

Introduction

Permafrost regions store an estimated 1,500 Pg of carbon, nearly twice the amount currently in the atmosphere, making them a critical and vulnerable component of the global carbon cycle (Zimov et al., 2006). As permafrost thaws, hydrologic flow paths deepen and shift (Fig. 1), altering how dissolved organic matter (DOM) is mobilized from soils into headwater streams. Shallow flow paths in high-permafrost systems favor the export of relatively unprocessed, terrestrial DOM, while deeper flow paths in lower-permafrost systems promote increased subsurface interaction and microbial processing. The Caribou Poker Creek Research Watershed (CPCRW) exports DOM that reflects a mixture of newer surface inputs and older, previously frozen carbon. In this study, fluorescence and absorbance data from two headwater catchments spanning a high to moderate permafrost gradient (54%–19%) are used to characterize spatial differences in DOM composition. This work provides a foundation for expanding analyses across additional sites and years and for integrating optical measurements with FT-ICR MS and radiocarbon ($\Delta^{14}\text{C}$) to better understand how permafrost extent influences DOM composition and age.

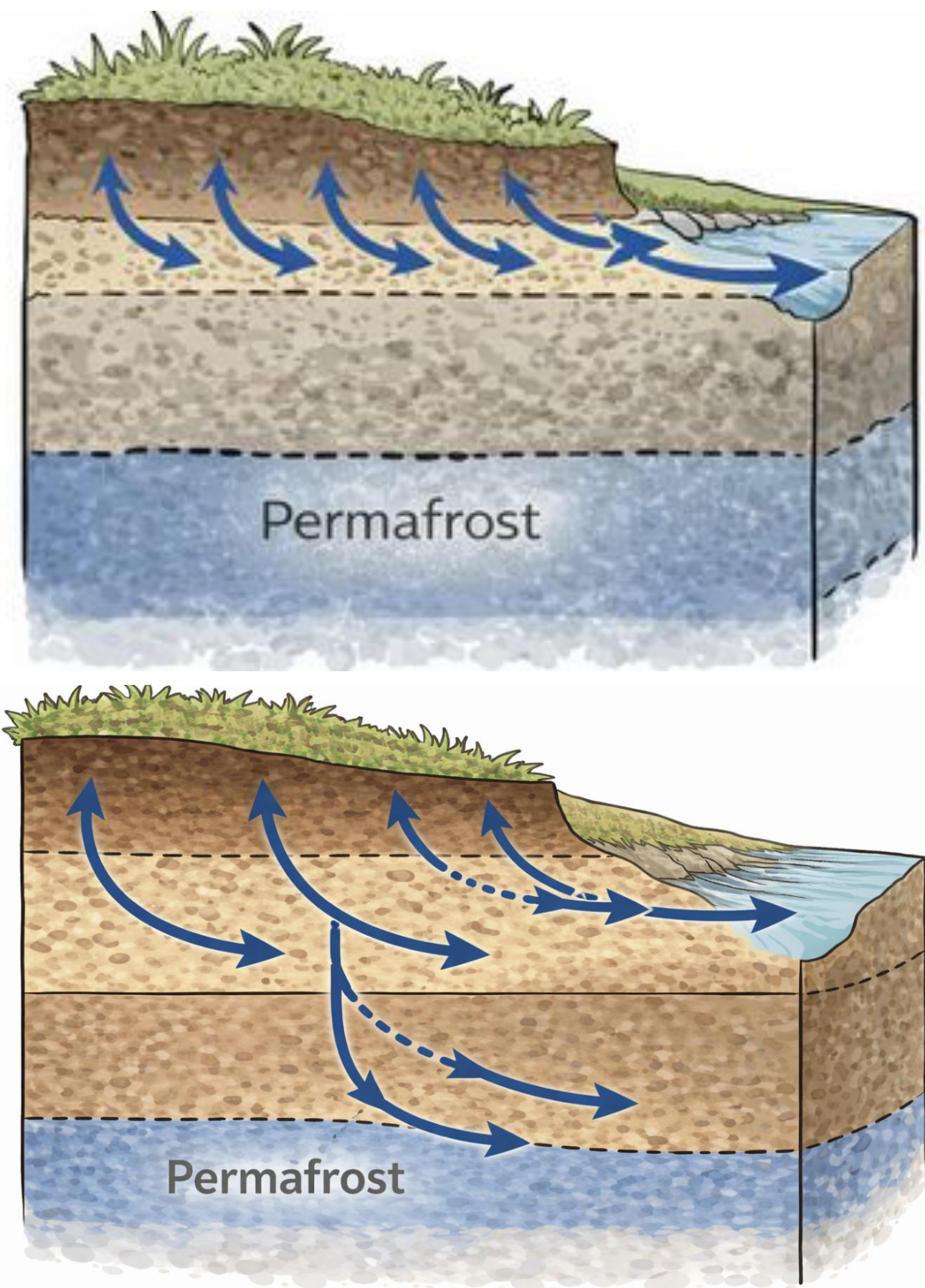


Figure 1. (A) In high-permafrost systems, a shallow active layer limits infiltration, promoting lateral flow through organic-rich soils and export of relatively unprocessed, terrestrial DOM. (B) In moderate permafrost systems, a deeper active layer enables greater infiltration and subsurface flow, increasing residence time and microbial processing prior to export.

Methods

Eighty archived stream samples from CPCRW were analyzed from two catchments with high and moderate permafrost extent, spanning years 2005, 2008, 2011, 2013, 2015, and 2018. Samples were run on a Horiba Aqualog absorbance-fluorescence spectrometer to collect absorbance spectra and excitation-emission matrices (EEMs). From these data, optical indices were calculated, including absorbance at 254 nm (a_{254}), fluorescence index (FI), and spectral slope ratio (Sr), following established methods (McKnight et al., 2001; Helms et al., 2008). EEMs were processed in MATLAB, and statistical summaries and box plots were generated in R to compare DOM characteristics between sites.

Results

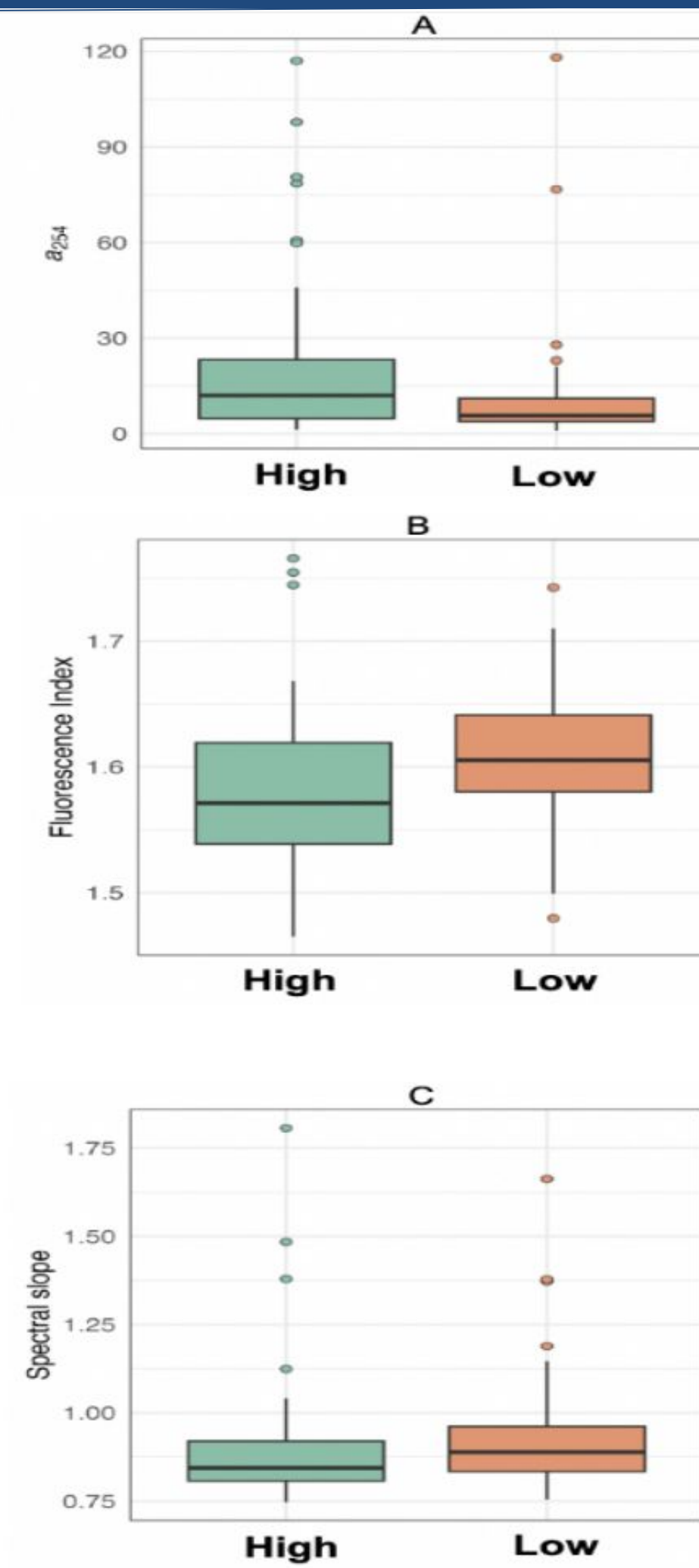


Figure 2. Boxplots of DOM optical properties for high- and moderate-permafrost catchments. (A) a_{254} (aromatic DOM), (B) fluorescence index (FI; positively correlated with microbial DOM), and (C) spectral slope ratio (Sr; negatively correlated with molecular weight). High-permafrost catchments exhibit higher a_{254} and lower FI and Sr, indicating more aromatic, terrestrial, high-molecular weight DOM than moderate-permafrost sites.

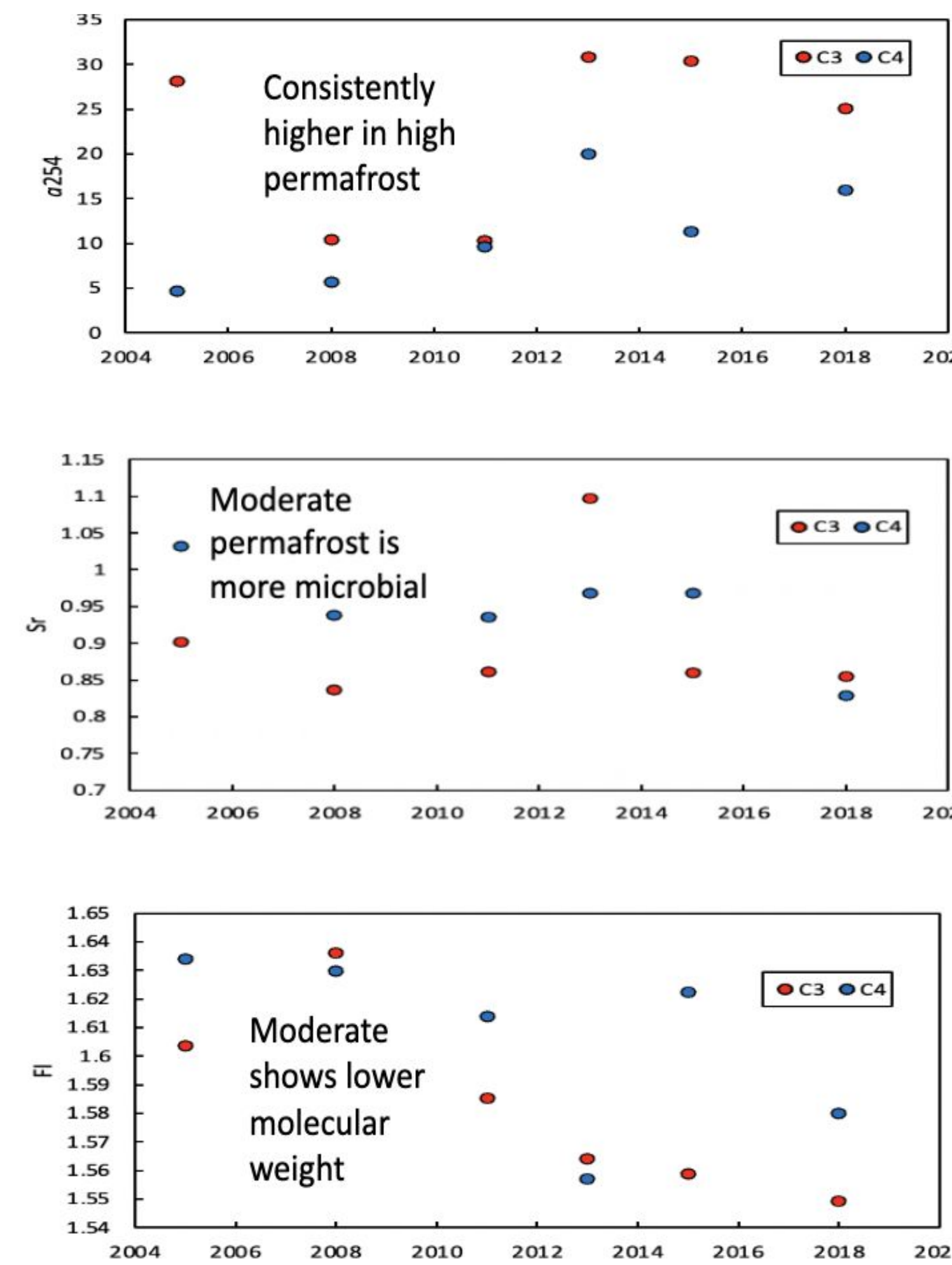
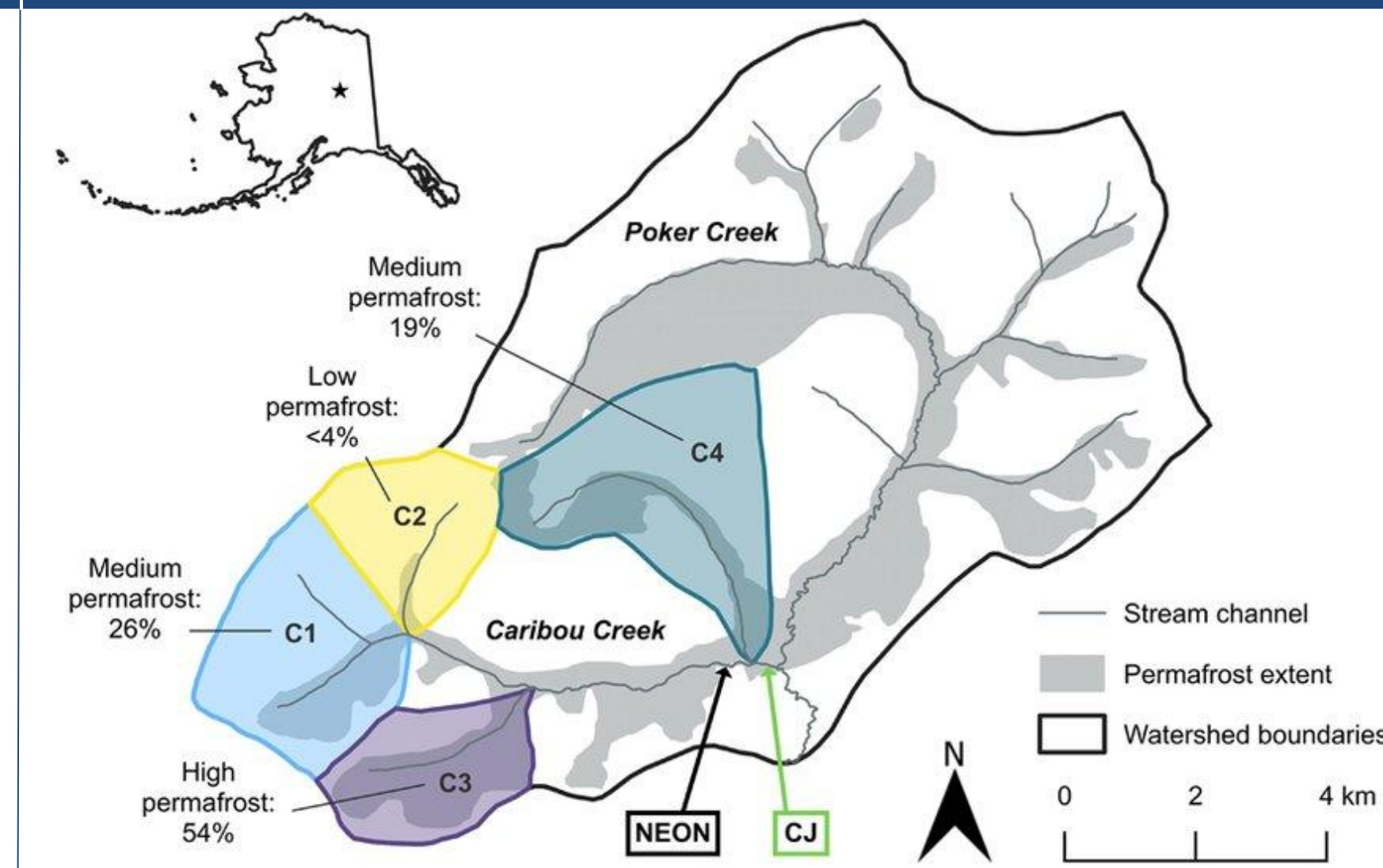


Figure 3. Boxplots of DOM optical properties for high- and moderate permafrost catchments (CPCRW): (A) a_{254} (aromatic DOM), (B) FI (source indicator), and (C) Sr (molecular weight; lower = higher MW). Boxes show IQR with median lines; whiskers exclude outliers ($>1.5 \times$ IQR). High-permafrost sites show higher a_{254} and lower FI and Sr, indicating more aromatic, terrestrial, high-molecular weight DOM.

Map of Study Site



(Iannucci et al., 2024)

Discussion

Observed differences in DOM composition between sites persist across sampling years, indicating that permafrost extent exerts a consistent control on DOM export despite substantial interannual variability. The high-permafrost catchment (C3) consistently exhibits higher a_{254} , suggesting greater concentrations of aromatic, terrestrially derived DOM, while lower Sr values indicate a higher molecular weight DOM pool. In contrast, the moderate-permafrost site (C4) generally shows lower a_{254} and higher Sr, consistent with more processed, microbially influenced DOM. Patterns in FI support this interpretation, although with greater variability, suggesting that source signatures may be more sensitive to short-term environmental conditions. Together, these results support a conceptual model in which high-permafrost catchments export DOM via shallow flow paths that mobilize organic-rich surface soils, whereas reduced permafrost extent allows deeper flow paths and increased microbial processing prior to export. The persistence of these patterns through time suggests that spatial differences in permafrost extent play a dominant role in structuring DOM composition in Arctic headwater systems.

Future directions

Future work will expand this analysis across a 23-year CPCRW dataset, incorporating an additional low-permafrost site ($<4\%$) and increasing the dataset to roughly 1200 samples. Optical measurements will be integrated with ultrahigh-resolution FT-ICR MS and radiocarbon ($\Delta^{14}\text{C}$) analyses to better constrain DOM molecular composition and age. This combined approach will provide a more comprehensive understanding of how permafrost thaw alters DOM export pathways and influences carbon cycling in Arctic headwater catchments.

I would like to thank URSA for funding this work as well as the Johnston Lab for facilitating this research. I would like to give special thanks to Zach Cureton-Hazard as my mentor.

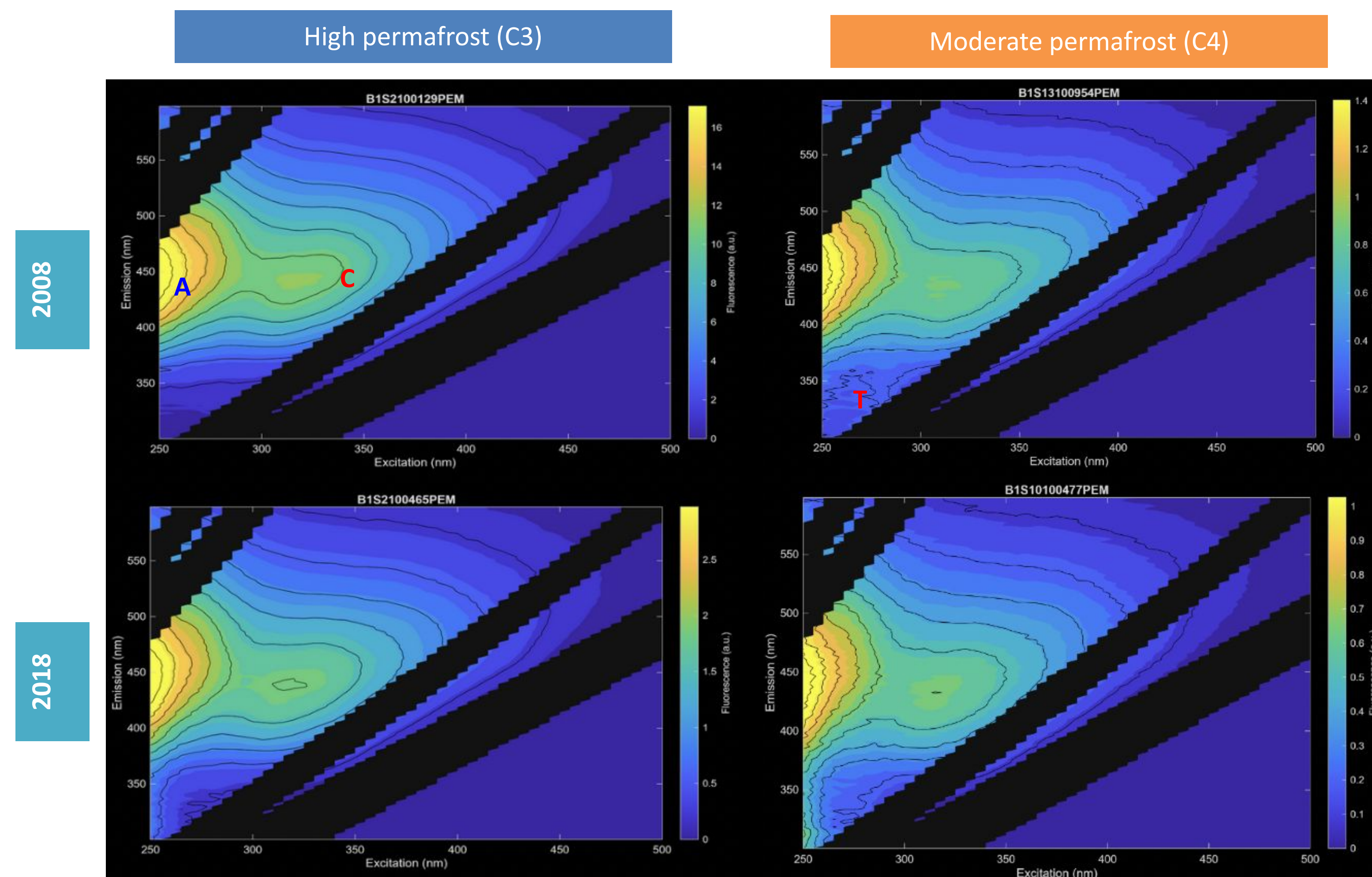


Figure 4. EEMs from high- and moderate-permafrost catchments (2008, 2018). High-permafrost shows stronger fluorescence with dominant humic (C) and terrestrial (A) peaks, while moderate-permafrost shows lower intensity, weaker C, and greater microbial (T) signal. In 2018, both sites show reduced intensity, with persistent A/C in high-permafrost and low-intensity C/T in moderate-permafrost, indicating increased DOM processing and deeper flow paths.