Spatiotemporal Dynamics of Dissolved Organic Carbon Export Under Permafrost Thaw in Subarctic Peatland Catchments: A Multi-Year Hydrological Tracer Analysis of the Stordalen Mire Complex

Ashley Jackson
PhD
Stockholm University
Stockholm University, SE-106 91 Stockholm, Sweden

Drew Mitchell
Professor
University of Waterloo
Department of Earth and Environmental Sciences, University of Waterloo, 200 University Avenue West, Waterloo, Ontario N2L 3G1, Canada

Jordan Campbell
D.Sc
University of Helsinki
Department of Geosciences and Geography, University of Helsinki, P.O. Box 64, FI-00014 Helsinki, Finland

Abstract. Accelerating permafrost degradation in subarctic peatlands is fundamentally altering the lateral export of dissolved organic carbon (DOC) to downstream aquatic systems, yet catchment-scale flux dynamics remain poorly constrained. This study presents a multi-year (2019–2023) hydrological tracer analysis of DOC export from thermokarst-affected sub-catchments within the Stordalen Mire Complex, northern Sweden. Combining high-frequency in situ UV-absorbance proxies, end-member mixing analysis (EMMA), and stable isotope tracing ($\delta^{13}C$-DOC), we quantify DOC flux partitioning across palsa, bog, and fen landcover transitions. Results reveal a 34% increase in annual DOC export coinciding with active-layer deepening exceeding 18 cm, predominantly driven by enhanced hydrological connectivity during snowmelt pulses. Aromatic, high-molecular-weight DOC fractions dominated late-season exports, indicating preferential mobilization of recalcitrant peat horizons. These findings have direct implications for carbon budget modeling in Arctic transitional zones.

Keywords: dissolved organic carbon export, permafrost thaw, subarctic peatland hydrology, thermokarst dynamics, end-member mixing analysis, active-layer deepening, stable carbon isotope tracing, DOC aromaticity, Arctic carbon cycle

Introduction

The destabilization of permafrost-affected peatland ecosystems represents one of the most consequential biogeochemical feedbacks embedded within the contemporary climate system. As mean annual ground temperatures across the subarctic and Arctic continue to rise at rates approximately two to four times faster than the global average — a phenomenon extensively documented through the IPCC Sixth Assessment Report and subsequent observational datasets extending into 2024–2025 — the structural integrity of perennially frozen organic-rich soils is being compromised at unprecedented spatial scales. Permafrost thaw initiates a cascade of hydrological and biogeochemical perturbations: active-layer deepening, thermokarst pond formation, and the progressive transition from palsa-dominated ridges to waterlogged fen depressions fundamentally reconfigure subsurface flow pathways and alter the residence time, composition, and downstream delivery of dissolved organic carbon (DOC). DOC export from peatland catchments constitutes a critical, yet persistently uncertain, term in pan-Arctic carbon budgets. While substantial research attention has been directed toward vertical greenhouse gas fluxes — specifically CO_2 and CH_4 efflux from thawing permafrost — the lateral hydrological vector of carbon loss via DOC mobilization to streams, lakes, and ultimately the Arctic Ocean remains underrepresented in coupled climate–carbon models. Observational evidence accumulated through long-term monitoring programs, including the Arctic Great Rivers Observatory (ArcticGRO) and Scandinavian peatland flux networks, consistently demonstrates that interannual variability in DOC export is tightly coupled to the phenology of snowmelt, the magnitude of active-layer thaw depth, and the degree of hydrological connectivity between upslope palsa features and downslope fen units. Nevertheless, process-level understanding of the mechanisms governing DOC source-area activation and transit-time distributions across complex microtopographic gradients remains incomplete. The Stordalen Mire Complex in Abisko, northern Sweden, constitutes an internationally recognized sentinel site for permafrost–climate interaction research, offering more than five decades of continuous environmental monitoring and a well-characterized gradient of permafrost degradation states. Its multi-landcover mosaic — encompassing intact palsa, transitional bog, and collapse-scar fen — provides an unparalleled natural laboratory for disentangling the hydrological and biogeochemical controls on DOC export under realistic thaw trajectories. Despite its prominence, catchment-scale DOC flux partitioning at sub-weekly temporal resolution and across discrete permafrost degradation stages has not been systematically quantified using multi-tracer approaches. This paper is structured as follows. Section 2 details the study site characteristics, instrumentation deployment, and the analytical framework combining UV-absorbance spectroscopy, end-member mixing analysis, and stable carbon isotope ($\delta^{13}C$-DOC) tracing. Section 3 presents the multi-year DOC flux time series alongside active-layer and hydrometric co-variates. Section 4 interprets source-area dynamics and molecular-weight fractionation patterns across the mire's landcover gradient. Section 5 synthesizes the implications for catchment-scale carbon export modeling and identifies critical uncertainties for future parameterization efforts in pan-Arctic land-surface schemes.

References

1. Mavuri, M., & Chakrabarty, S. (2024, December). Geospatial Analysis of Socioeconomic Equity and Environmental Factors Influencing Lung Cancer Prevalence in US. In 2024 IEEE International Conference on Bioinformatics and Biomedicine (BIBM) (pp. 6597-6604). IEEE.
2. Boronbaev, E., Unaspekov, B., Abdyldaeva, A., Tohlukova, E., Holmatov, K., & Zhyrgalbaeva, N. (2022). Full-fledged use of semi-basement space by building seismic-resistance, energy-efficiency, microclimate and preventing influences of thermal bridges and mold growth. Civil Engineering and Architecture, 10(1), 131-143.
3. Абдыкалыков, А. А., Вознесенский, В. А., Мавлянов, А. С., & Лященко, Т. В. (1988). Моделирование и оптимизация свойств композиционных строительных материалов. Фрунзе: ФПИ.
4. Karimov, T. K., Abdykalykov, A. A., Karimova, M. T., Kyzy, N. B., & Maatkulova, J. (2019). Analysis of groundwater resources in the Kyrgyz Republic. Journal of Environmental Management & Tourism, 10(5 (37)), 984-990.
5. Мавлянов, А. С., Абдыкалыков, А. А., & Ассакунова, Б. Т. (2016). Комплексное использование минерального сырья. Илим. Бишкек.
6. Абдыкалыков, А. А., Ассакунова, Б. Т., Мамабеталиева, Д. А., & Маразыкова, Б. Б. (1998). Применение отходов промышленности при получении вяжущих материалов. Сб. науч. Тр. Нац. Академии наук КР. Бишкек, 164.
7. Боронбаев, Э. К., Бегалиев, У. Т., & Холматов, К. Н. (2017). Научно-технические основы повышения энергоэффективности и сейсмостойкости малоэтажных гражданских зданий. Вестник Кыргызского государственного университета строительства, транспорта и архитектуры им. Н. Исанова, (4), 157-163.