

Supplementary Information:

Long-term trends in carbon and color signal uneven browning and terrestrialization of northern lakes

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Abstract:

The widespread “browning” of northern lakes has been associated with long-term increases in dissolved organic carbon (DOC) and color and should be linked to changes in surface water CO₂, yet the long-term covariation in these three key carbon components of lake functioning remains to be assessed. We present long-term trends in DOC, color, and CO₂ from lakes, with generally positive but highly variable trends in DOC and a large degree of uncoupling with color and CO₂. Overall, the highest rates of change in color and CO₂ were in lakes with greatest increasing DOC trends. Lakes with the lowest water retention times had greater overall increases and stronger coupling between all three parameters, coinciding with dominance of terrestrially derived DOC, and reflecting stronger links to land. These results suggest an uneven terrestrialization of northern lakes, where the increases and coupling in DOC, color or CO₂, depend on hydrology and watershed connectivity.

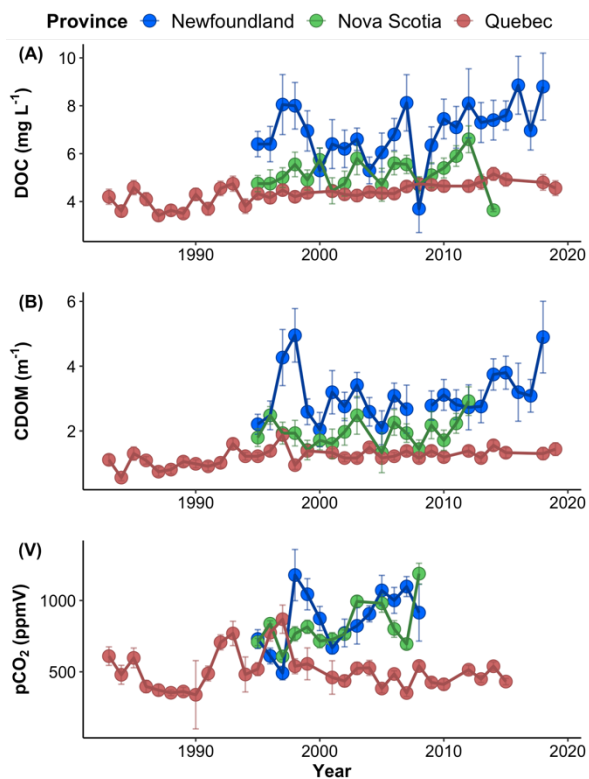


Figure S1. Time series of median annual concentrations of (A) DOC, (B) CDOM, and (C) pCO_2 for lakes in Newfoundland (blue), Nova Scotia (green), and Québec (red). Error bars represent standard error.

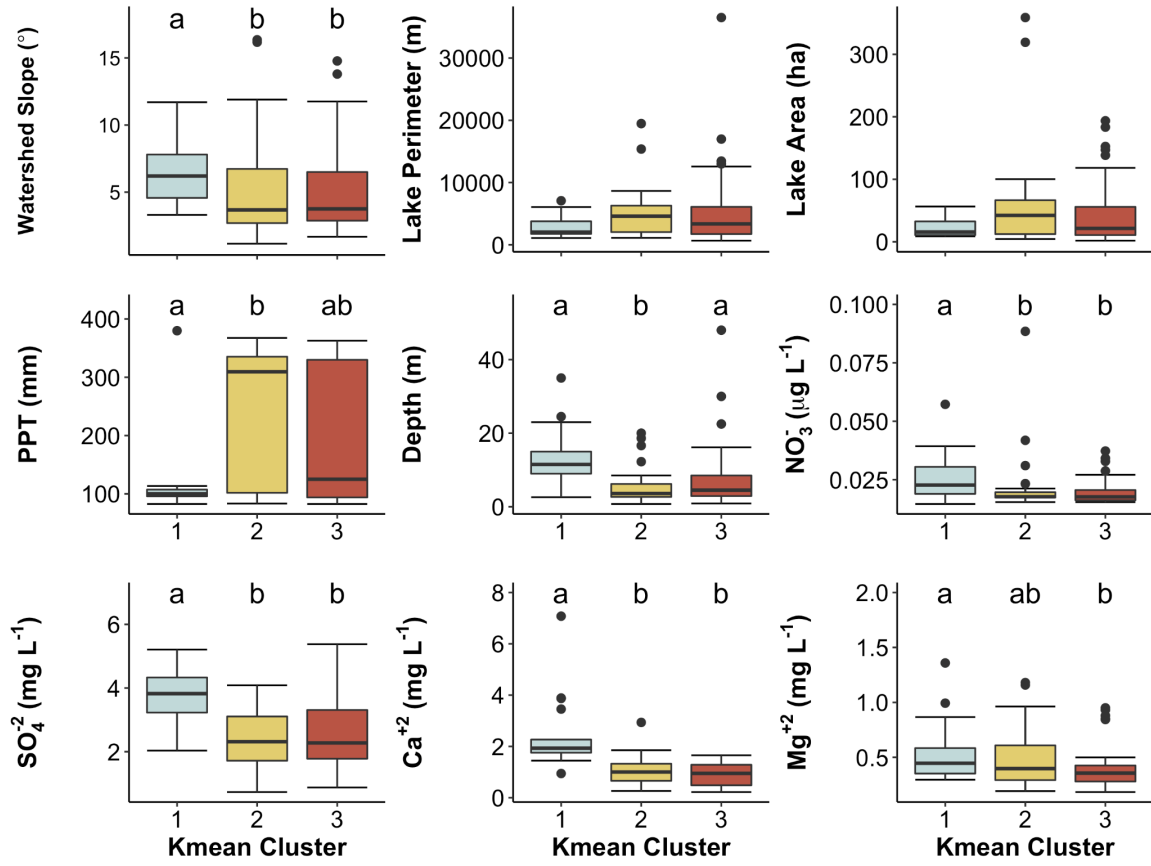


Figure S2. Boxplots of watershed slope, mean precipitation (PPT), concentration of SO_4^{2-} , lake perimeter, mean lake depth, concentrations of Ca^{+2} , lake area, concentrations of NO_3^- , and concentrations of Mg^{+2} for all lakes within each cluster. Solid black line denotes the median value for each cluster, whiskers represent 1.5 interquartile range, and points are possible outliers. Lowercase letters denote statistically significant differences ($\alpha=0.05$) across cluster groups based on a Kruskal-Wallis rank sum test.

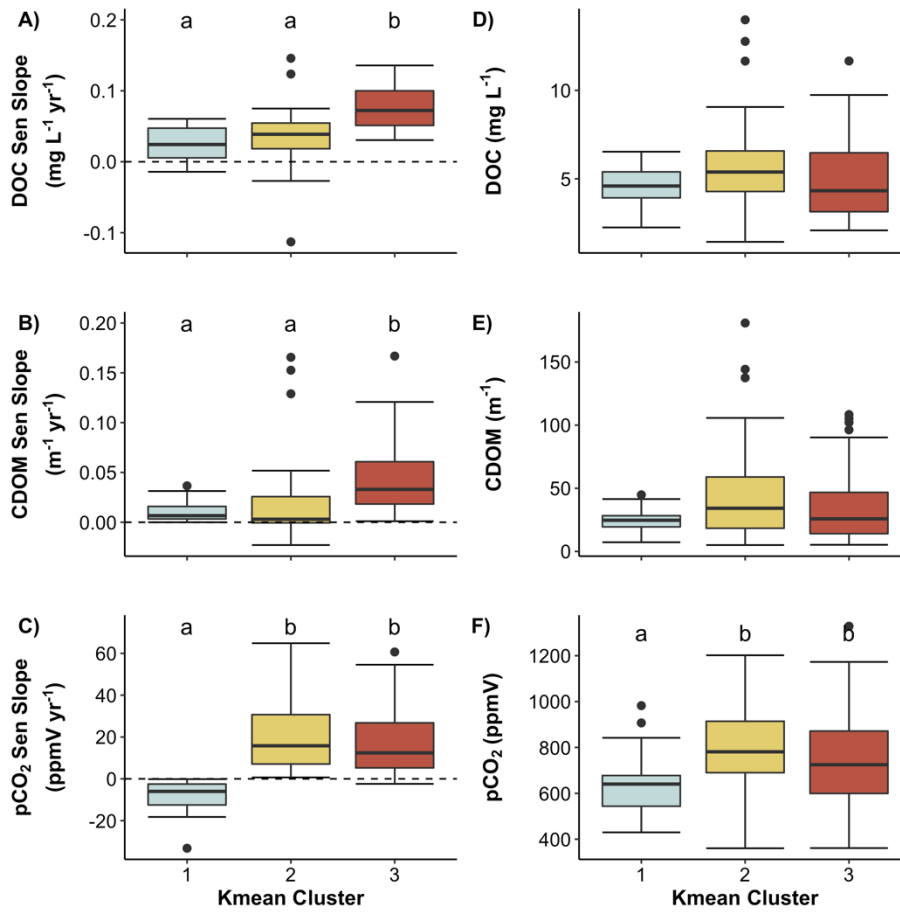


Figure S3. Boxplots of Sen slopes for **A)** DOC, **B)** CDOM, and **C)** pCO_2 and concentrations of **D)** DOC, **E)** CDOM, and **F)** pCO_2 for all lakes within each cluster. Solid black line denotes the median value for each cluster, whiskers represent 1.5 interquartile range, and points are possible outliers. Lowercase letters denote statistically significant differences ($\alpha=0.05$) across cluster groups based on a Kruskal-Wallis rank sum test. Dashed horizontal lines marks 0 to facilitate differentiation between positive and negative values.

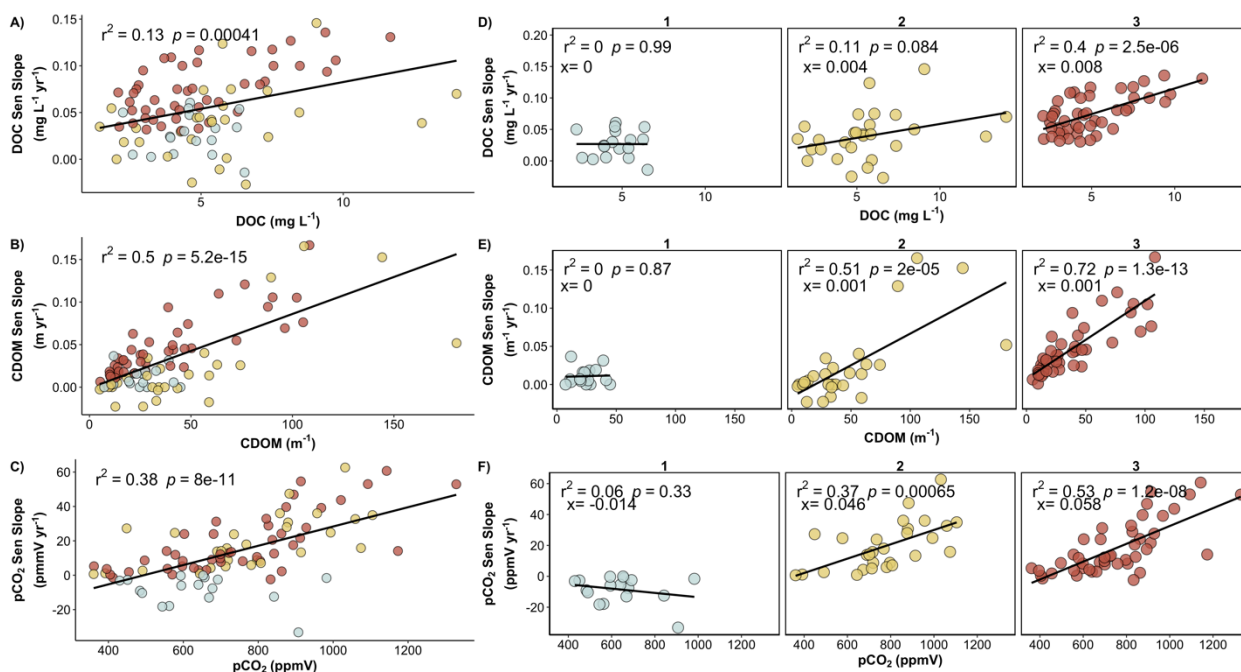


Figure S4. Regressions between A) DOC concentrations and DOC Sen slopes B) CDOM and CDOM Sen slopes, C) pCO₂ concentrations and pCO₂ Sen slopes, D) DOC concentrations and DOC Sen slopes by cluster group, E) CDOM and CDOM Sen slopes by cluster group, and F) pCO₂ concentrations and pCO₂ Sen slopes by cluster group.

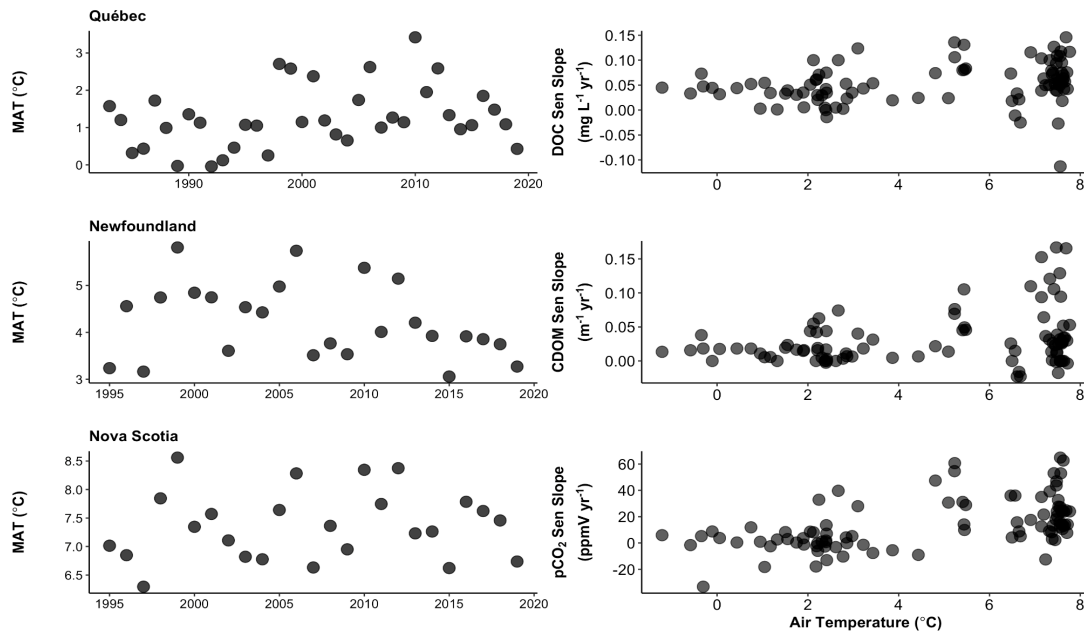


Figure S5. Mean annual air temperature (MAT) for Quebec, Newfoundland, and Nova Scotia as well as relating Sen slopes of DOC, CDOM, and pCO₂ with MAT across all lakes.

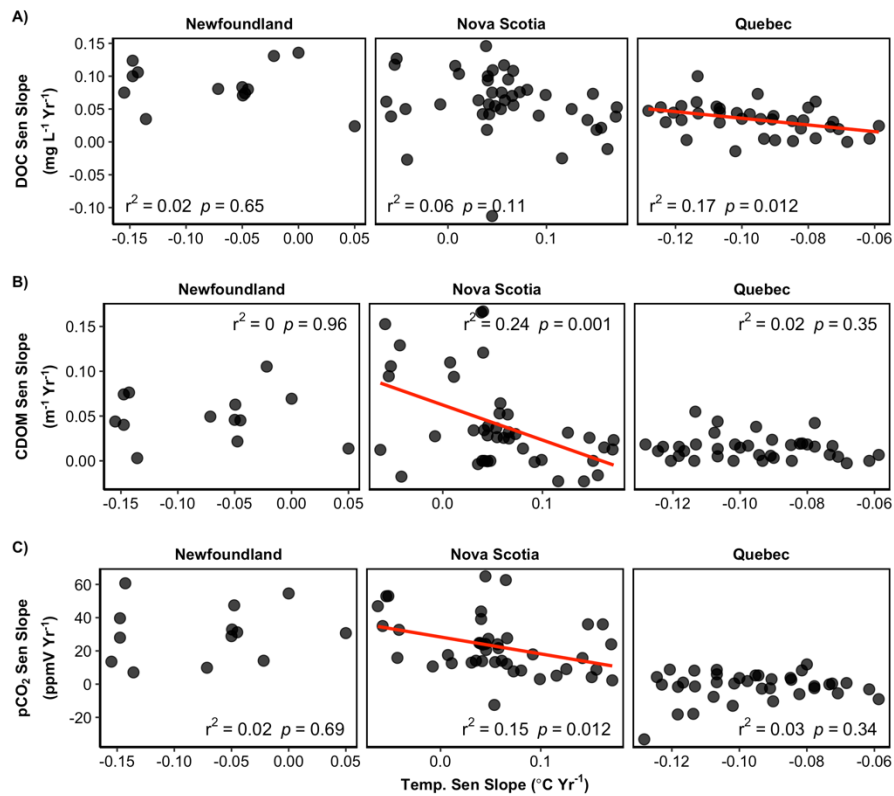


Figure S6. DOC, CDOM, and pCO₂ Sen slopes related to annual mean air temperature (Temp.) form each lake (from May-Sept to match the same time frames as C form Sen slopes) per region. Red lines are included for statistically significant regressions.

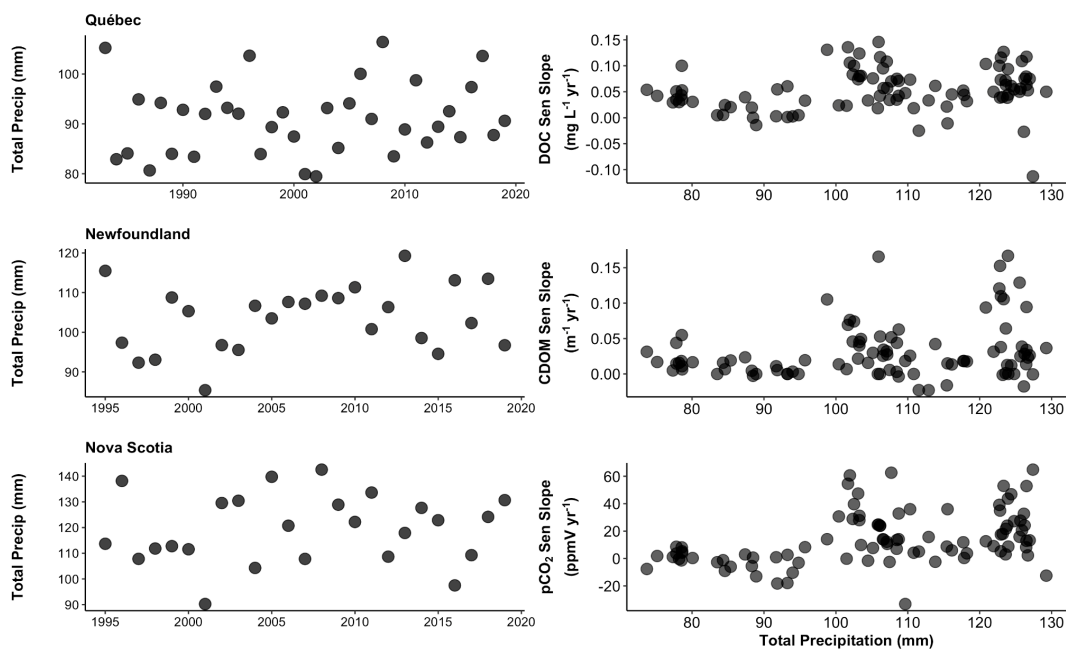


Figure S7. Time series of mean annual total precipitation for Québec, Newfoundland, and Nova Scotia as well as relating Sen slopes of DOC, CDOM, and pCO₂ with annual average of total precipitation across all lakes.

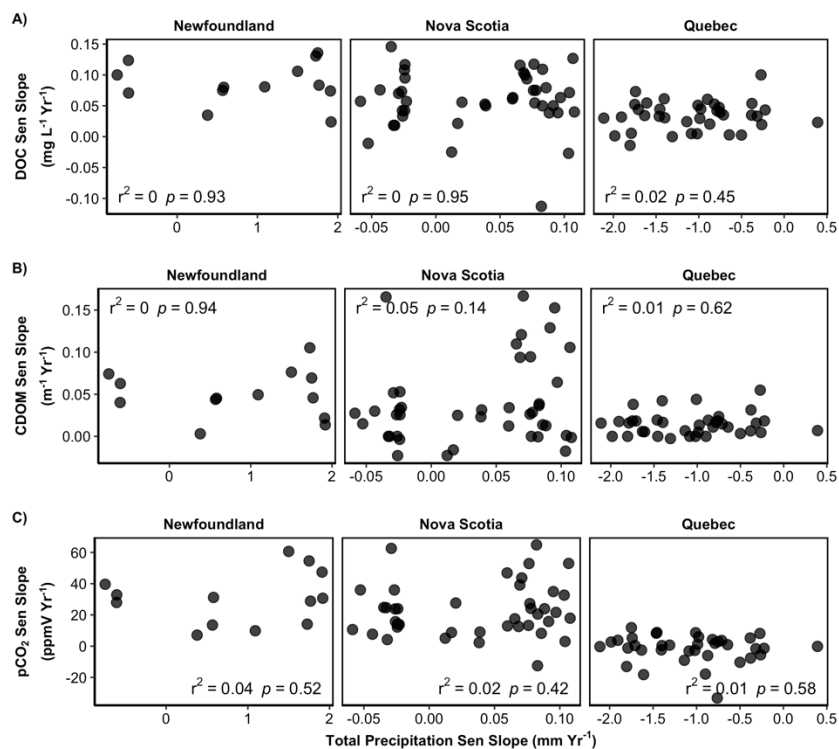


Figure S8. DOC, CDOM, and pCO₂ Sen slopes related to annual mean total precipitation (PPT) from each lake (from May-Sept to match the same time frames as C form Sen slopes) per region.

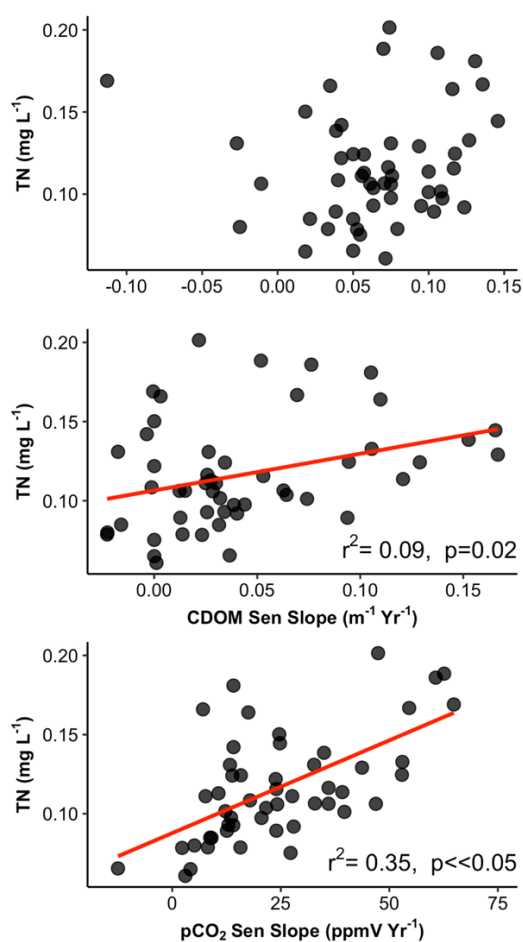


Figure S9. Relationship between median lake TN concentrations and a) DOC Sen slopes, b) CDOM Sen slope, and c) pCO_2 Sen slope for a subset of lakes where TN concentrations were available.

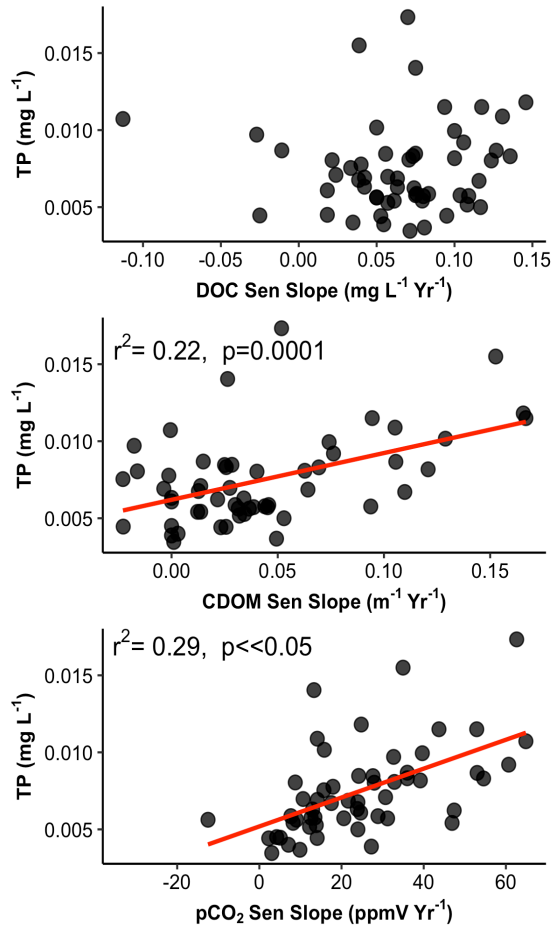


Figure S10. Relationship between median lake TP concentrations and a) DOC Sen slopes, b) CDOM Sen slope, and c) pCO₂ Sen slope for a subset of lakes where TP concentrations were available.

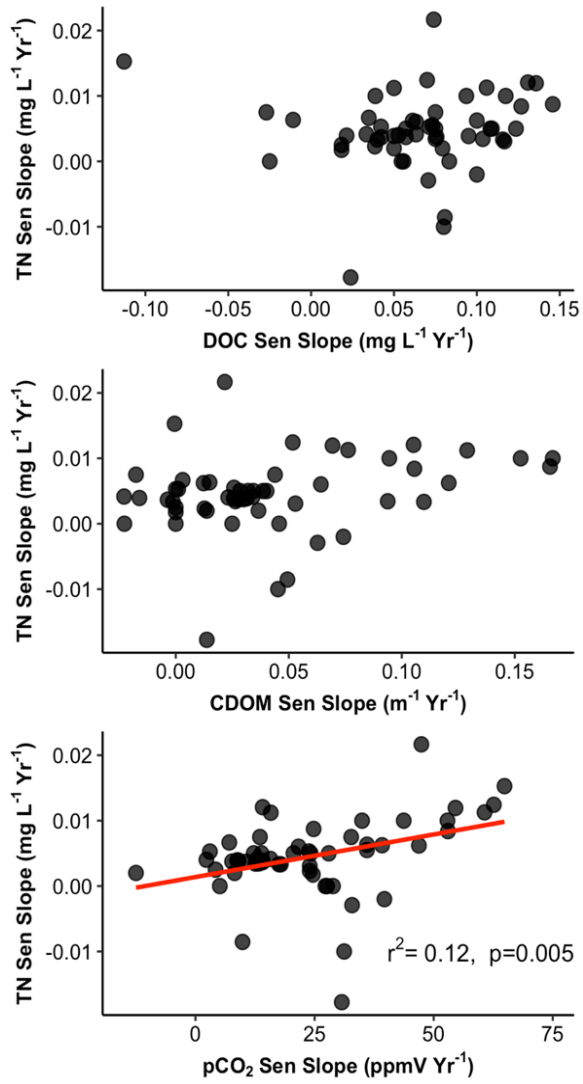


Figure S11. Relationship between TN Sen slopes and a) DOC Sen slopes, b) CDOM Sen slope, and c) pCO₂ Sen slope for a subset of lakes that had long-term TN concentrations.

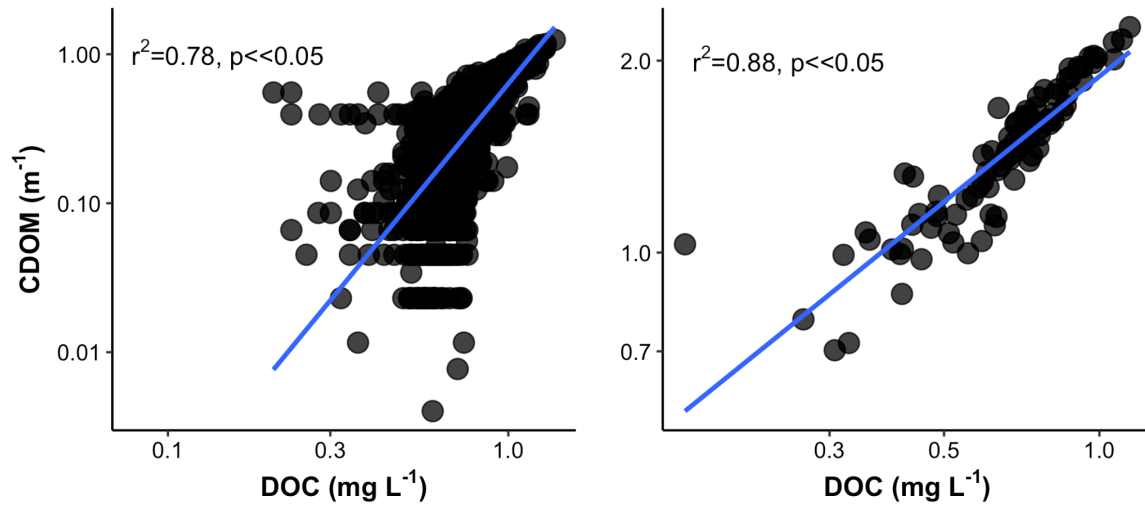


Figure S12. Regressions between a) the mean monthly averages of log transformed DOC and CDOM concentrations from all lakes and b) the annual averages of log transformed DOC and CDOM concentrations from all lakes.

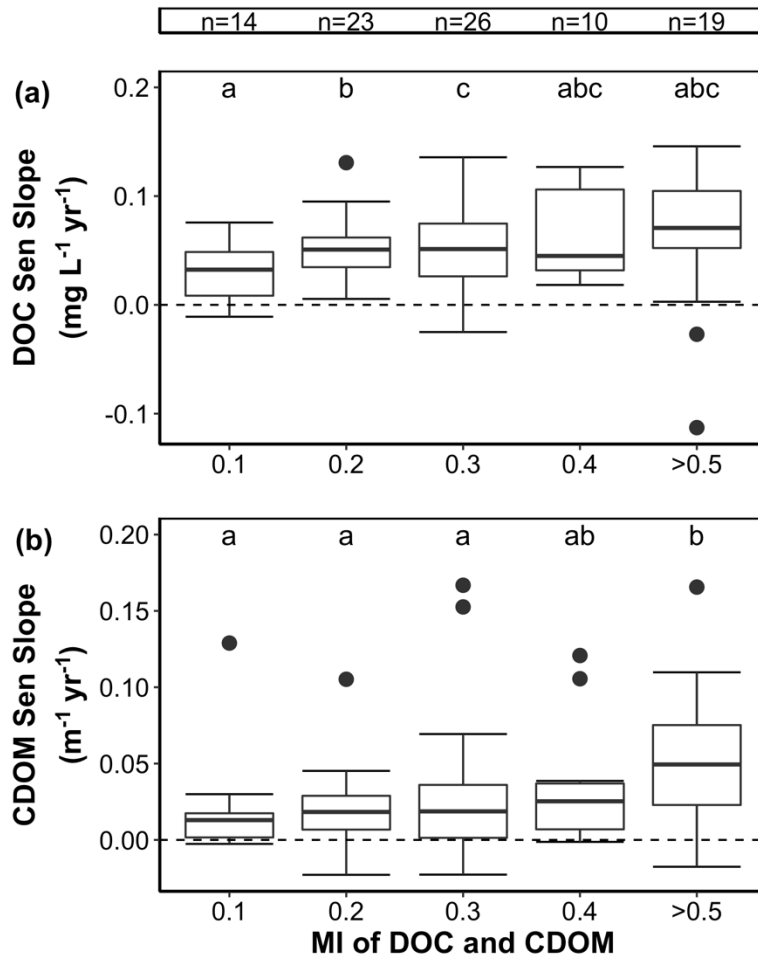


Figure S13. Boxplots of (a) DOC Sen Slope values and (b) CDOM Sen slope values for the grouped mutual information (MI) values between DOC and CDOM time series for each lake. MI group of 0.1 contain lakes with MI values <0.2; the 0.2 group with MI values between 0.2 and 0.3; the 0.3 group values between 0.3 and 0.4; the 0.4 group values between 0.4 and 0.5; and the >0.5 are lakes MI values greater or equal to 0.5, $p=0.02$. Lowercase letters denote statistically significant differences ($\alpha=0.05$) across MI groups; DOC Sen slope p -value=0.05, CDOM Sen slope p -value=0.04. The n values are the number of lakes in each MI bin. Dashed horizontal lines marks 0 to facilitate differentiation between positive and negative values.

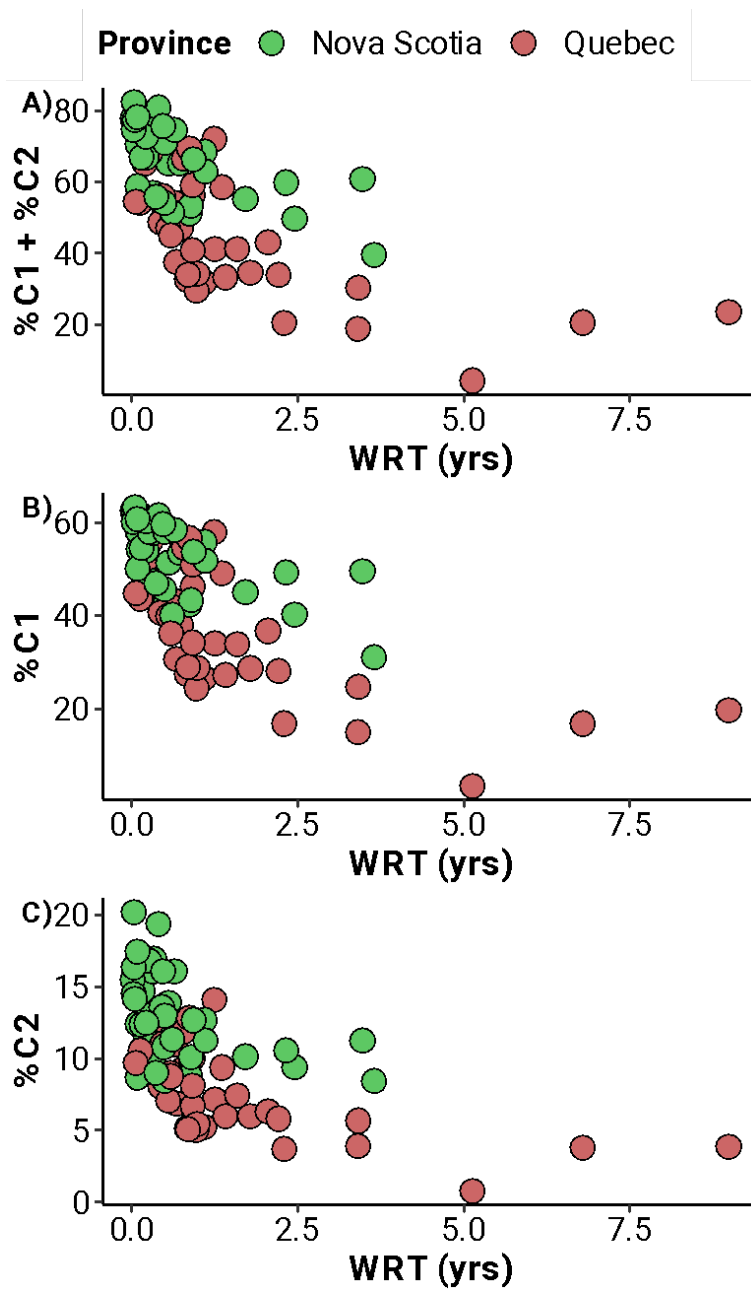


Figure S14. Water retention time (WRT) values for lakes in Nova Scotia (green) and Québec (red) related to **A)** the sum of percent C1 of C2, **B)** percent of C1, and **C)** percent of C2.

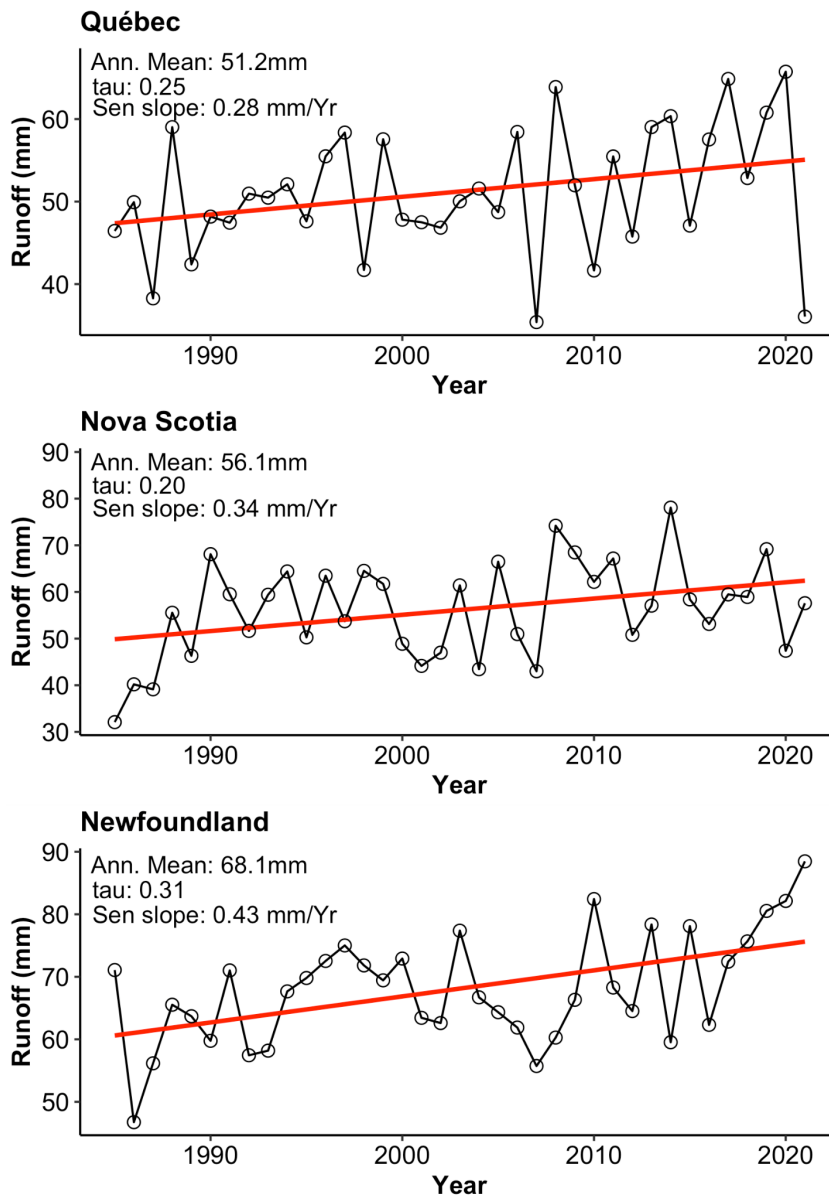


Figure S15. Annual surface runoff values obtained from the ERA5 model with an annual mean value, tau, and Sen slope value for each region. Red line describes the general trend over years.