BAMS
Meeting Summary

Research Priorities for the Coupled Arctic Land–Ocean Carbon Cycle: Integrating Scientific and Policy Perspectives

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Workshop on the Arctic Land–Ocean Carbon Cycle and Its Role in the Remaining Global Carbon Budget

What: An international and interdisciplinary workshop brought together about 40 researchers and representatives from policy and the science–policy interface to discuss the Arctic land–ocean carbon cycle and its significance for the remaining global carbon budget. Through keynote presentations and interactive panel discussions, participants assessed the current state of knowledge, identified key research gaps, and formulated concrete recommendations and priorities for future research and policy dialogue.

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1. Introduction

The Arctic stores vast amounts of carbon across interconnected terrestrial and marine reservoirs and has acted as a sink of anthropogenic carbon to date (Vonk et al. 2025). However, steadily increasing atmospheric greenhouse gas concentrations and rapid Arctic warming, currently 3–4 times faster than the global average (Rantanen et al. 2022), are intensifying carbon cycling across the region. While sea ice retreat exposes larger ocean surfaces to atmospheric carbon dioxide (CO_2) uptake, emissions of CO_2 and methane (CH_4) from thawing permafrost, inland waters, and disturbance-affected ecosystems are rising. Current scientific discourse increasingly focuses on whether the Arctic terrestrial biosphere is shifting from a net sink to a net source of CO_2 (Natali et al. 2024; Virkkala et al. 2025) and whether its CH_4 emissions are rising (Kuhn et al. 2025; Parmentier et al. 2024). Despite major advances and synthesis efforts (Vonk et al. 2025; Hugelius et al. 2024; Ramage et al. 2024; Yasunaka et al. 2023; Wadham et al. 2026), substantial uncertainties remain in quantifying Arctic carbon fluxes due to sparse observations, spatial heterogeneity, and inconsistencies between bottom–up and top–down approaches. These knowledge gaps limit our ability to quantify Arctic carbon–climate feedbacks and to assess their implications for the global carbon budget and international climate policy.

To address these challenges, an international, interdisciplinary workshop on the Arctic Carbon Cycle was held in Berlin, Germany, in September 2025. The meeting gathered ~40 participants from terrestrial and marine Arctic carbon research, policy, and the science–policy interface. Through keynote presentations, panel discussions, and open exchanges, participants assessed current understanding of the coupled Arctic carbon system, identified key knowledge gaps and research priorities, and explored pathways to strengthen interdisciplinary collaboration and policy dialogue. The following sections summarize the main discussions and outcomes.

2. Arctic carbon cycle: Current knowledge and key gaps

The workshop opened with a keynote synthesizing the state of the Arctic carbon cycle as a coupled land–ocean system. The Arctic currently functions as a modest net carbon sink, maintained largely by oceanic CO_2 uptake and organic carbon burial in shelf sediments, whereas terrestrial environments, including inland waters and disturbance-affected areas, are net sources of CH_4 and near neutral for CO_2 (Ramage et al. 2024; Vonk et al. 2025). Warming reshapes carbon cycling across terrestrial, freshwater, and marine systems, intensifying exchanges within and between major carbon reservoirs. Continued warming, increasing disturbance, and enhanced carbon turnover are expected to weaken this net sink, underscoring the need for integrated observations and models across the land–ocean continuum (Hugelius et al. 2024). Building on this overview, discussions focused on current understanding and key uncertainties in terrestrial (section 2a) and marine (section 2b) Arctic carbon fluxes, including their future evolution.

a. Terrestrial Arctic carbon fluxes. Two workshop sessions addressed terrestrial Arctic carbon fluxes. The first focused on the current terrestrial Arctic carbon budget, whose importance for the global carbon budget is clear: Arctic permafrost soils store over 1500 Gt of organic carbon—about one-third of global soil carbon (Schuur et al. 2022; Strauss et al. 2025). Because these landscapes are highly sensitive to warming, quantifying changing vertical and lateral CO_2 and CH_4 fluxes is essential for understanding the Arctic's role in the global carbon cycle.

Carbon exchange across tundra, boreal forests, and wetlands is strongly seasonal (Falvo et al. 2025). Long-term eddy-covariance records show strong CO_2 uptake during the short growing season due to high productivity (Natali et al. 2024; See et al. 2024; Liu et al. 2024). Increased growing-season uptake likely reflects longer growing seasons, vegetation shifts, and greater nutrient availability (Bolek et al. 2025) but is increasingly offset by rising shoulder-season emissions, especially in late autumn and early winter when soils remain biologically active under snow (See et al. 2024). Consequently, annual net CO_2 fluxes vary widely across regions, with no clear pan-Arctic trend toward greater sequestration (Virkkala et al. 2025).

Methane fluxes add further complexity. Wetlands and thermokarst landscapes are dominant CH_4 sources, while dry tundra and uplands may act as CH_4 sinks through microbial oxidation (Oh et al. 2020; Voigt et al. 2023). Regional CH_4 budgets are highly sensitive to uncertainties in land-cover classification, wetland extent, and map resolution, as fine-scale data are required to accurately identify methane hotspots (Ying et al. 2025; Hashemi et al. 2025; Ivanova et al. 2026).

Lateral carbon transfers also complicate the Arctic carbon budget. Coastal erosion mobilizes permafrost carbon into nearshore waters, where it can be degraded, emitted as greenhouse gases, buried, or transported offshore (Lantuit et al. 2012; Fritz et al. 2017; Tanski et al. 2019). Additionally, Arctic rivers export dissolved and particulate carbon, with strong seasonality and sensitivity to hydrology and thaw processes (McClelland et al. 2016; Vonk et al. 2025). These pathways decouple carbon mobilization from processing and atmospheric exchange and remain poorly constrained.

Participants agreed that beyond long-term trends, small-scale and short-term disturbances increasingly influence net terrestrial carbon fluxes (Phoenix et al. 2025). For example, both gradual and abrupt permafrost thaw alter hydrology, soil thermal regimes, and carbon availability and can shift ecosystems toward net carbon release (Turetsky et al. 2020; Webb et al. 2025). Wildfires, which are increasing in frequency and severity, produce large episodic CO_2 and CH_4 emissions (van der Werf et al. 2017; Natali et al. 2024) that can negate the increase in the boreal sink (Virkkala et al. 2025). Fire legacy effects, including deep organic-layer combustion and postfire vegetation changes, remain underrepresented in current carbon budgets.

Despite advances, large uncertainties remain in pan-Arctic terrestrial carbon budgets. Bottom–up estimates—based on field data, upscaling, and models—often diverge significantly from top–down atmospheric inversion results (Hugelius et al. 2024; Ramage et al. 2024). These discrepancies stem primarily from observational gaps, particularly in winter (Pallandt et al. 2022, 2024); limited spatial and thematic resolutions of the observational products; and incomplete representations of disturbances and lateral fluxes. To produce robust estimates of the Arctic carbon budget, integrated approaches combining expanded in situ observations, improved land-cover and disturbance mapping, and harmonized modeling are essential (Vogt et al. 2025). While efforts are under way to synthesize ecosystems' greenhouse gas budgets (e.g., Hugelius et al. 2024; Ramage et al. 2024), resolving flux heterogeneity and the impact of disturbance impacts remains a critical research priority.

In a second session, panelists discussed the future evolution of terrestrial Arctic CO_2 and CH_4 fluxes. These can be estimated through numerical land surface models that represent photosynthesis, biomass, soil respiration, vegetation and wetland distributions, and disturbances such as fire (Fisher and Koven 2020). Despite growing complexity, the models' representation of permafrost processes remains limited (Schädel et al. 2024). Current assessments mainly capture gradual thaw driven by slow vertical heat propagation (Webb et al. 2025), producing moderate, near-linear carbon losses of about 18 PgC °C^{-1} of global warming, increasing after 2100 (Canadell et al. 2021; Nitzbon et al. 2024). These losses are partly offset as woody vegetation expands northward (Ciais et al. 2013), increasing productivity, biomass, and peatland carbon (Charman et al. 2013; Orndahl et al. 2025). CO_2 fertilization may account for roughly half of productivity gains, with longer growing seasons providing the rest (Winkler et al. 2019). Peatlands remain key components of Arctic carbon dynamics (Hugelius et al. 2020) and are projected to expand with warming (Alexandrov et al. 2020; Qiu et al. 2022; Crichton et al. 2025), depending on moisture and temperature changes (Helbig et al. 2022). Increased productivity and wetland area enhance carbon sequestration but also raise CH_4 emissions (Kleinen et al. 2021, 2023).

Models insufficiently account for nitrogen limitation (Lacroix et al. 2022), vegetation diversity (Sulman et al. 2021), and a rising frequency of disturbances including extreme winter events, drought, fire, insect outbreaks, and abrupt permafrost thaw—all of which can enhance vegetation damage and carbon loss (Lambert et al. 2023; Matthes et al. 2025; Phoenix et al. 2025). Abrupt thaw remains difficult to model due to strong local heterogeneity (Nitzbon et al. 2020; Painter et al. 2023). Such events could add ~40% to gradual-thaw carbon losses, though uncertainty is high (Turetsky et al. 2020). Models also struggle to capture evolving Arctic hydrology, wetland dynamics, freshwater carbon transport (Matthes et al. 2025; Vonk et al. 2025), and the partitioning between CO_2 and CH_4 emissions (Parmentier et al. 2024).

Future Arctic carbon dynamics depend strongly on global emission pathways. High-end warming scenarios project substantial permafrost carbon losses, though still small relative to anthropogenic emissions (Kleinen and Brovkin 2018; McGuire et al. 2018). Under midrange scenarios, CO_2 fertilization may partly offset soil carbon losses from permafrost thaw (Kleinen and Brovkin 2018). Permafrost carbon impacts become most pronounced after 2100, especially under stabilization and overshoot pathways (Georgievski et al. 2025). These changes are effectively irreversible on human time scales: Even if temperatures return to preindustrial levels, depleted soil carbon stocks require centuries to rebuild (de Vrese and Brovkin 2021).

b. Marine Arctic carbon fluxes. A third session of the workshop focused on marine Arctic carbon fluxes. The Arctic Ocean currently acts as a sink for atmospheric CO_2, taking up roughly 1% of the global ocean total—consistent with its share of global ocean volume (DeVries et al. 2023; Yasunaka et al. 2023; Jakobsson 2002). This sink has strengthened in recent decades, increasing faster than the global ocean average, primarily due to rapid sea ice decline that exposes larger areas for air–sea gas exchange. Although marine carbon observations in the Arctic are sparse, the Arctic Ocean CO_2 uptake, estimated based on upscaling, models, and atmospheric inversions, is relatively well constrained compared to its terrestrial counterpart (Yasunaka et al. 2023). Arctic air–sea CO_2 fluxes show strong spatial variability, with highest uptake in seasonally ice-free regions like the Barents Sea (Yasunaka et al. 2023).

Despite this strengthening sink, the future evolution of Arctic Ocean carbon fluxes remains highly uncertain. While sea ice decline enhances air–sea gas exchange, increasing Atlantic inflow rich in anthropogenic carbon may weaken the Arctic sink or lead to localized outgassing (Anderson and Macdonald 2015). Strong ocean acidification—resulting from cold temperatures, high freshwater input, coastal erosion, and rising CO_2 (Semiletov et al. 2016; Yamamoto-Kawai et al. 2009)—reduces buffering capacity and may cause the Arctic to reach chemical saturation earlier than the global ocean (Canadell et al. 2021). Consequences for marine ecosystems are expected (Orr et al. 2022). Arctic marine ecosystems are already responding to warming, altered circulation, and shifting nutrient supply, complicating projections of marine carbon cycling and ecosystem feedbacks (Wassmann et al. 2011).

Land–ocean carbon transfers represent another major source of uncertainty. River discharge, coastal erosion, submarine groundwater inputs, and shelf sediment remobilization supply large but poorly constrained fluxes of carbon to Arctic waters (Vonk et al. 2025). Systems such as the Mackenzie River plume and Sermeq Kujalleq glacial meltwater can operate as carbon sinks or sources depending on process representation and parameterization (Bertin et al. 2025a,b; Wood et al. 2025). Coastal erosion releases terrestrial carbon into the ocean and may reduce the Arctic Ocean CO_2 uptake by around 10% (Nielsen et al. 2024; Oziel et al. 2025), although estimates remain subject to considerable modeling uncertainty.

The fate of terrestrial carbon remains difficult to quantify: Particulate organic carbon transport pathways across Arctic shelves are insufficiently known, and dissolved organic carbon undergoes strong transformations along salinity gradients, with its lability determining whether it is respired or sequestered (Bertin et al. 2025b; Nielsen et al. 2024). Improved observational constraints and explicit representation of terrestrial dissolved organic carbon (DOC) and particulate organic carbon (POC) tracers with specific lability in ocean and Earth system models are, therefore, critical, as most current-generation models lack an explicit representation of land-derived carbon dynamics.

Uncertainties also arise from gas-transfer parameterizations (Dutch et al. 2025). Sea ice–associated CO_2 fluxes, which may partially compensate across seasons, are typically neglected, and key processes such as fluxes associated with glacial outflow, river discharge, and sea ice biogeochemistry remain underrepresented.

Addressing these uncertainties to better assess the Arctic Ocean's evolving role in the global carbon cycle requires enhanced observational efforts in Arctic coastal regions, improved process understanding, and better representation of land–ocean interactions in predictive models.

3. Policy dialogue and knowledge transfer

As the Arctic experiences rapid and profound environmental changes, it becomes increasingly urgent to translate scientific insights from land–ocean carbon cycle research into actionable policy. In this context, the last panel of the workshop explored mechanisms of effective science–policy communication, challenges in knowledge translation, and opportunities for an inclusive, impactful dialogue.

Scientific bodies such as the Arctic Monitoring and Assessment Program (AMAP), a working group of the Arctic Council, play a key role by providing peer-reviewed assessments and concise summaries for policymakers (SPMs) on the status of the Arctic region to inform decision-making (AMAP 2024). The forthcoming 2026 Arctic Climate Change Update Report will include a synthesis of pan-Arctic carbon pools, fluxes, their drivers, and future projections. These reports provide critical input to international climate science–policy processes, including the IPCC Assessment Reports, where Arctic carbon feedbacks are still notably underrepresented (Natali et al. 2021).

Yet, many challenges persist. The panelists have underscored the lack of a unified voice of Arctic states or the cryosphere in international negotiations, such as the UNFCCC and the Paris Agreement, including its Global Stocktake, limiting the region's visibility in international climate discourse. While the Arctic's rapid warming and vulnerability are widely acknowledged, negotiations often focus on thematic areas (e.g., mitigation, adaptation, finance, just transition) rather than regional specificities. In addition, the breadth of topics covered in IPCC reports limits the space for Arctic-specific statements in its SPMs.

Scientific uncertainty presents an additional communication challenge. Low confidence levels and long time horizons of Arctic carbon feedbacks can reduce their policy salience. However, permafrost thaw and wildfire feedbacks could reduce the remaining carbon budget by up to 17% for 2°C warming pathways (Schädel et al. 2026; Georgievski et al. 2025). These emissions, once triggered, are largely irreversible on human time scales (Miner et al. 2022). The panel agreed that short, clear, evidence-based messages, even if they contain uncertainties, are more useful to policymakers than ambiguity. Visual tools such as graphs, infographics, and one-page summaries were highlighted as particularly valuable for decision-making contexts.

Effective communication must also be audience specific. National ministries, local climate offices, and municipal governments all require tailored and clear messaging. While global agreements like the Paris Agreement provide overarching frameworks, many consequential decisions are taken at regional and local levels. Stakeholder-specific communication and co-production of knowledge are, therefore, essential. Public debate can further help to increase political pressure.

Sustainable, long-term monitoring emerged as another priority. While joint calls for Arctic and permafrost research exist, implementation is often restricted to national budgets, limiting systemic observation efforts that are essential for understanding the Arctic carbon cycle. As abrupt thaw processes and cascading tipping points accelerate (Milkoreit et al. 2024), the panel called for a step change in investment and international coordination. With the Arctic Science Funders Forum, established at the Arctic Science Ministerial Meeting in Berlin 2018, international efforts to better coordinate funding for Arctic research are under way.

Importantly, Indigenous peoples must be engaged as equitable knowledge and rights holders. Collaboration should begin during the project design stage. Indigenous and traditional knowledge systems offer location-based, long-term observations and important insights into environmental change in the Arctic, strengthening classical science and enhancing its relevance for local decision-making processes (Jungsberg et al. 2025).

4. Ways forward: Research priorities and recommendations

The workshop aimed to generate actionable suggestions to address knowledge gaps in Arctic carbon research and improve science–policy dialogue. The related discussions focused on three overarching themes: 1) improving the coordination of research efforts, 2) deepening our process understanding, and 3) strengthening the connection between science and policy.

First, further improving the coordination of international research efforts in the Arctic is fundamental. While the ocean community has established robust reporting and data-sharing practices for marine carbon measurements (Bakker et al. 2016; Schoderer et al. 2025), coordination of land-based observations remains more fragmented. In this regard, the following recommendations arose from the workshop:

- enhance efforts to harmonize measurement techniques, data processing protocols, and field data formats to improve comparability across regions and studies;
- make field data accessible in a harmonized and standardized way, adhering to the findable, accessible, interoperable, and reusable (FAIR) principles;
- harmonize land-cover, permafrost, and wetland maps to reduce uncertainties in upscaling;
- identify and secure funding for a selected number of key long-term monitoring sites that are indispensable for detecting climate trends and disturbance signals over time;
- strengthen international partnerships to establish coordinated, sustained funding mechanisms across different national funding agencies; and
- use dedicated focus periods, such as the upcoming International Polar Year 2032–33, to coordinate intensive in situ and remote-sensing campaigns and help reconcile bottom-up and top-down assessments of the Arctic carbon cycle.

Second, our understanding of a number of key processes remains limited, leading to substantial uncertainties in the assessment of the current and future Arctic carbon cycle. Dedicated research programs should address knowledge gaps in particular related to

- abrupt, local-scale disturbances such as fires, thermokarst, erosion, and lake drainage;
- short- and long-term impacts of climate extremes, such as heat waves and heavy precipitation;
- the impact of Arctic hydrology across scales, including strengthened integration of terrestrial, freshwater, and nearshore processes to capture lateral carbon fluxes; and
- robust upscaling of local and regional observations and improved understanding of cross-scale interactions to enhance representation of key processes in large-scale models simulating future Arctic carbon dynamics.

Third, linking science more effectively to stakeholders, as well as involving Indigenous knowledge and local communities into research efforts, is essential. Workshop recommendations included the following:

- Scientists should provide clear, concise, and actionable information to policymakers, even amid uncertainties, translating complex scientific data into easily digestible summaries tailored to specific audiences.
- Indigenous communities should be involved early in research planning to ensure that local knowledge informs scientific understanding and that any suggested solutions are culturally appropriate.
- Additional platforms for continuous dialogue between scientists, policymakers, and local communities should be established to directly support decisions vital for Arctic and global climate resilience.

Finally, in times of growing international tension, workshop participants agreed that strengthening international research collaboration, keeping communication channels open, and strengthening efforts to protect the Arctic as a key climate region of our planet are arguably even more important today than ever before.

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