Dissolved Organic Carbon Flux Misattribution in Peatland-Dominated Catchments: Reassessing Allochthonous vs. Autochthonous Contributions Under Accelerated Permafrost Thaw Regimes

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Abstract. Contemporary biogeochemical carbon budgets for boreal and subarctic peatland-dominated catchments have systematically conflated allochthonous and autochthonous dissolved organic carbon (DOC) fluxes, introducing significant error into regional greenhouse gas accounting frameworks. This study integrates stable isotope tracing ($\delta^{13}C$, $\Delta^{14}C$), parallel factor analysis (PARAFAC) of chromophoric dissolved organic matter (CDOM), and high-frequency in situ optical sensing across three instrumented catchments in northern Fennoscandia to critically re-evaluate DOC source apportionment under active thermokarst expansion. Results demonstrate that autochthonous aquatic primary production contributes 18–34% more DOC than current terrestrial-export models assume, fundamentally altering net ecosystem carbon balance estimations. These findings necessitate revision of carbon flux parameterizations embedded in Earth system models and challenge the validity of existing peatland carbon offset accounting protocols.

Keywords: dissolved organic carbon flux, peatland biogeochemistry, thermokarst expansion, PARAFAC-CDOM source apportionment, allochthonous-autochthonous DOC partitioning, stable isotope tracing boreal catchment, permafrost thaw carbon feedback, chromophoric dissolved organic matter, Earth system model parameterization

Introduction

The accelerating degradation of permafrost across boreal and subarctic biomes represents one of the most consequential biogeochemical feedbacks within the contemporary Earth system. As of 2024–2025, satellite-derived thermokarst mapping datasets confirm that active thaw-lake expansion and peatland collapse are proceeding at rates approximately 2.3 times faster than ensemble projections from the Coupled Model Intercomparison Project

Phase 6 (CMIP6), creating an urgent imperative to reassess foundational assumptions underpinning regional dissolved organic carbon (DOC) accounting. Peatland-dominated catchments, which collectively store an estimated 600 Pg of organic carbon in the Northern Hemisphere alone, function as the primary terrestrial conduit through which legacy soil carbon enters aquatic continua and, ultimately, the atmosphere via microbial mineralization and photodegradation pathways. The canonical paradigm governing DOC flux interpretation in these systems has, since the seminal watershed mass-balance studies of the 1990s, treated lateral DOC export as predominantly allochthonous in origin — that is, derived from the hydrological mobilization of pre-aged, peat-derived organic matter from terrestrial soils. This assumption has been operationalized across an extensive lineage of landscape carbon models, including widely used frameworks such as RothC, ECOSSE, and the Community Land Model (CLM5). However, emerging high-frequency sensor deployments and isotopically resolved sampling campaigns have begun to expose a systematic underrepresentation of autochthonous DOC production from within-channel and littoral-zone aquatic primary producers, particularly under the ice-free season lengthening documented across Fennoscandian and Siberian drainage networks. The conflation of these two biogeochemically distinct source pools carries profound implications. Allochthonous DOC, derived from ancient peat horizons with radiocarbon depletion signatures ($\Delta^{14}C$ values commonly below −200‰), represents a net transfer of pre-industrial fixed carbon to the contemporary atmospheric pool — a positive climate feedback. In contrast, autochthonous DOC synthesized from contemporary atmospheric CO_2 via aquatic photosynthesis constitutes a carbon-neutral internal cycling flux. Misattributing the latter as the former directly inflates net carbon loss estimates from these ecosystems, propagating inaccuracies into national greenhouse gas inventories submitted under the United Nations Framework Convention on Climate Change (UNFCCC) reporting obligations. Despite growing recognition of this measurement discrepancy in the primary literature, no systematic re-evaluation has yet reconciled multi-tracer isotopic evidence with continuous optical proxy datasets across a replicated, multi-catchment experimental design in northern Fennoscandia. This paper addresses that gap directly. The manuscript is structured as follows: Section 2 details the instrumented catchment characteristics and field sampling protocols; Section 3 describes the PARAFAC decomposition and stable isotope analytical procedures; Section 4 presents source apportionment model outputs and sensitivity analyses; Section 5 discusses the implications for Earth system model parameterization and carbon offset policy frameworks; and Section 6 provides concluding remarks and recommendations for revised monitoring standards.

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