

# 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.

**When:** 22 - 23 September 2025

**Where:** Berlin, Germany

## 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 three to four 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<sub>2</sub>) uptake, emissions of CO<sub>2</sub> and methane (CH<sub>4</sub>) 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<sub>2</sub> (Natali et al. 2024; Virkkala et al., 2025) and whether its CH<sub>4</sub> 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<sub>2</sub> uptake and organic carbon burial in shelf sediments, whereas terrestrial environments, including inland waters and disturbance-affected areas, are

net sources of CH<sub>4</sub> and near neutral for CO<sub>2</sub> (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 1,500 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<sub>2</sub> and CH<sub>4</sub> 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<sub>2</sub> 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<sub>2</sub> 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<sub>4</sub> sources, while dry tundra and uplands may act as CH<sub>4</sub> sinks through microbial oxidation (Oh et al., 2020; Voigt et al., 2023). Regional CH<sub>4</sub> budgets are highly sensitive to uncertainties in land-cover classification, wetland extent, and map resolution, as fine-scale

data is 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<sub>2</sub> and CH<sub>4</sub> 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 post-fire 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 resolution 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 underway 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<sub>2</sub> and CH<sub>4</sub> 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 per °C 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<sub>2</sub> 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<sub>4</sub> 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., 2022). 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<sub>2</sub> and CH<sub>4</sub> 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 mid-range scenarios, CO<sub>2</sub> 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 timescales: even if temperatures return to

preindustrial levels, depleted soil carbon stocks require centuries to rebuild (de Vrese et al., 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<sub>2</sub>, 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 et al., 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<sub>2</sub> 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<sub>2</sub> 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 & Macdonald, 2015). Strong ocean acidification—resulting from cold temperatures, high freshwater input, coastal erosion and rising CO<sub>2</sub> (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<sub>2</sub> uptake by around 10% (Nielsen et al., 2024; Oziel et al. 2025), although estimates remain subject to considerable modelling 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 DOC and 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<sub>2</sub> 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 Programme (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, etc.) 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 timescales (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 underway.

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 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

- 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, lake drainage, etc.
- 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
- 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:

- 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 is arguably even more important today than ever before.

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### *Data Availability Statement.*

No datasets were generated or analyzed during the current study.

## REFERENCES

- Alexandrov, G. A., V. A. Brovkin, T. Kleinen, and Z. Yu, 2020: The capacity of northern peatlands for long-term carbon sequestration. *Biogeosciences*, **17** (1), 47–54, <https://doi.org/10.5194/BG-17-47-2020>.
- AMAP, 2024: Arctic Climate Change Update 2024: Key Trends and Impacts. Summary for Policy-makers. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway. 16 pp. Available online: <https://www.amap.no/documents/doc/amap-arctic-climate-change-update-2024-key-trends-and-impacts/3851>.
- Bertin, C., V. Le Fouest, D. Carroll, S. Dutkiewicz, D. Menemenlis, A. Matsuoka, M. Manizza, and C. E. Miller, 2025a: Colored dissolved organic matter (CDOM) alters the

- seasonal physics and biogeochemistry of the Arctic Mackenzie River plume. *Biogeosciences*, **22** (21), 6607–6629, <https://doi.org/10.5194/BG-22-6607-2025>.
- Bertin, C., and Coauthors, 2025b: Paving the Way for Improved Representation of Coupled Physical and Biogeochemical Processes in Arctic River Plumes—A Case Study of the Mackenzie Shelf. *Permafrost and Periglacial Processes*, **36** (3), 363–377, <https://doi.org/10.1002/PPP.2271>.
- Bolek, A., M. Schlutow, T. Yazbeck, N. Triches, M. Heimann, and M. Göckede, 2025: Impact of Long-Term Drainage on Carbon Fluxes in the High-Latitude Permafrost Region. *Global Change Biology*, **31** (7), e70346, <https://doi.org/10.1111/GCB.70346>.
- Canadell, J., and Coauthors, 2021: Global Carbon and Other Biogeochemical Cycles and Feedbacks. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 673–816 pp., <https://doi.org/10.1017/9781009157896.007>.
- Charman, D. J., and Coauthors, 2013: Climate-related changes in peatland carbon accumulation during the last millennium. *Biogeosciences*, **10** (2), 929–944, <https://doi.org/10.5194/BG-10-929-2013>.
- Ciais, P., and Coauthors, 2013: Carbon and Other Biogeochemical Cycles. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, T. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. Midgley, Eds., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 465–570.98
- Crichton, K. A., and Coauthors, 2025: Satellite data indicates recent Arctic peatland expansion with warming. *Communications Earth Environment*, **6** (1), 461–, <https://doi.org/10.1038/s43247-025-02375-1>.
- de Vrese, P., and V. Brovkin, 2021: Timescales of the permafrost carbon cycle and legacy effects of temperature overshoot scenarios. *Nature Communications*, **12** (1), 2688–, <https://doi.org/10.1038/s41467-021-23010-5>.
- DeVries, T., and Coauthors, 2023: Magnitude, Trends, and Variability of the Global Ocean Carbon Sink From 1985 to 2018. *Global Biogeochemical Cycles*, **37** (10), e2023GB007780, <https://doi.org/10.1029/2023GB007780>.
- Dutch, V. R., D. C. Bakker, A. Roobaert, P. Landschützer, N. P. Roden, M. Hoppema, and J. Kaiser, 2025: The Arctic Ocean CO<sub>2</sub> Sink: Trends, Uncertainties, and the Impact of Sea

- Ice. *Global Biogeochemical Cycles*, **39** (8), e2025GB008576, <https://doi.org/10.1029/2025GB008576>.
- Falvo, G., and Coauthors, 2025: Record 2024 winter carbon emissions coincide with record warmth across boreal forest, tundra, and wetland ecosystems. *Environmental Research Letters*, **20** (11), 114032, <https://doi.org/10.1088/1748-9326/AE09BB>.
- Fisher, R. A., and C. D. Koven, 2020: Perspectives on the Future of Land Surface Models and the Challenges of Representing Complex Terrestrial Systems. *Journal of Advances in Modeling Earth Systems*, **12** (4), e2018MS001453, <https://doi.org/10.1029/2018MS001453>.
- Fritz, M., J. E. Vonk, and H. Lantuit, 2017: Collapsing Arctic coastlines. *Nature Climate Change*, **7** (1), 6–7, <https://doi.org/10.1038/nclimate3188>.
- Georgievski, G., T. Kleinen, P. de Vrese, V. Brovkin, Y. Silvy, and T. L. Frölicher, 2025: Permafrost Thaw Impact on Remaining Carbon Budgets and Emissions Pathways in 2°C and 3°C Global Warming Scenarios. *Earth's Future*, **13** (7), e2024EF005153, <https://doi.org/10.1029/2024EF005153>.
- Hashemi, J., and Coauthors, 2025: Coarse land cover datasets bias Arctic-Boreal wetland methane budgets. *Communications Earth Environment*, **6** (1), 903, <https://doi.org/10.1038/s43247-025-02963-1>.
- Helbig, M., and Coauthors, 2022: Warming response of peatland CO<sub>2</sub> sink is sensitive to seasonality in warming trends. *Nature Climate Change*, **12** (8), 743–749, <https://doi.org/10.1038/s41558-022-01428-z>.
- Hugelius, G., and Coauthors, 2020: Large stocks of peatland carbon and nitrogen are vulnerable to permafrost thaw. *Proceedings of the National Academy of Sciences of the United States of America*, **117** (34), 20 438–20 446, <https://doi.org/10.1073/pnas.1916387117>.
- Hugelius, G., and Coauthors, 2024: Permafrost Region Greenhouse Gas Budgets Suggest a Weak CO<sub>2</sub> Sink and CH<sub>4</sub> and N<sub>2</sub>O Sources, But Magnitudes Differ Between Top-Down and Bottom-Up Methods. *Global Biogeochemical Cycles*, **38** (10), e2023GB007969, <https://doi.org/10.1029/2023GB007969>.

- Ivanova, K., and Coauthors, 2026: High-resolution remote sensing and machine-learning-based upscaling of methane fluxes: a case study in the Western Canadian tundra. *Biogeosciences*, **23** (1), 233–262, <https://doi.org/10.5194/BG-23-233-2026>.
- Jakobsson, M., 2002: Hypsometry and volume of the Arctic Ocean and its constituent seas. *Geochemistry, Geophysics, Geosystems*, **3** (5), 1–18, <https://doi.org/10.1029/2001GC000302>.
- Jungsberg, L., L. O. Vestergård, A. Karlsdottir, and A. Wardekker, 2025: Resilience, reflexivity, and decolonization: policy narratives in Kalaallit Nunaat. *Frontiers in Climate*, **7**, 1531036, <https://doi.org/10.3389/fclim.2025.1531036>.
- Kleinen, T., and V. Brovkin, 2018: Pathway-dependent fate of permafrost region carbon. *Environmental Research Letters*, **13** (9), 094 001, <https://doi.org/10.1088/1748-9326/AAD824>.
- Kleinen, T., S. Gromov, B. Steil, and V. Brovkin, 2021: Atmospheric methane underestimated in future climate projections. *Environmental Research Letters*, **16** (9), 094006, <https://doi.org/10.1088/1748-9326/AC1814>.
- Kleinen, T., S. Gromov, B. Steil, and V. Brovkin, 2023: Atmospheric methane since the last glacial maximum was driven by wetland sources. *Climate of the Past*, **19** (5), 1081–1099, <https://doi.org/10.5194/CP-19-1081-2023>.
- Kuhn, M., and Coauthors, 2025: Current and future methane emissions from boreal-Arctic wetlands and lakes. *Nature Climate Change*, **15** (9), 986–991, <https://doi.org/10.1038/s41558-025-02413-y>.
- Lacroix, F., S. Zaehle, S. Caldararu, J. Schaller, P. Stimmler, D. Holl, L. Kutzbach, and M. Göckede, 2022: Mismatch of N release from the permafrost and vegetative uptake opens pathways of increasing nitrous oxide emissions in the high Arctic. *Global Change Biology*, **28** (20), 5973–5990, <https://doi.org/10.1111/GCB.16345>.
- Lambert, M. S., H. Tang, K. S. Aas, F. Stordal, R. A. Fisher, J. W. Bjerke, J. A. Holm, and F. J. W. Parmentier, 2023: Integration of a Frost Mortality Scheme Into the Demographic Vegetation Model FATES. *Journal of Advances in Modeling Earth Systems*, **15** (7), e2022MS003 333, <https://doi.org/10.1029/2022MS003333>.
- Lantuit, H., and Coauthors, 2012: The Arctic Coastal Dynamics Database: A New Classification Scheme and Statistics on Arctic Permafrost Coastlines. *Estuaries and Coasts*, **35** (2), 383–400, <https://doi.org/10.1007/s12237-010-9362-6>.

- Liu, Z., and Coauthors, 2024: Seasonal CO<sub>2</sub> amplitude in northern high latitudes. *Nature Reviews Earth Environment*, **5** (11), 802–817, <https://doi.org/10.1038/s43017-024-00600-7>.
- Matthes, H., and Coauthors, 2025: Advances in Permafrost Representation: Biophysical Processes in Earth System Models and the Role of Offline Models. *Permafrost and Periglacial Processes*, **36** (2), 302–318, <https://doi.org/10.1002/PPP.2269>.
- McClelland, J. W., and Coauthors, 2016: Particulate organic carbon and nitrogen export from major Arctic rivers. *Global Biogeochemical Cycles*, **30** (5), 629–643, <https://doi.org/10.1002/2015GB005351>.
- McGuire, A. D., and Coauthors, 2018: Dependence of the evolution of carbon dynamics in the northern permafrost region on the trajectory of climate change. *Proceedings of the National Academy of Sciences of the United States of America*, **115** (15), 3882–3887, <https://doi.org/10.1073/pnas.1719903115>.
- Milkoreit, M., and Coauthors, 2024: Governance for Earth system tipping points – A research agenda. *Earth System Governance*, **21**, 100216, <https://doi.org/10.1016/J.ESG.2024.100216>.
- Miner, K. R., and Coauthors, 2022: Permafrost carbon emissions in a changing Arctic. *Nature Reviews Earth & Environment*, **3** (1), 55–67, <https://doi.org/10.1038/s43017-021-00230-3>.
- Natali, S. M., J. P. Holdren, B. M. Rogers, R. Treharne, P. B. Duffy, R. Pomerance, and E. MacDonald, 2021: Permafrost carbon feedbacks threaten global climate goals. *Proceedings of the National Academy of Sciences of the United States of America*, **118** (21), e2100163 118, <https://doi.org/10.1073/pnas.2100163118>.
- Natali, S. M., and Coauthors, 2024: NOAA Arctic Report Card 2024: Arctic Terrestrial Carbon Cycling. <https://doi.org/10.25923/OGPP-MN10>.
- Nielsen, D. M., and Coauthors, 2024: Reduced Arctic Ocean CO<sub>2</sub> uptake due to coastal permafrost erosion. *Nature Climate Change*, **14**, 968–975, <https://doi.org/10.1038/s41558-024-02074-3>.
- Nitzbon, J., S. Westermann, M. Langer, L. C. Martin, J. Strauss, S. Laboor, and J. Boike, 2020: Fast response of cold ice-rich permafrost in northeast Siberia to a warming climate. *Nature Communications*, **11** (1), 2201–, <https://doi.org/10.1038/s41467-020-15725-8>.

- Nitzbon, J., and Coauthors, 2024: No respite from permafrost-thaw impacts in the absence of a global tipping point. *Nature Climate Change*, **14** (6), 573–585, <https://doi.org/10.1038/s41558-024-02011-4>.
- Oh, Y., and Coauthors, 2020: Reduced net methane emissions due to microbial methane oxidation in a warmer Arctic. *Nature Climate Change*, **10** (4), 317–321, <https://doi.org/10.1038/s41558-020-0734-z>.
- Orndahl, K. M., and Coauthors, 2025: Next generation Arctic vegetation maps: Aboveground plant biomass and woody dominance mapped at 30 m resolution across the tundra biome. *Remote Sensing of Environment*, **323**, 114717, <https://doi.org/10.1016/J.RSE.2025.114717>.
- Orr, J. C., L. Kwiatkowski, and H. O. Pörtner, 2022: Arctic Ocean annual high in pCO<sub>2</sub> could shift from winter to summer. *Nature*, **610** (7930), 94–100, <https://doi.org/10.1038/s41586-022-05205-y>.
- Oziel, L., and Coauthors, 2025: Climate change and terrigenous inputs decrease the efficiency of the future Arctic Ocean’s biological carbon pump. *Nature Climate Change*, **15** (2), 171–179, <https://doi.org/10.1038/s41558-024-02233-6>.
- Painter, S. L., E. T. Coon, A. J. Khattak, and J. D. Jastrow, 2023: Drying of tundra landscapes will limit subsidence-induced acceleration of permafrost thaw. *Proceedings of the National Academy of Sciences of the United States of America*, **120** (8), e2212171120, <https://doi.org/10.1073/pnas.2212171120>.
- Pallandt, M. M., J. Kumar, M. Mauritz, E. A. Schuur, A. M. Virkkala, G. Celis, F. M. Hoffman, and M. Göckede, 2022: Representativeness assessment of the pan-Arctic eddy covariance site network and optimized future enhancements. *Biogeosciences*, **19** (3), 559–583, <https://doi.org/10.5194/BG-19-559-2022>.
- Pallandt, M. M., M. Jung, K. Arndt, S. M. Natali, B. M. Rogers, A. M. Virkkala, and M. Göckede, 2024: High-Latitude Eddy Covariance Temporal Network Design and Optimization. *Journal of Geophysical Research: Biogeosciences*, **129** (10), e2024JG008406, <https://doi.org/10.1029/2024JG008406>.
- Parmentier, F. J. W., B. F. Thornton, A. Silyakova, and T. R. Christensen, 2024: Vulnerability of Arctic-Boreal methane emissions to climate change. *Frontiers in Environmental Science*, **12**, 1460155, <https://doi.org/10.3389/fenvs.2024.1460155>

- Phoenix, G. K., and Coauthors, 2025: Browning events in Arctic ecosystems: Diverse causes with common consequences. *PLOS Climate*, **4** (1), e0000570, <https://doi.org/10.1371/JOURNAL.PCLM.0000570>.
- Qiu, C., and Coauthors, 2022: A strong mitigation scenario maintains climate neutrality of northern peatlands. *One Earth*, **5** (1), 86–97, <https://doi.org/10.1016/J.ONEEAR.2021.12.008>.
- Ramage, J., and Coauthors, 2024: The Net GHG Balance and Budget of the Permafrost Region (2000–2020) From Ecosystem Flux Upscaling. *Global Biogeochemical Cycles*, **38** (4), e2023GB007 953, <https://doi.org/10.1029/2023GB007953>.
- Rantanen, M., A. Y. Karpechko, A. Lipponen, K. Nordling, O. Hyvärinen, K. Ruosteenoja, T. Vihma, and A. Laaksonen, 2022: The Arctic has warmed nearly four times faster than the globe since 1979. *Communications Earth & Environment*, **3** (1), 1–10, <https://doi.org/10.1038/s43247-022-00498-3>.
- Schädel, C., and Coauthors, 2024: Earth system models must include permafrost carbon processes. *Nature Climate Change*, **14**, 114–116, <https://doi.org/10.1038/s41558-023-01909-9>.
- Schädel, C., T. Gasser, B. M. Rogers, R. Treharne, M. R. Turetsky, T. Smith, E. MacDonald, and S. M. Natali, 2026: Permafrost and wildfire carbon emissions indicate need for additional action to keep Paris Agreement temperature goals within reach. *Communications Earth & Environment*, <https://doi.org/10.1038/s43247-026-03189-5>.
- Semiletov, I., and Coauthors, 2016: Acidification of East Siberian Arctic Shelf waters through addition of freshwater and terrestrial carbon. *Nature Geoscience*, **9** (5), 361–365, <https://doi.org/10.1038/ngeo2695>.
- Schuur, E. A., and Coauthors, 2022: Permafrost and Climate Change: Carbon Cycle Feedbacks From the Warming Arctic. *Annual Review of Environment and Resources*, **47**, 343–371, <https://doi.org/10.1146/ANNUREV-ENVIRON-012220-011847>.
- See, C. R., and Coauthors, 2024: Decadal increases in carbon uptake offset by respiratory losses across northern permafrost ecosystems. *Nature Climate Change*, **14** (8), 853–862, <https://doi.org/10.1038/s41558-024-02057-4.190>
- Strauss, J., and Coauthors, 2025: Organic matter storage and vulnerability in the permafrost domain. *Encyclopedia of Quaternary Science*, S. Elias, Ed., 3rd ed., Elsevier, 399–410, <https://doi.org/10.1016/B978-0-323-99931-1.00164-1>.

- Sulman, B. N., V. G. Salmon, C. M. Iversen, A. L. Breen, F. Yuan, and P. E. Thornton, 2021: Integrating Arctic Plant Functional Types in a Land Surface Model Using Above- and Belowground Field Observations. *Journal of Advances in Modeling Earth Systems*, **13** (4), e2020MS002396, <https://doi.org/10.1029/2020MS002396>.
- Tanski, G., D. Wagner, C. Knoblauch, M. Fritz, T. Sachs, and H. Lantuit, 2019: Rapid CO<sub>2</sub> Release From Eroding Permafrost in Seawater. *Geophysical Research Letters*, **46** (20), 11 244–11 252, <https://doi.org/10.1029/2019GL084303>.
- Turetsky, M. R., and Coauthors, 2020: Carbon release through abrupt permafrost thaw. *Nature Geoscience*, **13** (2), 138–143, <https://doi.org/10.1038/s41561-019-0526-0>.
- Van Der Werf, G. R., and Coauthors, 2017: Global fire emissions estimates during 1997–2016. *Earth System Science Data*, **9** (2), 697–720, <https://doi.org/10.5194/ESSD-9-697-2017>.
- Virkkala, A. M., and Coauthors, 2025b: Wildfires offset the increasing but spatially heterogeneous Arctic–boreal CO<sub>2</sub> uptake. *Nature Climate Change*, **15** (2), 188–195, <https://doi.org/10.1038/s41558-024-02234-5>.
- Vogt, J., and Coauthors, 2025: ARGO: ARctic greenhouse Gas Observation metadata version 1. *Earth System Science Data*, **17** (6), 2553–2573, <https://doi.org/10.5194/ESSD-17-2553-2025>.
- Voigt, C., and Coauthors, 2023: Arctic soil methane sink increases with drier conditions and higher ecosystem respiration. *Nature Climate Change*, **13** (10), 1095–1104, <https://doi.org/10.1038/s41558-023-01785-3>.
- Vonk, J. E., Fritz, M., and Coauthors, 2025: The land–ocean Arctic carbon cycle. *Nature Reviews Earth Environment*, **6** (2), 86–105, <https://doi.org/10.1038/s43017-024-00627-w>.
- Wadham, J. L., and Coauthors, 2026: An Ice Sheet-to-Ocean Analysis of Carbon Stores and Fluxes in Earth’s Polar Regions (RECCAP2, Polar Ice Sheets). *Global Biogeochemical Cycles*, **40** (2), e2025GB008677, <https://doi.org/10.1029/2025GB008677>.
- Wassmann, P., C. M. Duarte, S. Agustí, and M. K. Sejr, 2011: Footprints of climate change in the Arctic marine ecosystem. *Global Change Biology*, **17** (2), 1235–1249, <https://doi.org/10.1111/J.1365-2486.2010.02311.X>.
- Webb, H., and Coauthors, 2025: A Review of Abrupt Permafrost Thaw: Definitions, Usage, and a Proposed Conceptual Framework. *Current Climate Change Reports*, **11** (1), 7–, <https://doi.org/10.1007/S40641-025-00204-3>.

- Winkler, A. J., R. B. Myneni, G. A. Alexandrov, and V. Brovkin, 2019: Earth system models underestimate carbon fixation by plants in the high latitudes. *Nature Communications*, **10** (1), 885–, <https://doi.org/10.1038/s41467-019-08633-z>.
- Wood, M., and Coauthors, 2025: Increased melt from Greenland’s most active glacier fuels enhanced coastal productivity. *Communications Earth Environment*, **6** (1), 626–, <https://doi.org/10.1038/s43247-025-02599-1>.
- Yamamoto-Kawai, M., F. A. McLaughlin, E. C. Carmack, S. Nishino, and K. Shimada, 2009: Aragonite undersaturation in the Arctic Ocean: Effects of ocean acidification and sea ice melt. *Science*, **326** (5956), 1098–1100, <https://doi.org/10.1126/SCIENCE.1174190>.
- Yasunaka, S., and Coauthors, 2023: An Assessment of CO<sub>2</sub> Uptake in the Arctic Ocean From 1985 to 2018. *Global Biogeochemical Cycles*, **37** (11), e2023GB007 806, <https://doi.org/10.1029/2023GB007806>.
- Ying, Q., and Coauthors, 2025: WetCH<sub>4</sub>: a machine-learning-based upscaling of methane fluxes of northern wetlands during 2016-2022. *Earth System Science Data*, **17** (6), 2507–2534, <https://doi.org/10.5194/ESSD-17-2507-2025>.