are also crucial, especially at ice-out. Since the timing of this is hard to estimate precisely, support from local collaborators is required to measure the instantaneous greenhouse gas release upon ice-melt. Integration of satellite data with ground measurements to map gas emissions across vast Arctic landscapes could assist research in hard to reach locations.

Freshwater systems provide vital ecosystem services (for example, food, drinking water, recreation and transport). Therefore, embedding Arctic freshwater research in local communities and co-developed science is fundamental. Research should ensure local communities have the level of involvement they want, from project conception to completion, including shared data generation and ownership, dissemination and publication.

Considering many research sites within the Arctic are often geographically remote, access to local resources (research stations, laboratories, equipment) is incredibly valuable to UK scientists, assisting collaborations, supporting logistics, maintaining deployed field equipment for long-term monitoring, providing equipment and facilities, and contributing to excellent research. Establishing and maintaining data repositories (for facilities such as gauging stations and other monitoring stations for example) improves data storing and sharing for secondary analysis.

ACRONYMS

Photo credit: Jeff Kerby

^{14}C	Radiocarbon
AI	Artificial Intelligence
a/eDNA	Ancient / environmental DNA
APSIS	Advanced Persistent Scatterer Interferometry System
BAS	British Antarctic Survey
C	Carbon
CARE	Collective Benefit, Authority to Control, Responsibility, Ethics
CH_4	Methane
CINUK	Canada–Inuit Nunangat–United Kingdom Arctic Research Programme
CO_2	Carbon dioxide
DEMs	Digital elevation models
ECR	Early career researcher
FAIR	Findable, Accessible, Interoperable, Reusable (data principles)
IPCC	Intergovernmental Panel on Climate Change
IPY5	International Polar Year 5
ISBAS	Intermittent Small Baseline Subset (interferometric radar technique)
ITEX	International Tundra Experiment
NERC	Natural Environment Research Council
PgC	Petagrams of carbon
RRS	Royal Research Ship
SIOS	Svalbard Integrated Arctic Earth Observing System
SPRI	Scott Polar Research Institute
UAVs	Uncrewed aerial vehicles
UKPN	UK Polar Network

Arctic Office
NATURAL ENVIRONMENT RESEARCH COUNCIL

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