From Drought to Deluge: Implications of variable hydrologic connectivity on lake ecosystem functions in the Boreal Plains of Western Canada

By

Emily Audrey Pugh

A thesis submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

In

Ecology

Department of Biological Sciences
University of Alberta

Abstract

Presence and functions of lakes are dependent on hydrological connectivity to the terrestrial landscape. Inter-annual wet-dry periods, and their amplification through climate change, can influence hydrological connectivity and affect the delivery of water and solutes from various terrestrial sources. Altered hydrological connectivity and delivery of water to lakes influences lake water residence times and the role of within-lake processes, but can also influence the risk of a lake to contract and even completely disappear. This thesis examined the influence of inter-annual wet-dry periods and subsequent hydrologic connectivity on different ecosystem functions of 34 lakes on the Boreal Plains in Western Canada. In Chapters 2 and 3, I focused on the influence of inter-annual wet-dry periods on hydrological connectivity of terrestrial sources and subsequently the concentration and chemical composition of lake dissolved organic carbon (DOC), a key water quality parameter that influences lake ecosystem functioning. In Chapter 4, I focused on how lake extent and water level responded to inter-annual wet-dry periods and show how lakes can have different combinations of resistance and resilience to dry periods, whilst identifying watershed and lake attributes which can increase lake susceptibility to terrestrialisation.

In Chapter 2, I found large spatial variability of lake DOC concentrations and aromaticity (as indicated by specific UV absorbance at 254 nm – $SUVA_{254}$) that was closely linked to surficial geology and thus wetland connectivity in the watershed. The aromaticity of DOC was further influenced by lake water residence time and the extent of within-lake processing of aromatic DOC via photodegradation. Large inter-annual variability in lake DOC characteristics (concentration and composition) was attributed to interactions between surficial geology and sub-humid climate. Inter-annual variability in DOC concentration had low synchronicity among lakes, with patterns of variability linked to surficial geology and short-term precipitation shifting connectivity of

terrestrial DOC sources. However, inter-annual variability in DOC composition had high synchronicity among lakes, where lake water residence time related to longer-term precipitation, and the extent of within-lake DOC degradation. This study shows that lake DOC characteristics vary spatially, but many lakes on the Boreal Plains are also highly sensitive to inter-annual wet-dry periods.

In Chapter 3, end-member mixing model analysis showed that lake DOC characteristics did not conform to conservative mixing of terrestrial sources, with lower observed DOC concentrations and A_{254} than modelled, suggesting net DOC and A_{254} losses in terrestrial end-members along the soil-stream-lake continuum. Losses were associated with lakes in coarse and fine hummocky watersheds. However, we found that in fine hummocky lakes with large proportions of connected wetland and fine plains watersheds, observed DOC concentrations exceeded modelled, suggesting autochthonous production of DOC. On an inter-annual basis, losses in A_{254} were greater during dry years, when lake water residence times are longer and within-lake photodegradation processes enhanced. This study highlights that the DOC pool of Boreal Plains lakes reflects mixing of water from terrestrial sources, but also processes of within-lake degradation of DOC which may be influenced by inter-annual wet-dry periods, and in lakes with high nutrients and productivity, autochthonous production of DOC.

In Chapter 4, I found large spatial variability in lake extent responses to dry periods, with many lakes exhibiting transient or long-term reduction in lake area. Lakes located in higher landscape positions and those with a lower proportion of connected wetland area in the watershed showed quicker responses to dry periods (i.e. shorter lag times), thus lake extent contracted relatively quickly. Resistance and resilience of lake extent to dry periods, i.e. the ability to withstand change and to return to pre-dry period extents, were highest for lakes with greater wetland connectivity and for lakes with straight-sided basin morphology. This study suggests that isolated lakes, with lower proportions of connected wetland in the watershed and lake beds that slope towards the lake centre with shallower depths of loose sediment are most susceptible to long-term terrestrialisation processes.

Overall, in this thesis, I analyzed both spatial and inter-annual variability of lake ecosystem functions at a landscape scale across the Boreal Plains, my results identified watershed and lake attributes (HRA, wetland connectivity, lake water residence time, lake basin morphology) which can be used to predict lakes on the Boreal Plains where the most rapid changes in lake function can be expected.

Preface

Truly collaborative science is essential to deepening our understanding of the natural world, and the continuation of scientific revolutions. Each chapter in this thesis reflects collaborative science efforts involving numerous colleagues, including those listed below, and resulting in manuscripts in review, or in preparation for submission to peer-reviewed journals outlined below. For all chapters, E.P., K.D. and D.O. designed the studies and formulated the conceptual understanding for each study with assistance and inputs from co-authors. E.P conducted field work and collected precipitation, water level and chemistry data over four years, including monthly winter fieldwork and more intensive summer field programs with weekly field work. The fieldwork conducted by E.P. contributed to a comprehensive existing long-term dataset developed by K.D. and previous members of the Devito Lab Group. E.P. also led data analysis and manuscript composition, whilst all supervisors and co-authors contributed to manuscript edits and contributed to conceptual model developments.

Chapter 2: Pugh, E.A., Olefeldt, D., Leader, S. N., Hokanson, K. J., & Devito, K. J. Characteristics of Dissolved Organic Carbon in Boreal Lakes: High spatial and inter-annual variability controlled by landscape attributes and wet-dry periods. In revision for *Water Resources Research*.

Chapter 3: Pugh, E.A., Devito, K. J., Orlova. J., & Olefeldt, D. Terrestrial sources versus within-lake processes: Controls on dissolved organic carbon quantity and quality in Boreal Plains lakes of Western Canada. In preparation for submission to *Hydrologic Processes*.

Chapter 4: Pugh, E.A, Olefeldt, D., Hehr, B. S., Leader, S. N., & Devito, K. J. Persistence of shallow lakes on the Boreal Plains: resistance and resilience to climate variability linked to lake and watershed attributes. In preparation for submission to *Ecohydrology*.

Acknowledgements

No one achieves anything alone.

Firstly, I would like to acknowledge that this research was conducted on Treaty No. 8 and No. 6 territory - the ancestral and traditional territory of the Cree, Dene, as well as the Métis, who have lived in and cared for these lands for generations.

I would like to thank the funding sources that made this research possible; a Collaborative Research and Development NSERC Grant with industry partners Syncrude Canada and Canadian Natural Resources received by my supervisor, Dr. Kevin Devito, and forWater, a pan-Canadian strategic research network awarded to both my supervisors (Dr. Kevin Devito and Dr. David Olefeldt) and numerous other partners. Funding support from UAlberta North and the Department of Biological Sciences also helped to make this work possible and allowed me to participate in conferences to communicate this research.

Thank you to my supervisors, Dr. Kevin Devito and Dr. David Olefeldt, for support and guidance throughout my graduate program. Working with both Kevin and David has transformed my perceptions and thinking of science and research to develop a holistic understanding of boreal systems, for which I will always be grateful. I would also like to thank Dr. Rolf Vinebrooke as part of my supervisory committee for sharing his time, and expertise on lake ecosystems, and offering new perspectives through a different lens on this research.

I cannot emphasise enough my thanks to my support network throughout this Ph.D. process. I thank members of the Devito and CAWS labs for their support, friendship, and encouragement over the last five years and have made life-long friendships in this time. Thank you Dr. Carolyn Gibson, Dr McKenzie Kuhn, Dr. Lorna Harris, Dr Liam Heffernan, soon to be Drs

Lauren Thompson, Becca Frei, Chris Schulze, Julia Orlova, Kelly Hokanson and Sam Leader for all the science conversations, feedback, and numerous coffee/tea breaks. I offer a huge thank you to the wonderful research assistants that truly made memorable field seasons. Thank you to Brooke Hehr, Erik Peterson, Megan Schmidt, Garret Malishewski, Jessica Ritz, Jayce Edie, and Brittany Hynes for all your assistance and for jumping into Alberta lakes for me. I also wish to thank previous Devito lab group members for many years of data collection that I was able to use in this research.

To my immediate family, Malcolm, Janice and Jamie, and extended family, Kath, Bob, Liz and Vic - thank you for all your encouragement and confidence boosts for any endeavors I have taken on. This has by far been the biggest and most difficult one yet, but your unwavering support to enable my dreams to become a reality have made this possible. Most importantly, to David Thomas, thank you for being my motivation and for being my person on the emotional rollercoaster that is a PhD. I truly could not have done this without you. Words do not do justice for how grateful I am for all your love, support, and belief in me and my choices. Even though he cannot read, I also want to thank my fat little Labrador, Twm, who without realising has brightened many days through his goofy smiles and demands for cuddles when I am desperately trying to write.

Now - dod yn ôl at fy nghoed.

Table of Contents

List of Tables

List of Figures

List of Appendices

1.0 General Introduction

1.1 Background

Hydrologic connectivity of lakes to their watersheds influences the amount and chemistry of inflowing water (Algesten et al., 2004; Gibson et al., 2015; Kothawala et al., 2014; Sepp et al., 2019; Tranvik & Jansson, 2002), and thus controls many key ecosystem functions. For boreal lakes, the concentration and chemical composition of dissolved organic carbon (DOC) is of particular importance for landscape carbon cycling and greenhouse gas exchange, (Algesten et al., 2004; Battin et al., 2009; Cole et al., 2007), nutrient cycling and lake productivity (Daggett et al., 2015; Peltomaa et al., 2013), habitat provision (Karlsson et al., 2009; Solomon et al., 2015; Williamson et al., 2015) and water provisioning for human use (Emelko et al., 2011). Inter-annual wet-dry periods, amplified by climate change, will interact with watershed and lake attributes (i.e. surficial geology and peatland / forest landcovers) to alter hydrologic connectivity in a watershed and thus determine the timing, magnitude and source of water entering boreal lakes (de Wit et al., 2018; Houle et al., 2020). Altered hydrological connectivity and delivery of water to lakes further influences lake water residence times, and thus the role of within-lake processes for the degradation of DOC (Curtis & Schindler, 1997; Ejarque et al., 2018; Evans et al., 2017), but can also ultimately influence the risk of a lake to contract, infill with flocculated DOC, and even completely disappear (Ferland et al., 2014; Ireland & Booth, 2011; Ireland et al., 2012). Understanding how hydrologic connectivity influences boreal lake DOC characteristics (concentration and chemical composition) and presence of lakes through space and time is critical to forecasting potential impacts to lake ecosystem services, especially under a changing climate.

The objective of this thesis is to **develop a conceptual understanding of how the spatial and inter-annual variability (year-to-year) in hydrologic connectivity across watersheds**

influences a) lake DOC characteristics and b) lake extent and persistence in the Canadian Boreal Plains ecozone. Lakes are prevalent on the Boreal Plains and often large, but with average depths less than 2 m which makes them difficult to define due to their shallow nature and typical cycles of terrestrial and open-water phases. Throughout this thesis we refer to Boreal Plains shallow open water wetlands as lakes with characteristics that are typical of the Boreal Plains. The Boreal Plains contrasts, in terms of climate and surficial geology, to other regions where significant work on boreal lake DOC characteristics (Couture et al., 2012; Kothawala et al., 2014; Mattson et al. 2005; Schindler et al 1997; Zhang et al 2010) and persistence of lake extent (Ireland et al., 2012; Riordan et al., 2006; Roach et al., 2011; Yoshikawa & Hinzman, 2003) has been undertaken. Therefore, if we are to predict the implications of a changing climate on boreal lake ecosystem functions relating to DOC and lake presence, we must understand what drives variability across interacting spatial and temporal scales, and acknowledge that vast differences in characteristics of boreal regions mean we should expect differences in lake ecosystem responses across these regions. This thesis will illustrate broader impacts of how lake ecosystem functions respond to climate differently under different climate, hydrologic, geomorphic and geologic conditions which can be applied and tested in other regions.

1.1.1 The Boreal Plains of Western Canada; A hydrologic perspective

The Northern Boreal region encompasses many ecozones with distinct characteristics, including differences in climate, moisture availability, bedrock geology, surficial geology, relief, and relative prevalence of peatlands (Geological Survey of Canada, 1995; 2014). All of these regional aspects have the potential to influence the hydrological and biogeochemical linkages between terrestrial and aquatic ecosystems, and thus the chemistry of water entering boreal lakes and the quantity of water the landscape conveys via different flow paths. The Boreal Plains ecozone covers large parts of Western Canada (Canadian Council on Ecological Areas, 2014), with characteristics that are distinct from more humid regions with topographically driven headwater catchments, where precipitation-runoff responses are well-correlated and allow for predictable lake biogeochemical and hydrologic (lake extent and water level) responses (Jencso & McGlynn, 2011; McNamara et al., 2011; Nippgen, McGlynn, Marshall, & Emanuel, 2011). In contrast, the Boreal Plains has sedimentary bedrock overlain by thick heterogeneous surficial geologies and a sub-humid climate where precipitation and potential evapotranspiration are the dominant components of the water balance (Ferone & Devito, 2004; Smerdon et al., 2005). In the Boreal Plains, the majority of annual precipitation (65 – 75%) arrives during the growing season from May to September, when evapotranspiration is also highest (Devito et al., 2012). During the non-growing season, approximately 30% of annual precipitation is received as snow and is also an important source of water for the landscape (Devito et al., 2012). Together, surficial geology, mosaic of landcovers, and sub-humid climate cause complex groundwater-surface water interactions to potentially reveal unexpected features of biogeochemical and hydrologic lake responses (Figure 1.1; Devito et al. 2012, 2017; Hokanson et al., 2019; Ireson et al. 2015; Winter 2001).

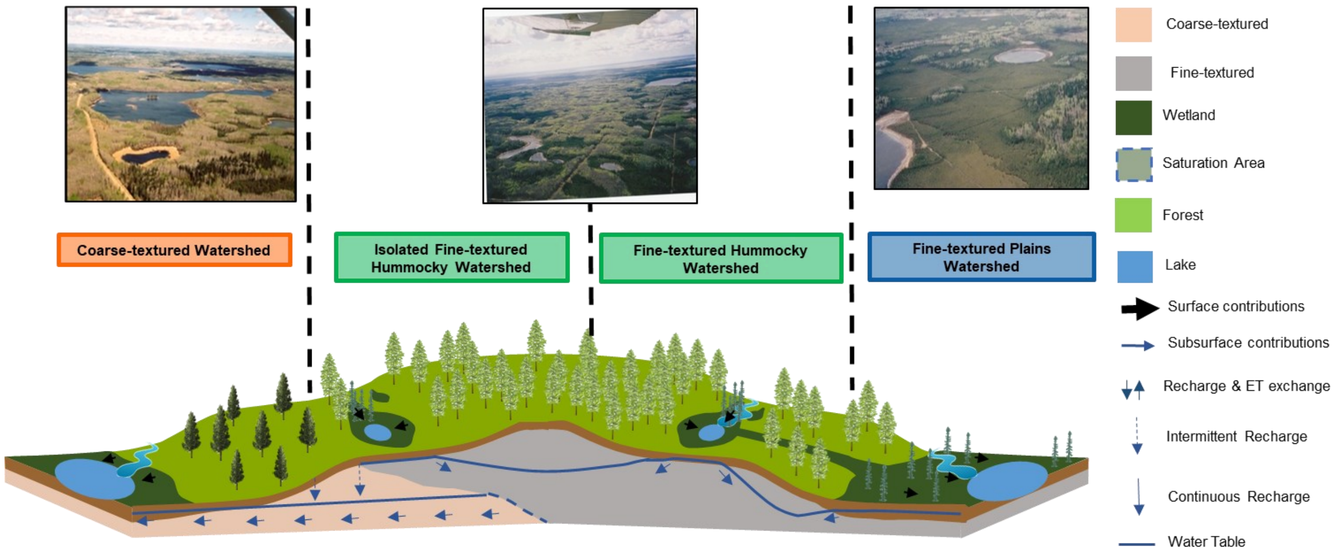


Figure 1.1: Conceptual Model of hydrologic flow paths across the Boreal Plains of Western Canada. Dark green areas represent peatlands whilst light green areas represent the forest, where aspen and pine trees are located in fine and coarse-textured HRAs, respectively. Blue and black arrows indicate subsurface and surface flow paths, respectively. The conceptual model presents a synthesis of significant work undertaken across the Boreal Plains in earlier studies and has been used to understand how variability in hydrologic connectivity at spatial and inter-annual scales influences lake DOC characteristics and the persistence of lake extent.

Three dominant landforms comprise the surficial geology across the Boreal Plains and form distinct hydrologic response areas (HRAs), differing in water storage capacity and transmissivity, and influencing the relative contribution of water to lakes from various flow paths (Figure 1.1; Devito et al., 2005; Hokanson et al., 2019; Olefeldt et al., 2013; Plach et al., 2016; Smerdon et al., 2008; Winter et al., 2001). These include fine-textured hummocky (FH), fine-textured plains (FP), and coarse-textured (CO) HRAs (Hokanson et al., 2019). Lakes in fine-textured settings are dominated by near-surface flow paths, with limited deeper subsurface inputs (Figure 1.1; Ireson et al., 2015; Winter, 2001). Lakes in coarse-textured settings receive relatively larger contributions from deep subsurface inputs than fine-textured lakes due to greater transmissivity (Ireson et al. 2015; Winter, 2001), with the exception of lakes in higher landscape positions underlain by local fine-textured lenses which limit inflows to short near-surface flow paths (Figure 1.1). As such, lakes in coarse-textured HRA at higher elevations behave similarly as lakes in fine hummocky HRA, and we group them as such (Figure 1.1; Hokanson et al. 2019).

The surficial geology is overlain by varying proportions of landcovers, including lakes, peatlands and forests. Peatlands are important sources of water to Boreal Plains lakes, as low water storage thresholds and low evapotranspiration cause shallow water tables, and relatively high runoff generation. Lakes receiving water from peatlands thus often have shorter water residence times than lakes with forested watersheds (Figure 1.1; Devito et al., 2005, 2017; Plach et al., 2016; Thompson et al., 2015, 2017; Waddington et al., 2015). The hydrologic function of forests depends on substrate texture (Bridge & Johnson, 2000; Devito et al., 2017; van der Velde et al., 2013). Forests in coarse-textured HRAs function as high recharge, consistent long-term sub-surface water sources (Ireson et al., 2015; Smerdon et al., 2008), whilst forests in fine-textured HRAs have large storage thresholds, requiring a series of extended wet periods to overcome their threshold storage and function as a water source to lakes (Figure 1.1; Holecek, 1988; Redding & Devito, 2008, 2010, 2011; Spence, 2010). Differences in water storage thresholds between peatlands and forests interact with inter-annual wet-dry precipitation periods to create variability in hydrologic connectivity and contributions of water peatlands and forests to lakes (Devito et al., 2017).

Lakes on the Boreal Plains are expected to experience both more frequent and extreme inter-annual wet-dry periods with potential effects to lake DOC characteristics and lake extent, potentially threatening a lake's existence (Cobbaert et al. 2015; Devito et al., 2005, 2012; Sass and Creed, 2008; Thompson et al., 2017). However, there are currently limited long-term studies that integrate dynamically changing hydrologic connectivity of watersheds with both spatial and inter-annual variability of lake DOC characteristics or lake extent. This research aims to understand the interactions between spatial and inter-annual controls on hydrologic connectivity and the consequences for lake DOC characteristics and lake extent, which is critical to understanding the implications to lake functions from climate change and shifts in inter-annual wet-dry periods.

1.1.2 Dissolved organic carbon (DOC) in lakes

The concentration of DOC, typically defined as organic carbon able to pass through a 0.45 μm filter (Aitkenhead-Peterson *et al.*, 2001), and its chemical composition, influence lake ecosystem functions, including; food-web dynamics, habitat provision (Karlsson et al., 2009; Solomon et al., 2015; Williamson et al., 2015), and importantly processing of DOC determines the source-sink function of lakes in the global carbon cycle (Cole et al., 2007; de Wit et al., 2018; Tranvik et al., 2009). DOC is also a major concern for drinking water treatment processes aimed at protecting public health (Health Canada, 2019). Specifically, aromatic-rich DOC, typically sourced from humified allochthonous organic matter, can cause operational issues and cause consumer complaints (Health Canada, 2019).

The aromaticity of DOC has been identified as a key measure of DOC chemical composition and can be used to both differentiate between various DOC sources (Aitkenhead-Peterson et al., 2003; Peuravuori & Pihlaja, 2007; Thurman, 1985), and be a strong indicator of DOC reactivity (Weishaar et al., 2003). High aromaticity is associated with DOC derived from humified allochthonous organic matter, such as that from organic-rich peatlands (Aitkenhead-Peterson et al., 2003; Thurman, 1985). Lower aromaticity is associated with DOC from fresh plant material, including aquatic autochthonous production, and with DOC derived from mineral soils where aromatic DOC has been preferentially adsorbed (Aitkenhead-Peterson et al., 2003; Kalbitz et al., 2003; Thurman, 1985; Wickland et al., 2007). However, autochthonous DOC is readily available for bacterial use (Kirchman et al. 1991; Søndergaard et al. 1995), whilst DOC from mineral soils usually is relatively refractory and poorly available for microbes (Aitkenhead-Peterson et al., 2003; Olefeldt et al., 2013).

Boreal lakes are hydrologically connected to their surrounding terrestrial environment, and often dominated by allochthonous DOC from the watershed (Aitkenhead-Peterson et al., 2003; Kolka et al., 2008). However, boreal lakes also act as biogeochemical reactors for the transformation and removal of DOC, where large proportions of the DOC pool are degraded via within-lake processes (Aitkenhead-Peterson et al., 2003; Algesten et al., 2004; Bertilsson and Jones, 2002; Tranvik et al., 2009). Biodegradation and photodegradation processes selectively act on specific DOC moieties, often leading to reduced aromaticity as one moves downstream in the terrestrial aquatic continuum (Tranvik et al., 1999). Water residence time has been found to be a strong predictor of DOC aromaticity when comparing between different ecosystems (Curtis & Schindler, 1997; Evans et al., 2017; Kothawala et al., 2014). As such, aromaticity of DOC in lakes is a function of the relative contribution of various allochthonous DOC sources as well as within-lake processes of DOC degradation and production.

While studies have shown shifts in DOC characteristics spatially across the aquatic continuum as related to watershed and lake characteristics (i.e. wetland connectivity and lake water residence times), there is much less knowledge with regard to how inter-annual wet-dry periods affect DOC characteristics over time. In chapter 2, we address this gap using a multi-year study that integrates watershed attributes and inter-annual responses of lake DOC characteristics (i.e., concentration and chemical composition) to inter-annual wet-dry periods to understand the sensitivity of lake functions to shifts in inter-annual wet-dry periods, and thus inform future responses with climate change. Furthermore, understanding the sources and balance of DOC added or removed through space and time is critical to forecasting potential impacts to boreal lake ecosystem services, especially under a changing climate. Yet, there remains a scarcity of studies that integrate our understanding of terrestrial DOC sources to lakes and change in DOC concentration and composition in a landscape context, which can capture the variability at spatial and inter-annual scales (Anas et al., 2015; Hall et al., 2018; Webb et al., 2019). In addition, most studies that examine the processes determining the DOC pool of boreal lakes take place in regions with either high DOC concentrations or high nutrient concentrations and with relatively shorter lake water residence times (Bade et al., 2007; Cole et al., 2000; Hanson et al., 2003; Prairie et al. 2002). However, Boreal Plains lakes are characterised by a sub-humid climate with long lake water residence times anticipated and both high DOC and nutrient concentrations. Thus, the dominance of certain within-lake processes, such as photodegradation and autochthonous production of DOC potentially have a greater influence in Boreal Plains lakes, and other regions with similar characteristics, with implications for the source-sink status amongst boreal lakes. The research in Chapter 3 expands on the results from Chapter 2 to assess the relative importance of various terrestrial sources of DOC to lakes, and different within-lake processes of DOC production and degradation across Boreal Plains lakes in different landscape settings.

1.1.3 Lake persistence from an open water lake extent perspective

Many shallow, small Boreal Plains lakes are gradually, over millennia, filling with flocculated DOC and autotrophic organics (Squires et al., 2006), so-called terrestrialisation. Under a warming climate, characterised by intensifying inter-annual wet-dry periods (Pachauri et al., 2014), the persistence of boreal lakes in the landscape, and more specifically their open water extent may be disrupted, and potentially irreversible ecosystem state shifts from aquatic to terrestrial systems via accelerated terrestrialisation could occur. Despite the ecological significance of boreal lake ecosystems, the influence of inter-annual wet-dry periods on ecosystem processes and potential triggering of abrupt ecosystem state shifts via terrestrialisation in these systems has received little attention.

Terrestrialisation is the permanent transition from an open water to vegetated wetland ecosystem (Kratz & DeWitt 1986; Mitsch & Gosselink, 2015). It is generally assumed that autogenic processes are the dominant drivers of terrestrialisation through sediment infilling promoting shallow basins for the colonization of vegetation (Kratz & DeWitt, 1986; Mitsch et al., 2009); however, studies have highlighted that climate associated water table fluctuations affect terrestrialisation rates and thus allogenic factors may be a more important driver. An allogenic model of floating mat initiation and episodic shoreline expansion proposed by Ireland et al. (2012) suggests that susceptibility of kettle-hole lakes to terrestrialisation is driven by temporal hydro-climatic variability (i.e., inter-annual wet-dry periods) and interactions with substrate type of the lake bed (i.e., firm and loose substrate), in addition to basin morphology (i.e. straight deeper lakes versus shallower sloping lakes). In this model, during dry periods, when terrestrial-aquatic linkages shut down, water level is lowered exposing lake sediments to colonization by vegetation. The exposure of the lake bed varies with lake basin morphology, where although the water level may be very dynamic, straight sided basins result in little exposure of the lake bed, whilst sloping sided basins expose more of the lake bed (Ireland et al., 2012). Upon rewetting, loosely rooted mats of vegetation are able to detach from loosely consolidated lake sediments (loose substrate) and float, creating a hydrologically stable substrate for further colonization of vegetation and peat accumulation from which the lake is unlikely to recover and a permanent loss in open water lake extent occurs (Ireland et al., 2012; Warner et al., 1989). However, if the newly colonized vegetation mats are attached to consolidated lake sediments (firm substrate), water levels will rise and flood vegetation mats, preventing floating mat initiation and allowing lakes to recover to pre-dry period states (Figure 4.4.1). Boreal Plains lakes likely operate within both frameworks for terrestrialisation, through autogenic infilling of lakes in combination with hydro-climatic influences on open water lake extent.

In Chapter 4, a conceptual model of lake and watershed attributes affecting the resistance and resilience of lakes to dry periods of varying severities was developed for the Boreal Plains to support robust assessments of lakes that will be most vulnerable to climate change with implications for both carbon cycling and the ecology of lake ecosystems.

1.2 Research objectives

Broadly, this research aims to understand how hydrologic connectivity to the watershed, during both dry and wet periods, influences ecosystem functions of lakes in different landscape settings. To address this overall research aim, a landscape-scale approach was used involving synoptic assessments of 34 study lakes and their watersheds in the Boreal Plains from 2012 to 2019, ranging in their individual lake and landscape attributes. This work was done in the Utikuma Region Study Area (URSA; AB), located in the Boreal Plains ecozone. The final data chapter (Chapter 4) used a longer-term dataset (1999 – 2019) of lake water levels and incorporated remotely sensed data from the Global Surface Water Explorer. Each chapter includes the development of a conceptual framework identifying key lake and landscape attributes influencing hydrologic connectivity of the watershed and thus spatial and inter-annual variability of different Boreal Plains lake ecosystem functions. While the main research findings are presented within separate chapters, they are conceptually linked to ideas of hydrologic connectivity and how this drives spatial and inter-annual variability in lake responses to the same inter-annual wet-dry period. In each chapter (Chp.2 to Chp.4), I use a landscape-scale approach to address three specific objectives through different lenses:

1. **Chapter 2:** Examine how lake and catchment characteristics influence spatial and inter-annual variability of lake DOC concentration and composition on the Boreal Plains.
2. **Chapter 3:** Assess for lakes in different settings whether inter-annual variability in lake DOC concentration and composition is driven by relative shifts in connectivity of terrestrial sources or driven by relative dominance of within-lake processes of DOC production and degradation.
3. **Chapter 4:** Assess how lake extent responds to inter-annual dry periods, with regards to resistance to change, lag times, and resilience, to understand which lake and catchment characteristics that render lakes vulnerable to future climate change.

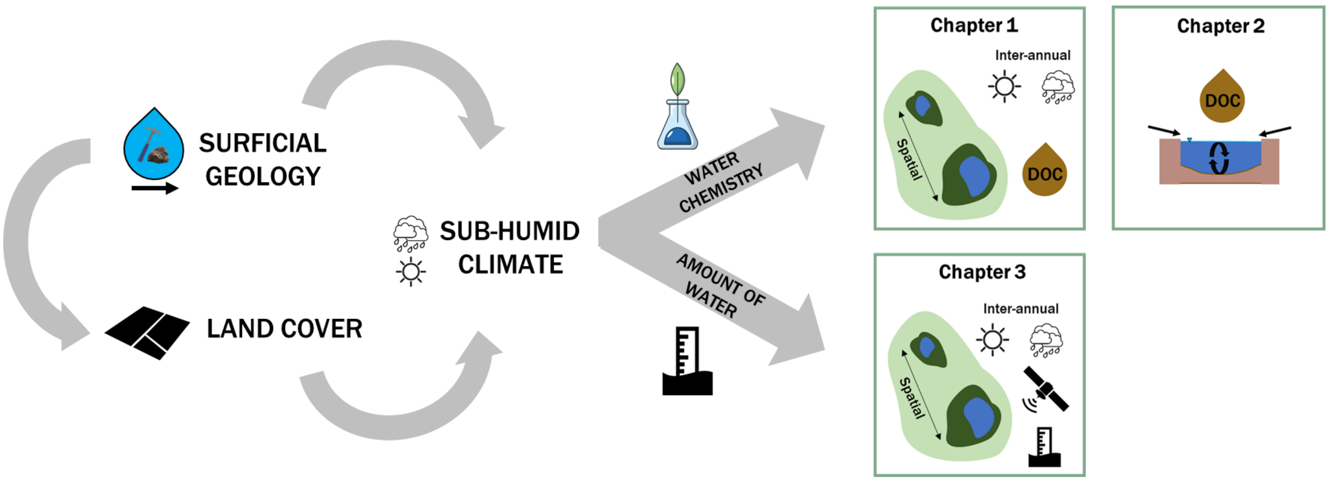


Figure 1.2: Conceptual summary of thesis data chapters. The surficial geology in each watershed is an important determinant of the proportion of wetland and forest landcovers in the watershed. Interactions between surficial geology and different landcovers with the sub-humid climate of the Boreal Plains (where precipitation is often less than or equal to potential evapotranspiration) can result in unexpected water chemistry and amount of water results in lakes due to differences in the timing and extent of hydrologic connectivity across different watersheds, with important ecological and human consequences. To address this problem, this thesis uses a landscape scale approach to assess lake responses (lake Dissolved Organic Carbon characteristics and lake extent) through three different lenses. Chapter 1 examines how lake and watershed attributes influence spatial and inter-annual variability in lake DOC characteristics. Chapter 2 looks at the importance of hydrologic connectivity versus within-lake processes for regulating lake DOC characteristics. And chapter 3 assesses how the lake extent of lakes in different settings responds to dry periods.

Chapter 5 provides a synthesis of the data chapters and offers insights on future research directions and emerging questions to further our understanding of how hydrologic connectivity varying at spatial and inter-annual scales influences lake ecosystem responses in hydrologically complex environments, especially under a changing climate.

2.0 Characteristics of Dissolved Organic Carbon in Boreal Lakes: High spatial and inter-annual variability controlled by landscape attributes and wet-dry periods

Key Points:

- Spatial variability of lake dissolved organic carbon characteristics were driven by dominant flow paths dictated by surficial geology.
- Inter-annual variability of lake dissolved organic carbon concentrations were driven by changing terrestrial sources.
- Aromaticity of lake dissolved organic carbon was highly sensitive to inter-annual wet-dry periods on the Boreal Plains.

Abstract

Concentration and chemical composition of dissolved organic carbon (DOC) influence several lake functions; greenhouse gas exchange, nutrient cycling, food webs and water treatability. To assess spatial and inter-annual controls on DOC characteristics, 34 lakes were sampled annually for eight years on the Boreal Plains, Western Canada – a region with heterogeneous surficial geology, and a sub-humid climate with pronounced inter-annual wet-dry periods. Large spatial variability in long-term average DOC concentration (10 to 49 mg C L^{-1}) and aromaticity ($SUVA_{254}$: 1.2 to 3.9 L mg^{-1} C m^{-1}) among lakes was found. Higher DOC concentrations and aromaticity were associated with lakes in watersheds with fine-textured surficial geology and with relatively large contributions through shallow, organic-rich flow paths. Lake DOC aromaticity was also higher in lakes with lower evaporative enrichment, regardless of surficial geology, indicating shorter lake water residence times and less within-lake degradation of allochthonous DOC. High inter-annual variability for both DOC and aromaticity was also

observed, with coefficients of variation at 10.9 ± 4.6% and 11.1 ± 2.5% among lakes, respectively. Inter-annual variability in DOC concentrations had low synchronicity among lakes, with patterns of variability linked to surficial geology and primarily responsive to short-term (1 month preceding) cumulative precipitation. Conversely, inter-annual variability in aromaticity had high synchronicity among lakes, driven by longer-term (24 month) cumulative precipitation and shifts in lake water residence times. Our study shows that DOC characteristics of many lakes on the Boreal Plains are highly sensitive to inter-annual wet-dry periods, with important implications for future lake functions.

2.1 Introduction

Lakes are an integral component of boreal landscapes, where the concentration and chemical composition of dissolved organic carbon (DOC) play a critical role in boreal lake ecosystem functioning (Algesten et al., 2004; Cole et al., 2007; Emelko et al., 2011; Karlsson et al., 2009; Solomon et al., 2015; Tranvik, 1988; Williamson et al., 2009). Boreal lakes are hydrologically connected to their surrounding terrestrial environment, and therefore often dominated by allochthonous DOC from the watershed (Aitkenhead-Peterson et al., 2003; Kolka et al., 2008); however, boreal lakes also act as biological reactors with substantial degradation and transformation of allochthonous DOC, and production of autochthonous DOC (Aitkenhead-Peterson et al., 2003; Algesten et al., 2004; Bertilsson and Jones, 2002; Tranvik et al., 2009). Watershed attributes, such as land cover (e.g., peatlands and forests), and inter-annual climate patterns have been shown to determine dominant allochthonous DOC sources to lakes and the extent of within-lake DOC processing (Algesten et al., 2004; de Wit et al., 2018; Kothawala et al., 2014; Schindler et al., 1997; Sepp et al., 2019; Sobek et al., 2007; Thurman, 1985; Tranvik & Jansson, 2002). However, there are limited long-term studies that integrate landscape attributes and inter-annual responses of lake DOC characteristics (i.e., concentration and chemical composition) to inter-annual wet-dry periods (Algesten et al., 2004; de Wit et al., 2018; Schindler et al., 1997; Tranvik & Jansson, 2002). Understanding the interactions between spatial and inter-annual controls on boreal lake DOC characteristics is critical to understanding the sensitivity of lakes and lake functions to climate change and shifts in inter-annual wet-dry periods (Ireson et al., 2015). This knowledge can also provide broader understanding of how DOC characteristics in lakes respond to climate differently under different hydrogeomorphological settings.

The aromaticity of DOC has been identified as a key measure of DOC chemical composition (Weishaar et al., 2003). Here, we use Specific Ultra-Violet Absorbance (SUVA), which is strongly correlated with aromaticity of DOC as a metric for DOC composition, or aromaticity (Weishaar et al., 2003). Aromaticity can be used to differentiate DOC sources (Aitkenhead-Peterson et al., 2003; Peuravuori & Pihlaja, 2007; Thurman, 1985), and as a strong indicator of DOC reactivity (Weishaar et al., 2003). High aromaticity is associated with DOC derived from humified allochthonous organic matter (Aitkenhead-Peterson et al., 2003; Thurman, 1985). Lower aromaticity is associated with DOC from fresh plant material, including aquatic autochthonous production, and with DOC derived from mineral soils, from which aromatic DOC is preferentially adsorbed (Aitkenhead-Peterson et al., 2003; Kalbitz et al., 2003; Thurman, 1985; Wickland et al., 2007). Furthermore, aromatic DOC is preferentially photodegraded by ultraviolet (UV) light in aquatic ecosystems, which often increases the bioavailability of DOC for further mineralization (Tranvik et al., 1999). Hence, water residence time has been found to be a strong predictor of DOC aromaticity when comparing lakes in different ecosystems (Curtis & Schindler, 1997; Evans et al., 2017; Kothawala et al., 2014). As such, aromaticity of DOC in lakes is a function of the relative contribution of various allochthonous DOC sources as well as within-lake processes of DOC degradation and production.

The circumpolar boreal biome encompasses many regions with distinct characteristics, including differences in climate, bedrock geology, surficial geology, topographic relief, and relative prevalence of peatlands (Geological Survey of Canada, 1995; 2014). All of these regional aspects have the potential to influence the hydrological and biogeochemical linkages between terrestrial and aquatic ecosystems, and thus lake DOC characteristics. The Boreal Plains ecozone covers large parts of Western Canada (Figure 2.2.1; Canadian Council on Ecological Areas, 2014), and has characteristics that are distinct from boreal shield regions, where a majority of work on boreal lake DOC has been conducted (Couture et al., 2012; Kothawala et al., 2014; Mattson et al. 2005; Schindler et al 1997; Sobek et al., 2007; Vachon et al 2017; Zhang et al 2010). In contrast to shield regions, the Boreal Plains has sedimentary bedrock overlain by thick heterogeneous surficial geologies and a sub-humid climate. Together, these characteristics result in complex groundwater-surface water interactions (Devito et al. 2012, 2017; Hokanson et al., 2019; Ireson et al. 2015; Winter 2001). As such, we should not expect similar sensitivities of lake DOC characteristics to inter-annual wet-dry periods across different boreal regions.

Surficial geology is a key factor influencing the relative contribution of water to lakes from various flow paths in the Boreal Plains (Hokanson et al., 2019; Olefeldt et al., 2013; Plach et al., 2016; Smerdon et al., 2008). Lakes in coarse-textured settings often have important contributions of water received through regional, deep groundwater subsurface flow paths (Ireson et al. 2015; Smerdon et al., 2008; Winter, 2001). Alternatively, lakes in fine-textured surficial geologies are dominated by contributions from near-surface flow paths (Ireson et al., 2015; Winter, 2001), through thick organic soils, representing an important source of aromatic-rich DOC from the terrestrial environment (Olefeldt et al., 2013).

A mosaic of peatlands and forests adds further complexity to contributions of water, and therefore DOC, to lakes from various flow paths in the Boreal Plains (Hokanson et al., 2019, 2020; Ireson et al., 2015). Peatland sources have thick organic soils with high DOC concentrations and aromaticity (Olefeldt et al., 2013). Peatlands also represent important sources of water to lakes, with low actual evapotranspiration rates and low water storage thresholds that promote shallow water tables, increased runoff, and shorter lake water residence times (Devito et al., 2005, 2017; Plach et al., 2016; Thompson et al., 2015, 2017; Waddington et al., 2015). Conversely, the concentration and aromaticity of DOC from forest sources is low (Olefeldt et al., 2013). Forests rarely act as sources of water to Boreal Plains lakes due to higher actual evapotranspiration rates, large water storage thresholds (Hokanson et al., 2020; Ireson et al., 2015; Redding & Devito, 2011), and in the absence of subsurface flow paths, lakes in forest-dominated watersheds would be expected to have longer lake water residence times. These differences in water storage thresholds between peatlands and forests interact with inter-annual wet-dry periods to create variability in hydrologic connectivity and contributions of water from land covers to lakes (Devito et al., 2017). Inter-annual wet-dry periods also interact with the antecedent moisture condition of peatlands and forests to cause land covers to behave independently in runoff generation (Devito et al., 2012, 2017; Spence, 2010). Hence, Boreal Plains lakes undergo frequent wet-dry phases in response to inter-annual wet-dry periods and subsequent hydrologic connectivity of the landscape (Cobbaert et al. 2015; Devito et al., 2005, 2012; Sass and Creed, 2008; Thompson et al., 2017).

Within-lake degradation of DOC is also sensitive to inter-annual wet-dry periods (Evans et al., 2017; Schindler et al., 1992, 1997) and has been shown to be higher in lakes with longer water residence times, often occurring during dry periods (Evans et al., 2017; Kothawala et al., 2014; Schindler et al., 1992, 1997). Thus, within-lake degradation of DOC is expected to be especially prevalent in characteristically shallow Boreal Plains lakes, with long water residence times, when compared to other boreal regions.

The objectives of this study were to: (a) examine spatial and inter-annual variability of the concentration and aromaticity of DOC in Boreal Plains lakes, and (b) assess their sensitivity to inter-annual wet-dry periods. We assessed annual DOC characteristics of 34 shallow lakes over eight years (2012 – 2019), a period that included multiple wet-dry periods. The shallow lakes were in watersheds with landscape attributes spanning fine to coarse-textured surficial geologies, and forest-peatland land cover proportions. We predicted: (a) higher lake DOC concentrations in watersheds with fine-textured surficial geology and high proportions of wetland connectivity; (b) lakes with longer lake water residence time would have lower lake DOC aromaticity due to enhanced within-lake preferential degradation of aromatic-rich allochthonous DOC; and (c) large inter-annual variability of lake DOC concentration and aromaticity, specifically: (c-i) landscape attributes will modify lake DOC concentration responses to wet-dry periods due to the connectivity and magnitude of different flow paths to lakes; and (c-ii) that wet-dry periods will influence DOC aromaticity due to differences in the extent of within-lake preferential degradation of aromatic-rich allochthonous DOC between years. These findings are vital to predicting the implications of changing lake DOC concentrations and aromaticity to lake ecosystem and downstream aquatic systems functioning under a changing climate.

2.2 Materials and Methods

2.2.1 Study Site

The study area extends across a 70 km transect near Utikuma Lake, Alberta, (known as the the Utikuma Region Study Area (URSA)) located in Treaty No. 8 Territory within the Boreal Plains Ecozone of Canada (Figure 2.2.1; Devito et al., 2017; EcoRegions Working Group, 1989). The average annual temperature is 1.2°C (Devito et al., 2016) and the average annual precipitation (P) and annual potential evapotranspiration (PET) are 423 and 519 mm, respectively (Appendices Table A.1.1). As such, the climate is considered sub-humid and has pronounced multi-year wet-dry periods (Figure 2.2.2; Devito et al., 2016; Mwale, 2009).

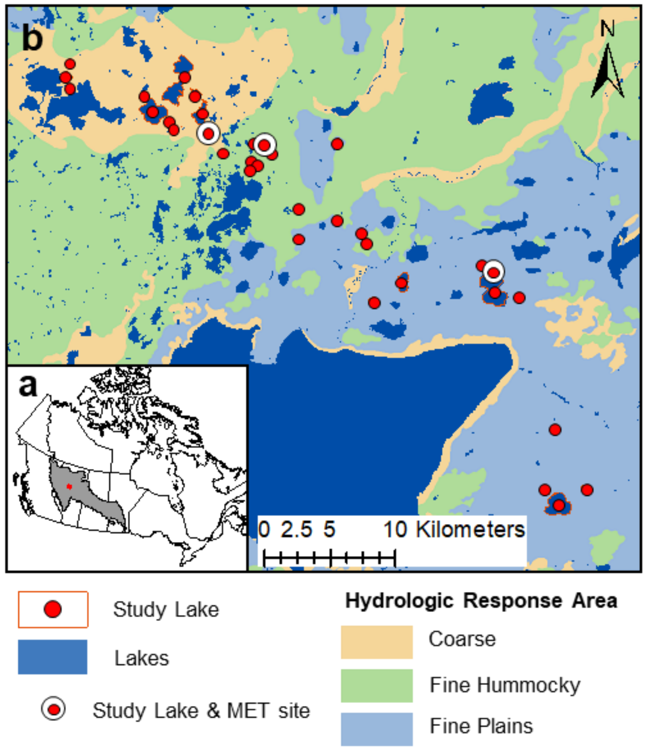


Figure 2.2.1: Map of the individual study lakes representative of Boreal Plains lakes of Western Canada. (a) The location of Utikuma Region Study Area (URSA; red rectangle) within the Boreal Plains ecozone (grey) in Canada; (b) location of the 34 study ponds across distinct hydrologic response areas (HRAs) within URSA. Lake sites (red circle) with a white outline indicate meteorological (MET) sites used for precipitation measurements.

The URSA is characterised by low relief and thick (50 – 200 m) heterogeneous glacial substrates overlying Cretaceous marine shale bedrock (Hokanson et al., 2019). The surficial geology comprises coarse-textured glaciofluvial deposits in the north-west section of the study area and fine-textured glacial till and glaciolacustrine deposits towards the south-east (Fenton et al., 2003). Forests are dominated by trembling aspen (*Populus tremuloides*) and Jack pine (*Pinus banksiana*) in fine-textured and coarse-textured surficial geologies, respectively (Devito et al., 2012). Three hydrologic response areas (HRAs) have been delineated along the study transect at URSA: coarse-textured (CO), fine hummocky (FH), and fine plains (FP; Figure 2.2.1; Hokanson et al., 2019) (Figure 2.2.1), from units mapped in the Alberta Geological Society surficial geology mapping (Fenton et al., 2013). Each HRA represents broad spatial differences in local relief, storage potential, and transmissivity (Devito et al., 2017; Hokanson et al., 2019; Winter, 2001).

The low relief of URSA leads to poor drainage and wetlands are therefore common, with organic-rich peatlands covering up to 50% of the land area (Devito et al., 2016). The peatlands have a sparse canopy of black spruce (*Picea mariana*) and tamarack (*Larix* sp.) with groundcover comprised of peat-forming mosses. The thickness of the peat deposits is up to 5 m. Peatland abundance varies between HRAs, with extensive peatlands on the fine plains and more spatially confined peatlands in the coarse and fine hummocky watersheds (A.1.2).

2.2.2 Inter-annual wet-dry periods

Precipitation data were collected from three locations within 24 km of each other along the URSA transect at open locations from 1998 to 2019. Prior to 1998 (1995 - 1997), long-term daily precipitation data from Fort McMurray (Carrara-Hernandez et al., 2011), a region also characterized by a continental sub-humid climate was used to set the climatic context for this study because precipitation data from more relevant weather stations were not available (i.e., Red Earth Creek). The combined data from 1995 to 2019 was used to set the climatic context for our study period (2012 – 2019; Figure 2.2). Precipitation data along the URSA transect were obtained using shielded tipping bucket rain gauges (adapted for snowfall using antifreeze), which were validated using multiple manual gauges and snow transect surveys. Precipitation data collected from URSA were also compared with, and occasionally gap filled using nearby provincial and federal government weather stations (i.e., Red Earth Creek & Peavine; data provided by Alberta Agriculture and Forestry, Alberta Climate Information Service, 2020). Total annual precipitation (P) was calculated for the period from July 1st to June 30th, i.e., to capture the effects of wet-dry periods on lake DOC concentration and aromaticity prior to our annual sampling campaigns that took place in early July of each year from 2012 to 2019. We used the ratio of long-term average potential evapotranspiration (PET; 519 mm) and average annual P (PET/P) for each annual period (July – June) to determine wet, mesic and dry conditions (Devito et al., 2012, 2016; A.1.1). PET/P categories for wet, mesic and dry years have been established as < 0.9, 0.9 – 1.15 and 1.15 – 1.8, respectively (Devito et al., 2012). Several relatively wet and dry periods were observed during the study period, but did not include extreme drought and flood conditions, which have been observed in preceding decades (Figure 2.2.2). To assess lag-times between inter-annual wet-dry periods and lake DOC concentration and aromaticity of DOC, we used the cumulative precipitation of three different periods preceding the sampling date (A.1.2). The precipitation periods represented (a) short-term monthly precipitation from summer storms (June 1st – 30th), (b) long-term cumulative one year (July 1st – June 30th), and (c) long-term cumulative of the past two years (July 1st – June 30th $^{+yr}$; A.1.2).

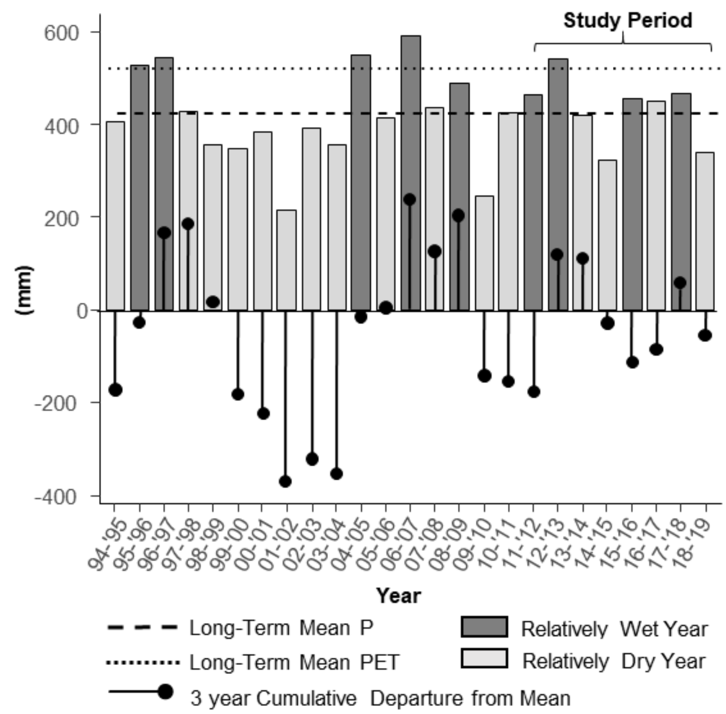


Figure 2.2.2: Annual precipitation data and 3-year cumulative departure from mean precipitation for URSA, before and during the study period (2012 – 2019). Long-term average annual P (423 mm; 1995–2019) and potential evapotranspiration (PET; 519 mm) are shown for context. Annual precipitation data used lake year (July 1st – June 30th) and relatively wet and dry weather pattern years were assigned based on PET:P.

2.2.3 Shallow lake sampling and analysis

Numerous shallow lakes (~ 0.5 – 5 m deep) cover approximately 10% of the study area (Figure 2.2.1; Olefeldt et al., 2013). The lakes in the study area are poorly stratified and naturally mesotrophic to hypereutrophic (Bayley et al., 2007; Nurnberg & Shaw, 1999; Plach et al., 2016). We conducted synoptic sampling of 34 shallow lakes annually from 2012 to 2019, with sampling always between June 30th and July 15th. Surface water samples were collected from the lake shore, or when required, from the edge of emergent vegetation using a 3-m sampling pole, at a depth of approximately 30 cm to ensure each sample was representative of the water column at each lake. Electrical Conductivity (EC), temperature and pH were measured in the field directly from each lake with a calibrated temperature/level/conductivity meter (Solinst, Canada) or EC and pH Ultrapens (Myron).

Lakewater samples were collected for analysis of isotope signatures ($^{18}O/^{16}O$ and $^{2}H/H$ ratios), and for characterization of DOC concentration and aromaticity. Water samples for isotope analysis were first filtered through a 1-mm HDPE filter into a 1-L HDPE bottle with no headspace, and then on the same day subsampled and filtered (0.45 µm pore-size PES filter) into 10-ml glass vials without headspace. Water samples for DOC concentration and absorbance (254 nm; A_{254}) analyses were filtered through 0.7-µm glass microfiber filters (Whatman GF/F) into 60-ml pre-washed amber glass bottles. A 4-ml subsample was taken for UV-vis analysis of A_{254} on the same day (see below), followed by acidification of the remaining sample (4 mL of 18% hydrochloric acid). The acidified sample was stored cool (4°C) until DOC analysis (see below).

Lake water DOC concentrations ([DOC]) were measured on a Shimadzu 5000A TOC analyser using the high temperature combustion method at the Biogeochemical Analytical Service Laboratory, University of Alberta (BASL). Samples were purged before injection to remove any dissolved inorganic carbon. A minimum of four calibration levels across 1 – 100 mg-L^{-1} ranges were established using DOC standards and blanks to ensure the instrument was operating correctly. Sample injections were repeated until a minimum of three replicate measurements were reproducible to within ± 2% relative standard deviation.

We measured absorbance spectra of filtered samples from 200 to 600 nm in a 1-cm quartz cuvette at 1 nm intervals using a Varian Cary 100 from 2012 to 2015 and an Ocean Optics UV-Vis spectrophotometer (model FLAME-S-UV-VIS-ES) from 2016 to 2019, with Milli-Q water as a blank. A correction was applied to all A_{254} data to account for the effects of iron on optical properties of DOC (Poulin et al., 2014). Specific Ultra-Violet Absorbance at 254 nm ($SUVA_{254}$, unit: L mg C^{-1} m^{-1}) is an indicator of DOC aromaticity (Weishaar et al., 2003) and was calculated by dividing absorbance at 254 nm (A_{254} unit: cm^{-1}) by the sample [DOC] and multiplying by 100.

Stable O and H isotope ratios in lake water were determined using a Los Gatos isotope analyser (model IWA-45EP) from 2012 to 2013 and a Picarro Cavity Ring-Down Spectroscopy L2130-i isotope analyser from 2014 to 2018 at BASL. Isotope results were expressed as a per mil (‰) difference relative to Vienna Standard Mean Oceanic Water (VSMOW). Isotope results were used to calculate the line-conditioned excess (lc-excess); a measure of the offset of a water sample from the Local Meteoric Water Line (LMWL) in dual-isotope space (Landwehr & Coplen, 2006). The Local Meteoric Water Line (LMWL) equation for the study area was provided by Hokanson (2019) and used to calculate lc-excess using the following equation:

$$\text{lc-excess} = \delta^{2}\text{H} - a \bullet \delta^{18}\text{O} - b$$

where *a* and *b* are the slope (7.25‰) and intercept (-11.25 ‰) of the LMWL, respectively. A negative lc-excess value is indicative of kinetic fractionation by evaporation. The isotopic composition of a lake, although influenced by source water composition, becomes isotopically heavier through kinetic fractionation processes and plots below the LWML (Craig et al., 1963; Figure 2.2.3). Similarly to conceptualizations from Sprenger et al. (2017) and the relationship already established between lc-excess and evaporation, this study assumes that with more negative lc-excess and greater evaporative enrichment lake water residence times will be longer. Therefore, this study uses lc-excess as a relative measure of lake water residence time.

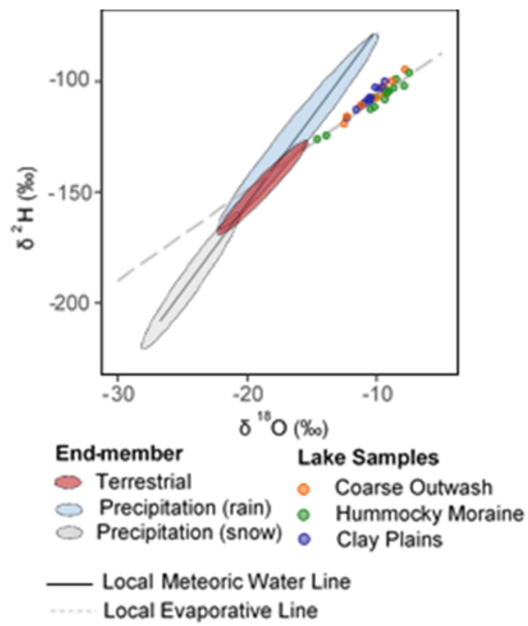


Figure 2.2.3: Isotopic compositions of study lakes and source waters. Dual isotope plot of mean $\delta^{18}O$ and $\delta^{2}H$ for terrestrial water sources (red ellipses) and lake samples (circles) collected annually throughout the study period. The URSA local meteoric waterline (LMWL) (solid line) and URSA local evaporation line (LEL) (dashed line) are shown for context. Blue and grey ellipses regions indicate isotopic signatures of precipitation as rain (n = 93) and snow (n = 25) samples, respectively.

2.2.4 Landscape and lake attributes

2.2.4.1 Watershed landscape attributes

We delineated the watersheds of the 34 lakes on the Boreal Plain assuming a 2-m ridgeline required to overcome watershed boundaries, typically at saddle locations. We used a combination of resources including; Canadian Digital Elevation Models (2-m and 30-m resolution; NRC, 2016) with associated flow models generated in ArcMap (Version 10.6), World Satellite Imagery provided by Esri, historical aerial photography, a landsat-based wetland map of the region (Enhanced Wetland Classification (DUC, 2011)), Lidar data (Montgomery et al., 2019), and our local knowledge of surface flow direction, culvert locations, and beaver activity from ground truthing.

The HRA of each watershed was defined as coarse, fine hummocky, or fine plain according to the dominant HRA type (i.e. 50% of watershed area or greater; A.1.3). However, two lakes located on the coarse HRA were grouped with the fine hummocky HRA. The two lakes are located in headwaters with hummocky morphology and ice-contact glacial-fluvial geology (Fenton et al. 2013), where fine-textured deposits overlay coarse deposits not indicated by the regional mapping (Coarse Outwash perched (CO-P) in Hokanson et al., 2019; Plach et al., 2016).

Connected wetland area as a proportion of the total watershed area (CW_A:C_A) was delineated using a combination of the World Satellite Imagery (Esri), the Enhanced Wetland Classification mapping (DUC, 2011) and Lidar data. Connected wetland area refers to the cumulative wetland area network or diffuse surface drainage that extends continuously from the lake edge through the topographic watershed. To assess effects of disturbance on the dominant source of terrestrial DOC to lakes, we determined the forest harvest area since 2012 (Alberta Biodiversity Monitoring Institute Human Footprint Inventory, 2020), and burn area within connected wetland area (Alberta Wildfire, 2020) following the 2011 wildfire for each lake watershed.

2.2.4.2 Lake attributes

Depth of water was measured at a permanent reference location concomitantly with chemistry sampling, denoted by a stake or staff gauge secured to the deep sediments with known elevation (MASL) at the edge of each lake. A survey of simultaneous water level measures at the permanent reference location and at the center of the lake (assumed maximum depth) undertaken in 2012 were used to estimate the maximum depth of the lake for remaining years (2013 to 2019). Maximum lake depth at the centre was then averaged for 2012 to 2019 for each lake, and a departure from mean water level for each year was determined for each lake.

We determined the relative elevation of each lake within a HRA sub-unit to indicate landscape position of each lake. HRA sub-units subdivide HRAs according to regional subsurface flow-systems, and were identified using the digital elevation models to indicate topographic subsurface flow path boundaries. Within each HRA sub-unit, relative elevation was calculated for each lake using a 30-m resolution digital elevation model. Relative elevation was then calculated as the percentile of the lake elevation compared to the elevations in the HRA-subunit, creating comparable relative elevations within a HRA.

2.2.5 Statistical analyses

We used the long-term (2012-2019) average values of lake [DOC], $SUVA_{254}$, lc-excess, EC, and lake depth to assess spatial variability in lake water chemistry. Inter-annual variability of lake water chemistry was assessed using the standard deviation (SD) of [DOC], $SUVA_{254}$, lc-excess, EC, and lake depth throughout the study period (n = 8 per lake). We also quantified inter-annual variability of lake water chemistry using the coefficient of variance (CV; SD divided by average ×100) of lake water chemistry variables throughout the study period. We used long-term average values to describe spatial variability and SD values to describe inter-annual variability in a one-way analysis of variance (ANOVA) and a Kruskal-Wallis (K-W) on ranks for parametric and non-parametric data, respectively, to test significant differences across HRAs. A Shapiro-Wilks test was conducted on lake water chemistry data (long-term average (spatial) and SD (inter-annual)) to test for normality. For each statistical test, p-values <0.05 (95% confidence interval) were considered significant.

We conducted an analysis of synchronicity for the inter-annual variability of [DOC], $SUVA_{254}$, lc-excess, EC, and lake depth across lakes by examining the correlation of each variable throughout the study period for each of the 34 possible lake pairs (Jane et al., 2017). Synchronicity, an indicator of whether controls on variability of observed DOC characteristics are common or individual, was then determined by averaging the Pearson correlation coefficients for all 34 lake pair correlations (Jane et al., 2017; Kratz et al., 1998; Magnuson et al., 1990; Pace and Cole, 2002) (A.1.4).

A correlation matrix was produced to show relationships between long-term (2012 – 2019) average DOC characteristics, lc-excess, EC, and lake and landscape attributes. This correlation matrix was also used for identifying potential collinearity of lake and landscape attributes and potentially spurious relationships. Linear regression analysis was performed using the function lm in stats v3.6.2 in base R (Chambers, 1992; Wilkinson and Rogers, 1973) to examine the strength of the relationships between DOC characteristics and lake and landscape attributes within each HRA and for the whole set of lakes. The relationships identified in this analysis were used to inform the predictor variables (fixed effects) we used in our generalized mixed effect models (GLMMs). A GLMM was used to test hypotheses regarding the controls of lake and landscape attributes on spatial variability of [DOC] and DOC aromaticity (Table 2.1), using the lmerTest (Kuznetsova et al., 2015) package in R. In both models (DOC concentration and aromaticity), fixed factors included long-term average lake and landscape attributes whilst random factors included lake ID and year, to account for repeat measures and environmental variation unaccounted for in different years.

Table 2.1: Summary of *a priori* lake and landscape attributes hypothesised to affect the DOC characteristics of lakes at URSA, representative of the Boreal Plains.

Metric	Categories / Range	Landscape / Lake Characteristic	Motivation / Apriori Prediction
External Process			
Relative Elevation (within a HRA) (%)	4 - 97 percentile elevation	Surface and Subsurface Connectivity	In coarse-textured HRAs, lakes located at a lower relative elevation receive higher relative subsurface contributions from groundwater, typically depleted of aromatic DOC. In fine-textured HRAs, lakes at lower relative elevations receive high surface contributions from surrounding DOC-rich peatlands.
Hydrologic Response Area (HRA)	Coarse Fine Hummocky Fine Plain	Surface Vs Subsurface Flow path	Fine textured HRAs are dominated by surface flow-paths, typically through DOC-rich peatlands whereas coarse-textured HRAs are dominated by subsurface flow-paths depleted of aromatic DOC.
Connected Wetland to Watershed Area (CW_A:C_A)	0.2 – 0.85	Runoff Area & Terrestrial DOC Sources	Lakes with large CW_A:C_A receive a greater amount of runoff from available DOC sources therefore increasing DOC concentrations and $SUVA_{254}$.
Burned Connected Wetland Area to Watershed Area	0 – 8.5	Wildfire Disturbance	Lakes with a larger proportion of burned wetland in their watershed receive water leached from peatlands containing highly aromatic DOC from char layers, thereby increasing DOC concentrations and $SUVA_{254}$.
Harvest Area to Watershed Area	0 - 1	Harvesting Disturbance	Lakes with a larger proportion of harvest occurrence are able to generate more runoff which leaches the leaf fibric humic layer thereby increasing DOC concentrations and $SUVA_{254}$ of lakes.
Electrical Conductivity (EC)	73 to 450 µS	Mineral Vs Organic Flow-path	Lakes with higher EC typically receive a greater amount water from mineral-dominant flow-paths typically depleted in aromatic DOM, whilst lakes with a lower EC typically receive water from organic-dominant flow-paths enriched with aromatic DOM.
Internal Process			
lc-excess	-3.6 to -50.7 ‰	Water Residence Time	Lakes with a more negative lc-excess are indicative of evaporative fractionation suggesting a longer lake water residence time, enhancing within lake degradation of aromatic DOC.
Lake depth (departure from average depth (DM)) (m)	0.3 – 5.85 m	Water Residence Time	Lakes with a lower than average lake depth are indicative of dry periods suggesting a longer lake water residence time, enhancing within lake degradation of aromatic DOC.

An inter-model comparison was carried out using the Akaike Information Criterion (AIC) to determine the most parsimonious model from a number of potential models that were developed using different combinations of landscape and lake metrics. The AIC for each model was obtained by using the nmle function within R, which calculates the AIC of a model from which a log-likelihood value can be obtained (Sakamoto et al., 1986). We used the 'MuMin' package in R (Barton & Barton, 2015) to obtain marginal and conditional R^2 values for each of our models which reflect the R^2 of fixed effects only and fixed and random effects, respectively. We then subtracted the marginal R^2 from the conditional R^2 to obtain the R^2 of the random effects representing lake ID and year only. The RMSE of each fitted model was also obtained using the qpcR package in R (Spiess & Spiess, 2018). We also ran simple ANOVA's between each model and a null model which included only random effects to further confirm whether our fixed effects played a significant role. For each ANOVA, p-values <0.05 (95% confidence interval) were considered significant.

2.3 Results

2.3.1 Lake and watershed attributes

Of the 34 lakes in this study, 8 were located in the coarse, 14 in the fine hummocky, and 12 in the fine plains (Figure 2.2.1; A.1.3). Lake size varied between 0.05 and 324 ha (A.1.3). Long-term (2012-2019) average lake depths ranged between 0.40 and 5.50 m among lakes, and varied across HRAs with greatest average lake depths in the coarse (2.0 ± 1.0 m, ±1 SD), followed by fine plains (1.8 ± 0.5 m), and fine hummocky (1.5 ± 0.5 m) (S3). Lake watershed areas varied between 8 and 9,500 ha, yielding ratios of lake watershed to lake size between 1.8 and 160 (A.1.3). The percent watershed connected wetland area was highest for fine plains lakes (ranging 47 – 85%), followed by the coarse (22 – 68%), and fine hummocky (16 – 59%; A.1.3). A 2011 wildfire affected seven watersheds in the coarse (12 - 40%; A.1.3), four in the fine hummocky (32 - 54%; A.1.3), and eight in the fine plains (39 - 85%; A.1.3). Harvesting that occurred in 2012 affected two watersheds in the coarse (1%; A.1.3), one in the fine hummocky (8%; A.1.3), and three in the fine plains (0.2 - 100%; A.1.3).

2.3.2 Spatial variability of long-term average lake water chemistry

Long-term (2012-2019) average lake DOC concentration ([DOC]) ranged between 10.3 and 49.4 mg C L^{-1} across the 34 lakes (Figure 2.2.4; A.1.3), and long-term average $SUVA_{254}$ ranged between 1.2 and 3.9 L mg^{-1} C m^{-1} (Figure 2.2.4; A.1.3). The long-term average lake [DOC] and $SUVA_{254}$ varied significantly among HRAs. We found that fine plains lakes had the highest long-term [DOC] at 40.8 ± 6.2 mg C L^{-1}, followed by fine hummocky lakes at 31.4 ± 8.3 mg C L^{-1}, and lowest in coarse lakes 17.1 ± 3.2 mg C L^{-1} (A.1.4). Average long-term $SUVA_{254}$ did not follow the same trend, and was higher in both fine hummocky lakes (2.8 ± 0.47 L mg^{-1} C m^{-1}) and fine plains lakes (2.8 ± 0.49 L mg^{-1} C m^{-1}) compared to the coarse (1.9 ± 0.40 L mg^{-1} C m^{-1}; A.1.4).

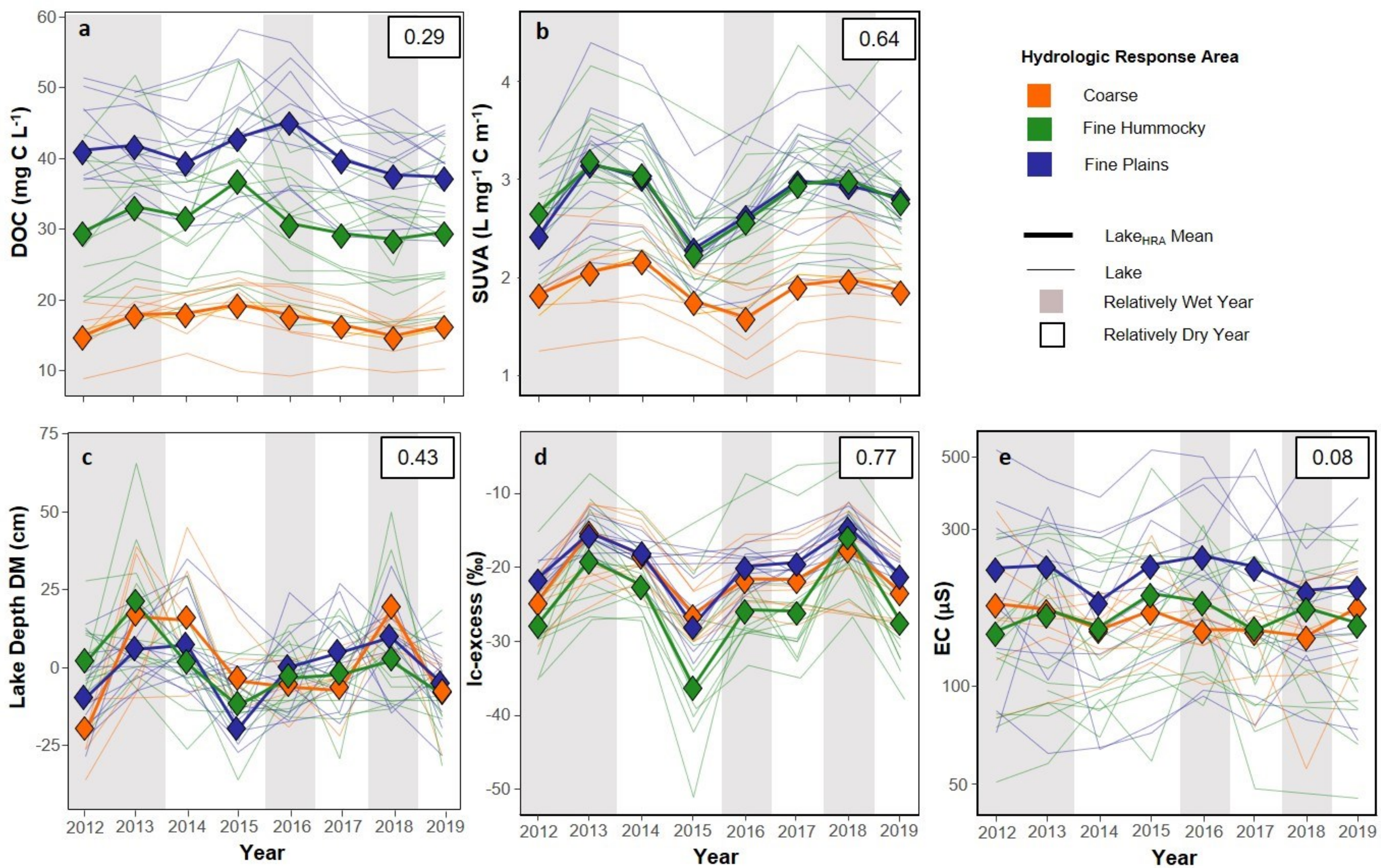

a
0.29
DOC (mg C L-1)
b
0.64
SUVA (L mg-1 C m-1)
Hydrologic Response Area
Coarse
Fine Hummocky
Fine Plains
LakeHRA Mean
Lake
Relatively Wet Year
Relatively Dry Year
c
0.43
Lake Depth DM (cm)
d
0.77
lc-excess (‰)
e
0.08
EC (µS)
Year

Figure 2.2.4: Time-series showing annual measurements of (a) DOC concentration, (b) $SUVA_{254}$, (c) Departure from mean lake depth, (d) lc-excess and (e) EC for 34 shallow lakes at URSA from 2012 – 2019. Thin lines represent annual measurements collected from individual lakes whilst thick lines represent the mean of annual lake measurements within a given Hydrologic Response Area (HRA). Grey and white panels differentiate between relatively wet (PET:P = 0.9 – 1.1) and dry years (PET:P = 1.2 – 1.8) respectively. Average synchronicity of the 34 lake-pair measurements for each variable are presented in the top right corner of each plot.

All lakes had long-term average isotopic signatures that plotted along the local evaporative line in dual-isotope space, whilst long-term average isotopic signatures of terrestrial source waters plotted along the LMWL (Fig. 2.3). Long-term average lake lc-excess were negative for all lakes, and varied from -9.80 to -32.06 ‰ (Figure 2.3 & Figure 2.2.4). Lake lc-excess varied significantly among the HRAs (A.1.4), being least negative in the fine plains (-19.1 ± 1.5‰), followed by the coarse (-21.2 ± 4.2‰), and most negative in the fine hummocky (-24.4 ± 6.4‰). Long-term average lake EC ranged between 74 and 445 µS cm^{-1} (Figure 2.2.4), with no significant differences between HRAs (A.1.4).

2.3.3 Inter-annual variability of lake water chemistry and water level

Lakes showed inter-annual variability in [DOC] and $SUVA_{254}$ (Figure 2.2.4; A.1.4), quantified using the coefficient of variation (CV) to assess how much each lake's DOC concentration or chemical composition varied over time. The CV for inter-annual lake [DOC] was 13.0 ± 5.7% for fine hummocky lakes, 10.9 ± 2.9% for coarse lakes, and 8.6 ± 2.3% for fine plains lakes. We also identified large variability in the CV for [DOC] and $SUVA_{254}$ within HRAs (A.1.4); fine hummocky lakes had the largest coefficient of variation range for [DOC] and $SUVA_{254}$ (DOC: 5.8 – 27.5%; $SUVA_{254}$: 5.9 – 16.1%). The coarse lakes had a larger coefficient of variation for [DOC] than fine plains lakes, however, fine plains lakes had a larger coefficient of variation for

$SUVA_{254}$ than coarse lakes (coarse - DOC: 5.9 – 17.0%; $SUVA_{254}$: 8.3 – 13.5%; fine plains - DOC: 4.9 – 11.6%; $SUVA_{254}$: 8.2 – 16.5%). In relative terms, we found that the DOC concentration and $SUVA_{254}$ of coarse and fine hummocky lakes changed on average by 30% from one year to another, whilst in fine plains lakes although $SUVA_{254}$ also changed by 30%, DOC concentration changed on average by 20% from one year to another. A key difference between [DOC] and $SUVA_{254}$, was that we found relatively low inter-annual synchronicity among lakes for [DOC] (0.29), while synchronicity was relatively high for $SUVA_{254}$ (0.64) (Fig. 2.4; A.1.5).

The SDs for lake depth, lc-excess, and EC throughout the study averaged 0.15 ± 0.05 m, 4.65 ± 2.00‰, and 43.2 ± 26.2 μS cm^{-1}, respectively across all lakes (Fig 2.4). There were no differences in the magnitude of the lake depth variability or in lake EC between HRAs (A.1.4). We did find a significantly greater SD in lake lc-excess for fine hummocky lakes (6.05 ± 2.26‰), than in the fine plains (3.98 ± 0.98‰) and coarse lakes (3.19 ± 0.57‰). Lakes had high synchronicity in lake depth (expressed as a departure from mean lake depth throughout the study) (0.43) and in lake lc-excess (0.77), while there was low synchronicity among lakes in EC (0.08) (Figure 2.2.4; A.1.5).

2.3.4 Controls on the variability of lake DOC and $SUVA_{254}$

We explored potential controls on the spatial variability of lake [DOC] and $SUVA_{254}$ through regression and GLMM analysis (Figure 2.2.5; Table 2.2). The most parsimonious GLMM explained 79% the spatial variability of annual lake [DOC]. In both the GLMM and regression analysis, lakes in fine-textured HRAs had increasing [DOC] with a greater proportion of connected wetland in the watershed (Table 2.2; Figure 2.2.5). However, the opposite was found for lakes in the coarse-textured HRA, where [DOC] decreased with increasing proportions of connected wetland (Table 2.2; Figure 2.2.5). For spatial variability in $SUVA_{254}$, surficial geology (HRA) interactions with EC, and lc-excess explained 75% of the spatial variability (Table 2.2). Lakes with less negative (higher) lc-excess and lower EC were found to have higher $SUVA_{254}$, but lakes in coarse had overall lower $SUVA_{254}$ than fine-textured hummocky and plains lakes (Table 2.2; Figure 2.2.5). None of the five most parsimonious models for explaining spatial variability included proportion of burned connected wetland area or harvest area within the watershed for either lake DOC or $SUVA_{254}$.

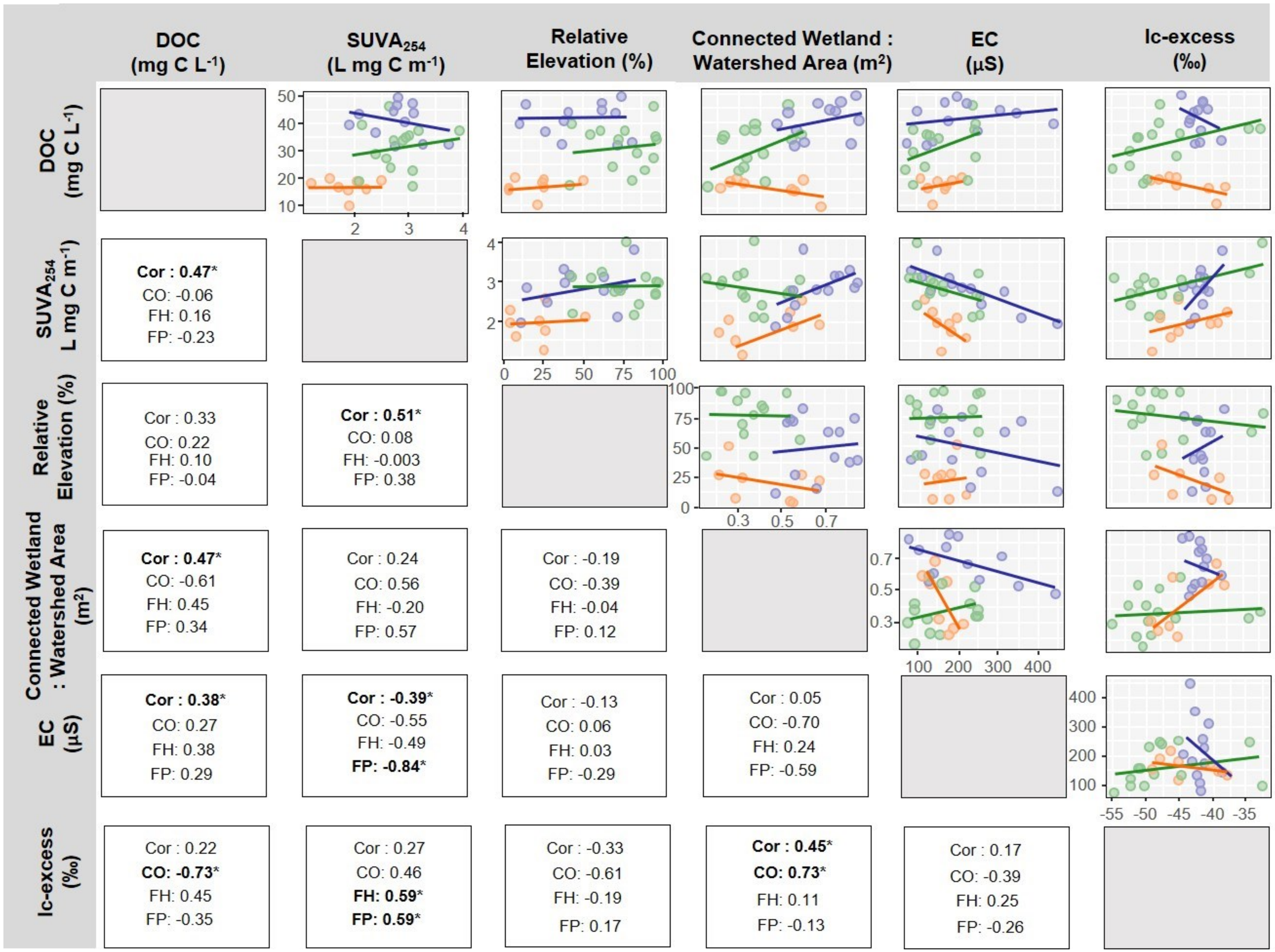

DOC (mg C L-1)
SUVA254 (L mg C m-1)
Relative Elevation (%)
Connected Wetland : Watershed Area (m2)
EC (µS)
lc-excess (‰)
Cor : 0.47*
CO: -0.06
FH: 0.16
FP: -0.23
Cor : 0.33
CO: 0.22
FH: 0.10
FP: -0.04
Cor : 0.51*
CO: 0.08
FH: -0.003
FP: 0.38
Cor : 0.47*
CO: -0.61
FH: 0.45
FP: 0.34
Cor : 0.24
CO: 0.56
FH: -0.20
FP: 0.57
Cor : -0.19
CO: -0.39
FH: -0.04
FP: 0.12
Cor : 0.38*
CO: 0.27
FH: 0.38
FP: 0.29
Cor : -0.39*
CO: -0.55
FH: -0.49
FP: -0.84*
Cor : -0.13
CO: 0.06
FH: 0.03
FP: -0.29
Cor : 0.05
CO: -0.70
FH: 0.24
FP: -0.59
Cor : 0.22
CO: -0.73*
FH: 0.45
FP: -0.35
Cor : 0.27
CO: 0.46
FH: 0.59*
FP: 0.59*
Cor : -0.33
CO: -0.61
FH: -0.19
FP: 0.17
Cor : 0.45*
CO: 0.73*
FH: 0.11
FP: -0.13
Cor : 0.17
CO: -0.39
FH: 0.25
FP: -0.26

Figure 2.2.5: Correlation matrices showing relationships between average DOC characteristics (DOC concentration [DOC] and $SUVA_{254}$) and lake and landscape attributes across URSA lakes. Each point represents annual lake measurements within a given Hydrologic Response Area (Coarse = orange, Fine Hummocky = green, Fine Plains = blue). Lake and landscape attributes include lc-excess, EC, Connected wetland to watershed area (CW_A:C_A) and relative elevation within a HRA. Pearson r values for each regression line are presented in the left hand panels (Cor = overall correlation, CO = Coarse, FH = Fine Hummocky, FP = Fine Plains). * indicate $p < 0.05$.

Table 2.2: Generalised linear mixed effect model results used to test hypotheses for explaining the spatial variability in A [DOC] and B $SUVA_{254}$ observed across URSA lakes.

#	Model Parameters	Intercept	AIC	RMSE	R^2 fixed effects	R^2 random effects	ANOVA
	A: [DOC]						
1	Fine HRA : Connected Wetland (0.83)* + Coarse HRA : Connected Wetland (-0.71)*	3.12	1419.90	0.1	0.79	0.10	4.24E-06*
2	Fine HRA : EC (0.58)* + Coarse HRA : EC (0.26)	2.25	1425.30	0.1	0.75	0.14	6.18E-05*
3	Fine HRA (0.73)* (Coarse HRA (-0.73)*)	2.81	1426.44	0.1	0.71	0.16	5.66E-05*
4	EC (0.59) + lc-excess (0.01)	2.28	1442.70	0.1	0.22	0.52	3.80E-01
5	Burned Connected Wetland Area (0.25) + Harvest (0.36)	3.30	1443.60	0.1	0.13	0.58	6.04E-01
	B: $SUVA_{254}$						
1	Fine HRA : EC (-0.63) + Coarse HRA : EC (-0.82)* + lc-excess (0.02)*	2.78	-43.2	0.07	0.75	0.12	8.20E-06*
2	Fine HRA : EC (-0.54) + Coarse HRA : EC (-0.74)*	2.22	-37.7	0.08	0.68	0.17	8.21E-05*
3	Fine HRA (0.41)* (Coarse HRA (-0.41)*)	0.60	-32.4	0.07	0.57	0.25	7.17E-04*
4	EC (-0.58)* + lc-excess (0.01)	2.52	-23.6	0.08	0.35	0.41	9.61E-02
5	Burned Connected Wetland Area (0.10) + Harvest (-0.2)	0.89	-19.3	0.08	0.05	0.62	8.06E-01

*Note. Model parameters and their representative landscape process are outlined in Table 2.1. A ':' indicates an interaction term in the model. Models are ranked by AIC, from low to high. Root mean standard error (RMSE), R^2 of fixed variables (lake and landscape attributes), R^2 of random variables (Year and Lake ID) and ANOVA results comparing each model to a null model are also provided. *Fixed variables are significant ($p > 0.05$).*

To explore the influence of inter-annual controls on $SUVA_{254}$, annual $SUVA_{254}$ for individual lakes was regressed with lc-excess and lake depth departure from mean (Figure 2.2.6). We found positive relationships between lake $SUVA_{254}$, lake lc-excess, and lake depth departure from mean for all lakes, but lakes in each HRA had its distinct combination (Figure 2.2.6). Lakes in coarse-textured watersheds had lower $SUVA_{254}$ at comparable lc-excess compared to the other HRAs, and also had the weakest relationship between $SUVA_{254}$ and lake depth departure from mean. Lakes in fine hummocky had high $SUVA_{254}$, but also the most negative (lowest) and variable lc-excess. Lakes in fine plains also had high $SUVA_{254}$, but at the least negative (highest) values of lc-excess.

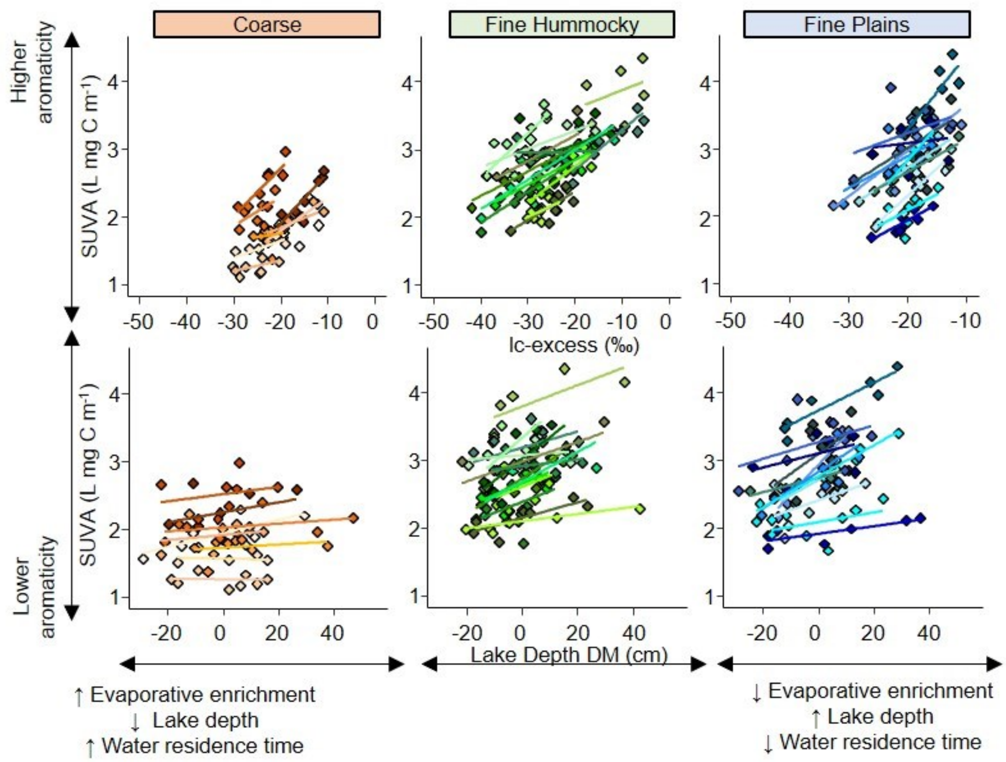


Figure 2.2.6: Relationships between $SUVA_{254}$ and lc-excess (top row) and $SUVA_{254}$ and departure from mean lake depth (Lake Depth DM; bottom row) across individual URSA lakes grouped by Hydrologic Response Area (HRA). Different shades of colour represent the individual lakes with each HRA.

2.3.5 Response of lake DOC characteristics to wet-dry periods

The response of lake DOC characteristics within each HRA to relative wet and dry periods of different length and severity is shown in Figure 2.2.7 (A.1.7). In general, we found that wet-dry periods had greater influence on lake $SUVA_{254}$ than [DOC]. Fine hummocky and coarse lakes showed that [DOC] decreased as the short-term monthly cumulative precipitation increased, while the [DOC] of fine plains lakes did not respond to short-term monthly cumulative precipitation. Longer-term wet-dry periods (i.e., 12- and 24-month cumulative precipitation) had no significant influence on lake [DOC]. In contrast, lake $SUVA_{254}$ was most influenced by the 24-month cumulative precipitation, with a significant positive relationship for lakes in all three HRAs.

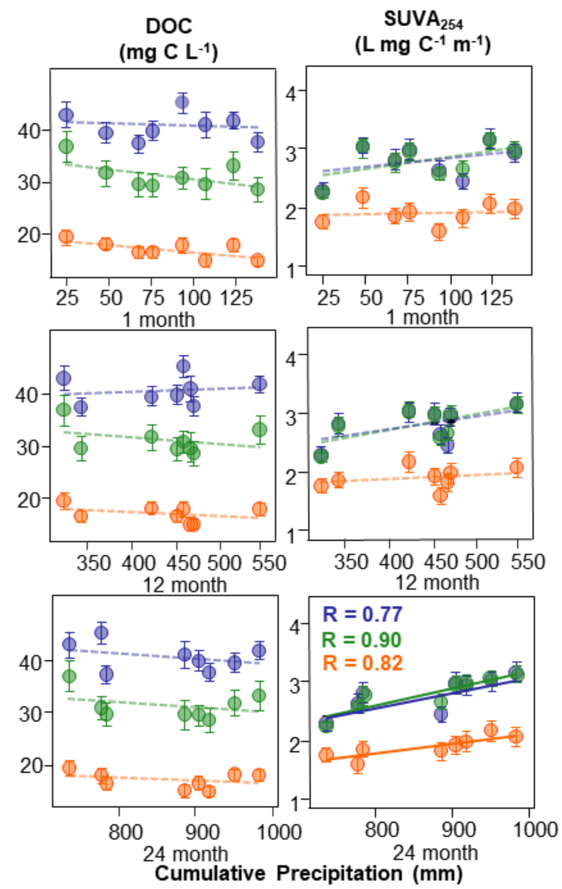


Figure 2.2.7: Relationships between mean lake DOC concentration [DOC] (left column) and SUVA254 (right column) sampled annually from 2012 - 2019 within each hydrologic response area (HRA) and different cumulative total precipitation periods (1 month, 12 month and 24 month). Statistically significant relationships ($p < 0.05$) are indicated with a solid regression line and R values provided in the top left corner of the panel. Statistically insignificant relationships show a dashed line, R values can be found in A.1.6. The colour for each point and regression line represents lakes in each HRA, Coarse (orange), Fine Hummocky (Green) and Fine Plains (Blue) lakes.

2.4 Discussion

This study found large spatial and inter-annual variability in DOC concentration and chemical composition (using $SUVA_{254}$ as a proxy for aromaticity of DOC) in lakes on the Boreal Plains of Western Canada. Below, we reason that the large spatial variability in lake DOC concentration was primarily a result of the heterogeneous surficial geology in the region, and differences in proportion of wetland connectivity across watersheds. Also, the spatial variability in aromaticity of lake DOC was influenced by lake water residence times and the extent of within-lake processing of aromatic-rich allochthonous DOC. We further reason that high inter-annual variability in lake DOC characteristics was a consequence of interactions between surficial geology, and the sub-humid climate of the Boreal Plains. While inter-annual wet-dry periods were found to shift connectivity of terrestrial DOC sources, and thus DOC concentration, the most important driver of inter-annual variability in lake DOC aromaticity was lake water residence time, and the degree to which within-lake processes caused DOC degradation. Our study allowed us to develop a conceptual model of interactions between landscape and climate controls on lake DOC characteristics on the Boreal Plains, referred to throughout the discussion (Figure 2.2.8). As one of few studies that have monitored variability in small boreal lake DOC characteristics over a period of almost a decade, this study provides new insights into the sensitivity of lake DOC characteristics to inter-annual wet-dry periods, and thus potential consequences for lake functions on the Boreal Plains in the future.

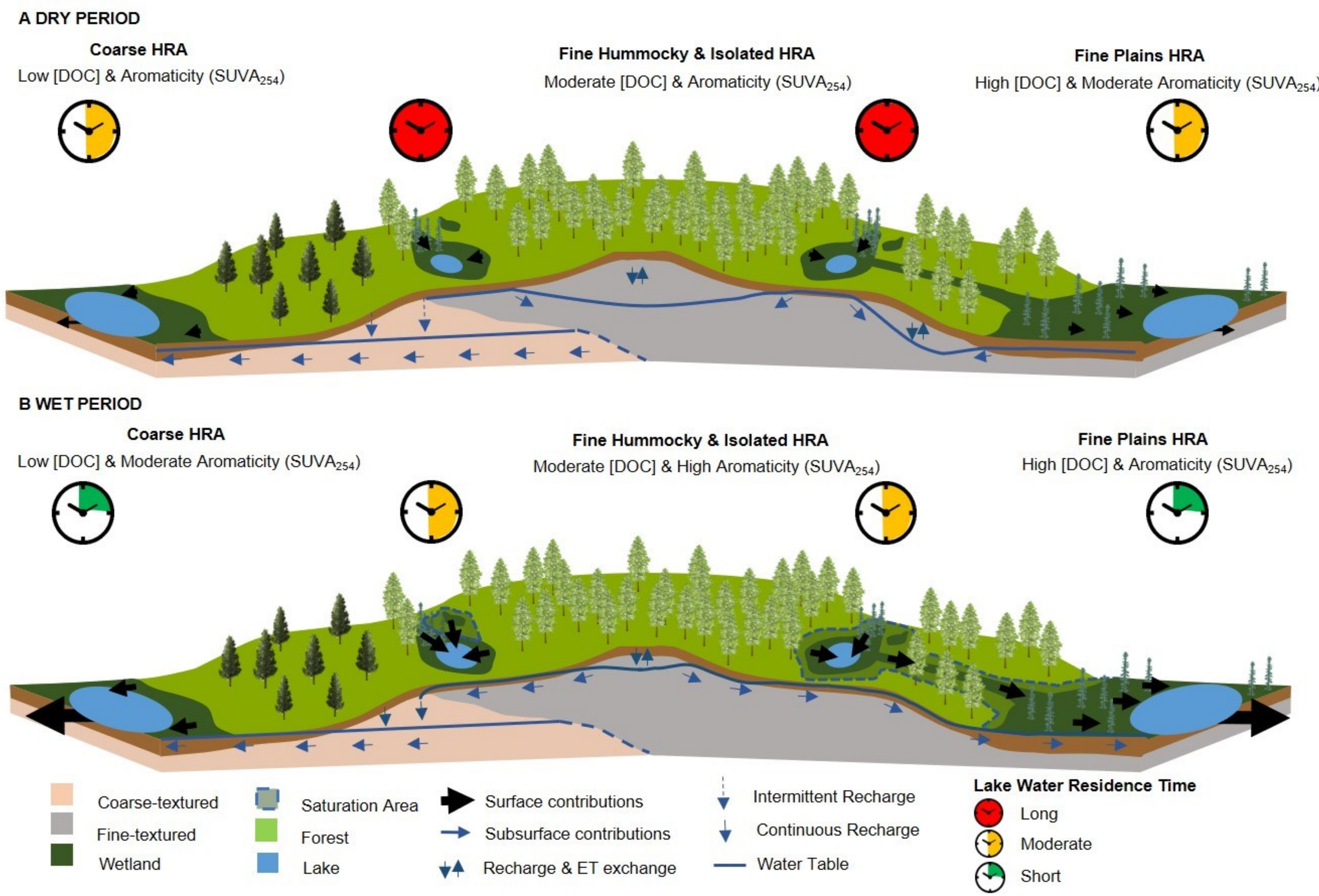

A DRY PERIOD
Coarse HRA
Low [DOC] & Aromaticity (SUVA254)
Fine Hummocky & Isolated HRA
Moderate [DOC] & Aromaticity (SUVA254)
Fine Plains HRA
High [DOC] & Moderate Aromaticity (SUVA254)
B WET PERIOD
Coarse HRA
Low [DOC] & Moderate Aromaticity (SUVA254)
Fine Hummocky & Isolated HRA
Moderate [DOC] & High Aromaticity (SUVA254)
Fine Plains HRA
High [DOC] & Aromaticity (SUVA254)
Coarse-textured
Fine-textured
Wetland
Saturation Area
Forest
Lake
Surface contributions
Subsurface contributions
Recharge & ET exchange
Intermittent Recharge
Continuous Recharge
Water Table
Lake Water Residence Time
Long
Moderate
Short

Figure 2.2.8: Conceptual model of DOC concentration and aromaticity ($SUVA_{254}$) responses of shallow lakes located in each HRA to relatively A dry (top) and B wet (bottom) periods. Dark green areas represent peatlands whilst light green areas represent the forest, where aspen and pine trees are located in fine and coarse-textured HRAs, respectively. Blue and black arrows indicate subsurface and surface flow paths, respectively. Larger black arrows indicate greater contributions of water from different terrestrial sources of allochthonous DOC. The ranges of [DOC] and aromaticity for low, moderate and high are: [DOC] 0 – 20, 20 – 40 and > 40 mg C L-1; and aromaticity ($SUVA_{254}$) 0 – 2, 2 – 3, >3 L mg^{-1} C m^{-1}. We propose that lake DOC concentration is sensitive to spatial differences in HRA and subsequent dominance of subsurface and surface flow paths. DOC concentrations are lowest in coarse lakes with greater contributions from subsurface flow paths and limited surface contributions, followed by fine-textured isolated and hummocky lakes with surface contributions from adjacent wetlands, and the highest DOC concentrations found in fine plains lakes which receive large surface contributions from the extensive peatlands in the watershed. In contrast, aromaticity of lake DOC is sensitive to inter-annual wet-dry periods, however, spatial dependencies of DOC aromaticity to surficial geology remain. We propose that during a dry period, aromaticity of lake DOC is lower due to increased opportunities for within-lake processing of DOC, whilst a wet landscape state will promote water movement through the landscape, thereby reducing opportunities for within-lake processing of DOC.

2.4.1 Spatial variability of lake DOC characteristics

This study found large spatial variability in DOC concentration and aromaticity in lakes on the Boreal Plains. We found generally higher lake DOC concentrations in the Boreal Plains than in other boreal and northern temperate regions. For example, in 70% of the study lakes long-term DOC concentrations were between 20 and 50 mg C L^{-1}, whereas research undertaken in the Boreal Shield and northern temperate lakes only report up to 20% of study lake DOC concentrations over 20 mg C L^{-1} (Carignan et al., 2000; Curtis & Schindler, 1997; D'Arcy & Carignan, 1997; Houle et al., 2020; Jonsson et al., 2003; Sepp et al., 2019; Sobek et al., 2003). Whilst extensive peatlands can explain high DOC concentrations in the Boreal Plains, the pH of the study lakes is also higher than those in Boreal Shield and northern temperate settings (Carignan et al., 2000; D'Arcy & Carignan, 1997; Jonsson et al., 2003; Sobek et al., 2003), thereby potentially enhancing DOC solubility in soils and thus causing higher lake DOC concentrations (Curtis & Adams, 1995; Kang et al., 2018). The range of $SUVA_{254}$ values measured in the study lakes were generally lower than those recorded in other boreal (Erlandsson et al., 2012; Kothawala et al., 2014; Mueller et al., 2012), and northern temperate regions (Sepp et al., 2019; Warner & Saros, 2019). The lower $SUVA_{254}$ observed in Boreal Plains lakes may be due to differences in soil type, where other boreal regions are typically characterized by podsolic soils, the Boreal Plains has calcareous soils that increase pH, which has also been shown to enhance within-lake processing of aromatic DOC (Soil Classification Working Group 2001; Pace et al., 2012; Sepp et al., 2019). Alternatively, lower $SUVA_{254}$ could also be due to Boreal Plains lakes undergoing greater within-lake processing of aromatic DOC in relation to extended lake water residence times when compared to other boreal regions (D'Arcy & Carignan, 1997; Jane et al., 2017; Kothawala et al., 2014).

We found that the three distinct surficial geologies in our study area had strong influence on lake DOC characteristics. Our conceptual model proposes that the differences in local relief, storage potential, and transmissivity between surficial geologies influence the degree of surface and subsurface contributions (Devito et al., 2005, 2017; Hokanson et al., 2019; Plach et al., 2016; Winter, 2001), which controls the delivery of allochthonous aromatic-rich DOC to lakes (Olefeldt et al., 2013). As important watershed sources of DOC, the proportion of peatland in a watershed also determines the delivery of allochthonous aromatic-rich DOC to lakes (Aitkenhead-Peterson et al., 2003; Arvola et al., 2016; Dillon & Molot, 1997; Kortelainen, 1993; Mattsson et al., 2005; Rantakari et al., 2004; Sepp et al., 2019; Thurman et al., 1985). In a Boreal Plains setting, the proportion of peatland in a watershed is intrinsically linked to surficial geology and relative elevation in the HRA. Specifically, the proportion of peatland is spatially constrained in coarse and fine hummocky watersheds, but extensive across fine plains watersheds (Figure 2.2.8). Despite the average proportion of peatlands connected to coarse lakes (45% of watershed (A.1.3)), DOC concentrations and aromaticity were likely lower in coarse lakes because of the degree of subsurface contributions depleted in aromatic-DOC, which may overwhelm surface contributions from surrounding peatlands (Figure 2.2.8; Hokanson et al., 2019; Qualls & Haines, 1992; Olefeldt et al., 2013; Smerdon et al., 2005; Thurman, 2012). Long-term average DOC concentrations and aromaticity of fine hummocky lakes were higher in watersheds with greater peatland connectivity, even with the narrow range of peatland proportions within fine hummocky watersheds (35% of watershed; A.1.3), likely due to the dominance of surface contributions to lakes via adjacent peatlands and riparian zones, with limited subsurface contributions (Figure 2.2.8; Ferone & Devito, 2004; Olefeldt et al., 2013; Plach et al., 2016). Fine plains lakes had the highest long-term average DOC concentration and average peatland connectivity (65% of watershed (A.1.3)) indicating dominance of surface contributions via extensive peatlands, and again limited subsurface contributions (Figure 2.2.8; Hokanson et al., 2019; Olefeldt et al., 2013; Smerdon et al., 2005).

The spatial variability in lake DOC aromaticity ($SUVA_{254}$) was strongly influenced by lake water residence times (lc-excess), which we conceptualise to be partly driven by the degree of surface and subsurface contributions across surficial geologies (Figure 2.2.8). Although not explicitly measured here, longer water residence times are expected to be prevalent in Boreal Plains lakes due to the sub-humid climate of the region, despite Boreal Plains lakes being generally shallower than their Boreal Shield counterparts that often exhibit water residence times between 0

– 5 years (D'Arcy & Carignan, 1997; Jane et al., 2017; Kothawala et al., 2014). Furthermore, longer water residence times of Boreal Plains lakes enhance opportunities for within-lake selective degradation (e.g., photodegradation, biodegradation, and flocculation), and autochthonous production of DOC, which is associated with decreasing aromaticity of DOC (Figure 2.2.6; Catalán et al., 2016; Ejarque et al., 2018; Kothawala et al, 2014; Schindler et al., 1992, 1997). In contrast to the relationship between water residence time and DOC aromaticity observed in other studies, the lc-excess data suggested that coarse lakes had relatively short water residence times, and the lowest aromaticity of DOC. In coarse lakes, the shorter water residence time and lower DOC aromaticity could be due to the degree of groundwater contributions depleted in aromatic-DOC, and lake-to-lake flow through systems maintaining water movement through the landscape (Figure 2.2.8; Hokanson et al., 2019; Smerdon et al., 2005), rather than influences of within-lake selective DOC degradation. Fine plains lakes had a long-term lc-excess that indicated shorter lake water residence times, relative to fine hummocky lakes, due to the dominance of surface flow paths via low-storage, runoff generating peatlands (Figure 2.2.8; Devito et al., 2005, 2017; Plach et al., 2016; Thompson et al., 2015, 2017; Waddington et al., 2015). Fine plains lakes reinforced the relationship between water residence time and DOC aromaticity, where generally shorter water residence times corresponded to higher aromaticity of DOC due to reduced opportunities for within-lake selective degradation of aromatic DOC. Fine hummocky lakes had more negative long-term lc-excess values, indicative of longer water residence times, where due to limited hydrological connectivity to local flow systems, and in some cases a lack of an outflow, water residence times can be in excess of thirty years (Devito et al., 2012; Plach et al., 2016). However, fine hummocky lakes also had higher aromaticity of DOC, when compared to fine plains lakes, which is likely due to differences in terrestrial sources of DOC between different fine-textured

HRAs (Olefeldt et al., 2013). In fine hummocky watersheds, large water table fluctuations in the adjacent riparian soils cause greater humification, whereas fine plains peatlands maintain stable water tables with less humification of near surface terrestrial DOC sources. The lower DOC concentration in fine hummocky lakes compared to fine plains lakes may also be due to differences in terrestrial sources (i.e. riparian soil waters have lower DOC with higher SUVA than sphagnum-peatland derived sources that typically occur in Fine Plains watersheds). Alternatively, there are greater preferential losses of aromatic DOC in fine hummocky lakes compared to fine plains, but the initial aromaticity of terrestrial riparian soil sources was so much higher than peatland sources that fine hummocky lake DOC remains aromatic even after more exposure to photodegradation processes.

Disturbances, such as wildfire and harvesting, did not have a detectable influence on lake DOC characteristics in our study area. The lack of an influence of disturbances on lake DOC characteristics largely contrasts other studies that show lake DOC concentrations increase post-disturbance in other boreal regions (Emelko et al., 2011; McEachern et al., 2000; Pinel-Alloul et al., 2002). This study did not include pre-fire data, and it is likely that wildfire disturbance would have different effects in different HRAs, for which our study did not have enough lakes to detect an effect of wildfire on lake DOC characteristics. However, a study by Olefeldt et al., (2013) also detected no influence of wildfire on lake DOC characteristics in the Boreal Plains. Thompson et al., (2018) also found limited impacts of harvesting on hydrology of the Boreal Plains, and thus the delivery of allochthonous aromatic-rich DOC to lakes. The lack of influence of wildfire and harvest found in these studies (Olefeldt et al., 2013; Thompson et al., 2018) can be attributed to the sub-humid climate of the region with low frequency of large storms to overcome the large storage capacity of heterogeneous glacial surficial geologies, which could also explain why disturbance effects were not detected in this study. We did not include an assessment of beaver influence on lake DOC characteristics in Boreal Plains lakes, however, beavers can introduce lots of DOC into an aquatic system (Hillman et al., 2004) and their presence may add to the spatial variability observed. Although beavers introduce DOC into lake systems, it is assumed to be a small proportion of the already high DOC sources of water entering Boreal Plains lakes via organic rich peatlands.

2.4.2 Inter-annual variability of lake DOC characteristics

Our results show that inter-annual wet-dry periods cause much of the observed inter-annual variability in lake DOC characteristics. The inter-annual variability of lake DOC characteristics observed in the study lakes was larger than studies from northern temperate regions (Sepp et al., 2019; Toming et al., 2016). Although there are many similarities in landscape characteristics of the Boreal Plains ecozone and northern temperate regions, the climate of temperate regions is generally wetter, thereby stabilising lake water residence times resulting in less inter-annual variability in lake DOC characteristics. However, there are very few studies that have quantified inter-annual variability in lake DOC characteristics (Zhang et al., 2010), particularly in smaller boreal lakes such as those on the Boreal Plains.

We found high inter-annual variability of individual lake DOC concentrations, but low synchronicity among the 34 study lakes. Our low synchronicity results contrast long-term studies that show higher synchronicity in overall lake DOC concentration across other boreal and northern temperate regions (Hudson et al., 2003; Jane et al., 2017; Pace & Cole, 2002; Zhang et al., 2010). Some consistent patterns in DOC concentration were however observed among the study lakes, especially when considering distinct responses to different cumulative precipitation periods within each HRA. In particular, we found that lakes in different HRAs responded differently to short-term cumulative precipitation. In coarse and fine hummocky lakes, DOC concentrations were influenced by short-term cumulative precipitation, compared to fine plains lakes which did not respond to wet-dry periods. Coarse and fine hummocky lakes were likely diluted by groundwater and direct precipitation inputs, respectively, which outweighed the delivery of allochthonous DOC from the watershed (Sass et al., 2008). The reasons why dilution occurs in response to short-term precipitation likely vary between the fine hummocky and coarse lakes. Coarse lakes are well connected to groundwater sources, which are unlikely to respond to short-term cumulative precipitation; however, they likely dilute lake DOC concentrations due to direct precipitation to the lake (Engstrom, 1987). In fine hummocky lakes, dilution of lake DOC concentrations is likely due to the inability of short-term precipitation to hydrologically connect the forests within a fine hummocky landscape (Redding & Devito, 2008, 2010), and thus limits the influx of allochthonous DOC. Fine plains lakes were not sensitive to short-term cumulative precipitation likely due to maintained hydrologic connectivity of expansive peatlands that easily overcome their water storage thresholds and allow for continued delivery of allochthonous DOC to lakes regardless of cumulative precipitation, and thus counteract the direct dilution effect (Engstrom, 1987; Sass et al., 2008).

In contrast to DOC concentration, there was high temporal synchronicity of DOC aromaticity among the studied lakes. Our conceptual model proposes that aromaticity of lake DOC is more sensitive to within-lake processes rather than delivery of DOC from various allochthonous sources (Figure 2.2.8; Jane et al., 2017; Kratz et al., 1998; Magnuson et al., 1990). The synchronicity of DOC aromaticity in the study lakes was also higher than those observed in northern temperate lakes (Jane et al., 2017). The high correlation between DOC aromaticity and lc-excess for individual lakes suggests that shifts in inter-annual wet-dry periods are reflected in lake water residence times, where lower lc-excess during dry periods indicate longer water residence times and enhanced preferential photo-degradation of aromatic DOC. Departure from mean lake level also showed relatively high synchronicity among lakes, where lower water levels corresponded with an lc-excess indicative of longer water residence times, and decreased aromaticity of lake DOC as a result of enhanced within-lake photo-degradation opportunities. In contrast to DOC concentration, the aromaticity of lake DOC was sensitive to long-term (24-month) cumulative precipitation in lakes across all HRAs (Figure 2.2.7), and DOC aromaticity decreased when long-term cumulative precipitation was lower. We attributed this observation to the ephemerality of terrestrial-aquatic linkages and extension of water residence times, causing increased rates of within-lake processes (Algesten et al., 2003; Schindler et al., 1992, 1997). Therefore, small shifts in precipitation of a sub-humid climate, such as the Boreal Plains, leads to large shifts in drying of lakes and relative water residence times, largely contrasting other long-term studies that are undertaken in humid climates (Hudson et al., 2003; Jane et al., 2017; Pace & Cole, 2002; Zhang et al., 2010).

2.4.3 Implications for lake ecosystem functions on the Boreal Plains

Given that the variability in precipitation is intensifying globally (Pachauri et al., 2014), lake DOC characteristics will also be changing in response, and could give rise to important ecological consequences. By 2050, the Boreal Plains ecozone is predicted to warm by 2 to 4°C (Lemmen, 2008). This climatic change is projected to affect the landscape water balance by increasing both precipitation (Lemmen, 2008) and potential evapotranspiration (Schneider et al., 2013). Hence, the most likely outcome will be an overall drier landscape in the Boreal Plains, but also with greater inter-annual variability in wet-dry periods (Schneider et al., 2013; Thompson et al., 2017). With a changing climate and the high sensitivity of DOC characteristics to inter-annual wet-dry periods shown in this study, we can expect changes to DOC characteristics, particularly DOC aromaticity, to shift drastically as water residence times lengthen and opportunities of within-lake degradation of aromatic DOC is enhanced. However, the impacts of climate change on DOC concentration may be less consistent among lakes, with different responses in lake DOC among HRAs. We expect fine hummocky lake DOC characteristics to be most sensitive to inter-annual wet-dry periods as their already long water residence times increase in a climate change induced drier landscape, thereby promoting extensive within-lake photodegradation of aromatic-DOC.

There are multiple possible impacts of reduced DOC concentration and aromaticity on lake ecosystem functioning in the Boreal Plains. Firstly, reduced DOC concentrations in lakes could limit provisions of carbon for food webs subsequently reducing zooplankton production with cascading effects on wildlife (Seekell et al., 2015; Solomon et al., 2015). Secondly, light penetration depths could increase and promote visibility and photosynthesis, thereby influencing vertical habitat gradients, food-web structures, UV-protection for aquatic organisms, and predator-prey relationships (Solomon et al., 2015; Williamson et al., 2015). Alternatively, there are potential benefits to reduced DOC concentration and aromaticity of lakes on the Boreal Plains. For example, with potential for the proportion of allochthonous DOC entering lakes to decrease with decreased hydrologic connectivity in the landscape, the amount of available DOC for mineralisation or flocculation also decreases, which may lead to lower greenhouse gas emissions to the atmosphere (de Wit et al., 2018; von Wachenfeldt & Tranvik, 2008). Furthermore, there are many small northern communities across the Boreal Plains that rely on surface water as sources of drinking water (Government of Alberta, 2010), which may be affected by the influence of decreased aromaticity of lake DOC on treatability potential of surface waters (Ritson et al., 2014).

2.5 Conclusion

These results support our hypotheses, demonstrating large variability of DOC concentration and aromaticity across space and time in Boreal Plains lakes. As predicted, we found that surficial geology and proportion of wetland in the watershed were a determinant of lake DOC characteristics in the Boreal Plains both spatially and inter-annually. Specifically, fine-textured lakes showed higher DOC concentrations and aromaticity compared to coarse-textured lakes, and fine-textured hummocky lakes limited to local hydrologic flow paths had lower lake DOC aromaticity due to enhanced photodegradation processes occurring with prolonged lake water residence times. However, all lakes showed lower aromaticity of DOC during dry periods due to reduced hydrologic connectivity, longer lake water residence times, and increased opportunity for photodegradation processes. From these results, a conceptual model is proposed to highlight the complexity of landscape attributes and their interactions with inter-annual wet-dry periods upon lake DOC characteristics within a Boreal Plains setting, which largely contrasts responses of lake DOC characteristics in other boreal and northern temperate regions. As changes in climate are predicted to cause variations in precipitation quantity and timing, thereby altering the water balance and hydrologic connectivity across many regions, it is likely that DOC characteristics will also change in many aquatic ecosystems with implications for aquatic carbon cycling and ecological functioning of lakes. Changes in climate and the effects on lake responses is especially important in a Boreal Plains setting where shallow lakes receiving aromatic-rich allochthonous DOC exist in a region with an overall moisture deficit, and small changes in the water balance cause large shifts in water residence times and, thus, within-lake degradation of DOC. As one of few studies that have monitored inter-annual variability of DOC characteristics in Boreal Plains lakes, we show that DOC characteristics, particularly aromaticity, of many lakes on the Boreal

Plains are highly sensitive to inter-annual wet-dry periods, with important implications for future lake functions, including; greenhouse gas exchange, nutrient cycling, food webs and water treatability. The conceptual model presented in this study also provides a generalizable framework that uses universally applicable processes and can be applied in different hydrogeomorphology settings to assess differences in how DOC characteristics in lakes respond to climate.

3.0 Terrestrial sources versus within-lake processes: Controls on Dissolved Organic Carbon quantity and composition in Boreal Plains lakes of Western Canada

Key Points:

- Within-lakes processes significantly alter the DOC (dissolved organic carbon) concentration and composition of terrestrial sources reaching lakes.
- Relative importance of within-lake processes varied among lakes and years due to differences in surficial geology and wetland cover influencing lake productivity (autochthonous production) and lake water residence time (photodegradation).
- DOC composition was more sensitive to inter-annual wet-dry periods than DOC concentration, and aromaticity decreased during dry periods when opportunities for photodegradation were enhanced.

Abstract

The concentration and chemical composition of dissolved organic carbon (DOC) in boreal lakes is critical for several ecosystem services. Understanding the dominant processes that regulate lake DOC characteristics is important for robust predictions of future lake responses to climate change with implications for water quality and global carbon cycling. Here, we characterize the water chemistry of key terrestrial DOC sources to Boreal Plains lakes; including, organic peatland, and mineral forest and groundwater sources across heterogeneous surficial geologies. End-member mixing model analysis showed that within-lakes processes significantly altered the DOC concentration and composition of terrestrial sources reaching lakes. We found that lake DOC characteristics did not conform to conservative mixing of terrestrial sources, with generally lower observed DOC concentrations and consistently lower A_{254} than modelled based on conservative mixing, suggesting net DOC and A_{254} losses in terrestrial end-members along the soil-stream-lake

continuum. We found greater differences between modelled and observed A_{254} than of DOC, which was consistent with substantial photodegradation of aromatic terrestrial DOC in these shallow lakes with long residence times. Larger differences between modelled and observed DOC and A_{254} (losses) were associated with lakes in coarse and fine hummocky watersheds, whilst DOC concentrations observed in fine plains watersheds were higher than those modelled, thereby suggesting autochthonous production of DOC. We also identified inter-annual patterns in the difference between modelled and observed DOC characteristics, with greater losses of A_{254} during dry years, when lake water residence times were longer and opportunities for within-lake photodegradation processes enhanced. Our study shows variability in the hydrologic connectivity of different terrestrial sources to Boreal Plains lakes, and subsequently the balance of lake DOC concentration and composition that is significantly altered by the occurrence of within-lake processes. Thus, with climate change and likely extended lake water residence times with increased opportunity for within-lake processing, we can expect large changes in the DOC balance of small boreal lakes with implications for ecosystem functioning along the stream-lake continuum.

3.1 Introduction

Boreal lakes are active sites for mixing, transport, transformation, and storage of dissolved organic carbon (DOC), and hence are important components of the carbon cycle across regional and global scales (Algesten et al., 2004; Cole et al., 2007; Prairie 2008; Tranvik et al., 2009; Weyhenmeyer et al., 2012). Yet, there remains a scarcity of studies that integrate our understanding of terrestrial DOC sources to lakes, and controls on DOC quantity (DOC concentration) and chemical composition (Absorbance (A_{254})) in a landscape context that can capture the variability at spatial and inter-annual scales (Anas et al., 2015; Hall et al., 2018; Webb et al., 2019). The DOC concentration and composition in boreal lakes depends both on the hydrologic connectivity to terrestrial DOC sources (Aitkenhead-Peterson et al., 2003; Kolka et al., 2008), as well as within-lake processes of production and degradation of DOC (Aitkenhead-Peterson et al., 2003; Algesten et al., 2004; Bertilsson and Jones, 2002; Tranvik et al., 2009). Within-lake processing of terrestrially derived DOC includes degradation by biological and photo-mediated processes, which selectively act on non-aromatic and aromatic DOC, respectively (Benner & Kaiser, 2011; Moran & Zepp, 1997; von Wachenfeldt et al., 2008). However, autochthonous production of algal DOC, largely of non-aromatic compositions, also occurs in lakes (Guillemette et al., 2013). Understanding the sources and balance of DOC added or removed through space and time is critical to forecasting potential impacts to boreal lake ecosystem services, especially under a changing climate; including, food-web dynamics, greenhouse gas function, nutrient cycling, and water quality and treatability (Algesten et al., 2004; Cole et al., 2007; Emelko et al., 2011; Karlsson et al., 2009; Solomon et al., 2015; Tranvik, 1988; Williamson et al., 2009).

The composition of DOC differs between autochthonous DOC produced within-lakes and various allochthonous sources from the surrounding terrestrial watershed (Aitkenhead-Peterson et al., 2003; Bertilsson and Jones, 2002). Autochthonous DOC is considered relatively biolabile, with low aromaticity (Kirchman et al. 1991; Nguyen et al., 2005; Søndergaard et al. 1995). However, autochthonous DOC can become biologically refractory through time as reactivity decreases and transformation processes occur (Tranvik & Kokalj, 1998). In contrast, allochthonous DOC is biologically refractory (Tranvik 1992), but the composition of allochthonous DOC differs among terrestrial sources. Highly aromatic high-molecular-weight humic and fulvic acids are associated with DOC derived from humified organic matter, such as peatlands (Kalbitz et al., 2003; Thurman, 1985; Wickland et al., 2007). In contrast, DOC comprised of aliphatic, low-molecular-weight carbohydrates are derived from fresh plant material, and mineral soils (Aitkenhead-Peterson et al., 2003). While fresh plant material and mineral soils are both of low aromaticity, they have vastly different chemical compositions. Fresh plant material DOC is rich in sugars and proteins, whereas mineral soil DOC is low-aromatic DOC desorbed from mineral surfaces, thus DOC from fresh plant material is highly biolabile but DOC from deep mineral soils is usually of low biodegradability (Aitkenhead-Peterson et al., 2003; Olefeldt et al., 2013). Biodegradation processes usually selectively removes biolabile, low-molecular-weight aliphatic material with the exception of deep mineral soil DOC (Berggren et al. 2009; Hansen et al., 2016; Olefeldt et al., 2013), whilst aromatic DOC is photolabile and preferentially degraded by photo-mediated processes into bioavailable compounds that can then be removed from the DOC pool via biological processes (Bertilsson & Tranvik, 2000). Both bio- and photodegradation processes can cause DOC losses through the conversion of DOC to inorganic carbon compounds (e.g., CO_2), thereby altering the DOC pool of lakes from a concentration and composition perspective.

Inter-annual climate variability may lead to shifts in lake DOC concentration and composition. These changes can be due to relative shifts in the dominance of various terrestrial allochthonous DOC sources or due to altered importance of within-lake autochthonous DOC production and degradation, thus controlling the DOC pool of boreal lakes (Berggren et al., 2009; Kellerman et al., 2014; Sobek et al., 2007). However, there are vast differences in characteristics and hydrologic connectivity of boreal lake watersheds across the boreal biome influencing terrestrial-aquatic linkages for DOC transport to lakes and DOC lake processing, including climate, bedrock geology, surficial geology, topographic relief and permafrost presence. Hence, we cannot expect spatially and inter-annually varying controls on terrestrial DOC sources to lakes, and DOC degradation or production in lakes to remain the same across different boreal regions.

The Boreal Plains ecozone constitutes a distinct physiographic region within the circumpolar boreal with thick heterogeneous surficial geology, widespread peatlands, and abundant shallow lakes. Given the distinct characteristics and large variability of the lakes and landscapes within the boreal plains, the controls on terrestrial DOC sources to lakes and the fate of DOC in lakes likely contrasts Boreal Shield regions of Canada and Scandinavia, where significant work on boreal lake DOC losses has been conducted (Algesten et al., 2004; Dillon & Molot, 1997; Hall et al., 2019; Hanson et al., 2004; Jonsson et al., 2007). The Boreal Plains has highly complex hydrologic connectivity (Devito et al., 2005, 2017; Hokanson et al., 2019), and equally complex hydrological and biogeochemical responses to precipitation (Chp. 2; Plach et al., 2016; Sass et al., 2008) due to interactions between sedimentary bedrock overlain by thick heterogeneous surficial geologies and a sub-humid climate. There is large spatial and inter-annual variability in lake DOC concentration and aromaticity of DOC across Boreal Plains lakes as a result of differences in the dominance of surface versus subsurface flow paths between surficial geologies and interactions with inter-annual wet-dry periods (Chp. 2). Watersheds with fine-textured surficial geology, dominated by surface flow paths through organic-rich peatlands, show high concentrations of aromatic-rich DOC when compared watersheds with coarse-textured surficial geology that are dominated by subsurface flow paths depleted of aromatic-rich DOC (Chp. 2; Ferone & Devito, 2004; Hokanson et al., 2019; Qualls & Haines, 1992; Olefeldt et al., 2013; Plach et al., 2016); Smerdon et al., 2005; Thurman, 2012).

Boreal Plains lakes are also characteristically shallow (0 – 2 m), and exist in a moisture-deficit landscape where lake water residence times are generally longer than those observed in Boreal Shield regions and shift in response to inter-annual wet-dry periods (i.e. longer lake water residence time during dry periods and shorter during wet periods; Chp. 2). However, lake water residence times can also be modified by landscape attributes, including surficial geology. Fine-textured plains watersheds with extensive runoff generating peatlands and coarse-textured watersheds dominated by subsurface flow paths, are considered to have relatively short lakewater residence times with reduced within-lake processing opportunities; whilst fine-textured hummocky relief lakes dominated by limited local surface flow paths have relatively long water residence times (Chp. 2). Hence it is possible that the response of DOC characteristics of Boreal Plains lakes to climate variability is more sensitive than other boreal regions, and also likely have a high variability within the Boreal Plains due to its heterogeneous landscape.

The objective of this study was to determine the processes responsible for the observed spatial and inter-annual variability in DOC characteristics of lakes on the Boreal Plains. In particular, we wanted to assess for lakes in different settings whether inter-annual variability in lake DOC concentration and composition is driven by relative shifts in connectivity of terrestrial sources or driven by relative dominance of within-lake processes of DOC production and degradation. For this purpose, we characterized the water chemistry and DOC characteristics of various terrestrial water sources, and we monitored water chemistry and DOC characteristics of 33 lakes over eight years. A number of streams were further monitored during the last year of the study to distinguish whether bio- and photo-degradation processes occurring in streams altered DOC characteristics rather than within-lake processes. A simple mixing model was applied to determine how well lake and stream DOC characteristics behaved conservatively with respect to mixing of terrestrial sources. Discrepancies between modelled and observed lake DOC characteristics, based on the mixing model, were explored to assess whether they were primarily consistent with losses during transport in the stream networks, resulting from autochthonous production, or caused by within-lake bio- and photodegradation. We predicted that within-lake processes significantly alter the DOC concentration and composition of terrestrial sources reaching lakes. Specifically, the difference between observed and modelled lake A_{254} will be higher than that of DOC change due to selective degradation of aromatic fractions of DOC via photo-mediated processes. We predicted that the difference between modelled and observed DOC and A_{254} would vary among surficial geologies due to differences in water chemistry between dominant terrestrial sources (surface versus subsurface flows) and lake water residence times. Additionally, we predicted that during dry years, with longer water residence times, the difference in modelled and observed lake A_{254} will be larger, suggesting greater losses in A_{254} in dry years relative to wet years. However, we expect that varying surficial geologies of lake watersheds will modify the difference between modelled and observed lake DOC characteristics between relatively wet and dry years due to differences in lake water chemistry and residence times. Determining the dominant processes that regulate the spatial and inter-annual variability in DOC characteristics allows us to better predict future impacts to boreal lake ecosystem services in response to climate change.

3.2 Methods

3.2.1 Study Site

The studied lakes, streams, and wells are located across a 70-km transect in the Utikuma Region Study Area (URSA) in the Boreal Plains Ecozone (EcoRegions Working Group, 1989) in Western Canada, located on Treaty No. 8 Territory (Figure 3.**3.1**; Devito et al., 2016). The climate of this region is sub-humid with multi-year wet-dry cycles (Figure 3.3.2; Mwale, 2009), where long-term precipitation and potential evapotranspiration is 483 mm and 519 mm respectively (Devito et al., 2016). The mean annual temperature is 1.2°C (Devito et al., 2016).

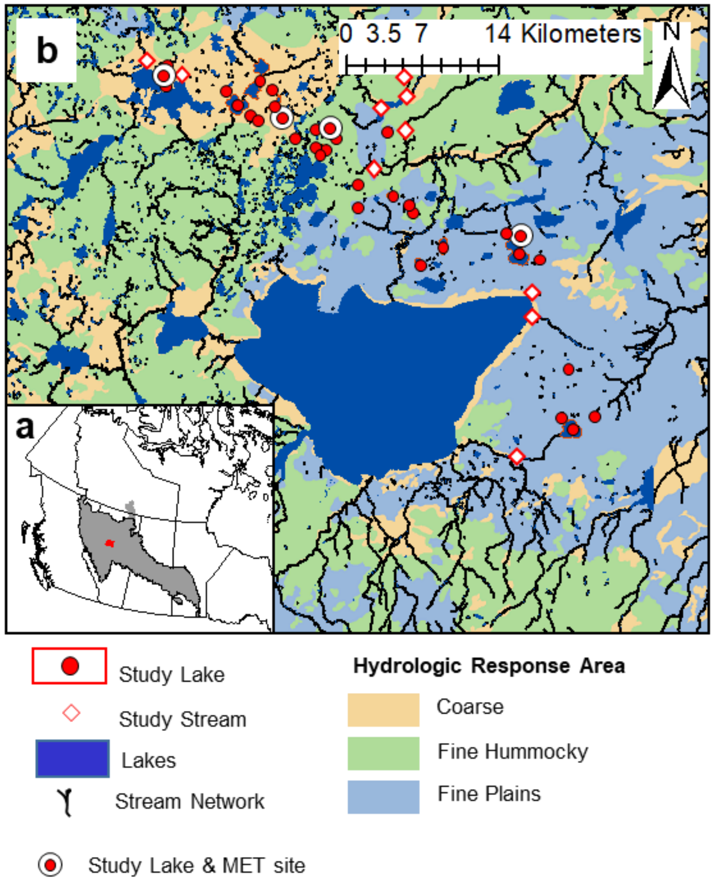


Figure 3.3.1: Map of the individual study lakes and streams representative of Boreal Plains of Western Canada. (a) The location of Utikuma Region Study Area (URSA; red rectangle) within the Boreal Plains ecozone (grey) in Canada; (b) location of the 33 study lakes (red circles) and 10 study streams (red diamonds with white fill) across distinct hydrologic response areas (HRAs) within URSA. Lake sites (red circle) with a white outline indicate meteorological (MET) sites used for precipitation measurements.

The URSA is characterised by low relief and thick heterogeneous glacial substrates (20 – 240 m) comprising coarse-textured glaciofluvial deposits in the north-west region of the study area, and fine-textured glacial till and glaciolacustrine deposits towards the south-east (Fenton et al., 2003). Three hydrologic response areas (HRAs) have been delineated along the study transect at the URSA (Figure 3.**3.1**) which includes the coarse-textured, and fine-textured hummocky and plains (Figure 3.**3.1**; Hokanson et al., 2019). Each HRA represents broad spatial differences in local relief, storage potential and transmissivity (Devito et al., 2005; 2017; Hokanson et al., 2019).

Most of URSA is low relief encouraging extensive wetland formation, with organic rich peatlands covering up to 50% of the land area (Devito et al., 2016). Peatland coverage varies among HRAs, with average peatland coverages of 45%, 35% and 65% in the coarse, fine hummocky and fine plains, respectively (Chp. 1). Peatlands in this region typically have a sparse canopy of black spruce (*Picea mariana*) and tamarack (*Larix sp.*) with groundcover comprised of mosses and organic accumulations of 2 to 5 m. Forestlands occupy approximately 40% the remaining landscape (Chp. 2) and are dominated by trembling aspen (*Populus tremuloides*) or pine (*Pinus banksiana*), in fine-textured and coarse-textured HRAs, respectively (Devito et al., 2012). Numerous polymictic shallow lakes (~ 0.5 – 5 m deep) of between 0.05 and 324 ha occupy approximately 10% of the total landcover (Figure 3.**3.1**; Chp. 2; Ferone & Devito, 2004; Olefeldt et al., 2013; Smerdon et al., 2005; Squires et al., 2005). The study lakes are also nutrient-rich (mesotrophic to hyper-eutrophic), and DOC-rich (Bayley et al., 2007; Chp. 2; Plach et al., 2016). Lakes in this region fluctuate in water level in response to multi-year wet-dry cycles (Cobbaert et al. 2015; Devito et al., 2012; Sass and Creed, 2008; Thompson et al., 2017).

3.2.2 Shallow lake and terrestrial source sampling and analysis

Synoptic sampling of 33 shallow lakes and representative end-members for terrestrial sources was conducted between June 30th and July 15th annually between 2012 and 2019. Terrestrial water sources were also sampled across 4 seasons (Spring (April/May), Summer (June/July), Fall (August/September) & Winter (November to February)) from representative end-members. Terrestrial water sources were sampled from either surface water, shallow (0 to 600 cm below ground) or deep (> 600 cm below ground) polyvinyl chloride monitoring wells, installed several years prior to the sampling campaigns, and then characterised by their water chemistry for use in an end-member mixing model. Furthermore, terrestrial sources were also sampled during spring freshet (April/May) from 2012 to 2019 for comparison with summer (June/July) sample concentrations (See section 2.5). Peatland water sources were collected at the surface and from shallow monitoring wells in both coarse and fine-textured lake watersheds, representing both surface and shallow subsurface organic peatland sources. Shallow groundwater from forests adjacent to the study ponds were sampled from monitoring wells ranging between 450 to 560 cm below ground in coarse-textured watersheds and 110 to 430 cm below ground in fine-textured watersheds, whilst deeper groundwaters were sampled from monitoring wells at depths between 600 to 1800 cm below ground in coarse-textured watersheds and 900 to 1500 cm below ground in fine-textured watersheds. Ephemeral draw and isolated wetland samples were collected at the surface, whilst swamps were sampled both at the surface and from shallow monitoring wells (50 to 180 cm below ground); however, there were no representative sites for swamps or isolated wetland located in the coarse-textured study lake watersheds.

Lake water samples were collected from the lake shore, or when required, from the edge of emergent vegetation, using a 3-m sampling pole. Samples were collected from a depth of approximately 30 cm to ensure each sample was representative of the water column. DOC, absorbance, geochemical, and oxygen isotope samples were collected from each lake and terrestrial source. Stream samples were collected for DOC, absorbance, and geochemistry from 10 streams during late June or early July in 2019 and compared with lake samples also collected in early July of 2019. Electrical Conductivity (EC; units: uS cm^{-1}), temperature (°C) and pH were measured in the field directly from each lake and terrestrial source. Samples were analysed for

DOC concentration (unit: mg C L^{-1}), a geochemical suite (including Magnesium (Mg^{2+}) and Calcium (Ca^{2+}); unit: mg L^{-1}), and isotopes ($^{18}O/^{16}O$ and $^{2}H/H$ ratios) at the Biogeochemical Analytical Service Laboratory, University of Alberta (BASL). Absorbance spectra of filtered samples at 254 nm were using a Varian Cary 100 from 2012 to 2015 and Ocean Optics UV-Vis spectrophotometer from 2016 to 2019, with Milli-Q water as a blank. Specific Ultra-Violet Absorbance at 254 nm ($SUVA_{254}$, unit: L mg C^{-1} m^{-1}) was calculated by dividing absorbance at 254 nm (A_{254} unit: cm^{-1}) by the sample [DOC] and multiplying by 100.

Similar to Chapter 2, isotope ($^{18}O/^{16}O$ and $^{2}H/H$ ratios) results were used to calculate the line-conditioned excess (lc-excess); used as a proxy for water residence times of lakes relative to other lakes in the same region. The lc-excess is a measure of the offset of a water sample from the Local Meteoric Water Line (LMWL) due to evaporative enrichment in dual-isotope space (Landwehr & Coplen, 2006). For full methods of shallow lake sampling and analysis in this study, refer to Chapter 2.

3.2.3 Relative wet-dry cycles

Precipitation data were collected from three locations within 24 km of each other along the URSA transect from 2012 to 2019 (Devito et al., 2016; Hokanson et al. 2019). Total annual precipitation (P) for the lake year was calculated from July 1st to June 30th. We used the ratio of long-term average potential evapotranspiration (PET; 519 mm) and average annual P (PET/P) for each annual period (July – June) to determine wet, mesic and dry conditions (Devito et al., 2012, 2016; Chp 2 – A.1.1). PET/P categories for wet, mesic and dry years were established as < 0.9, 0.9 – 1.15 and 1.15 – 1.8, respectively (Devito et al., 2012). Several relatively wet and dry periods were observed during the study period (Figure 3.3.2). Refer to Chapter 2 for full methods relating to precipitation data collection.

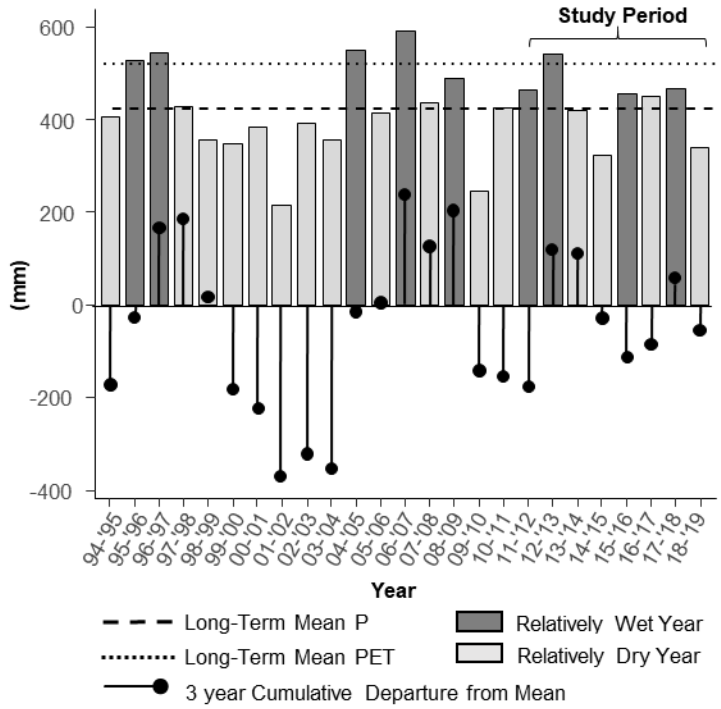


Figure 3.3.2: Annual precipitation data and 3-year cumulative departure from mean precipitation for URSA, before and during the study period (2012 – 2019). Long-term average annual P (423 mm; 1995–2019) and potential evapotranspiration (PET; 519 mm) are shown for context. Annual precipitation data used lake year (July 1st – June 30th) and relatively wet and dry weather pattern years were assigned based on PET:P.

3.2.4 Landscape and lake attributes

We delineated the watersheds of the 33 lakes on the Boreal Plain as outlined in Chapter 2. The study lakes were classified into three dominant hydrologic response areas (HRAs) according to the dominant HRA type (i.e. 50% of watershed area or greater; Chp 2 - A.1.3), as per Chapter 2. Connected wetland area (CW_A), and relative elevations of each study lake were determined using the methods described in Chapter 2.

3.2.5 Using a hydrological mixing model to assess relative importance of terrestrial sources and within-lake processes for lake DOC characteristics

A simple end-member mixing model was constructed to assess broad differences between lakes and between inter-annual wet-dry periods in terms of the relative contribution of various terrestrial DOC sources and the relative importance of different within-lake processes causing the observed lake DOC characteristics. The model was adapted from that used in Olefeldt (2013), and includes two end-members as potential allochthonous DOC sources; delivered to lakes by water from near-surface organic soils (EM1) or through deeper mineral soils (EM2; Ferone & Devito, 2004; Hokanson et al., 2019). The two end-members were defined by the observed water chemistry in wells, where the sum of Mg and Ca concentrations was assumed to behave conservatively during mixing, while the concentration of DOC and A_{254} were considered to potentially act non-conservatively. We decided not to use isotopic signatures of terrestrial sources in our end-member mixing model as due to evaporative fractionation in lakes, using isotopes as a 'conservative' tracer would violate the assumptions of an end-member mixing model analysis. Furthermore, using isotopes would also violate the assumption of tracers that are significantly distinct from each other as groundwater and precipitations isotopic compositions in the Boreal Plains often overlap. We chose to focus on two primary end-members (shallow organic (EM1) and deep mineral (EM2)), which together with precipitation function as the main water sources to lakes on the Boreal Plains (Devito et al., 2017; Ferone & Devito, 2004; Plach et al., 2016; Smerdon et al., 2005). Additional terrestrial wetland sources including swamps, isolated wetlands and ephemeral draws function more like conveyors in the landscape, where they pass through shallow organics surrounding lakes (e.g. swamp and ephemeral draw), or function like lakes (e.g. isolated wetland); thus their signature is likely captured in the shallow organic end-member (EM1). Discrepancies between modelled and observed lake DOC concentrations and A_{254} were assumed to indicate influence of within-lake processes (e.g. degradation, transformation, or production). Using known ratios of DOC to A_{254} losses during bio and photodegradation, as well as having the concentrations of Chl-*a* as an indicator of autochthonous DOC production, we were able to assess the relative importance of various within-lake processes both between lakes and years.

In the first step of the mixing model, we calculated the fractional contribution from mineral (f_m) and organic (f_o) sources to each lake in each year from 2012 to 2019 (*Eqn. 2):*

$$MgCa_{Lake} = f_m \cdot MgCa_m + f_o \cdot MgCa_o / 1\text{-}C, \qquad (Eqn.\ 2)$$

where the fractional contribution from mineral (f_m) and organic (f_0) sources sum to 1 (A.2.1), $MgCa_{Lake}$ is the June-July synoptic sampling measurement of MgCa in the lake; and $MgCa_m$ and $MgCa_o$ are representative values of mineral and organic terrestrial sources (A.2.2). For $MgCa_m$, we used the average MgCa measured in mineral subsurface sources. However, geochemical signatures of mineral subsurface sources are significantly different between coarse- and fine-textured watersheds, thus separate average MgCa for coarse- (68 mg L^{-1}) and fine-textured (110 mg L^{-1}) mineral sources were used (Figure 3.3.3; Table 3.1; A.2.3). An average MgCa of 4.73 mg L^{-1} was used for organic sources representing shallow subsurface flow (0 to 10 cm) through peatlands as there was no significant difference in peatland MgCa between coarse (4.84 mg L^{-1}) and fine-textured (4.63 mg L^{-1}) watersheds (Table 3.1; A.2.3). We account for the occurrence of concentration and dilution effects in lakes between years using the factor *C*. The factor *C* represents the fractional amount by which each lake has been diluted or concentrated over the year preceding the lake sampling according to the moisture surplus or deficit between evapotranspiration and precipitation (*Eqn. 3*). We estimated factor *C* for each lake and each year of sampling from 2012 – 2019:

$C = (ET_0 - P) / D$, (*Eqn. 3*)

where ET_0 is the cumulative potential evapotranspiration (PET) over the preceding year (July 1st – June 30th) estimated using the Hamon equation (Hamon, 1963). P is the cumulative precipitation for the same period; and D is lake depth at centre calculated from lake depth at reference locations during synoptic June-July sampling trips within a given year (Chp. 1). The Hamon equation for calculating PET takes into account mean daily air temperature, day length and saturated vapour pressure, all of which were obtained from daily data collected at Red Earth weather station, located approximately 70 km from the URSA (data provided by Alberta Agriculture and Rural Development, 2020). Assuming the moisture deficit or surplus of the year preceding sampling determines concentration and dilution effects in the study lakes, we estimate that the lakes concentrate from between 4% and 22%, and dilute by 4% during our study period. The variation in concentration and dilution effects between years is dependent on lake depth and inter-annual wet-dry periods.

In the second step of the mixing model, we assumed that DOC and A_{254} act conservatively, and estimated lake DOC concentration and A_{254} using the fractional contributions of water to lakes from mineral (f_m) and organic (f_0) sources (*Eqn. 4*). However, we adjusted the end-member DOC characteristics to reflect differences in terrestrial water contributions during spring freshet and summer that reach lakes when said lakes receive the majority of inputs. We assumed that two thirds of the water received by the lake prior to summer sampling campaigns in July was received during spring freshet, and one third following spring freshet. Freshet included average water chemistry data collected from terrestrial end-member sources from April to May (2012 – 2019), when snowmelt typically occurs and often dilutes chemical constituents of the terrestrial water sources entering lakes. We found significant differences in DOC concentration and A_{254} of organic sources (EM1) between spring freshet and summer (A.3.4), thus we adjusted end-member concentrations to account for differences in DOC concentrations and A_{254} between spring freshet (April to May) and summer (July) samples. There were no significant differences in DOC concentrations between deeper mineral (EM2) samples collected during spring freshet and summer, and therefore the mixing model does not use freshet values for mineral sources (A.3.4). There was insufficient data to test for differences between A_{254} and $SUVA_{254}$ between spring freshet and summer samples in forest and groundwater samples.

The second step uses the following equation, and assumed no within-lake losses of terrestrially derived DOC and A_{254}, and no algal DOC contributions to the lake DOC pool (i.e. if DOC and A_{254} mixed conservatively).

$$DOC_{Est} = f_m \cdot DOC_m + f_o \cdot DOC_o, \qquad (Eqn.\ 4)$$

where, DOC_{Est} is the estimated lake DOC concentration in the event of no within-lake transformation of DOC or algal DOC contributions; and DOC_m and DOC_o are the DOC concentration for mineral and organic sources, respectively. After adjustments of end-member concentrations to reflect differences in terrestrial water contributions during spring freshet and summer, we found that the DOC concentration and A_{254} of organic sources were not significantly different between coarse and fine-textured watersheds (A.3.3) and used values of 46.28 mg C L^{-1} and 1.68 cm^{-1} in the mixing model, respectively. $SUVA_{254}$ of organic sources was calculated using average A_{254} and [DOC] for both coarse and fine-textured watersheds as 3.63 L mg^{-1} C m^{-1}. The DOC concentration of mineral sources was not significantly different between coarse (11.60 mg C L^{-1}) and fine-textured (14.09 mg C L^{-1}) watersheds, thus an average DOC concentration of 12.38 mg C L^{-1} was used (A.3.3). However, A_{254} of mineral sources was significantly different between coarse (0.12 cm^{-1}) and fine-textured (0.35 cm^{-1}) watersheds and separate values used in the model

(A.3.3). The $SUVA_{254}$ of mineral sources used in the end-member model was calculated using average A_{254} and DOC concentration for coarse and fine-textured watersheds as 0.97 L mg^{-1} C m^{-1} and 2.83 L mg^{-1} C m^{-1}, respectively.

The difference between modelled and observed terrestrial DOC (ΔDOC) and A_{254} (ΔA_{254}) was estimated by subtracting observed field values for DOC concentration or A_{254} from modelled values calculated in the mixing model. We estimated the loss of DOC and A_{254} attributed to different mechanisms (photodegradation and biodegradation) using the overall losses estimated (ΔDOC and ΔA_{254}), and the ratio between DOC and A_{254} losses during light incubations. The ratio between DOC and A_{254} losses during light incubations was obtained from incubation experiments undertaken on stream samples collected in 2019 and was estimated that for every 10.11 units of A_{254} lost, 1 unit of DOC was lost (Orlova et al., in prep). We then estimated the loss of DOC attributed to photodegradation mechanisms, and assumed that all A_{254} lost was attributed to photodegradation mechanisms using the following equation:

$$\Delta DOC^{Photo} = \Delta A_{254}{}^{Photo} \cdot Inc^{UV} \qquad \textit{(Eqn. 5)}$$

Using the residual DOC loss ($\Delta DOC - \Delta DOC^{Photo}$), we also estimated whether the remaining difference could be attributed to biodegradation processes (positive values) or autochthonous DOC production (negative value).

3.2.6 Statistical analyses

We used principal component analysis to characterise the water quality of different terrestrial sources. Principal component analysis was performed using the function prcomp in stats v3.6.2 in base R (Venables & Ripley, 2002) and factoExtra package (Kassambara & Mundt, 2017). All 15 water quality variables were scaled before conducting a principal component analysis because this analysis uses sums of squares where if a variable is on a different scale it will dominate the principal component analysis procedure. The separate groups, representing distinct terrestrial sources, identified in this analysis were used to as end-members in a hydrological mixing model. To identify significant differences in water chemistry variables between terrestrial sources, both within and between coarse and fine-textured HRAs, we conducted a series of two-sample *t*-tests following Shapiro-Wilks tests for normality.

We used the long-term (2012-2019) average net lake DOC and A_{254} change to assess spatial variability in average loss or gain of DOC and A_{254} in the study lakes, and the mechanisms by which DOC and A_{254} were lost or gained. Inter-annual variability of DOC and A_{254} loss or gain was assessed using the standard deviation (SD) of net lake DOC and A_{254} change throughout the study period (n = 8 per lake). We used long-term average values (spatial variability; 2012 - 2019) and SD values (inter-annual variability) in a Kruskal-Wallis test on ranks for data, to test significant differences across HRAs. For each statistical test, p-values <0.05 (95% confidence interval) were considered significant. To identify which HRAs were significantly different, we also conducted multiple pairwise-comparisons between groups using the 'pairwise.wilcox.test' function within the 'stats v3.6.2' package in R.

3.3 Results

3.3.1 Water chemistry of terrestrial sources in the Boreal Plains

We found broadly distinct water chemistry for each sampled terrestrial end-member, with 63% of the total variance of 15 water quality variables explained by two principal components (Figure 3.3.3). Water quality variables including pH, EC, and base cations and anions (potassium (K), sodium (Na), sulphate (SO_4), magnesium (Mg), calcium (Ca) & bicarbonate (HCO_3)) loaded on principal component 1 (PC1; 48.7%). Nutrient water quality variables (total dissolved nitrogen (TDN) & total dissolved phosphorus (TDP)), total iron (Fe) and chloride (Cl) loaded on principal component 2 (PC2; 14.4%). Although auto-correlated as $SUVA_{254}$ is a product of aromatic-rich DOC, DOC characteristics (DOC, $SUVA_{254}$ & A_{254}) loaded between PC1 and PC2.

Water samples from deeper peat and shallow peat tended to cluster, both with relatively dilute, acidic waters with high DOC. Although there was some overlap, water samples from deeper peat (>25 cm below ground) showed significantly higher DOC concentration and A_{254} compared to shallow peat water (0 – 25 cm below ground; Figure 3.3.3; Table 3.1; A.2.4) in both coarse and fine-textured watersheds. However, $SUVA_{254}$ showed no significant difference between shallow and deep peatland sources (A.2.4). We conceptualised shallow water from the peatland acrotelm, and with higher hydraulic conductivity that the underlying catotelm, to be the dominant organic source to lakes, and hereafter, peatland sources refer to shallow (0 – 25 cm) flow path samples. Furthermore, there was no significant difference in the DOC concentration, A_{254}, and $SUVA_{254}$ of shallow peatland sources between coarse and fine-textured watersheds (Table 3.1; A.2.6).

Forest groundwater, both shallow and deep, had higher ion concentrations and lower DOC concentrations and A_{254} than peatland water (Figure 3.3.3; Table 3.1; A.2.6). The water chemistry of forest groundwater was in turn influenced both by depth (shallow versus deep) and by HRA (fine vs coarse). Forest groundwater (shallow and deep) differed between coarse and fine-textured watersheds, with deeper groundwater in coarse watersheds similar to shallower forest groundwater, but deep groundwater in fine-textured watersheds characterized as significantly more ion rich and DOC poor when compared to shallower forest sources (Table 3.1; A.2.7).

Ephemeral draw, isolated marsh and swamp sources were characterised by high nutrients, iron, DOC concentration, and A_{254} (Figure 3.3.3; Table 3.1). As there was overlap between ephemeral draw, isolated wetland, and swamp sources (Figure 3.3.3; Table 3.1), and we conceptualised these sources to have specific landscape functions for conveying water and solutes through the landscape, we grouped these sources as conveyors (see conveyor definition in methods).

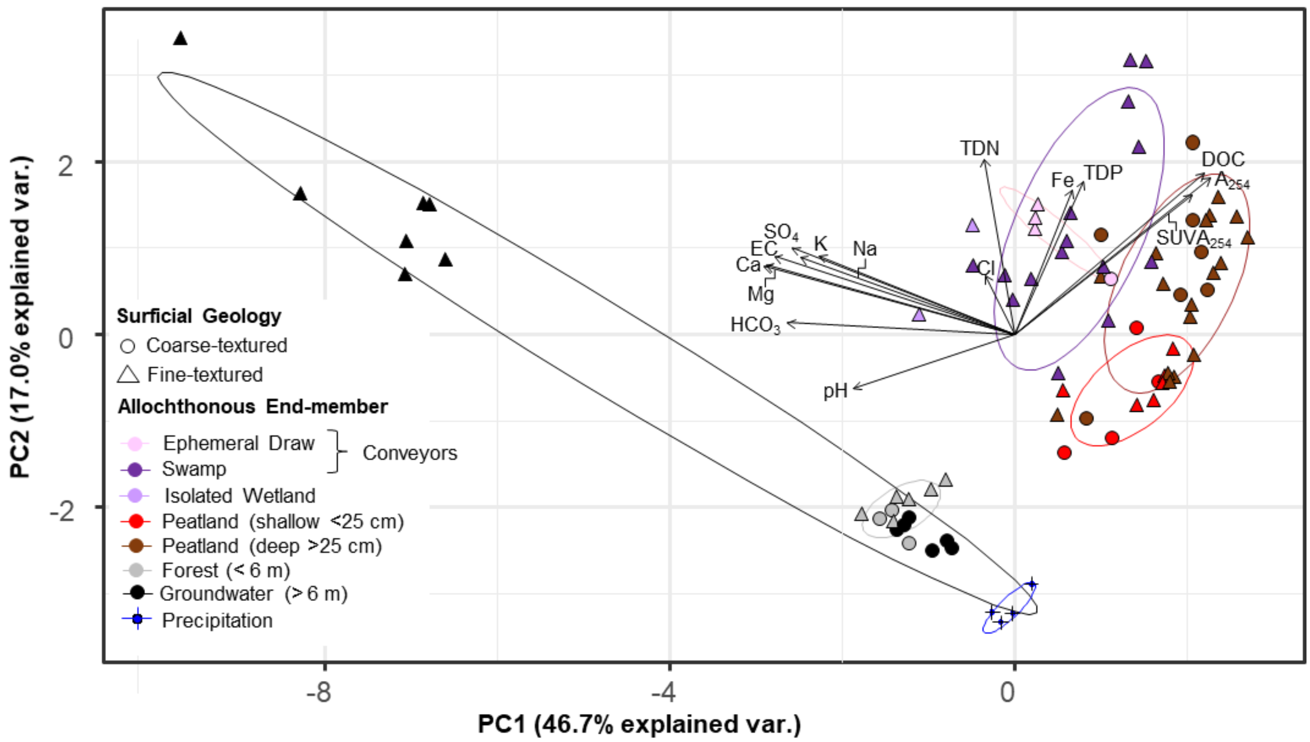


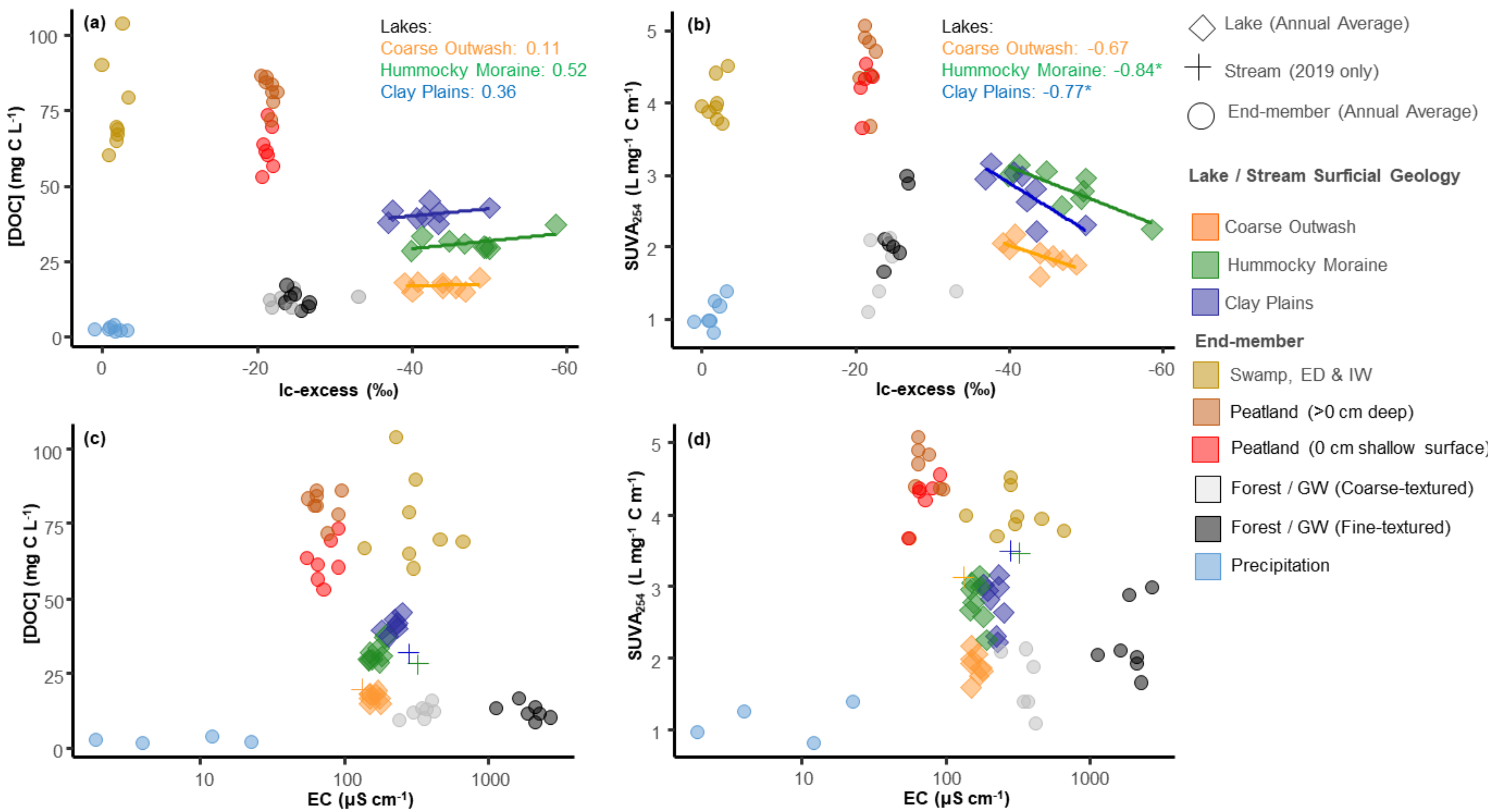
Figure 3.3.3: Principal component analysis of water quality parameters from samples representing different terrestrial end-member sources. Each point represents a site from a terrestrial end-member source for a given year within the study period (2012 – 2019). The shape of each point indicates the substrate texture of each site (coarse-textured = triangle, fine-textured = circle), or precipitation samples (cross). The statistically generated ellipses shown represents the terrestrial end-member sources that group together based on their individual water quality signatures.

Table 3.1: Comparison of average water chemistry parameters for terrestrial end-member sources to lakes between lakes in fine- and coarse-textured watershed settings. Averages±1 standard deviation reported unless otherwise noted.

Surficial Geology	End-member	# of Sites	Sample #	DOC (mg C L^{-1})	A_{254} (cm^{-1})	$SUVA_{254}$ (L mg^{-1} C m^{-1})	EC (µS cm^{-1})	lc-excess (‰)	TDN (µg L^{-1})	TDP (µg L^{-1})	MgCa (mg L^{-1})
Coarse-textured	Peatland (shallow)	*2*	*7*	55.7±10.7	1.9±0.5	3.8±0.3	61.3±22.1	-22.0±0.7	1100±760	101.4±84.2	1.4±0.7
	Peatland (deep)	*3*	*16*	79.2±11.6	3.6±0.8	4.6±0.9	60.9±14.0	-21.8±1.7	2290±1560	371±398	5.3±1.1
	Ephemeral Draw	*1*	*2*	106±26.4	5.0±0.5	4.9±1.7	91.3±15.1	-1.0±1.6	2180±1480	3.0±0	19.6±2.3
	Swamp	0	---	---	---	---	---	---	---	---	---
	Isolated Wetland	0	---	---	---	---	---	---	---	---	---
	Forest	*1*	*5*	9.6±3.9	0.1±0.03	1.1±0.5	339±71.0	-22.3±0.5	1860±564	33.8±56.2	76.2±4.0
	Groundwater	*6*	*19*	12.6±6.2	0.1±0.02	2.1±0.2	351±124	-25.1±7.9	1110±854	70.4±197	65.4±32.5
	Lake	*8*	*64*	17±3.6	0.3±0.1	1.9±0.4	160±47.2	-43.8±5.2	1040±428	12.6±8.9	32.2±7.8
Fine-textured	Peatland (shallow)	*3*	*17*	65.0±7.6	2.7±0.2	4.3±0.4	76.7±25.8	-21.0±0.7	1290±1260	101±283	5.1±4.0
	Peatland (deep)	*4*	*25*	81.7±12.6	3.6±0.8	4.4±0.7	79.9±22.2	-21.5±1.7	1280±515	289±317	4.2±1.8
	Ephemeral Draw	*3*	*11*	86.7±28.9	3.3±0.9	3.5±0.3	489±139	0.3±1.3	2970±1350	107±62	92.3±14.0
	Swamp	*3*	*27*	70.2±15.5	2.9±0.8	4.1±0.6	320±220	-1.4±1.6	2210±1280	400±413	58.5±26.0
	Isolated Wetland	*4*	*11*	61.2±34.3	1.7±0.9	4.0±0.6	176±170	-3.8±5.0	2890±1500	1740±1370	30.1±35.9
	Forest	*4*	*11*	14.1±7.6	0.3±0.1	2.8±1.1	450±82.9	-24.5±1.9	1230±2020	17.4±28.3	113±37.3
	Groundwater	*3*	*20*	12.0±5	0.2±0.1	1.9±1	2620±946	-25.6±2.7	2070±1230	61.2±108	671±53.5
	Hummocky Lake	*12*	*107*	31.2±9.2	0.9±0.3	2.8±0.5	164±81.3	-47.5±9.0	1750±479	43.6±75.8	27.2±15.9
	Plains Lake	*12*	*96*	40.7±7	1.1±0.3	2.8±0.7	217±122	-41.9±4.4	1920±681	111±140	36.8±18.2
	Precipitation	*2*	*30*	2.4±1.4	0.02±0.004	1.1±0.6	7.2±9.4	-1.4±5.9	371±362	33.8±48.6	0.4±0.5

3.3.2 Comparison of water chemistry of lakes, streams, and terrestrial end-members

We found that lakes had DOC, $SUVA_{254}$, and EC characteristics that were intermediate between the terrestrial end-members, but also that lakes had more depleted lc-excess than any of the terrestrial end-members (Figure 3.3.4). Lakes in coarse, fine hummocky, and fine plains watersheds, had general differences, where DOC concentrations, $SUVA_{254}$, and EC concentrations were lower in coarse lakes compared with lakes in fine-textured watersheds (Figure 3.3.4). We found similar ranges in lc-excess values among lakes in different HRAs; however, lakes in fine-textured watersheds, particularly fine hummocky systems, typically showed more variability than coarse lakes (Figure 3.3.4). Lake $SUVA_{254}$ was higher in years when lc-excess was less depleted, while neither DOC concentration nor EC of lakes co-varied temporally with lc-excess (Figure 3.3.4). Lakes generally had lower $SUVA_{254}$ (1.90 - 2.81 L mg^{-1} C m^{-1}) than streams (average 3.43 L mg^{-1} C m^{-1}; Figure 3.3.4; Figure 3.3.5). Lake DOC concentrations were however similar to the streams (average stream DOC – 28.1 mg C L^{-1}; Lake DOC - 16.56 - 38.78 mg C L^{-1}), although lakes in fine-plains HRA were found even to have higher DOC concentration than the streams (Figure 3.3.4; Figure 3.3.5).



(a)
Lakes:
Coarse Outwash: 0.11
Hummocky Moraine: 0.52
Clay Plains: 0.36
[DOC] (mg C L-1)
lc-excess (‰)
(b)
Lakes:
Coarse Outwash: -0.67
Hummocky Moraine: -0.84*
Clay Plains: -0.77*
SUVA254 (L mg-1 C m-1)
lc-excess (‰)
(c)
[DOC] (mg C L-1)
EC (μS cm-1)
(d)
SUVA254 (L mg-1 C m-1)
EC (μS cm-1)
Lake (Annual Average)
Stream (2019 only)
End-member (Annual Average)
Lake / Stream Surficial Geology
Coarse Outwash
Hummocky Moraine
Clay Plains
End-member
Swamp, ED & IW
Peatland (>0 cm deep)
Peatland (0 cm shallow surface)
Forest / GW (Coarse-textured)
Forest / GW (Fine-textured)
Precipitation

Figure 3.3.4: Mixing plots demonstrating annual average DOC characteristics, lc-excess, and electrical conductivity signatures of lakes relative to terrestrial end-member sources. Mixing plots show annual average measurements of [DOC] and $SUVA_{254}$ against lc-excess (top), and electrical conductivity (bottom). Lakes and stream points are grouped by hydrologic response area (HRA), representing the average for a given variable of all lakes located within each HRA (Coarse (orange, n = 8), Fine Hummocky (green, n = 13), and Fine Plains (blue, n = 12)) for each year from 2012 – 2019 (note streams represent 2019 data only). Each point for terrestrial end-member sources represents the average for a given variable of all sites that are classified as an individual end-member (conveyor, peatland (shallow & deep), forest / groundwater (coarse or fine), and precipitation) for a given year from 2012 – 2019. The shape of each point distinguishes terrestrial sources (circles), lakes (diamonds) and streams (crosses). Linear regressions are applied to annual lake measurements in panels (a) and (b), * indicates a significant relationship ($p < 0.05$)

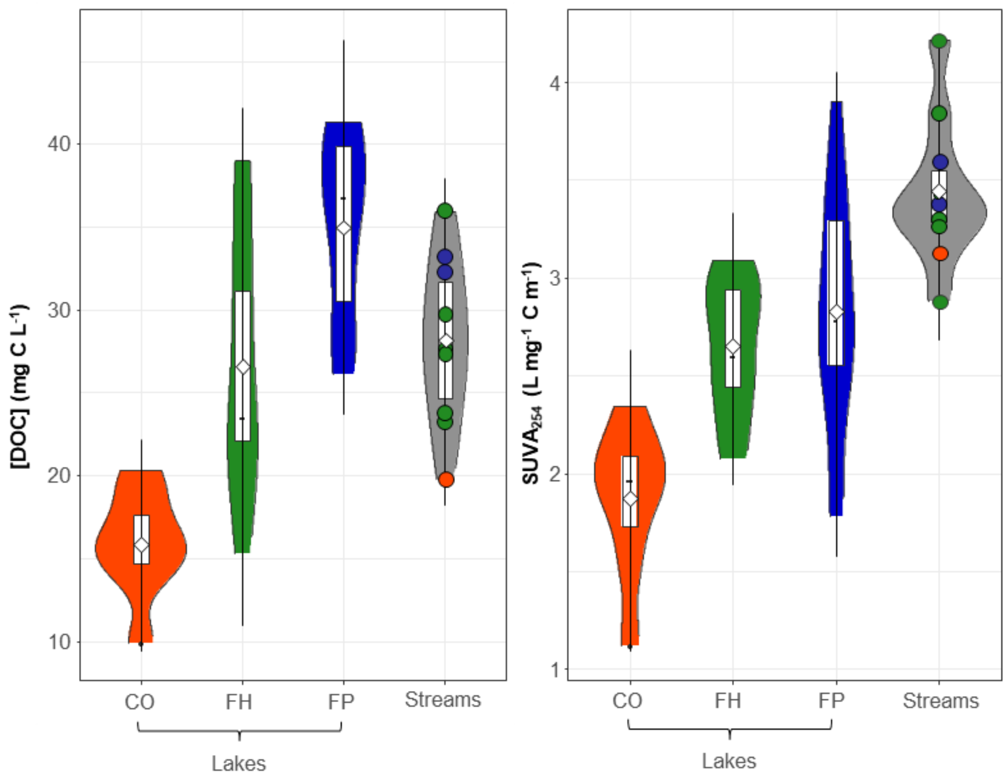


Figure 3.3.5: Violin-plots showing (a) DOC concentration, and (b) $SUVA_{254}$ of lakes located in each Hydrologic Response Area (HRA; Coarse (CO; orange, *n* = 8), Fine Hummocky (FH; green, *n* = 13), and Fine Plains (FP; blue, *n* = 12)), and streams (grey, *n* = 10) in 2019. Error bars in panels (a) & (b) represent standard deviation. The point range represents the mean for lakes in each HRA (black circle), and standard deviation (black line), whilst bars represent the median and white boxes represent the inter-quartile range. The stream violin-plot also includes individual data points for each stream in different HRAs (Coarse (orange, n = *1*), Fine Hummocky (green, *n* = 2), and Fine Plains (blue, *n* = 7)).

3.3.3 Hydrological mixing model results

3.3.3.1 Differences between observed and modelled lake DOC and A_{254}

Using the two end-member mixing model, where Mg+Ca was the conservative tracer, we were able to estimate the proportion of lake water derived from mineral or peat sources, and assess whether observed lake DOC concentrations and A_{254} were lower or higher than expected based on mixing of the terrestrial end-members. When modelled and observed DOC concentrations and A_{254} do not match, it suggests that these behave non-conservatively. Lower observed DOC concentrations or A_{254} than modelled in the mixing model suggests that there have been net DOC or A_{254} losses in the terrestrial end-members along the soil-stream-lake continuum, while greater observed than modelled concentrations suggests that there have been net DOC or A_{254} gains.

The average proportion of mineral water contributions received by coarse lakes (42%) was larger than mineral water contributions to fine-textured lakes (fine hummocky: 21%; fine plains: 29%; A.2.1). However, lakes in all HRAs received, on average, a greater proportion of peatland waters, where fine hummocky lakes received the largest contributions from peatland sources (79%), followed by fine plains (71%) and coarse lakes (58%). We determined that lakes in coarse and fine hummocky had observed lake DOC concentrations that were on average across lakes and years 15 and 10 mg C L^{-1} lower, respectively, than modelled based on conservative mixing (Figure 3.3.6; Table 3.2). Lakes in fine plains watersheds had DOC concentrations that were, on average, higher than modelled based on conservative mixing (Figure 3.3.6; Table 3.2). All lakes had lower observed A_{254} than modelled from the mixing model, although this difference was lower for lakes in the fine plains than in the coarse and fine hummocky lake watersheds (Figure 3.3.6; Table 3.2). We also found that the difference between modelled and observed DOC concentrations of streams in 2019 were similar to differences observed in the study lakes for that same year

(Figure 3.3.6). However, the difference between modelled and observed A_{254} in streams were lower than A_{254} differences in study lakes across all HRAs (Figure 3.3.6).

Similar trends in the relative differences between modelled and observed DOC characteristics were found among HRAs across three different model scenarios (Figure 3.3.6);, however, the magnitude of losses or gains determined from modelled minus observed values varied across the scenarios.

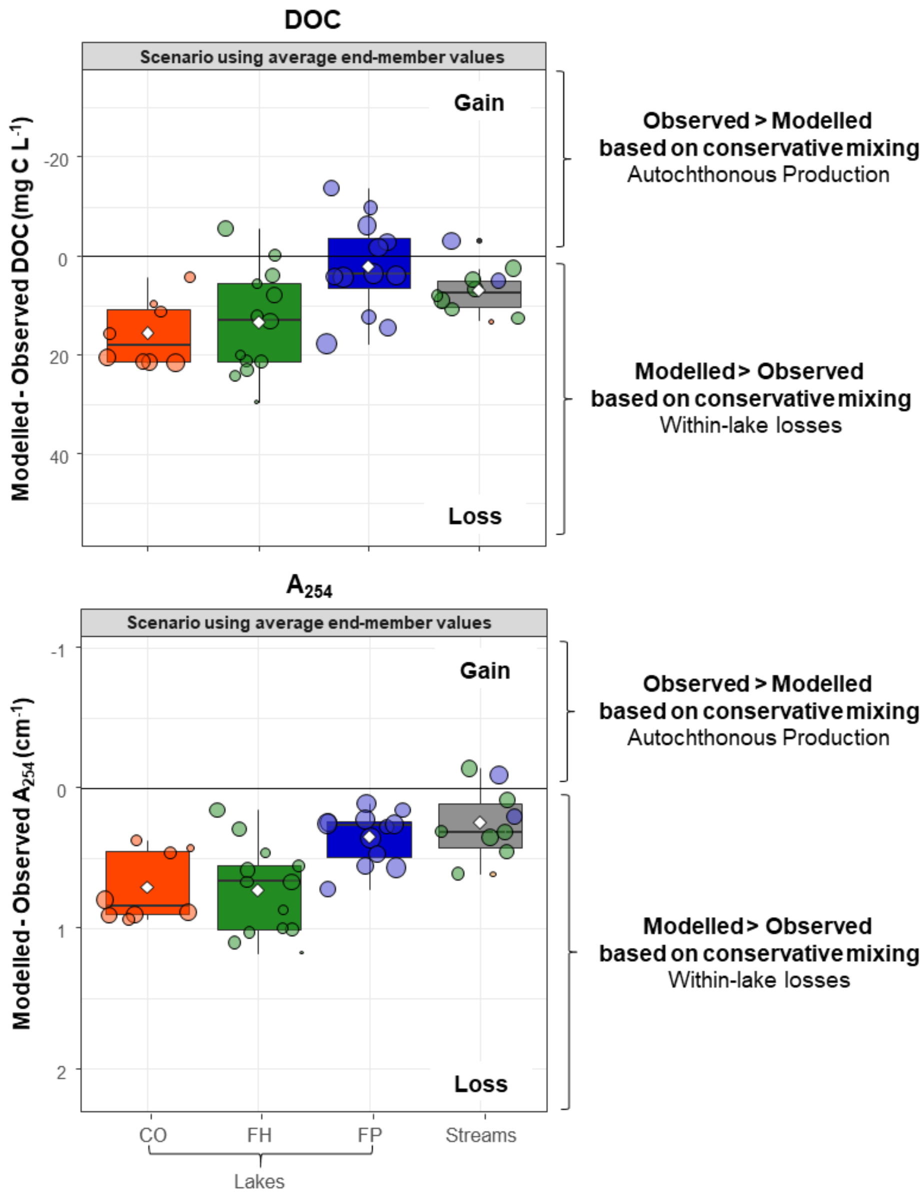

DOC
Scenario using average end-member values
Gain
Loss
Modelled - Observed DOC (mg C L-1)
-20
0
20
40
Observed > Modelled
based on conservative mixing
Autochthonous Production
Modelled > Observed
based on conservative mixing
Within-lake losses
A254
Scenario using average end-member values
Gain
Loss
Modelled - Observed A254 (cm-1)
-1
0
1
2
Observed > Modelled
based on conservative mixing
Autochthonous Production
Modelled > Observed
based on conservative mixing
Within-lake losses
CO
FH
FP
Streams
Lakes

Figure 3.3.6: Difference in modelled and observed DOC (top panel) and A_{254} (bottom panel) in lakes located in each Hydrologic Response Area (Coarse (CO; orange, *n* = 8), Fine Hummocky (FH; green, *n* = 13), and Fine Plains (FP; blue, *n* = 12)), and streams (grey, *n* = 10) calculated in the end-member mixing analyses. White diamonds on each plot represent the average difference between modelled and observed DOC or A_{254}. Each point (circle) represents the difference between modelled and observed DOC or A_{254} within a lake for a given year, and the size of each circle indicates the extent of connected wetland in each lake watershed. The lower and upper hinges of each boxplot correspond to the first and third quartiles (the 25th and 75th percentiles) of the difference between modelled and observed DOC and A_{254} for lakes in each HRA and streams. Upper and lower whiskers represent the largest and smallest values for the difference between modelled and observed DOC and A_{254}, but no further than 1.5 x the interquartile range of the upper and lower hinges. Data outside 1.5 x the interquartile range are represented as black circles and considered outliers.

Table 3.2: Spatial and Inter-annual variability in the difference between observed and modelled DOC concentration and A_{254} calculated in a hydrological mixing model for lakes in each Hydrologic Response Area throughout the study period from 2012 to 2019.

	Spatial Variability of the difference between observed and modelled lake DOC characteristics					Inter-annual Variability of the difference between observed and modelled lake DOC characteristics				
	Minimum	Maximum	Average	Standard Deviation	p-value	Minimum	Maximum	Average	Standard Deviation	p-value
Modelled - Observed DOC (mg C L^{-1})										
Coarse Outwash *n* =8	9.83	22.81	15.33	4.18	4.38E-04*	2.24	5.45	3.31	1.00	0.20
Hummocky Moraine *n* = 13	-8.47	28.27	10.23	11.18		1.76	9.55	4.77	2.44	
Clay Plains *n* = 12	-13.44	19.24	-2.27	2.27		1.56	6.53	4.66	4.66	
Modelled - Observed A_{254} (cm-1)										
Coarse Outwash *n* = 8	0.48	0.86	0.71	0.13	5.51E-04*	0.09	0.25	0.15	0.05	0.15
Hummocky Moraine *n* = 13	-0.12	1.11	0.61	0.36		0.08	0.42	0.21	0.10	
Clay Plains *n* = 12	-0.12	0.83	0.22	0.22		0.12	0.34	0.20	0.20	

Note: The signs provided for minimum, maximum and average values indicate gains (where modelled values are less than observed values resulting in a –ve value) and losses (where modelled values are greater than observed values resulting in a +ve value).

Using the assumption that the difference between modelled and observed A_{254} is due to photodegradation, and that photochemical loss of A_{254} is associated with DOC loss at a 10:1 ratio, we could also assess how much of the difference between modelled and observed DOC concentration may be due to photodegradation (Figure 3.3.7). Differences between modelled and observed DOC concentrations suggested that the net DOC loss attributed to photochemical degradation were similar between coarse and fine hummocky lakes, while photochemical losses were lower for lakes in the fine plains (Figure 3.3.7). The net A_{254} loss attributed to photodegradation was also greatest in coarse and fine-hummocky lakes, followed by the fine plains (Figure 3.3.7).

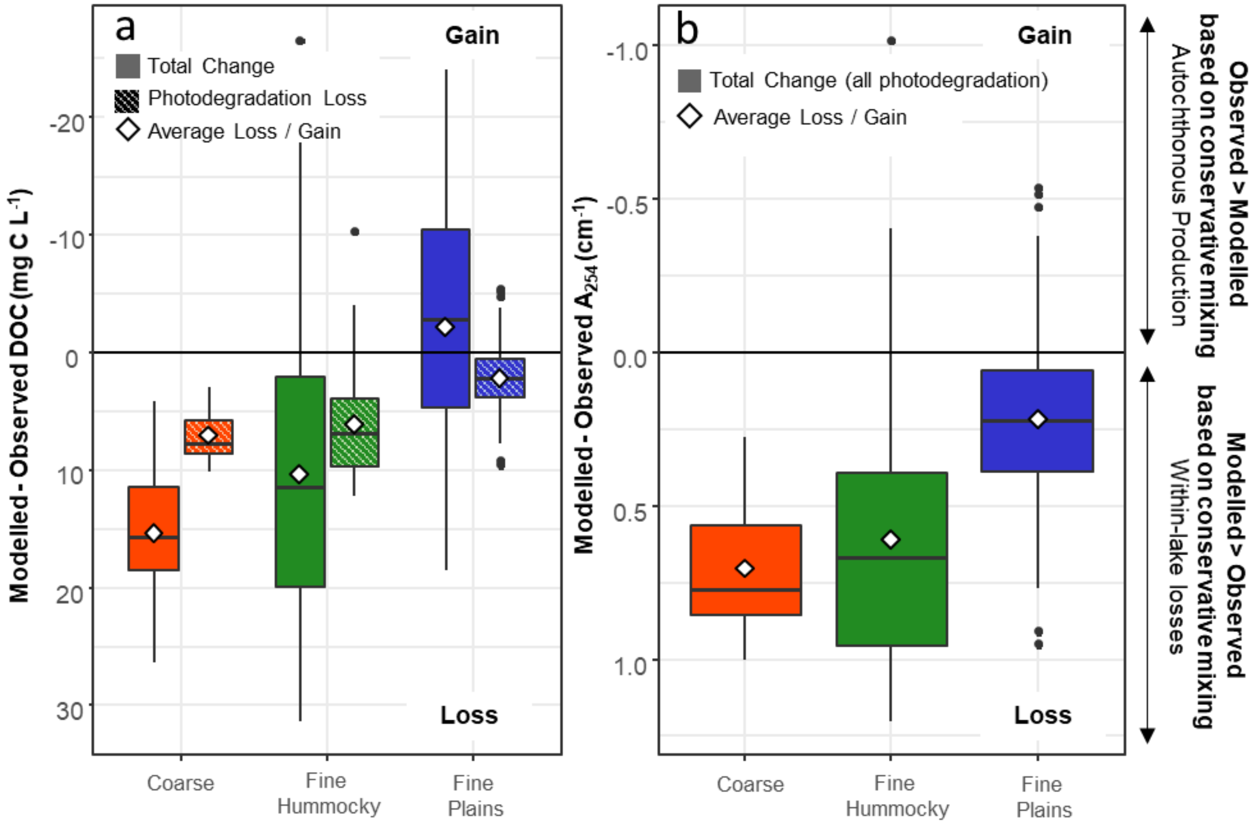


Figure 3.3.7: Relative importance of within-lake processes (autochthonous DOC production and photodegradation) for differences between modelled and observed (a) DOC and (b) A_{254} change for lakes located in each Hydrologic Response Area from 2012 to 2019. Coarse (orange, n = 8), Fine Hummocky (green, n = 13), and Fine Plains (blue, n = 12)). The diagonal stripe patterning of boxplots in panel (a) indicates estimated DOC losses attributed to photodegradation processes, whilst solid portions of each bar represent total net DOC change (losses attributed to photodegradation and biodegradation or gains via autochthonous production). In panel (b), all losses are assumed to be due to photodegradation. White diamonds represent the average differences between observed and modelled DOC or A_{254}.

Processes responsible for the differences between modelled and observed lake DOC and A_{254} could be further explored by examining differences for individual lakes across all years (Figure 3.3.8). The relationship between the difference in modelled and observed DOC change and lc-excess varied among HRAs and showed weaker correlation when compared to A_{254} and lc-excess. Fine plains and coarse lakes had no significant relationship between the difference in modelled and observed DOC and lc-excess, as the overall negative relationship was driven by the relationship with fine hummocky lakes. We also determined that overall difference between modelled and observed DOC had a positive linear relationship with Chl-*a* (Figure 3.3.8). Greater observed than modelled DOC in lakes with high Chl-*a* suggests that autochthonous DOC production is greater than DOC losses, and vice versa. This relationship was general across lakes in all HRAs, but especially showed that fine-plains lakes and fine hummocky lakes had larger proportions of connected wetland in the watershed that were strongly influenced by autochthonous DOC production. In contrast, we found significant positive linear relationships between A_{254} and lc-excess in fine-textured lakes, both Fine Hummocky and Fine Plains, where a more depleted lake lc-excess, as an indicator of longer lake water residence time, was associated with greater differences between modelled and observed A_{254} across all lakes. There was no relationship between A_{254} and lc-excess in coarse outwash lakes. The difference between modelled and observed A_{254} also showed a positive linear relationship with Chl-*a*; however, more lakes showed greater modelled than observed A_{254} in lakes when compared to DOC, thus suggesting A_{254} losses are greater than production or that the coloured fraction of autochthonous DOC is low enough that the effects on A_{254} are negligible.

We also assessed the relationship between lc-excess with Chl-*a* and connected wetlands in the watershed across lakes to establish any spurious relationships with the difference in modelled and observed DOC or A_{254}. We found no significant relationships between lc-excess and Chl-*a* among HRAs. The relationship between lc-excess and connected wetland in the watershed of each lake showed positive relationships in coarse and fine hummocky lakes, whilst fine plains lakes showed no relationship.

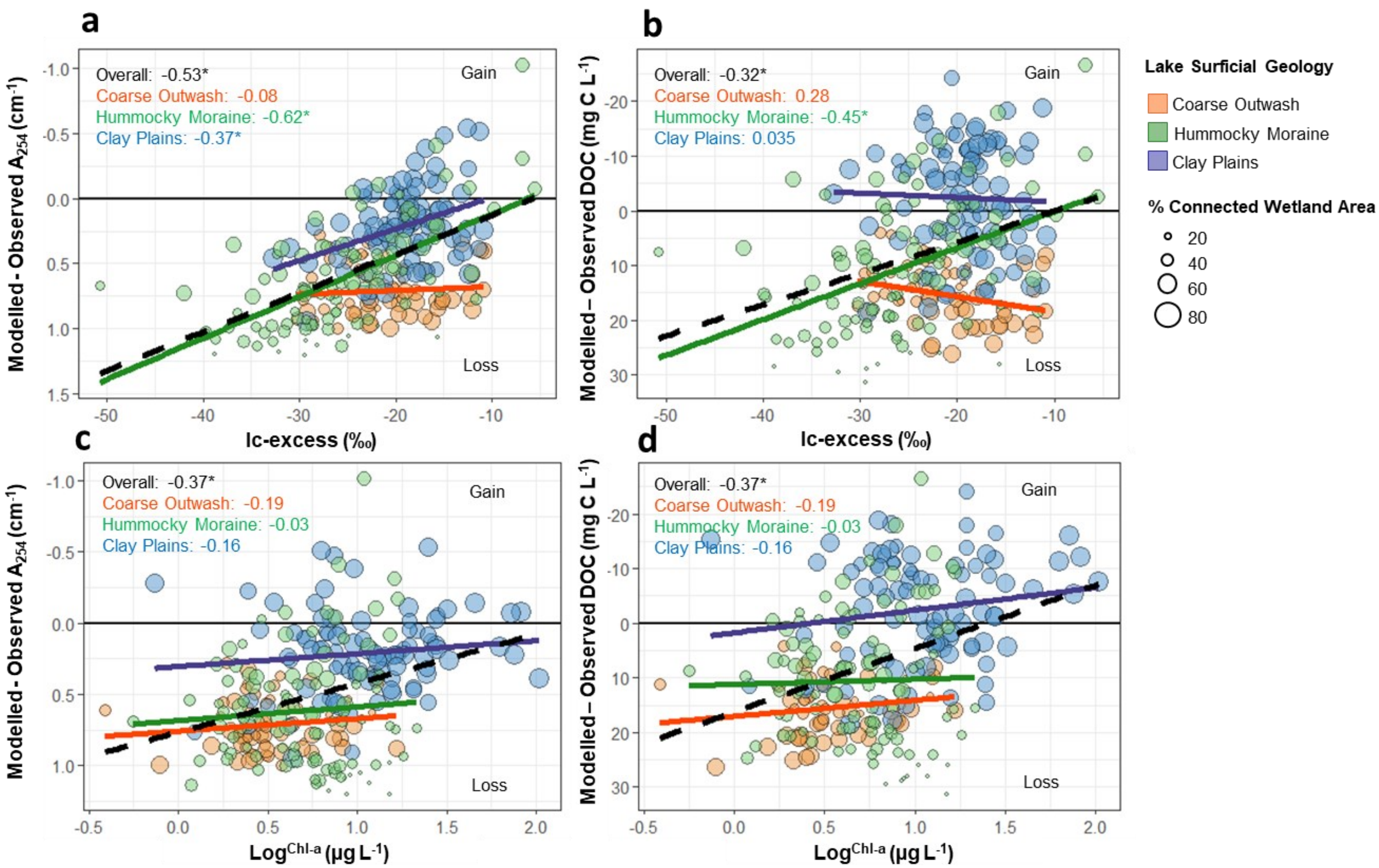


Figure 3.3.8: Relationships between modelled and observed A_{254} and DOC change with lc-excess, and chlorophyll-a across all study lakes from 2012 to 2019. Each point represents a sample collected from an individual lake in an individual year during the study period (2012 – 2019), and is coloured according to HRA of the lake watershed (CO = Coarse (orange, *n* = 8), FH = Fine Hummocky (green, *n* = 13), and FP = Fine Plains (blue, *n* = 12)). In panels (a-d), the size of each point indicates the proportion of connected wetland in the watershed. A linear regression line is presented for the relationships between variables for lakes in each HRA, whilst the black dashed line represents a linear regression applied to all lakes in the study area. R values (correlation coefficients) for each regression are presented in the top left of panels.

3.3.4 Inter-annual variability in the difference between modelled and observed lake DOC and A_{254}

We examined the inter-annual variability in the difference between modelled and observed lake DOC and A_{254} to make assessments on the sensitivity on the relative dominance of various processes that either remove or produce DOC and A_{254} to inter-annual wet-dry cycles. For both DOC and A_{254}, greater differences between modelled and observed values were associated with generally dry cycles; however, this trend was more pronounced for A_{254} when compared to DOC.

Inter-annual variability was quantified using the standard deviation (SD) of the difference between modelled and observed DOC and A_{254} throughout the study period (n = 8 per lake (2012 – 2019); Figure 3.3.9; Table 3.2). The average SD in the difference between modelled and observed DOC and A_{254} varied among HRAs and was greatest for fine hummocky lakes (DOC: 4.77 ± 2.44 mg C L^{-1}; A_{254}: 0.21 ± 0.10 cm^{-1}), and fine plains lakes (DOC: 4.66 ± 1.55 mg C L^{-1}; A_{254}: 0.20 ± 0.07 cm^{-1}), and least in coarse lakes (DOC: 3.31 ± 1.00 mg C L^{-1}; A_{254}: 0.15 ± 0.05 cm^{-1}). However, differences in the inter-annual variability of the removal or production of DOC and A_{254} among HRAs were not statistically significant (Table 3.2). We also found that, on average greater modelled than observed DOC and A_{254}, which suggests losses were greater during dry years, with exception of fine plains lakes, which showed greater observed than modelled values, indicative of autochthonous production in most years.

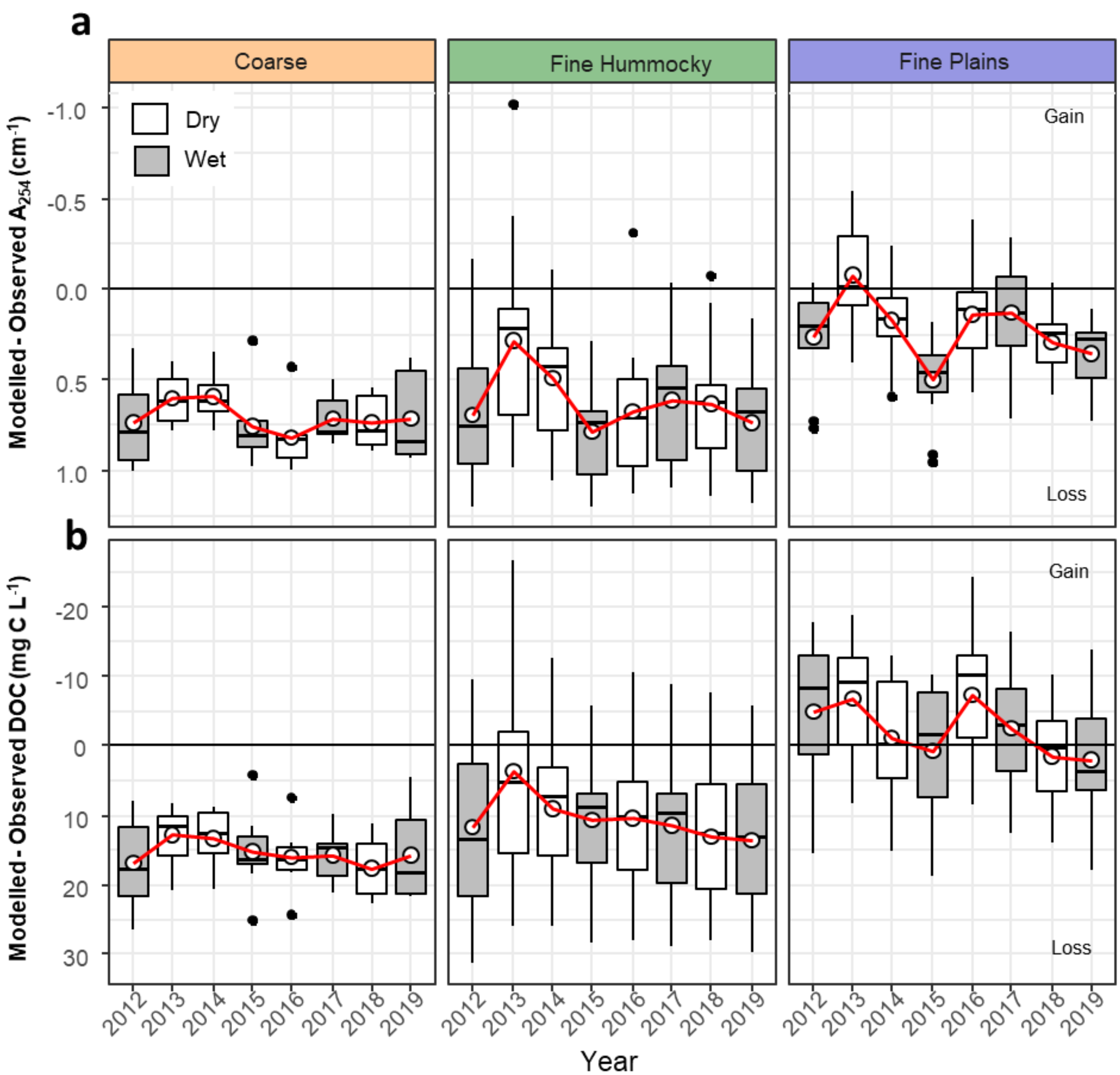


Figure 3.3.9: Time series showing the difference between modelled and observed (a) A_{254}, and (b) DOC, for lakes in each Hydrologic Response Area from 2012 – 2019. The red line facilitates visualisation of the time series trend. Grey bars indicate relatively dry years and white bars indicate relatively wet years. White circles represent the average difference between observed and modelled A_{254} or DOC for each year.

3.4 Discussion

Our study showed that spatial variability in lake DOC concentration and chemical composition was predominantly influenced by mixing of terrestrial sources, whilst inter-annual variability was strongly influenced by within-lake processes such as photochemical degradation and autochthonous production. The relative importance of these processes was found to vary both among lakes and years, with the variability tied to lake and lake watershed attributes – especially surficial geology and wetland cover in the lake watershed. This study confirms results from other studies that show Boreal Plains lakes received varying quantities of water from terrestrial sources associated with differences in surficial geology, including 1) organic peatland, and 2) shallower forest groundwater and deeper groundwater (hereafter peatland and mineral soil, respectively), in addition to precipitation, each with different water chemistry signatures (Devito et al., 2000; Ferone & Devito, 2004, Hokanson et al., 2019; Plach et al., 2016). Synthesis of this synoptic lake study and years of research on hydro-chemical sources and processes on the Boreal Plains allowed the development of a conceptual model demonstrating the loss or production of DOC and A_{254} in Boreal Plains lakes associated with landscape and inter-annual wet-dry periods (Figure 3.3.10). This study provides new insights into the determinants of lake DOC quantity and composition in landscape settings with lakes that are both DOC and nutrient rich, have complex hydrologic connectivity to the surrounding landscape, and have equally complex hydrologic and biogeochemical responses to inter-annual wet-dry periods. Therefore, this study is important for predicting the implications of a shifting climate upon the balance of DOC in Boreal Plains lakes, which has been shown to be critical for several ecosystem services (Algesten et al., 2004; Cole et al., 2007; Emelko et al., 2011; Karlsson et al., 2009; Solomon et al., 2015; Tranvik, 1988; Williamson et al., 2009).

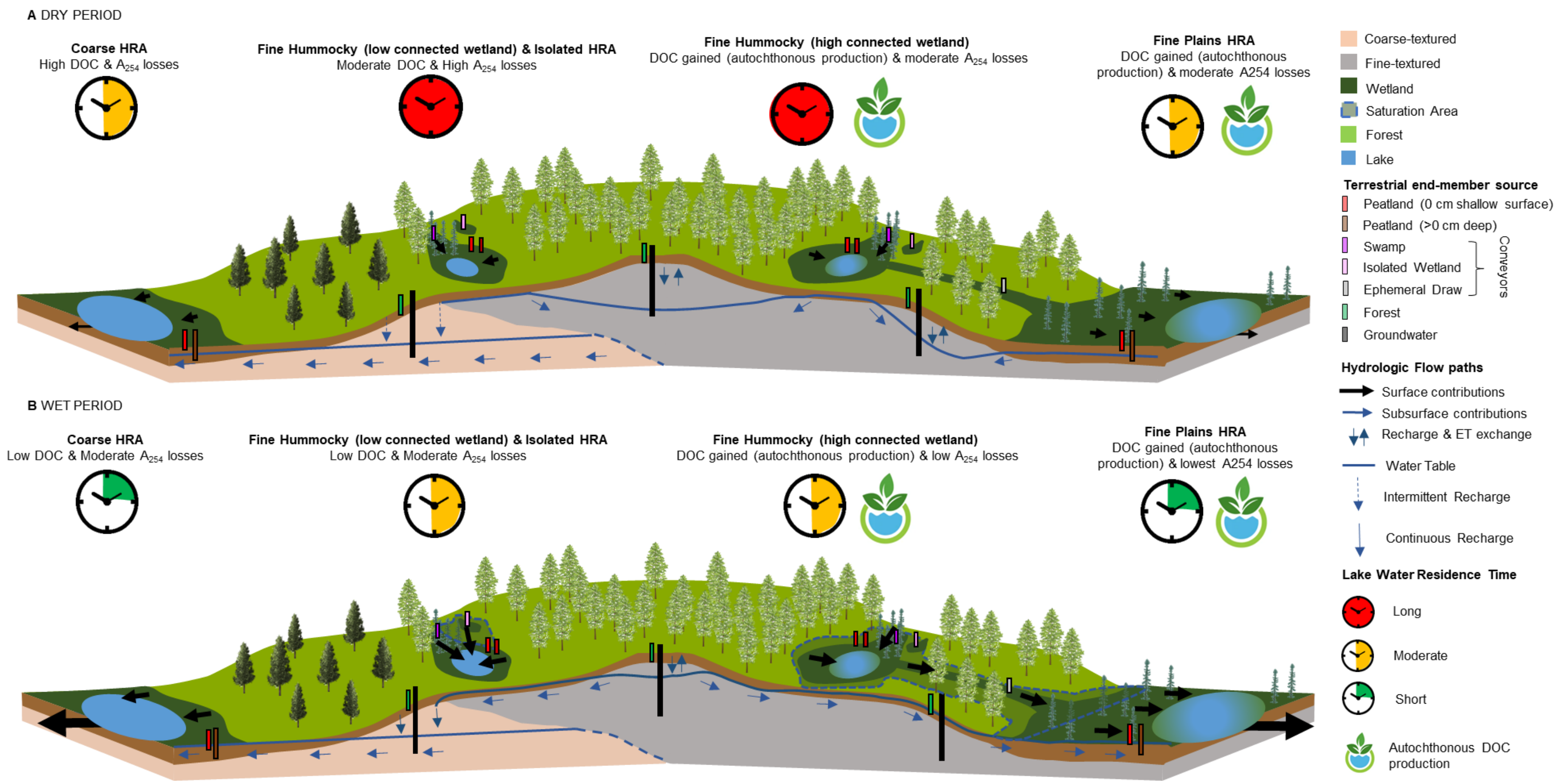

A DRY PERIOD
Coarse HRA
High DOC & A254 losses
Fine Hummocky (low connected wetland) & Isolated HRA
Moderate DOC & High A254 losses
Fine Hummocky (high connected wetland)
DOC gained (autochthonous production) & moderate A254 losses
Fine Plains HRA
DOC gained (autochthonous production) & moderate A254 losses
B WET PERIOD
Coarse HRA
Low DOC & Moderate A254 losses
Fine Hummocky (low connected wetland) & Isolated HRA
Low DOC & Moderate A254 losses
Fine Hummocky (high connected wetland)
DOC gained (autochthonous production) & low A254 losses
Fine Plains HRA
DOC gained (autochthonous production) & lowest A254 losses
Coarse-textured
Fine-textured
Wetland
Saturation Area
Forest
Lake
Terrestrial end-member source
Peatland (0 cm shallow surface)
Peatland (>0 cm deep)
Swamp
Isolated Wetland
Ephemeral Draw
Conveyors
Forest
Groundwater
Hydrologic Flow paths
Surface contributions
Subsurface contributions
Recharge & ET exchange
Water Table
Intermittent Recharge
Continuous Recharge
Lake Water Residence Time
Long
Moderate
Short
Autochthonous DOC production

Figure 3.3.10: Conceptual model of net DOC and A_{254} changes across Boreal Plains lakes during inter-annual wet-dry periods. Dark green areas represent peatlands whilst light green areas represent the forest, where aspen and pine trees would dominate in fine and coarse-textured Hydrologic Response Areas, respectively. Blue and black arrows indicate subsurface (mineral) and surface flow (surface peatland) pathways, respectively. Larger black arrows indicate greater contributions of water from different terrestrial sources of allochthonous DOC. Our study suggests that a lake's DOC concentrations and its aromaticity are strongly influenced by both the relative contribution of various terrestrial water sources determined by lake watershed soil texture and wetland cover, and by the relative importance of within-lake processes such as autochthonous DOC production and bio- and photochemical DOC degradation. We show that peatland contributions enriched in aromatic-DOC is high for lakes in fine-textured HRAs, whilst moderate for lakes in the coarse-textured HRA. However, no lakes have low contributions of water from peatland sources and these contributions do not appear to change significantly between wet and dry years, at least within our study period. We propose that the difference between modelled and observed DOC across Boreal Plains lakes is sensitive to spatial differences in HRA and subsequent dominance of subsurface and surface flow paths, and connectivity to wetlands determining lake productivity and thus autochthonous DOC production. In contrast, the difference between modelled and observed A_{254} change across Boreal Plains lakes is more sensitive to lake water residence times, determined by dominance of different hydrologic flow paths and inter-annual wet-dry periods, which also influences the extent of within-lake processing via photodegradation. We propose that during a dry period, A_{254} is preferentially lost due to increased opportunities for within-lake processing of aromatic-rich coloured fractions of DOC, whilst a wet landscape state will promote water movement through the landscape, thereby reducing opportunities for within-lake processing. Together, differences in the characteristics of HRAs and their interactions with inter-annual wet-dry periods creates variability in DOC concentration and aromaticity among lakes and between years.

3.4.1 Variability and connectivity of terrestrial water sources on the Boreal Plains

This study showed that Boreal Plains lakes received larger relative contributions of water from near-surface peatland sources compared to subsurface shallow forest groundwater and deeper groundwater, in addition to direct inputs from precipitation (Olefeldt et al., 2013; Plach et al., 2016). However, surficial geology strongly influenced relative contributions of water from peatland and mineral groundwater sources, each with different source water chemistry signatures, thereby resulting in large variability in lake DOC concentrations and composition (Chp. 2; Olefeldt et al., 2013; Figure 3.3.10). With over half of the water received by Boreal Plains lakes estimated to come from peatland sources rich in aromatic-DOC, we found that the DOC concentration and aromaticity of DOC was higher than lakes in other boreal and northern temperate regions (Carignan et al., 2000; Curtis & Schindler, 1997; D'Arcy & Carignan, 1997; Houle et al., 2020; Jonsson et al., 2003; Sepp et al., 2019; Sobek et al., 2003). Other water sources in the watersheds, including near-surface groundwater in organic-rich swamps, ephemeral draws and isolated wetlands were considered to primarily convey water from upland into lakes, and were found to have water chemistry that had taken on characteristics of both the mineral soil (high ion concentrations) and peatland soil waters (high DOC concentrations with high aromaticity).

Mineral groundwater sources were distinguished from peatland sources by higher concentrations of cations due to lengthened contact times of subsurface flow paths with soils and rocks allowing for greater dissolution (Gibbs, 1970). However, we identified differences in cation concentrations within mineral soil sources, where coarse-textured HRAs generally showed lower cation concentrations than fine-textured HRAs, likely due to higher hydraulic conductivities and subsequent reduced contact time in coarse-textured HRAs (Gibbs, 1970; Toth, 1999). However, studies across the Boreal Plains have also shown considerable ranges in lake cation concentrations associated with connectivity to different groundwater flow path systems within a HRA, where coarse textured lakes connected to larger-scale groundwater flow systems will have increased concentrations due to the distance traveled along hydrologic flow paths (Devito et al., 2000; Webster et al., 1996).

Peatland contributions to lakes were strongly related to lake DOC concentration and A_{254}. As found by Olefeldt et al., 2013, large differences were shown in the DOC characteristics between peatland and mineral soil terrestrial DOC sources, with mineral soil sources depleted in aromatic-rich DOC and peatland sources enriched in aromatic-rich DOC (Aitkenhead-Peterson et al., 2003; Kalbitz et al., 2003; Thurman, 1985; Wickland et al., 2007). Although, DOC characteristics of peatlands among HRAs were similar, within HRAs we identified differences in the DOC characteristics of shallow (<25 cm) and deep (>25 cm) peat. As shown by Olefeldt et al., 2013, we also found that shallow peatland sources had lower DOC and A_{254} compared to deeper sources across both coarse and fine-textured HRAs due to differences in the humification of peat with depth (Aitkenhead-Peterson *et al*., 2001; Kalbitz & Geyer, 2002; Thurman, 1985), thus we conceptualised shallow fibric peat with high hydraulic conductivity to be the dominant organic source to lakes (Wong et al., 2009).

Surficial geology strongly influenced the relative contribution of mineral groundwater and near-surface peatland sources to the study lakes, which lead to large variability in lake DOC characteristics among lakes. Greater proportions of mineral groundwater sources were received by coarse lakes due to their connectivity to local and larger-scale ground water flow systems expected within more permeable sediments (Smerdon et al., 2005; To´th, 1963). Dominance of mineral groundwater contributions in coarse lakes resulted in lower lake DOC concentrations and A_{254} from preferential adsorption of aromatic-DOC (Aitkenhead-Peterson et al., 2003; Thurman, 1985). In contrast fine-textured lakes received more near-surface organic peatland contributions that represent an important source of aromatic-rich DOC from the terrestrial environment (Ferone & Devito, 2004; Olefeldt et al., 2013).

3.4.2 Importance of mixing terrestrial sources versus within-lake processes

Although the lake DOC characteristics were intermediate between that of peat and mineral water sources, our mixing model suggests that the vast majority of water and terrestrial DOC was derived from peatlands, particularly for fine-textured lakes. This discrepancy between mixing model results and where the lakes sit in mixing plot space suggests that shifts in DOC concentration and composition ($SUVA_{254}$) are largely due to within-lake degradation of terrestrially sourced DOC, rather than shifting terrestrial sources. Studies undertaken in characteristically wetter boreal regions reveal that shifts in lake and stream DOC characteristics are related to shifts in terrestrial sources, where forested areas frequently function as runoff generating areas and active terrestrial sources of DOC during wetter conditions (Ågren et al. 2008; Laudon et al., 2011). However, in the Boreal Plains forests rarely act as sources of water and thus are not seen as active sources of aromatic-rich DOC sources to Boreal Plains lakes, where the water table often slopes against the topographic gradient and water actually moves into forestlands located adjacent to peatlands and lakes (Figure 3.3.10; Hokanson et al., 2020; Ferone & Devito, 2004; Redding & Devito, 2010). Furthermore, lakes in fine-textured HRAs typically receive little to no groundwater depleted in aromatic DOC by adsorption processes due to the low hydraulic conductivity of fine-textured substrates (Figure 3.3.10; Ferone & Devito, 2004; Plach et al., 2016; Qualls & Haines, 1992; Olefeldt et al., 2013; Thurman, 2012). Meanwhile, coarse lakes received larger mineral groundwater contributions depleted in aromatic-rich DOC, and therefore showed lower DOC concentrations and $SUVA_{254}$ in mixing space.

Our study identified that DOC characteristics of Boreal Plains lakes were strongly influenced by within-lake processes. We found that lake DOC aromaticity decreased with longer lake water residence times (i.e. more negative lc-excess) when compared to DOC concentration. Extrapolating the linear relationship between DOC composition and lc-excess supports our mixing model results that the vast majority of aromatic-DOC is received by peatland sources, especially for fine-textured lakes; however lake water residence time seems to facilitate processes that alter the DOC composition so that it does not reflect peatland DOC sources any more. Therefore, mixing plots of lake DOC characteristics showed that although Boreal Plains lakes received a mix of terrestrial DOC sources, within-lake processes occurred, resulting in DOC characteristics that, without understanding the hydrologic connectivity of the Boreal Plains landscape, would suggest larger contributions from mineral sources. Similarly to lakes, Boreal Plains streams received greater proportions of peatland sources in fine-textured HRAs whilst coarse streams received more mineral groundwater sources compared to fine-textured streams, yet the DOC compositions between Boreal Plains streams and lakes differ, which suggests large processing occurs within lakes rather than streams. However, stream and lake DOC concentrations were similar further suggesting that DOC composition is more sensitive to within-lake processing than DOC concentration. Discrepancies between mixing plots and mixing model outputs in this study highlight the importance of considering both the climatic and geologic context of a landscape and what this means for hydrologic connectivity and subsequent chemistry of lakes in the region.

3.4.3 Explaining spatial variability in difference between modelled and observed DOC and A_{254}

This study found large spatial variability in the difference between modelled and observed DOC and A_{254} in lakes across the Boreal Plains. The mixing model estimated that on average across all study lakes, there was a net loss of 17% (± 40 ±1 SD) and 39% (± 31) of terrestrial DOC and A_{254} reaching lakes, respectively, where bio- and photo-degradation of terrestrial DOC were greater than autochthonous production of DOC. Due to coloured fractions of DOC being preferentially degraded via photo-mediated mineralisation and flocculation processes, we assumed that all A_{254} lost was attributed to photodegradation processes (Backlund, 1992; Bertillson & Tranvik, 2000; Olefeldt et al., 2013; Strome & Miller, 1978, Tranvik et al., 1998; Weyhenmeyer et al., 2012). The average difference between modelled and observed DOC and A_{254} includes both losses and gains, thus of the lakes reporting losses, their average losses across all lakes are likely higher. A study on the Scandinavian Boreal Shield by Algesten et al. (2004) reports total DOC losses from lakes in very large watersheds with several chains of lakes of between 30 to 80%. While our study shows net DOC losses (i.e. modelled – observed) instead of absolute loss of terrestrial DOC, given that our study lakes are small headwater lakes we likely see comparable losses to the Algesten et al. (2004) study, where loss rates on a lake by lake comparison in the Boreal Plains may be equal or greater than in the Boreal Shield. The large variability among lakes in the average difference between modelled and observed lake DOC and A_{254} can also be due to highly heterogeneous surficial geology, proportions of connected wetland in individual lake watersheds and subsequent differences in the dominance of surface and subsurface flow paths that are characteristic of the Boreal Plains landscape (Devito et al. 2012, 2017; Hokanson et al., 2019; Olefeldt et al., 2013). These differences lead to large variability in water chemistry, DOC concentration and composition, nutrient availability for autochthonous DOC production, and lake water residence time that influence the processes determining the DOC pool of Boreal Plains lakes.

When assessing the fate of terrestrial DOC and A_{254} reaching lakes in each HRA, we found that within-lake degradation of terrestrial DOC was greatest in coarse lakes compared with fine-textured lakes. Average net DOC loss (modelled minus observed) in coarse lakes represented 47% of the terrestrially derived DOC, whilst average net A_{254} loss represented 68% of terrestrially derived A_{254}. Coarse lakes did not show net DOC gains via autochthonous production, likely due to lower Chl-*a* (used as a surrogate for primary productivity as influenced by nutrients) compared to fine-textured HRAs. Larger losses in DOC and A_{254} of coarse lakes may be associated with already low DOC concentrations and A_{254} in coarse-textured lakes which is often considered more biolabile (low molecular weight from subsurface sources) and increases clarity for penetration depths for UV-mediated photodegradation to occur (Koehler et al., 2012; Molot & Dillon 1997; Morris & Hargreaves, 1997). However, given the typically moderate water residence times of coarse lakes and lower sensitivity to inter-annual wet-dry periods relative to fine hummocky lakes (Chp. 2), UV-mediated photodegradation is likely to act as a less dominant mechanism for observed losses compared to fine hummocky lakes (Curtis & Schindler, 1997). Thus, initially low A_{254} resulting from dominance of subsurface flow paths depleted in aromatic-DOC likely cause changes in A_{254} to appear greater in coarse lakes (Figure 3.3.10; Qualls & Haines, 1992; Olefeldt et al., 2013; Smerdon et al., 2005; Thurman, 2012). However, due to the sub-humid climate of the region, longer lakewater residence times in general are anticipated in the Boreal Plains when compared to Boreal Shield regions (Chp. 2; D'Arcy & Carignan, 1997; Jane et al., 2017; Kothawala et al., 2014), still allowing for significant photodegradation processes to occur.

Fine-textured hummocky lakes lost on average 23% and 41% of terrestrially derived DOC respectively; however, several lakes in the fine hummocky HRA showed net gains in DOC attributed to autochthonous production. On average, fine plains lakes had a net 10% gain of DOC due to autochthonous DOC production and lost on average 15% of terrestrially derived A_{254}. Studies undertaken in other boreal regions have also found that metabolic balances in lakes vary across gradients of lake DOC and nutrient concentrations, where net autotrophy is typically associated with higher nutrient concentrations and lower DOC concentrations (Cole et al., 2000; Hanson et al., 2003; Prairie et al., 2002). However, in Boreal Plains lakes, we found that net autotrophy (gain of DOC via autochthonous production) was greater in both nutrient and DOC rich lakes, likely due to Boreal Plains lakes receiving nutrients from adjacent peatlands that also represent important terrestrial sources of DOC (Olefeldt et al., 2013; Plach et al., 2016). Thus, fine hummocky lakes with a greater proportion of connected wetland in the watershed and fine plains lakes that are characterised by extensive wetland connectivity showed greater Chl-*a* concentrations and gained DOC via autochthonous production. Similarly to Guillemette et al. (2013), our study suggests that in some lakes parallel processing of terrestrially-derived DOC and autochthonous DOC production may be occurring because of interactions with nutrients and terrestrial DOC in lakes.

We also suggest that lake water residence times are an important determinant in the balance of terrestrial aromatic-rich DOC sources in lakes, particularly fine hummocky lakes. Large losses in A_{254} of fine-hummocky lakes can be attributed to photodegradation processes. Limited hydrologic connectivity to local flow paths characteristic of fine hummocky watersheds with large water storage thresholds for fill and spill to occur result in longer lake water residence times, and increased opportunity for within-lake losses compared to coarse and fine plains HRAs (Figure 3.3.10; Chp. 2; Devito et al., 2012; 2017; Evans et al., 2017; Kothawala et al., 2014; Plach et al., 2016; Schindler et al., 1992, 1997; Spence, 2010). In contrast, fine plains lakes showed the lowest net A_{254} losses attributed to photodegradation processes because of extensive surface water contributions via peatlands to lakes, and thus relatively shorter water residence times with reduced opportunities for photodegradation processes to occur (Figure 3.3.10; Chp. 2; Devito et al., 2017; Evans et al., 2017; Kothawala et al., 2014; Plach et al., 2016; Schindler et al., 1992, 1997).

Although the mixing model used in this study is sensitive to several assumptions outlined in the methods, we found strong agreement among lake results with regards to relative differences in the balance of within-lake losses and autochthonous production between HRAs from different model scenarios. The similarity in relative differences across different mixing models allows the study to use the mixing model to provide valuable information about relative differences among lakes in different HRAs rather than absolute losses in DOC and A_{254}. However, even though the magnitude of losses or gains are sensitive to the model assumptions, the scenarios using the maximum and minimum ranges of end-member concentrations are representative of the extremes in variability of DOC and A_{254} losses or gains. We did not include an assessment of beaver influence on lake DOC characteristics or nutrients in Boreal Plains lakes, however, beavers can introduce lots of DOC and nutrients into an aquatic system (Devito & Dillon, 1993; Hillman et al., 2004) and their presence may add to the spatial variability observed. Although beavers introduce DOC and nutrients into lake systems, it is assumed to be a small proportion of the already high DOC and high nutrient sources of water entering Boreal Plains lakes via organic rich peatlands.

3.4.4 Explaining inter-annual variability in the difference between modelled and observed DOC and A_{254}

Our study suggests that dry periods on the Boreal Plains substantially increased the influence of photodegradation on lake DOC characteristics, thereby leading to preferentially increased net losses of A_{254} and thus reduced lake DOC aromaticity (Hall et al., 2019; Schindler 1997). Losses of DOC in dry years were smaller and likely partially offset by inter-annual variability in autochthonous DOC production. The losses observed during dry periods were common across lakes in each HRA, suggesting larger regional influences from inter-annual wet-dry periods (Jane et al., 2017; Kratz et al., 1998; Magnuson et al., 1990) rather than more local influences occurring in the watershed, such as switching terrestrial sources (i.e., changing dominant contributions from shallow peat to deeper peat sources). However, we also found that the influence of inter-annual wet-dry periods on lake DOC characteristics differed in magnitude among lakes in different HRAs, supporting observations in Chapter 2; that DOC composition is more sensitive to inter-annual wet-dry periods when compared to DOC concentration. Greater inter-annual variability in net DOC and A_{254} change (modelled minus observed) suggests that the relative dominance of processes that either remove or produce DOC and A_{254} is sensitive to inter-annual wet-dry periods, whilst low inter-annual variability means that these functions are more stable, and resistant to inter-annual wet-dry periods.

Coarse-textured lakes showed the lowest inter-annual variability in net DOC and A_{254} change. Low inter-annual variability of net DOC and A_{254} change in coarse-textured lakes is likely due to connectivity to groundwater sources and lake-to-lake flow through systems maintaining water movement through the landscape, which can act to buffer lakes against the influence of inter-annual wet-dry periods that enhance within-lake photodegradation processes during dry years (Figure 3.3.10; Hokanson et al., 2019; Schindler et al., 1992, 1997; Smerdon et al., 2005). In contrast, fine-textured hummocky and plains lakes showed larger inter-annual variability in net DOC and A_{254} change, likely due to the dominance of surface flow paths via riparian wetlands which may be more sensitive to inter-annual wet-dry periods (Figure 3.3.10; Ireson et al., 2015; Winter, 2001). Thus, during a dry year, terrestrial-aquatic linkages between fine-textured lakes and surrounding wetlands may be limited, or shut down; therefore, increasing lake water residence times as less water moves through the landscape and simultaneously enhancing within-lake photodegradation opportunities for aromatic-rich DOC (Catalán et al., 2016; Ejarque et al., 2018; Kothawala et al, 2014; Schindler et al., 1992, 1997).

3.5 Conclusion

These results demonstrate that DOC concentration and aromaticity in Boreal Plains lakes do not only reflect mixing of water from terrestrial sources, but also processes of within-lake degradation and production of DOC. Our results support a conceptual model that highlights how watershed characteristics, surficial geology in particular, influence both the spatial and temporal variability of lake DOC characteristics as resulting from both external supply of DOC and within-lake processes. We find that our results contrast with studies from other boreal regions, where within-lake processes of photodegradation and autochthonous DOC production appear to be more important on the Boreal Plains in terms of influencing lake DOC characteristics. The importance of within-lake processes in regulating DOC characteristics on the Boreal Plains is linked to longer residence times, shallow lakes, and higher nutrient availability than in many other boreal regions. As changes in precipitation quantity and timing, and increased evapotranspiration rates are predicted globally in response to the ongoing climate emergency, we can expect watersheds to undergo more frequent dry periods with shutdown of terrestrial-aquatic linkages and increased lake water residence times and opportunities for within-lake processing of DOC and A_{254}. Thus, in the Boreal Plains, where shallow lakes receiving aromatic-rich DOC exist in a region with an overall moisture deficit, and small changes in the water balance cause large shifts in water residence times, net DOC and A_{254} changes in lakes are highly sensitive to within-lake processes with implications for lake ecosystem services, including greenhouse gas exchange, nutrient cycling, food webs and water treatability.

4.0 Persistence of Shallow Lakes on the Boreal Plains: Resistance and Resilience to Climate Variability Linked to Lake and Watershed Attributes

Key Points:

- Contraction and expansion of lakes during and after dry periods varied depending surficial geology, wetland connectivity, and lake basin morphology.
- During severe dry periods, the impacts from the shutdown of terrestrial-aquatic linkages between lakes and peatlands exceeded resistance to change across the study lakes (i.e. lakes contracted); however, lakes in different surficial geologies had different resistance thresholds.
- Lag times between the occurrence of a dry period and lake contraction were longer in lakes with higher wetland connectivity and in lower topographic landscape positions.
- Lake resilience to droughts, i.e. ability to recover to pre-drought surface area, was related to lake basin morphology and interactions between wetland connectivity and lake substrate.

Abstract

Within the Boreal Plains of Western Canada, ecologically significant lake ecosystems exist in a delicate hydrologic balance, which may be disrupted by climate change, with potentially irreversible ecosystem state shifts from aquatic to terrestrial systems. To assess the persistence of shallow lakes on the Boreal Plains, we used long-term (1996 - 2019) monthly lake extent data to generate metrics for resistance, lag times, and resilience of lake extent to dry periods of varying severities, and thus indicate the risk of terrestrialisation processes occurring in lakes. The variability in lakeshore dynamics within lakes over time differed between lakes, with many lakes exhibiting transient or long-term loss. Lag times of how quickly a lake's open water extent contracts in response to a dry period were shorter in lakes located in high landscape positions with

a lower proportion of connected wetland area in the watershed. Resistance and resilience of lake extent to dry periods, i.e. the ability to withstand change and to return to pre-dry period extents, were highest for lakes with greater wetland connectivity and for lakes with straight-sided basin morphology. In contrast, lakes that had low resistance and low resilience, and thus those that may have accelerated terrestrialisation following future dry periods, included isolated lakes with low wetland connectivity and shallow depths of loose substrate. Five lake groups were identified by similarities in resistance, lag time, and resilience to dry periods, which were primarily controlled by connected wetland area and lake basin morphology. This study found that differences in the contraction and expansion of Boreal Plains lake extent during and after dry periods were dependent on surficial geology (i.e. dominance of surface versus subsurface flow paths), wetland connectivity and lake basin morphology. Thus, new insights into the controls on lake extent responses to dry periods are provided in this study and can be used to identify lakes that will be most vulnerable to accelerated terrestrialisation in response to an increasingly changing climate.

4.1 Introduction

Lakes across boreal landscapes provide essential ecosystem services, including climate regulation through greenhouse gas exchange (Algesten et al., 2004; Cole et al., 2007) and carbon sequestration (Squires et al., 2005), provisioning of drinking water (Emelko et al., 2011), and support for biodiversity (Williamson et al., 2009). Climate warming along with shifting patterns of precipitation, likely including both more extreme dry and wet periods (Pachauri et al., 2014), may cause changes to spatial extents of lakes and even threaten lake permanence.

The spatial extents, and even presence or absence of lakes, can vary due to the influence of both short-term and long-term processes. Short-term inter-annual variability in the water balance as a result of dry periods can influence hydrologic connectivity of the watershed and reduce the quantity of water received by lakes from the landscape, thus causing open water lake extents to contract. Exposure of the lake bed for extended periods of time can enable long-term processes, such as terrestrialisation, to occur. Terrestrialisation is the permanent transition from an open water to terrestrial ecosystem (Kratz & DeWitt 1986; Mitsch & Gosselink, 2015). Terrestrialisation is driven by the accumulation of organic matter infilling lakes which elevates the sediment above the lake water level allowing for vegetative colonization. The mechanism of terrestrialisation can interact with inter-annual wet-dry periods to potentially accelerate the occurrence of terrestrialisation processes in a lake, where a temporary lowering of the water level during a dry period combined with gradual lake infilling leads to the colonization of vegetation (Ireland et al., 2012). However, interactions between terrestrialisation and hydroclimatic variations in the landscape likely depend on both regional and local watershed and lake attributes (e.g. surficial geology, wetland cover, relief, permafrost presence). Therefore, the spatial extents of lakes in different boreal regions may respond to inter-annual wet-dry periods and amplification of inter-annual wet-dry periods through climate change differently.

The response of lake area to dry periods can be characterized by resistance, lag-time, and resilience. The resistance of a lake's extent to a dry period can be thought of as the ability of a lake to not be affected by said dry periods. Lag time is the time taken for an individual lake's extent to respond to a dry period. Resilience is the ability of said lake to return to the same water level and open water lake extent observed prior to being affected by a dry period. Between regions and within the same region, there could be varying combinations of resistance and resilience types among lakes, i.e., lakes that are resistant to dry periods, those that are not resistant yet show high resilience, and lakes with both low resistance and resilience that are following a trajectory of drying out completely.

The circumpolar boreal biome spans several ecozones with distinct characteristics, including differences in climate, moisture availability, bedrock geology, surficial geology, relief, permafrost presence, and peatland coverage (Brown, 1997; Geological Survey of Canada, 1995; 2014). Over the past few decades, dramatic hydrological changes have been observed, particularly across subarctic boreal lakes, including net reductions in lake size, attributed to combined effects of permafrost thaw, increased evapotranspiration, and terrestrialisation processes (Klein et al., 2005; Smith et al., 2005; Riordan et al., 2006; Roach et al., 2011, Yoshikawa & Hinzman, 2003). Boreal kettle basin systems have also been subjected to abrupt state shifts and reductions in lake size attributed to episodic terrestrialisation processes (Ireland et al., 2012; Ireland & Booth, 2011). Despite the body of research assessing controls on widespread hydrological changes across sub-arctic boreal and boreal lakes, individual ecosystem responses to changing precipitation patterns make predicting responses in other regions challenging, especially when regions such as the boreal biome have vast differences in characteristics, thus we should not expect the same controls on the resistance and resilience of lake extents across regions.

The Boreal Plains ecozone covers large portions of Western Canada (Canadian Council on Ecological Areas, 2014), and has a high density of lakes. The Boreal Plains ecozone has characteristics that are distinct from many other boreal regions, with a sub-humid climate and thick heterogeneous glacial surficial geology deposits. Together, these characteristics create large spatial heterogeneity in lake watershed attributes, which further amplify complex groundwater-surface water interactions (Devito et al. 2012, 2017; Hokanson et al., 2019; Ireson et al. 2015; Winter 2001). Due to this spatial heterogeneity in lake and watershed attributes, we should expect different trajectories of neighbouring Boreal Plains lakes in their hydrologic responses (i.e., lake extent) to inter-annual wet-dry periods (Perales et al., 2020), and thus differences in the resistance and resilience of lakes within the same region to climate variability.

The hydrological response of lakes (lake extent) to dry periods is likely to be influenced by lake watershed attributes. Research in the Boreal Plains shows that distribution of coarse relative to fine textured glacial deposits determine relative contributions of water from subsurface and surface flow paths to lakes (Hokanson et al., 2019; Plach et al., 2016; Smerdon et al., 2008). Therefore, the surficial geology of a lake watershed should be a determining factor for the stability of lake extent responses to inter-annual wet-dry periods. In coarse-textured lakes, topographic landscape position determines relative contributions from different flow paths, with lakes in lower topographic landscape positions receiving larger groundwater contributions via lake-to-lake flowthrough, and larger surface water contributions from peatlands (Devito et al., 2017; Hokanson et al., 2019; Smerdon et al., 2005). Thus, coarse-textured lakes receiving larger relative contributions of groundwater are likely to be buffered against the effects of dry periods on their open water lake extents (Winter, 2001). In contrast, lakes within fine-textured surficial geology are dominated by contributions from local near-surface flow paths via peatland connectivity (Devito et al., 2017) that are generally more susceptible to inter-annual wet-dry periods (Ireson et al., 2015; Winter, 2001). However, the topographic landscape position and relief of fine-textured lake watersheds can determine the stability of lake extent responses to inter-annual wet-dry periods. Fine-textured lakes in low topographic positions with low relief receive surface water from expansive peatlands that may actually limit the effects of dry periods on lake extent. Conversely, lakes in higher topographic landscape positions with smaller watersheds are limited to local flow paths and contributions from adjacent peatlands will be more vulnerable to dry periods (Hokanson et al. 2019; Ireson et al., 2015; Winter, 2001). As such, we should expect spatial differences in the resistance lag times, and resilience of lake extent to dry periods due to differences in landscape attributes (i.e. surficial geology, peatland connectivity, and topographic landscape position), which determines the dominance of hydrologic flow paths in each watershed.

Lakes within a region also have individual attributes, including basin morphology and lake substrate type that can influence variability in water level and open water lake extent dynamics among lakes. A model of drought-triggered terrestrialisation proposed by Ireland et al. (2012) suggests that lake basin morphology exerts a strong influence on changes to lake extent by determining relative resistance and resilience of shallow and deep basins to dry periods. Translated to a Boreal Plains framework, a shallow basin has sloping sides and would have lower resistance and thus greater susceptibility to terrestrialisation processes during relatively low magnitude or shorter duration dry periods (Figure 4.4.1). In contrast, deeper basins would be steep sided and show greater resistance, requiring extreme and/or prolonged dry periods to drop water levels holding relatively large volumes of water and expose the lakebed to allow terrestrialisation processes to occur (Figure 4.4.1). Susceptibility of terrestrialisation in lakes can also be driven by dry periods and interactions with substrate type of the lakebed (e.g., firm and loose substrate), in addition to basin morphology. During dry periods, the water level of a lake decreases, thus exposing lake sediments to colonization by vegetation. Upon rewetting, loosely rooted mats of vegetation are able to detach from loosely consolidated lake sediments (loose substrate) and float, which creates a hydrologically stable substrate for further colonization of vegetation and vertical peat accumulation from which the lake is unlikely to recover, thus showing low resilience in the lake (Ireland et al., 2012; Warner et al., 1989; Figure 4.4.1). However, if the newly colonized vegetation mats are attached to consolidated lake sediments (firm substrate), water levels will rise and flood vegetation mats, thereby preventing floating mat initiation and allowing open water lake extents to recover to pre-dry period states, thus resulting in a resilient lake (Figure 4.4.1). Therefore, we should expect differences in basin morphology and lake substrate type to cause lakes within the same region to exhibit unique lake extent responses, e.g., amplify, delay, or extend the realisation of inter-annual wet-dry period signals in the lake (Ireland et al., 2012; Magnuson et al., 2004).

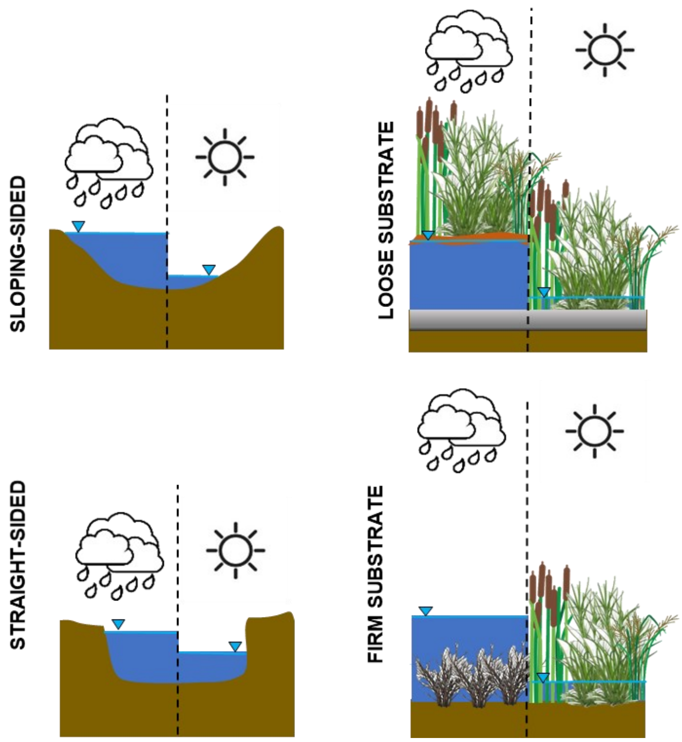


Figure 4.4.1: A conceptual model of the influence of lakebed substrate and basin morphology on lake extent. Rain and sun symbols indicate relatively wet and dry periods, respectively. The left panels present a conceptual understanding of how lake basin morphology (steep-sided or sloping-sided) would influence variability in water level dynamics and open water lake extent. Right panels show the influence of lake substrate (loose or firm) on variability in water level dynamics and open water lake extent, where loose substrate allows the formation of a floating mat but in firm substrate the vegetation floods out and dies. We hypothesize a difference between straight and sloping sided lakes as you go into a dry period, where the changing lake volume does not lead to a shift in lake area during a dry period while it does in a sloping sided lake basin. During a dry period, many sloping sided lakes may develop new vegetation along the lake edges. This vegetation may persist in a re-wetting phase if the substrate is loose and allows the vegetation to float with the rising water.

The main objective of this study was to determine how lake and watershed attributes affect the resistance, lag-time and resilience of lakes in a Boreal Plains landscape to dry periods of varying severities. We used water history data from the Global Surface Water Explorer from 1996 – 2019 (Francois Pekel, 2016) for 33 lakes in conjunction with, water level data collected in the field from 1999 to 2019 during inter-annual wet-dry periods characteristic of the Boreal Plains ecozone. In general, we predicted that lakes with watershed attributes that promote stable hydrological connections would have greater resistance, resilience, and longer lag-times – especially lakes with stable groundwater connections in lower regional settings and lakes with a greater connectivity to runoff-generating peatlands. We further predicted that lake attributes can modify these general responses; where straight-sided lakes have greater resistance and longer lag-times, whilst lakes with loose substrates have lower resilience as new vegetation may persist even as water levels rise again. These findings are important to understanding the controls on different trajectories of neighbouring lakes, and to making robust assessments of lakes that will be most vulnerable to climate change.

4.2 Methods

4.2.1 Study Site

The study area is part of the Boreal Plains ecozone of north-central Alberta, Canada, located near Utikuma Lake (known as the Utikuma Region Study Area (URSA)) in Treaty No. 8 Territory (Figure 4.4.2; Devito et al., 2016 EcoRegions Working Group, 1989). The climate is sub-humid, where precipitation is less than or equal to evapotranspiration, and has pronounced inter-annual wet-dry periods, with an annual temperature of 1.2°C (Devito et al., 2016; Mwale, 2009). The average annual precipitation (P) during the study (1996 to 2019) was 424 mm (± 94 mm; 1 standard deviation; Appendices A.3.1). Long-term average annual potential evapotranspiration using Penman models is 519 mm at the URSA, and rarely varies more than 30 mm from the average (Devito et al., 2016).

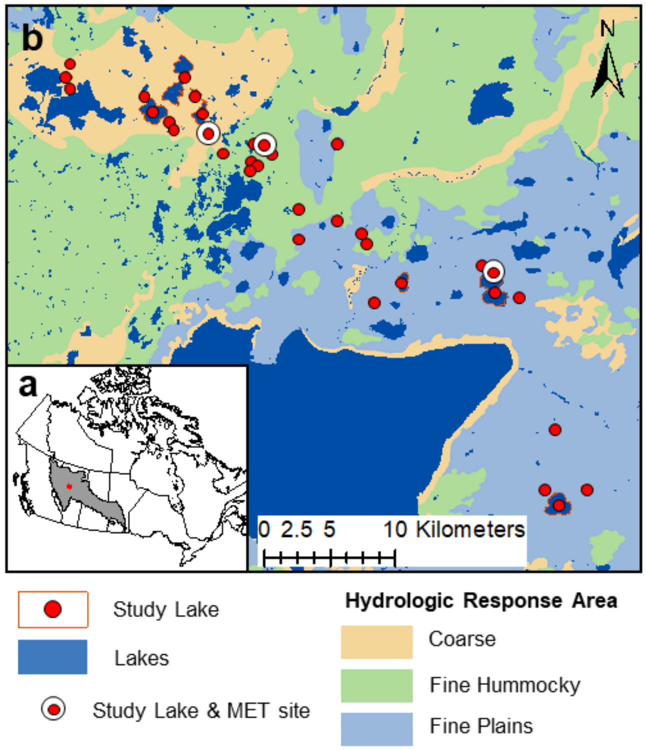


Figure 4.4.2: (a) The location of the Boreal Plains in Canada (grey) with the Utikuma Region Study Area (URSA) highlighted by a red rectangle; (b) location of the 33 study ponds across distinct hydrologic response areas (HRAs) within the URSA.

Thick (50 – 200 m) heterogeneous glacial surficial geology characterises the URSA (Fenton et al., 2003; Hokanson et al., 2019). The surficial geology comprises coarse-textured glaciofluvial deposits in the north-west section of the study area and fine-textured glacial till (fine hummocky) and glaciolacustrine (fine plains) deposits towards the south-east (Fenton et al., 2003). These three hydrologic response areas (HRAs) have been delineated as coarse outwash, fine textured hummocky moraine, and clay plains along the study transect at the URSA (Figure 4.4.2; Hokanson et al., 2019), from units mapped in the Alberta Geological Society surficial geology mapping (Fenton et al., 2003). Each HRA represents broad spatial differences in local relief, storage potential and transmissivity (Devito et al., 2017; Hokanson et al., 2019; Winter, 2001).

The low relief of URSA results in poor drainage and organic-rich peatlands covering on average up to 50% of the land area at thicknesses of up to 5 m (Devito et al., 2016). Peatland abundance varies between HRAs, with extensive connected peatlands on the clay plains (47 – 85%; Chp. 2 – A.1.3) and more spatially confined peatlands in the coarse outwash (22 – 68%; Chp. 2 – A.1.3) and hummocky moraine (16 – 59%; Chp. 2 – A.1.3). The peatlands include bogs and fens with ranging canopies of black spruce (*Picea mariana*) and tamarack (*Larix sp.*) and groundcover comprised of mosses and shrubs. Forests cover approximately 40% of the URSA and are dominated by trembling aspen (*Populus tremuloides*) and Jack pine (*Pinus banksiana*) in fine-textured and coarse-textured soils, respectively (Devito et al., 2016).

4.2.2 Inter-annual wet-dry periods

Precipitation data were collected from four meteorological sites within 24 km of each other along the URSA transect at open locations from 1999 to 2019 (Figure 4.4.2). Prior to 1999 (1996 - 1998), long-term daily climatological data from Fort McMurray, a region also characterised by a continental sub-humid climate was used to set the climatic context for our study period (1996 - 2019) because precipitation data from more relevant weather stations (i.e., Red Earth Creek & Peavine) were not available (Figure 4.4.3; Carrera-Hernández et al., 2011). At the URSA, precipitation data were obtained using shielded tipping bucket rain gauges (adapted for snowfall using antifreeze in the reservoir) and validated using multiple manual gauges and snow transect surveys. Precipitation data collected at the URSA were compared with, and occasionally gap filled using data collected from nearby weather stations (Red Earth Creek & Peavine; data provided by Alberta Agriculture and Forestry, Alberta Climate Information Service). Total annual precipitation was summarized for the period from July 1st to June 30th for each year, i.e., to capture the effects of inter-annual wet-dry periods on lake extent, when lake extents in the Boreal Plains are considered ice-free and at their maximum. Average annual (July 1st to June 30th) precipitation for the study period (1996 to 2019) was 424 mm, with the highest annual precipitation occurring in 2007 (590 mm), and lowest annual precipitation occurring in 2002 (214 mm; Figure 4.4.3). We also used the 3-year cumulative departure from average (3yrCDM) precipitation for each year to identify dry hydrologic years, because the 3yrCDM has been shown to capture the strong influence of antecedent moisture conditions on hydrologic responses in the Boreal Plains (Devito et al., 2005; Hokanson et al., 2019; A.1.1). We classified hydrologically mesic years when the net moisture deficit is near zero, where slight moisture deficits (-100 mm 3yrCDM) are countered by slight moisture surpluses (+100 mm 3yrCDM) (Devito et al., 2012). Hydrologically dry and wet years were then classified when the moisture deficit using the 3yrCDM was less than -100 mm and greater than +100 mm, respectively. The severity of hydrologically dry years was quantified by accumulating the 3yrCDM for the duration of each dry period. The intensity of hydrologically dry years was also quantified by dividing the severity by the duration (in years) of each dry period.

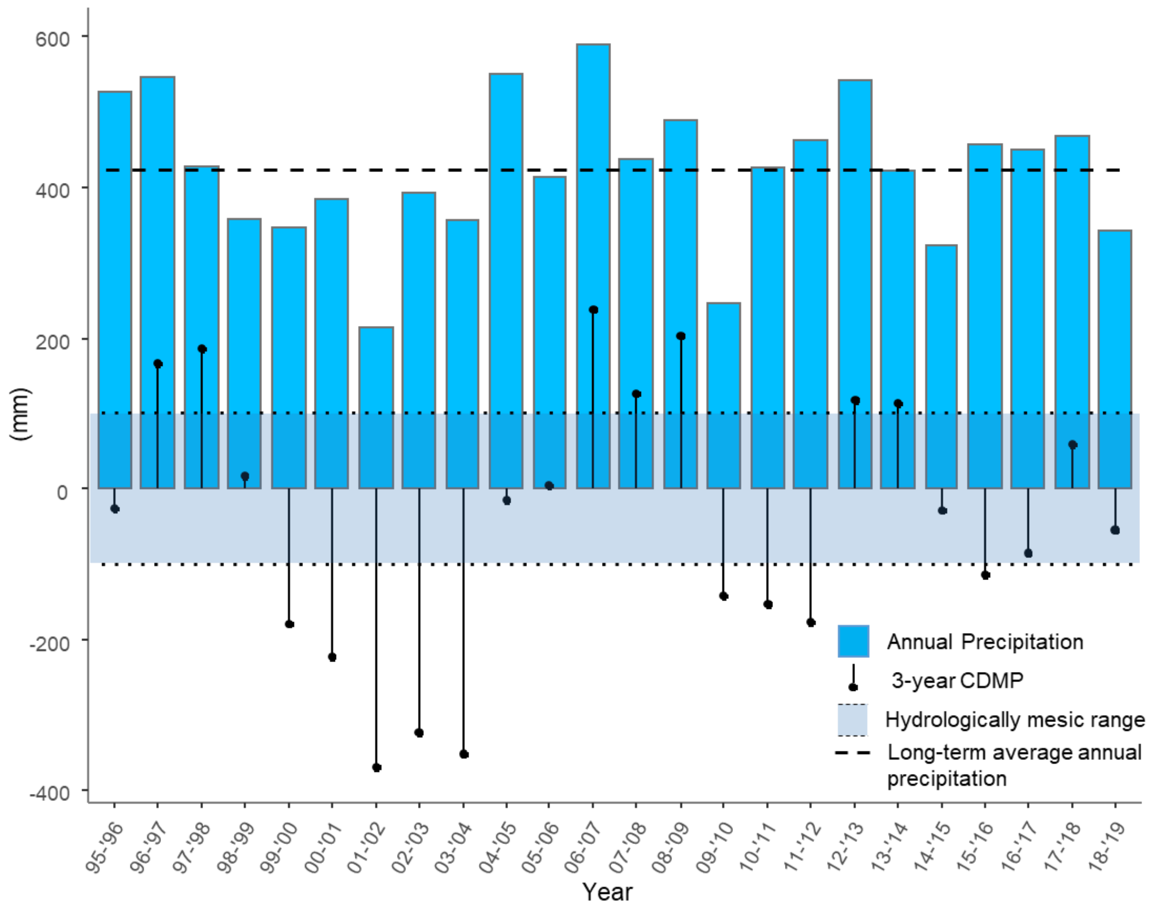


Figure 4.4.3: Precipitation data (July 1st – June 30th and 3-year cumulative departure from mean precipitation (CDMP) for the URSA from 1996 to 2019. Long-term average annual precipitation (424 mm) provides context. Shaded region indicates the range for a hydrologically mesic 3-year CDMP (+100 mm to -100 mm).

4.2.3 Global surface water data extraction

Long-term monthly water history data (1996 - 2019) of 33 lakes on the Boreal Plains were extracted from the Global Surface Water dataset (Pekel et al., 2016) via Google Earth Engine. The Global Surface Water dataset used orthorectified Landsat satellite images at a 30-metre resolution to develop water history datasets of monthly water history data with information on water detections or absence (Pekel et al., 2016). Each pixel (representing a Landsat satellite image) was classified as either water (pixel value 2), land (pixel value 1), or non-valid observations (pixel value 0; snow, ice, cloud, or satellite issues; Pekel et al., 2016; Figure 4.4.4). The Global Surface Water Explorer used an expert system performance to deal with problems related to uncertainty and quality issues in the dataset. This expert system performance was further validated in terms of errors of omission at a pixel scale and were overall less than 5%. We averaged the number of water detections (pixel value 2) for each individual lake from June to August of each year to generate one value of water detection for an individual lake representing maximum inundation during summer. We also validated the water detection data to ensure algal blooms did not mask water detections in the study lakes by examining anomalies against previous months' water detections and lake water levels. Where there were a significant number of pixels in the no observation category, we assessed previous and subsequent months' water detections and made educated assumptions as to whether the pixels spanned areas where water would be detected if there was no cloud cover causing pixels to be classified as no observation. Additionally, we used historical aerial photographs taken in 2000 (1:6000; Air Photo Library, Alberta Government) when lake sediments were known to be exposed to cross-reference with the water detection data and check whether water detections excluded exposed sediment without vegetation establishment. The permanent presence of water in some lakes was too small to be captured by the monthly water history data, but were captured at annual timescales. Seasonal water presence was also included in the annual water history data, rather than only permanent water detections which are used in the monthly water history dataset. Therefore, in four of the 33 study lakes, we use the seasonal water presence from the annual water data history in the Global Surface Water Explorer. Pekel et al. (2016) defines a seasonal water surface as under water for less than 12 months of the year, whereas a permanent water surface as underwater throughout the year. In regions such as the Boreal Plains, where observations are not available year-round due to snow and ice cover, water detections are considered seasonal if the number of months where water is detected is less than the number of months for which valid observations were acquired (Pekel et al., 2016).

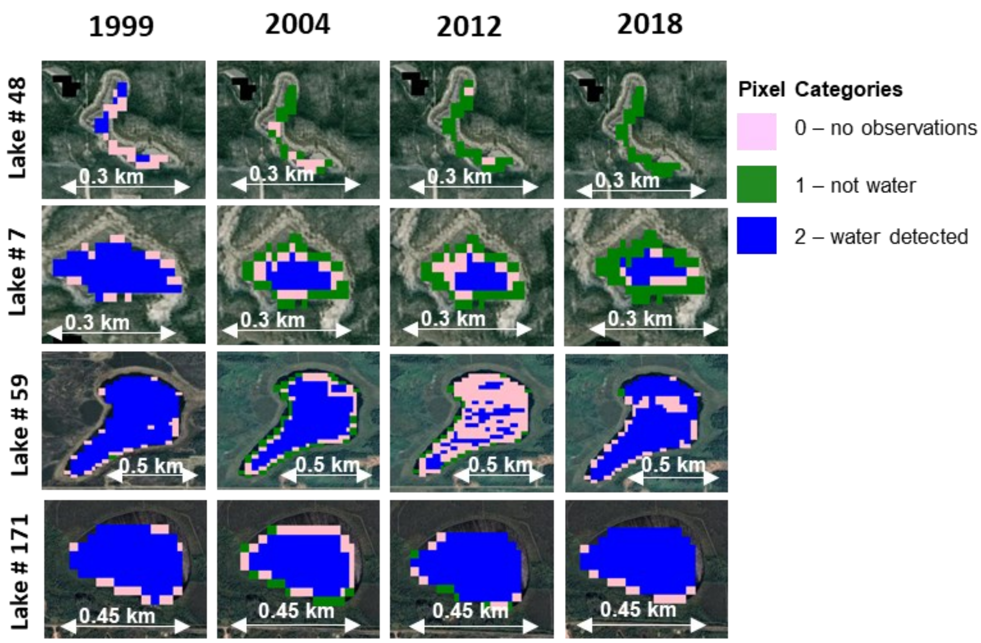


Figure 4.4.4: Example of pixels used for monthly Global Surface Water data extraction for the study lakes. Each column shows an example study lake within a given year and the different pixel categories classified for a said lake, where pink pixels represent a Landsat image (30x30 m) classified as no observations, green pixels represent not water detected, and blue pixels represent an image where water was detected.

4.2.4 Change in lake diameter

To quantify the change in lake diameter relative to the maximum lake diameter in each year, we first multiplied the total number of pixels representing water detection by the resolution of the Landsat imagery (30 x 30 m) to obtain the open water lake area for each lake. The open water lake area was then converted into a diameter ($\sqrt{\frac{Area}{\pi}} \cdot 2$). We used average diameter to represent the changes in lake extent through time as this provided us with an indication of how much shoreline was exposed for potential terrestrialisation to occur. An area of open water extent could be used but in larger lakes, a large change in area doesn't necessarily mean that significant portions of the shoreline is exposed, whereas a diameter can represent the change in shoreline more effectively. The maximum open water lake diameter recorded for each lake (1996 – 2019) was then subtracted from the open water lake diameter recorded in each year to obtain the annual lake diameter relative to the maximum lake diameter. Therefore, the change in lake diameter between years shows how much of the lakebed is exposed in each year.

4.2.5 Lag time

We regressed the change in lake diameter for each lake against different cumulative departure from mean precipitation (CDMP) periods (ranging from 1 year through to 5 years CDMP) between 1996 and 2019. The strongest relationships between change in lake diameter and different cumulative departure from mean precipitation periods were used to identify a lag time between the occurrence of a dry period and how quickly an individual lakes diameter responds (A.3.2).

4.2.6 Resistance

Resistance was expressed by the magnitude of an individual lake's response to a dry period. We used the maximum change in lake diameter that occurred during each dry period to quantify relative resistance of each lake. Relative resistance was quantified for each lake during each of the three dry periods considered, which varied in severity. To account for permanent changes to lake diameter resulting from earlier dry periods, the maximum change in lake diameter was relative to the maximum lake diameter (maximum open water lake extent) recorded prior to the onset of each dry period. Therefore, to quantify lake resistance during the high severity dry period (2000 to

2004), we subtracted the maximum change in lake diameter from 2000 to 2004 from the maximum lake diameter recorded between 1996 to 1999.

4.2.7 Resilience

We defined resilience as the ability of a lake to return to the average lake diameter observed during the pre-dry period, in between any onsets of previous dry periods. To quantify resilience, we subtracted the average post-dry event lake diameter from the pre-dry event lake diameter. Thus, a lake would be considered to have high resilience when the difference between pre- and post-dry period lake diameter is lower.

4.2.8 Lake and landscape attributes

4.2.8.1 Lake attributes

The 33 lakes used in this study are distributed along a 70-km transect at the URSA. The lakes in the study area are shallow (~ 0.5 – 5 m deep; Chp. 2; Olefeldt et al., 2013) and naturally mesotrophic to hypereutrophic (Bayley et al., 2007; Nurnberg & Shaw, 1999; Plach et al., 2016). The lakes range in size from 0.71 to 324 ha (Chapter 2).

Substrate type (firm or loose), and lake basin morphology (sloping or straight-sided) were identified in *a-priori* predictions as potential primary controls on lake resistance and resilience to inter-annual wet-dry periods (Table 4.2). Both substrate type and lake basin morphology were determined by assessments undertaken during annual lake sampling trips from 2017 to 2019 in conjunction with visual assessments of historical photographs and aerial images representing lake conditions (e.g., presence of floating mats) prior to the high severity dry period from 2000 to 2004. To test substrate type, we walked out into each individual lake, where possible, at representative sections of the lake shoreline. In lakes with loose sediment depths more than 20 cm, the lake substrate was considered sufficiently loose to allow any rooted vegetation established during a dry year to float upon rewetting. Lakes with less than 20 cm of loose sediment were considered firm enough for rooted vegetation to remain attached to the lakebed upon rewetting. The basin morphology was assessed at representative edges of each lake where lakes with vertical peat accumulation at the aquatic-terrestrial interface were considered straight-sided. We also assessed change in lake depth as you progress further into the lake (up to 10 m, where possible) to determine straight versus sloping sided basins where floating mats were present. Lakes where change in lake depth increased as you get further into the lake were defined as sloping sided, whilst lakes with no relationship between lake depth and distance to centre of lake were straight-sided. Visual assessments of the shoreline at each lake were also undertaken during annual lake sampling (2017 – 2019), and the presence of floating mats at the reference location for each lake recorded and then cross-referenced against recent and historical photography, in addition to satellite imagery.

To obtain lake water levels, depth of water was measured at a permanent reference location with known elevation (MASL) at the edge of each lake during the summer from 1999 to 2019. In 2012, a survey of simultaneous water level measures at the permanent reference location and at the centre of the lake (assumed maximum depth) was undertaken and then used to estimate the maximum depth at the centre of each lake in other years.

To test *a-priori* predictions for the resilience of lakes to inter-annual wet-dry periods (i.e., whether lakes return to original extent, or undergo a permanent loss in open water lake extent where a new lake extent is established; Table 4.2), lake water level was regressed against departure from maximum lake diameter for each lake from 1999 to 2019. We used visual assessments to classify relationships between lake depth and lake diameter for each lake using linear regressions as positive, absent, or negative, each indicative of different processes that may drive open water lake extent responses to dry periods. A positive relationship between lake diameter and lake water level suggested lakes with sloping basins and/or firm substrates, where a decrease in lake water level gradually exposes the lakebed, then upon rewetting if the lake substrate is firm any vegetation established is flooded out as the vegetation is secured to the lakebed. An absence of relationship between lake water level and lake diameter could arise due to two *a-priori* hypotheses. Firstly, a change in lake water level but no change in lake diameter suggests the presence of floating vegetation mats that rise and fall with changing water levels. Secondly, a change in lake diameter with no change in lake water level, may suggest sloping-sided lakes with benches for deeper portions of the lake allowing for exposure of lakebed at the lake edge, but minimal changes in lake water level at lake centre. A negative relationship, where lake diameter increases as lake water level decreases, may suggest drivers that overwhelm the influence of inter-annual wet-dry periods (e.g. larger groundwater contributions (indicated by surficial geology and landscape position), beaver control). However, in some lakes a negative relationship could represent the occurrence of permanent shrinkage as a lake reaches a new stable state where a new maximum lake diameter has been established following a dry period.

The relative elevation of each lake within a HRA sub-unit created comparable relative elevations and an indication of landscape position for each lake (Chp. 2). We used HRA sub-units which subdivided HRAs according to regional subsurface flow-systems (Chp. 2). The relative elevation for each lake was then calculated using a 30-m resolution digital elevation model as the percentile of the highest and lowest lake elevation compared to other elevations in the HRA-subunit (Chp. 2).

4.2.8.2 Landscape attributes

The watersheds of the 33 lakes in this study were delineated in Chapter 2. Furthermore, this study uses the HRA classifications of each lake identified in Chapter 2, where the HRA of each watershed was defined according to the dominant HRA type (i.e., 50% of watershed or greater). We also used the connected wetland area (CWA) calculated in Chapter. 2 to quantify the proportion of connected wetland in each lake watershed (DUC, 2011).

4.2.9 Statistics

To test for significant differences in spatial variability of lake responses to dry periods among HRAs, we used two standard deviations (2SD) of the departure from maximum lake diameter (spatial variability) in a Kruskal-Wallis one-way analysis of variance. To test for differences in resistance and resilience among lakes in each HRA, we used a Wilcox Rank test on the maximum change in lake diameter that occurred during each dry period (resistance), and post-dry event minus pre-dry event lake diameter values (resilience). For each statistical test, *p*-values <0.05 (95% confidence interval) were considered significant. To identify which HRAs were significantly different, we also conducted multiple pairwise-comparisons between groups using the 'pairwise.wilcox.test' function within the 'stats v3.6.2' package in R.

A multivariate regression tree was performed using the 'mvpart' package in R (De'ath, 2002, Therneau & Atkinson, 2004) to group lakes based on similarities in their resistance, lag times, and resilience in response to dry periods. We condensed resistance and resilience values across each of the dry periods into a singular value to disentangle inter-annual patterns among lakes. We ranked the resistance and resilience values for each dry period from high to low values (low rank value = low resilience / resistance), and then averaged the rank position across the dry periods to quantify overall resistance and resilience of each lake across the dry periods used in this study. Response variables including resistance, lag times, and resilience, were normalised via min-max scaling to account for differences in units of measurement and range in data between response variables. We also conducted a Shapiro-Wilks test for normality on each response variable and found that both resistance and resilience values were normally distributed, whilst lag times were not normally distributed (p = 0.003). Explanatory variables included watershed dominant HRA type (surficial geology), proportion connected wetland in watershed, landscape position, substrate type, and lake basin morphology. The final tree was selected after pruning to identify the tree with the smallest cross-validated relative error.

We conducted an analysis of synchrony for the groups of lakes identified in a multivariate regression tree by examining the correlation of change in lake diameter throughout the study period for each of the possible lake pairs in each group. We also conducted an overall synchrony analysis on the 33 lakes used in this study to compare with the synchronicity of individual lake groups. Synchronicity, an indicator of whether controls on variability lake responses are common or individual, was determined by averaging the Pearson correlation coefficients for each group of lakes, and an overall synchronicity for all 33 lake pair correlations (Jane et al., 2017; Kratz et al., 1998; Magnuson et al., 1990; Pace and Cole, 2002).

4.3 Results

4.3.1 Inter-annual wet-dry periods

Using the 3yrCDMP (3-year cumulative departure from average precipitation), we identified three hydrologically dry periods (3yrCDM < -100 mm) during the study period (2000-2004, 2010-2012 & 2016; Figure 4.4.3; Table 4.1). The dry period from 2000 to 2004 had the highest severity and intensity, followed by the 2010 to 2012, and 2016 periods (Table 4.1).

Table 4.1: Summary of characteristics for each hydrologic dry period.

Hydrological Dry Periods	Average Precipitation (mm)	Severity (mm)	Intensity (mm year^{-1})	Pre-Dry Period	Post-Dry Period
2000 - 2004	339.18	-1094.77	-218.95	1996-1999	2005-2009
2010 - 2012	379.03	-471.95	-157.32	2005-2009	2013-2015
2016	456.30	-113.29	-113.29	2013-2015	2017-2019

Note. Hydrologic years extend from 1 July to 30 June in each year. Severity of hydrologically dry years quantified by accumulating the 3yrCDM for the duration of each dry period and intensity quantified by dividing severity by the duration (in years) of each dry period.

4.3.2 Spatial variability in lake diameter responses to dry periods

All lakes exhibited contraction and expansion during the study period, but there was large variability among lakes with regards to how much their lake diameter fluctuated (Figure 4.4.5). Two standard deviations (2SD) of the departure from maximum lake diameter were used to compare spatial variability in lake diameter and it ranged from 5.0 to 371 m among study lakes (A.3.3). Lake diameter variability (2SD) was significantly different between HRAs ($p < 0.05$), being highest on the fine plains (67.3 m), followed by the fine hummocky (41.9 m), and least in the coarse (16.0 m; Figure 4.4.5; A.3.3). Two lakes (Lake ID # 43 & 48) within the fine hummocky dried out completely; Lake 43 during 2003, and Lake 48 from 2016 onwards (Figure 4.4.5). However, from ground-truthing, although Lake 48 had decreased in lake extent substantially, there remained some open water as revealed by field visits that was not captured by the Global Surface Water Explorer after 2016. Furthermore, we know from historical photographs that Lake 43 dried out completely in 2002, yet this was not captured in the Global Surface Water Explorer data. Both lakes that dried out were relatively small lakes (Average Lake Diameter: #43 – 112 m; #48 191 m), with loose substrate, straight sided basin morphology that slopes towards the centre, and located in higher topographic landscape positions.

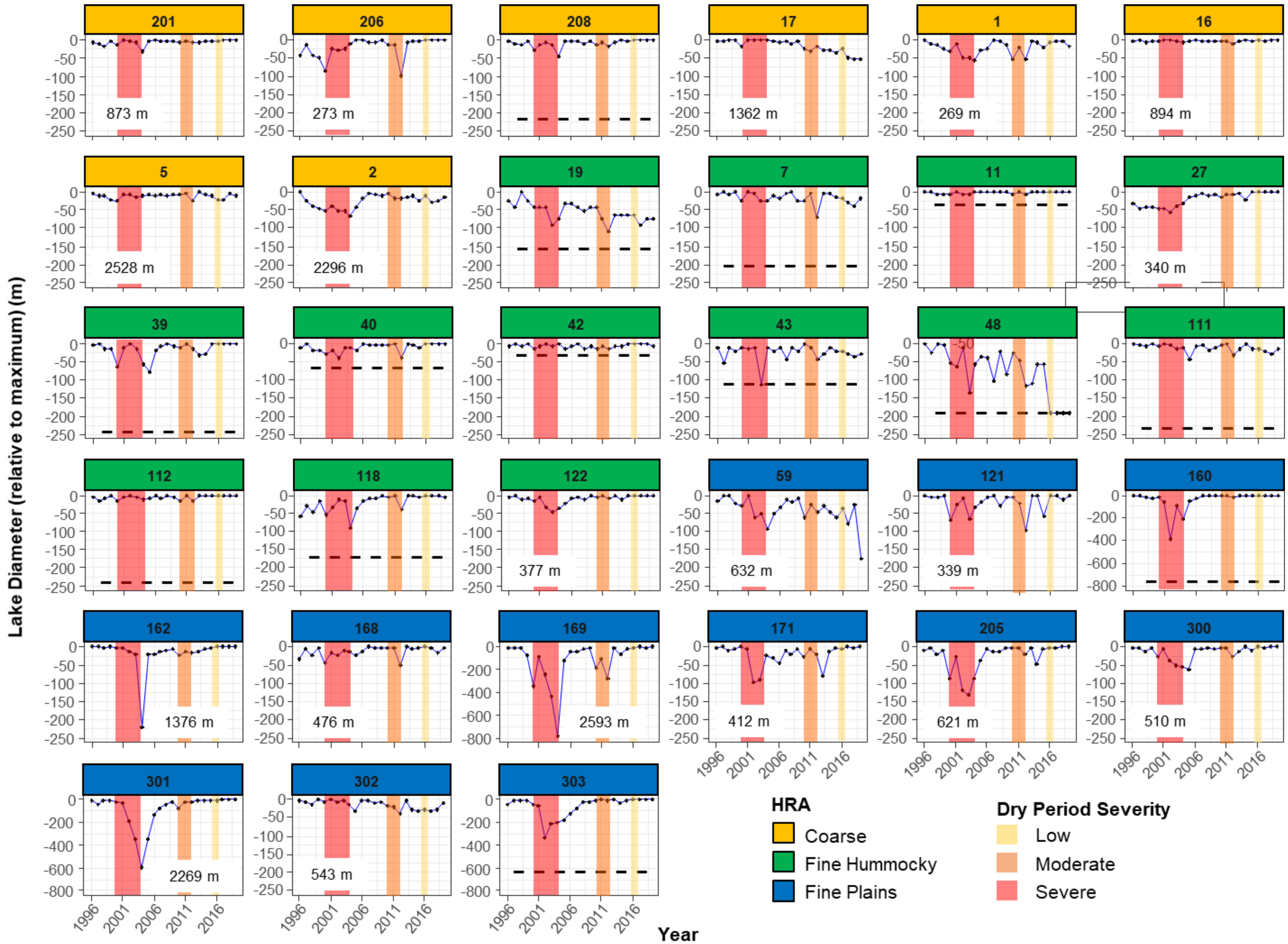

201
206
208
17
1
16
5
2
19
7
11
27
39
40
42
43
48
111
112
118
122
59
121
160
162
168
169
171
205
300
301
302
303
873 m
273 m
1362 m
269 m
894 m
2528 m
2296 m
340 m
377 m
632 m
339 m
1376 m
476 m
2593 m
412 m
621 m
510 m
2269 m
543 m
Lake Diameter (relative to maximum) (m)
Year
HRA
Coarse
Fine Hummocky
Fine Plains
Dry Period Severity
Low
Moderate
Severe

Figure 4.4.5: Time-series showing lake diameter across each study lake from 1996 – 2019. Lake diameter is expressed as the difference between annual lake diameter and the maximum lake diameter recorded between 1996 and 2019, where 0 m is the maximum lake diameter and a negative departure from this indicates exposure of the lakebed. Vertical lines on each plot represent dry periods of different severities quantified by calculating the accumulated departure from average precipitation for the duration of a dry event; red – severe dry period, orange – moderate dry period, yellow – mild dry period (Table 4.2). The black dashed line in each plot indicates the loss in lake diameter required for each lake to dry out completely. For large lakes, this is indicated by the value located in the bottom of each panel. The coloured boxes above each plot indicate which HRA the lake is located in (orange = coarse, green = fine hummocky, blue = fine plains). Note that lakes #160, 169, 301 and 303 are on a different scale on the y-axis.

Variability in lake diameter was controlled by an interaction between lake area and HRA, while neither lake depth, watershed to lake area ratio, landscape position, nor wetland connectivity influenced lake diameter variability (Figure 4.4.6). Larger lakes were generally found to have greater absolute lake diameter variability ($2SD_{log}$, [m]), although smaller lakes had greater lake diameter variability when expressed in relative terms (2SD, [%]). The generally smaller lakes in the fine hummocky HRA thus had the greatest relative lake diameter variability. For lakes with similar size, we found that lakes in coarse HRA had lower lake diameter variability than those in fine HRAs.

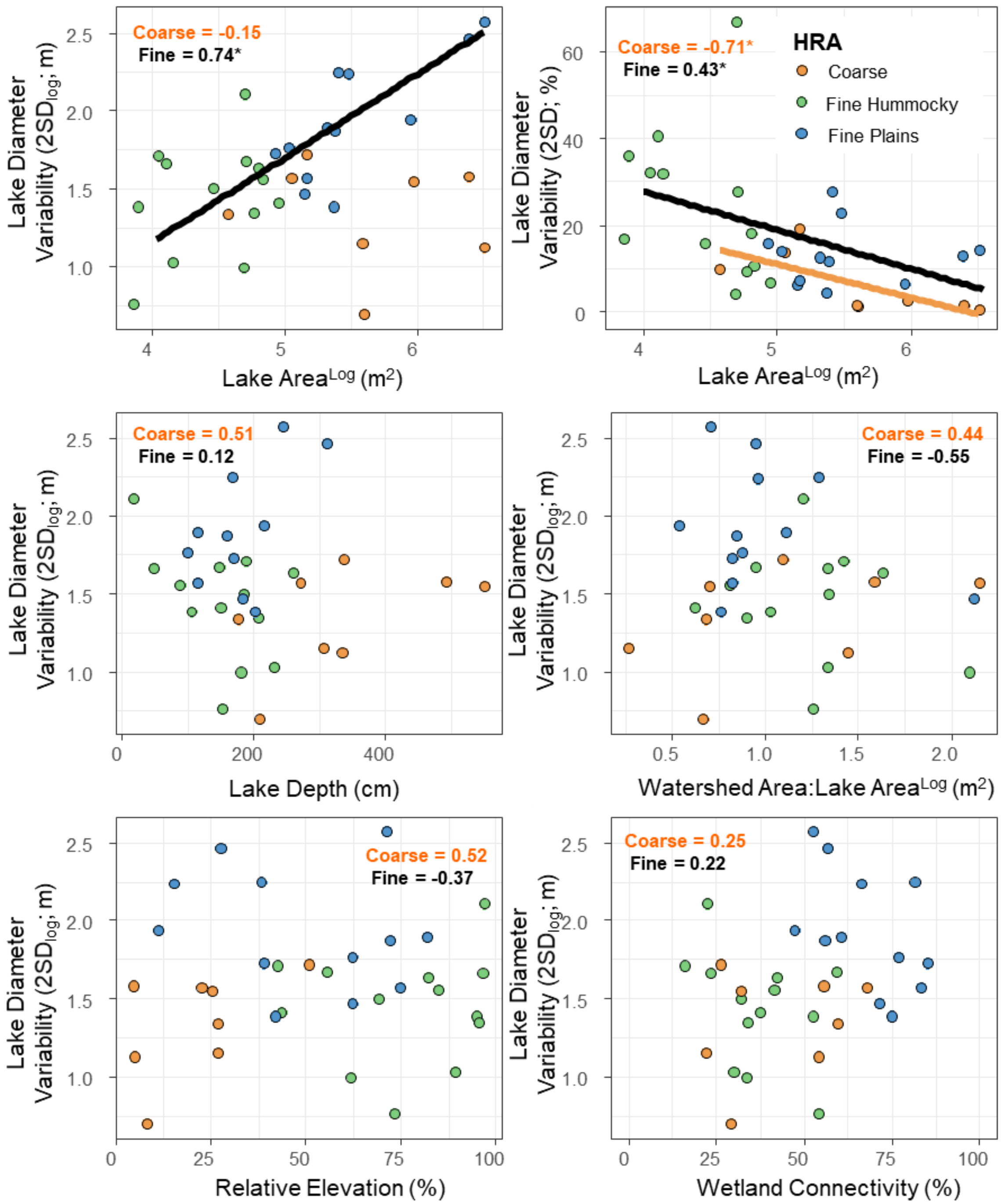

Coarse = -0.15
Fine = 0.74*
Lake Diameter Variability (2SD$_{log}$; m)
Lake Area^{Log} (m^2)
Coarse = -0.71*
Fine = 0.43*
HRA
Coarse
Fine Hummocky
Fine Plains
Lake Diameter Variability (2SD; %)
Lake Area^{Log} (m^2)
Coarse = 0.51
Fine = 0.12
Lake Depth (cm)
Coarse = 0.44
Fine = -0.55
Watershed Area:Lake Area^{Log} (m^2)
Coarse = 0.52
Fine = -0.37
Relative Elevation (%)
Coarse = 0.25
Fine = 0.22
Wetland Connectivity (%)

Figure 4.4.6: Correlations between lake diameter variability (2 Standard Deviations; $2SD_{log}$) and lake and landscape attributes (lake area, lake depth, watershed area to lake area, relative elevation and wetland connectivity) across URSA lakes. Each point represents an individual lake coloured by Hydrologic Response Area (Coarse = orange, Fine Hummocky = green, Fine Plains = blue). Solid linear regression lines coloured by coarse and fine (grouped fine hummocky and fine plains lakes) HRAs in the top two panels were the only significant relationships identified ($p < 0.05$). Pearson R correlation coefficients for coarse and fine textured lakes are presented in orange and black, respectively, in each panel. Significant Pearson correlations (r) are indicated by *.

4.3.3 Resistance, lag times and resilience of Boreal Plains Lakes to dry periods

4.3.3.1 Links between water level and lake extent

To determine the influence of substrate type (e.g., shoreline floating vegetation) and lake basin morphology on the inter-annual variability of lake diameter, correlations between lake diameter and lake water level were assessed (Figure 4.4.7). A conceptual model demonstrating the combinations of substrate type and lake basin morphology that influence whether lake shorelines exhibit floating mat vegetation or flooded out vegetation informed *a priori* predictions (Table 4.2). The relationships between lake depth and lake extent were then used to test *a-priori* predictions outlined in Table 4.2.

Of the 33 lakes, we found that 11 lakes had a positive relationship between lake level and lake diameter (Figure 4.4.7). There were 13 lakes that showed "absent" responses, but with different relationships between lake water level and diameter. Of the 13 lakes, eight lakes (Lake ID# 16, 11, 111, 121, 160, 169, 171, 302) showed substantial variability in lake level without any shifts in lake diameter, whilst five lakes (Lake ID# 27, 43, 118, 168, 301) showed substantial variability in lake diameter with limited shifts in lake water level (Figure 4.4.7). Lastly, nine lakes had a negative relationship between lake water level and diameter (Figure 4.4.7). Given the hypothesized influence of lake substrate type and lake basin morphology (Table 4.2; Figure 4.4.7), we found that 16 lakes followed our predictions while 17 did not (Table 4.2; Figure 4.4.7).

Table 4.2: Summary of a priori predictions for lake attributes (substrate and lake basin morphology) hypothesised to influence lake extent responses to dry periods at URSA, representative of the Boreal Plains.

Lake ID	Bathymetry	Substrate	A-priori Predictions		
			Relationship between ΔD and ΔWL	Process	Motivation
201	Straight	Firm	***Absent***	*Floating*	Floating mat approximately 10 m wide with reed vegetation extending approximately 2 m into the lake. Beaver control at lake, small watershed & groundwater connectivity. Straight sides allow WL to rise at a pace reed vegetation can keep up with rather than flood vegetation out.
206	Straight	Loose	***Absent***	Floating	Expansive floating mat development since high severity dry period and beaver control. Floating mats allows vegetation to rise with rising lake water levels, thus spatial extent of lake in response to dry periods is limited.
208	Straight	Firm	***Absent***	*Floating*	Floating mat approximately 10 m wide with reed vegetation extending approximately 2 m into the lake. Straight sides allow WL to rise at a pace reed vegetation can keep up with rather than flood vegetation out. Expansive floating mat development since high severity dry period.
17	Sloping	Firm	***Positive***	Floods	Reeds / Grasses extending approximately 20 m into lake. Firm substrate and sloping sides results in shifts in lake extent during dry periods and any vegetation established is flooded out upon rewetting.
1	Sloping	Firm	Positive	Floods	Reeds / Grasses extending approximately 10 m into lake. Firm substrate and sloping sides results in shifts in lake extent during dry periods and any vegetation established is flooded out upon rewetting.
16	Straight	Firm	Absent	*Floating*	Small watershed & groundwater connectivity. Areas of lake shore with floating mats approximately 10 m wide, some areas with less floating mat presence, particularly along south east shoreline where water discharges from upstream lake.
5	Sloping	Firm	Positive	Limited response	Limited response to inter-annual wet dry periods, but firm substrate and sloping sides promotes flooding responses. Large watershed, groundwater connectivity & beaver influence
2	Sloping	Firm	***Positive***	Limited response	Limited response to inter-annual wet dry periods, but firm substrate and sloping sides promotes flooding responses. Large watershed, groundwater connectivity & beaver influence
19	Sloping	Loose	Negative	Permanent Shrinkage	Loose substrates but slight enough slope that basin edges drained to create firmer edges with lake at centre of depression. Expansive vegetation established during dry periods and has not recovered within study period, lake appears to have undergone permanent change in lake extent and is at a new equilibrium.
7	Sloping	Loose	***Absent***	Floating	Floating mat rings lake and allows vegetation to rise with rising lake water levels, thus spatial extent of lake in response to dry periods is limited.
11	Straight	Loose	Absent	Floating	Floating mat rings lake and allows vegetation to rise with rising lake water levels, thus spatial extent of lake in response to dry periods is limited.
27	Sloping	Loose	Absent	Floating	Floating mat rings lake and allows vegetation to rise with rising lake water levels, thus spatial extent of lake in response to dry periods is limited.
39	Sloping	Loose	***Absent***	Floating	Floating mat rings lake and allows vegetation to rise with rising lake water levels, thus spatial extent of lake in response to dry periods is limited.
40	Straight	Loose	Absent	Limited response	Limited response to wet dry periods and receives water from upstream watersheds (43 & 48). Straight, then slightly sloping to lake centre. Peat build-up at lake edges creating straight slides and extensive peatland connectivity in watershed. Straight sides need to be overcome to flood out, but build-up of peat likely prevents flooding.
42	Straight	Loose	***Absent***	Floating	Floating mat rings lake and allows vegetation to rise with rising lake water levels, thus spatial extent of lake in response to dry periods is limited.
43	Straight	Loose	***Negative***	Permanent Shrinkage	Slightly steeper slope than Lake 40. Large changes in lake diameter and water level. Expansive floating mats established during dry periods.

48	Straight	Loose	Negative	Permanent Shrinkage	Slightly steeper slope than Lake 40 & 43, but smaller, more isolated watershed. Large changes in lake diameter and water level. Expansive floating mats established during dry periods which have now become firmer ground and has not recovered in study period, lake appears to have undergone permanent change in lake extent.
111	Sloping	Firm	Absent	Floating	Expansive floating mats formed during dry period, even though substrate is firm. Floating mats allows vegetation to rise with rising lake water levels, thus spatial extent of lake in response to dry periods is limited.
112	Straight	Loose	***Absent***	Floating	Floating mats with beaver control. Floating mats allows vegetation to rise with rising lake water levels, thus spatial extent of lake in response to dry periods is limited.
118	Sloping	Loose	Absent	Floating	Lake expanding through time due to beaver control. However floating mats are also present.
122	Sloping	Loose	***Absent***	Floating	Small floating mats in lake. Floating mats allows vegetation to rise with rising lake water levels, thus spatial extent of lake in response to dry periods is limited.
59	Sloping	Loose	***Absent***	Floating	Floating mat rings lake and allows vegetation to rise with rising lake water levels, thus spatial extent of lake in response to dry periods is limited.
121	Straight	Loose	Absent	Floating	Small floating mats in lake. Floating mats allows vegetation to rise with rising lake water levels, thus spatial extent of lake in response to dry periods is limited.
160	Straight	Firm	Absent	Floating	Peat build-up at lake edges creating straight slides. Straight sides need to be overcome to flood out, but build-up of peat likely prevents flooding.
162	Sloping	Firm	Positive	Floods	Sloping sides with reed vegetation extending approximately 20 m into lake. Firm substrate and sloping sides results in shifts in lake extent during dry periods and any vegetation established is flooded out upon rewetting.
168	Straight	Loose	Absent	Floating	Limited response to wet dry periods. Large watershed to lake area. Peat build-up at lake edges creating straight slides. Straight sides need to be overcome to flood out, but build-up of peat likely prevents flooding.
169	Sloping	Firm	Absent	*Floating*	Expansive floating mats formed during dry period, even though substrate is firm. Floating mats allows vegetation to rise with rising lake water levels, thus spatial extent of lake in response to dry periods is limited.
171	Straight	Loose	Absent	Floating	Peat build-up at lake edges creating straight slides. Straight sides need to be overcome to flood out, but build-up of peat likely prevents flooding. West side of lake has expansive floating mat, whilst remaining shoreline has approximately 1 -2 m floating mat.
205	Straight	Loose	***Absent***	Floating	Peat build-up at lake edges creating straight slides. Straight sides need to be overcome to flood out, but build-up of peat likely prevents flooding. Evidence of floating mats around lake.
300	Straight	Loose	***Absent***	Floating	Peat build-up at lake edges creating straight slides. Straight sides need to be overcome to flood out, but build-up of peat likely prevents flooding. Limited extent of floating mat, extending approximately 1-2 m into lakes and relatively firm attachment to surrounding peatland.
301	Straight	Firm	***Positive***	Floods	Reeds / Grasses extending approximately 10 m into lake. Firm substrate and straight sides results in limited shifts in lake extent during dry periods and any vegetation established is flooded out upon rewetting.
302	Straight	Loose	Absent	Floating	Peat build-up at lake edges creating straight slides. Straight sides need to be overcome to flood out, but build-up of peat likely prevents flooding. Evidence of floating mats around lake.
303	Straight	Loose	***Absent***	Floating	Peat build-up at lake edges creating straight slides. Straight sides need to be overcome to flood out, but build-up of peat likely prevents flooding. Evidence of floating mats around lake.

Note. Italicised and bolded classifications for a-priori predictions for the relationship between lake water level and lake diameter indicate lake classifications that contradict the relationships identified in Figure 4.6. Lake ID colours indicates the HRA of each lake (orange = coarse, green = fine hummocky, blue = fine plains). Italics used to indicate that the lake has characteristics that contradict what we might expect from the conceptual model (Figure 4.1).

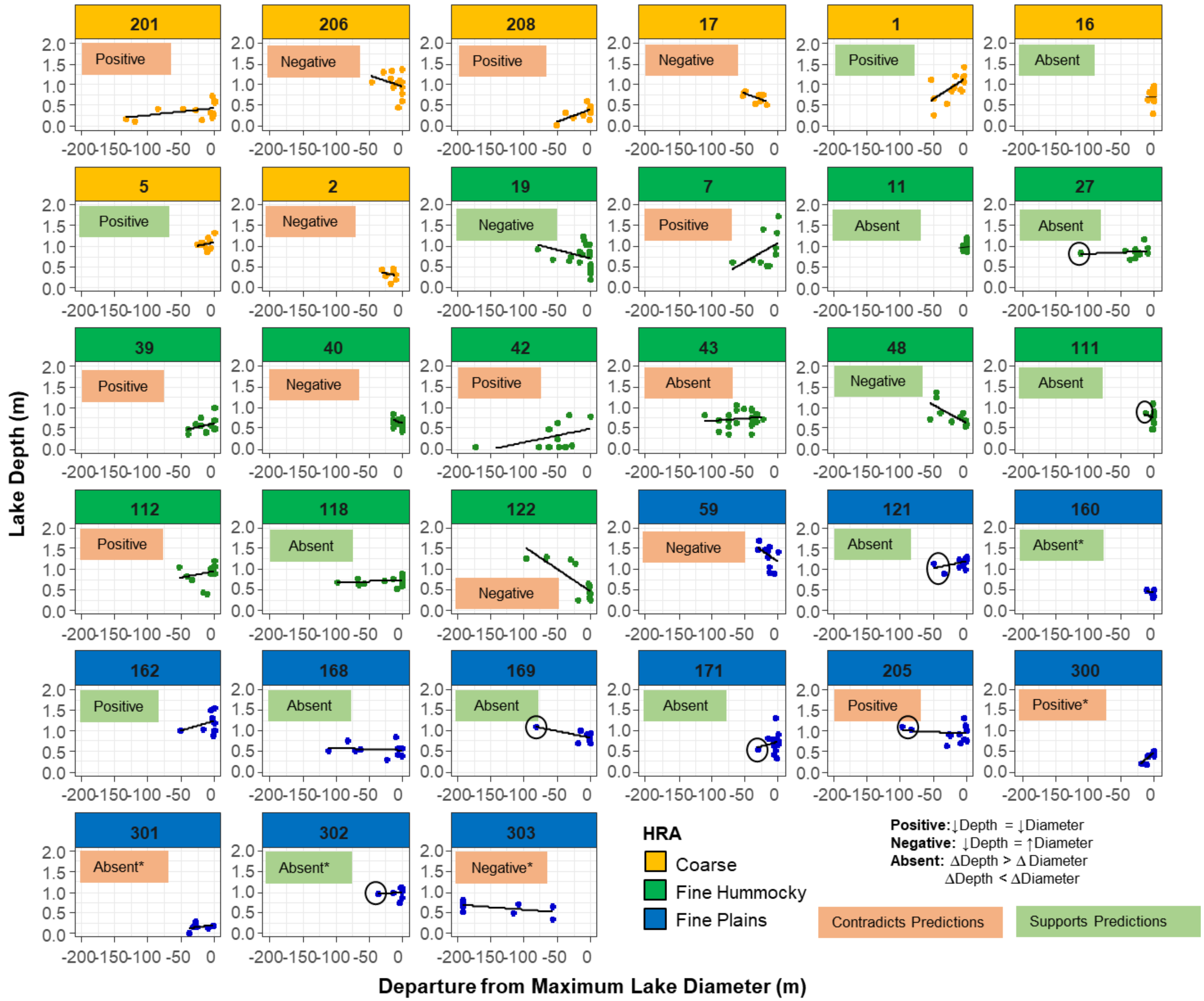

Lake Depth (m)
Departure from Maximum Lake Diameter (m)
201 Positive
206 Negative
208 Positive
17 Negative
1 Positive
16 Absent
5 Positive
2 Negative
19 Negative
7 Positive
11 Absent
27 Absent
39 Positive
40 Negative
42 Positive
43 Absent
48 Negative
111 Absent
112 Positive
118 Absent
122 Negative
59 Negative
121 Absent
160 Absent*
162 Positive
168 Absent
169 Absent
171 Absent
205 Positive
300 Positive*
301 Absent*
302 Absent*
303 Negative*
HRA
Coarse
Fine Hummocky
Fine Plains
Positive: ↓Depth = ↓Diameter
Negative: ↓Depth = ↑Diameter
Absent: ΔDepth > ΔDiameter
ΔDepth < ΔDiameter
Contradicts Predictions
Supports Predictions

Figure 4.4.7: Evaluation of predicted versus observed relationships between lake water level and change in lake diameter recorded between 1996 and 2019. Each panel has a linear regression line fitted to identify positive, negative or absent relationships between lake water level and lake diameter in response to inter-annual wet-dry periods. A positive relationship suggested lakes with sloping basins and/or firm substrates, where a decrease in lake water level gradually exposes the lakebed, then upon rewetting if the lake substrate is firm any vegetation established is flooded out as the vegetation is secured to the lakebed. An absence of relationship could arise due to two a-priori hypotheses; a change in lake water level but no change in lake diameter suggests the presence of floating vegetation mats that rise and fall with changing water levels, or a change in lake diameter with no change in lake water level, may suggest sloping-sided lakes with benches for deeper portions of the lake allowing for exposure of lakebed at the lake edge, but minimal changes in lake water level at lake centre. A negative relationship, where lake diameter increases as lake water level decreases, may suggest drivers that overwhelm the influence of inter-annual wet-dry periods. The text box in each panel indicates whether *a-priori* predictions in Table 4.2 were supported (green) or contradicted (red). The coloured boxes above each plot indicate which HRA the lake is located in (orange = coarse, green = fine hummocky, blue = fine plains). Black circles indicate data points from the high severity dry period, and thus represents extreme responses in the relationship between lake water level and were excluded when assessing relationships. Note that lake water levels were not available in every year (i.e. 2012 to 2019) for all lakes as indicated by an *.

4.3.3.2 Resistance

Resistance was expressed by the magnitude of an individual lake's response to a dry period. The resistance of lake responses to dry periods depended on the severity of the dry period, with overall lake diameter shrinking by a median of 65, 29, and 2 m during the severe, moderate, and mild dry periods, respectively (Figure 4.4.8). Lake contraction during the severe dry period was dependent on lake HRA, with median contractions of 116 m, 49 m, and 39 m in the fine plains, fine hummocky, and coarse HRAs, respectively (Figure 4.4.8). The median contraction of lakes on the fine plains during the severe dry period was significantly greater than for lakes in the other

HRAs ($p < 0.05$; Figure 4.4.8; A.3.4). No differences between any HRAs were found for the moderate and lesser dry periods, but we note that there was a shift in order, with the fine plains having the least contraction during the lesser dry period ($p > 0.05$; Figure 4.4.8; A.3.4).

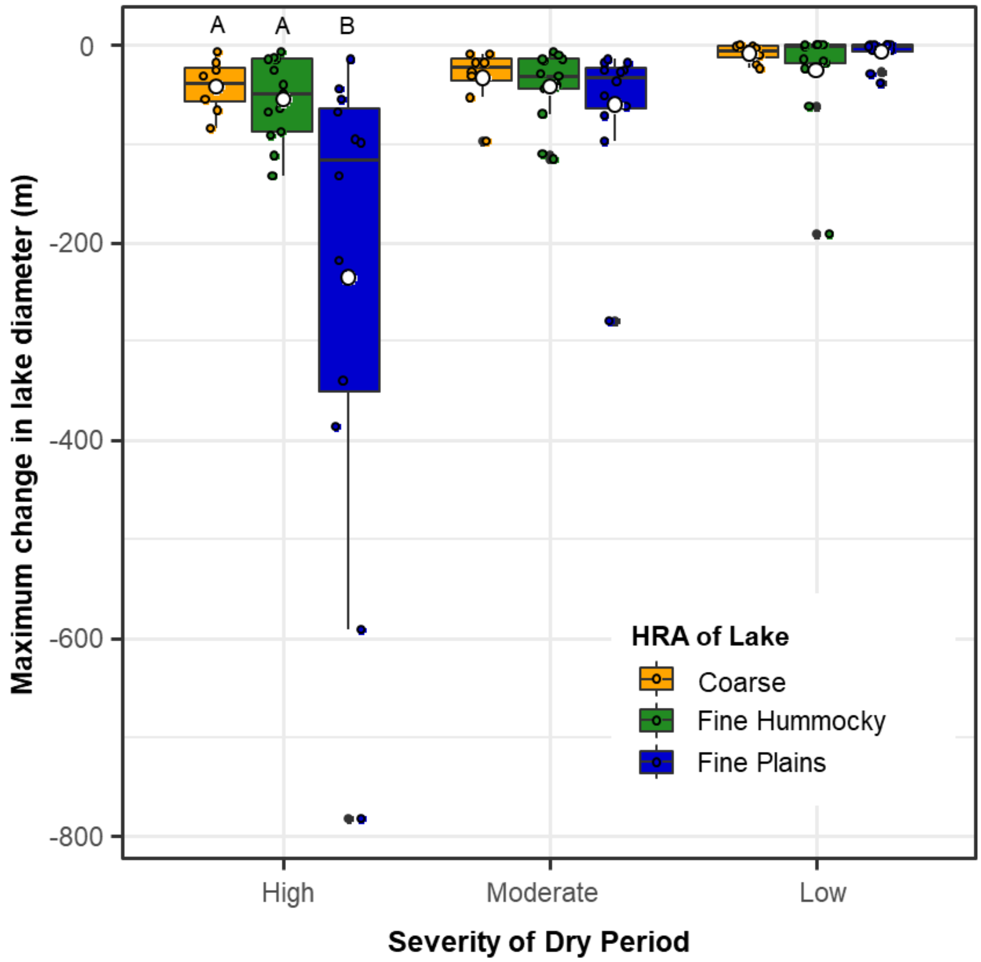


Figure 4.4.8: Boxplots showing the maximum change in lake diameter (i.e., resistance) in response to dry periods of differing severities. Larger negative departure from 0 m indicates lower resistance to a dry period. Maximum change in lake diameter is grouped by HRA for each dry period. White circles indicate the average change in lake diameter for lakes and black horizontal lines represent median lake diameter change within each HRA. Median lake diameter for lakes within each HRA are significantly different if letters are shown and they have no uppercase letters in common (Pairwise Wilcox Test, $p < 0.05$). Note that median was used due to non normal distributions of change in lake diameter in each HRA.

4.3.3.3 Lag times

Lag times of lakes (i.e. time taken for open water lake extent to respond to a dry period and determined from regressions between change in lake diameter and different cumulative departure from mean precipitation periods) showed no statistically significant relationships with watershed attributes, however trends observed with topographic landscape position and wetland connectivity are noteworthy. (Figure 4.4.9; A.3.2). Lake lag times across all HRAs ranged between 1 to 5 years and were generally shorter in lakes located at higher landscape positions with lower proportions of connected wetland in the watershed (Figure 4.4.9; A.3.2). Four lakes (Lake ID# 5, 16, 118, 201) had negative or no relationship ($p > 0.05$) between lake extent and the different cumulative departure from mean precipitation periods used in this study. Subsequently, no lag times between the occurrence of a dry period and how quickly an individual lakes diameter responds were quantified for these four lakes (A.3.2).

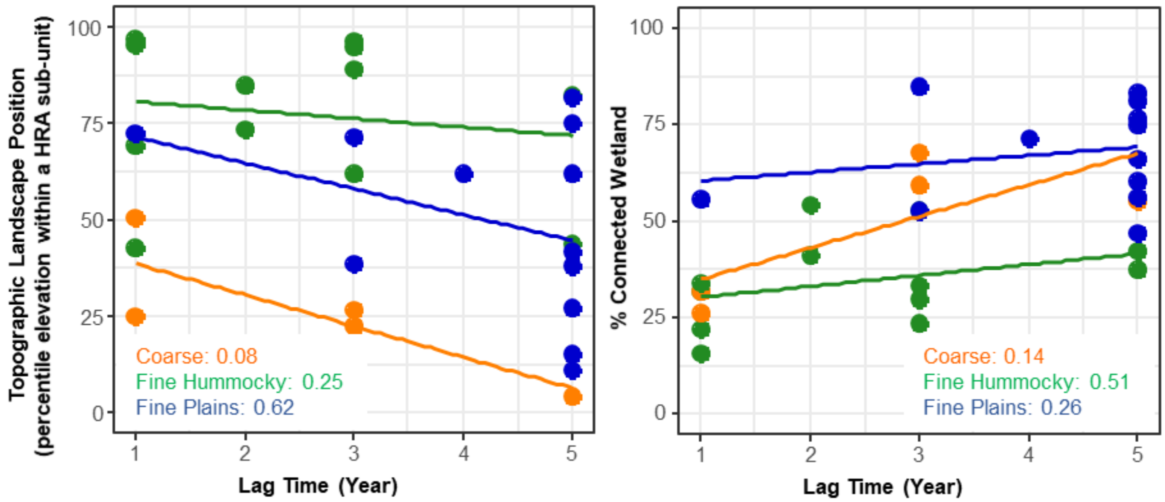


Figure 4.4.9: Relationships between lake lag times and (a) topographic landscape position, and (b) proportion of connected wetland in the watershed. Individual lakes are coloured according to HRA (coarse = orange, fine hummocky = green, fine plains = blue. Lag times were quantified from correlations between lake diameter and cumulative departure from mean (CDM) precipitation calculated across five different scenarios (CDM 1 year to CDM 5 year; A.3.2).

4.3.3.4 Resilience

Of the 33 lakes, 19 were resilient, i.e. their lake areas had in 2019 recovered completely from the contractions caused by the preceding dry periods (Figure 4.4.5). The 14 lakes that had lower resilience could be characterized by a few lake and watershed attributes, i.e., floating mat expansion. Four of the 14 lakes with lower resilience showed no recovery at all and led to the establishment of new stable states (Lake ID # 19, 43, 48, 59; Figure 4.4.5).

Although no statistical differences in resilience between lakes in different HRAs were found ($p > 0.05$), several trends are noteworthy. (Figure 4.4.10). Fine plains lake had a median lake diameter that contracted by 4 m between the pre- and post- high severity dry period, while the median difference was 0 m for lakes in the fine hummocky and coarse HRAs (Figure 4.4.10). Conversely, coarse and fine hummocky lakes showed the largest median contraction of 3 m and 0 m, respectively, in response to a moderate and no change (0 m) following a low severity dry period, whilst fine plains lakes expanded by approximately 1 m during both moderate and low severity dry periods (Figure 4.4.10).

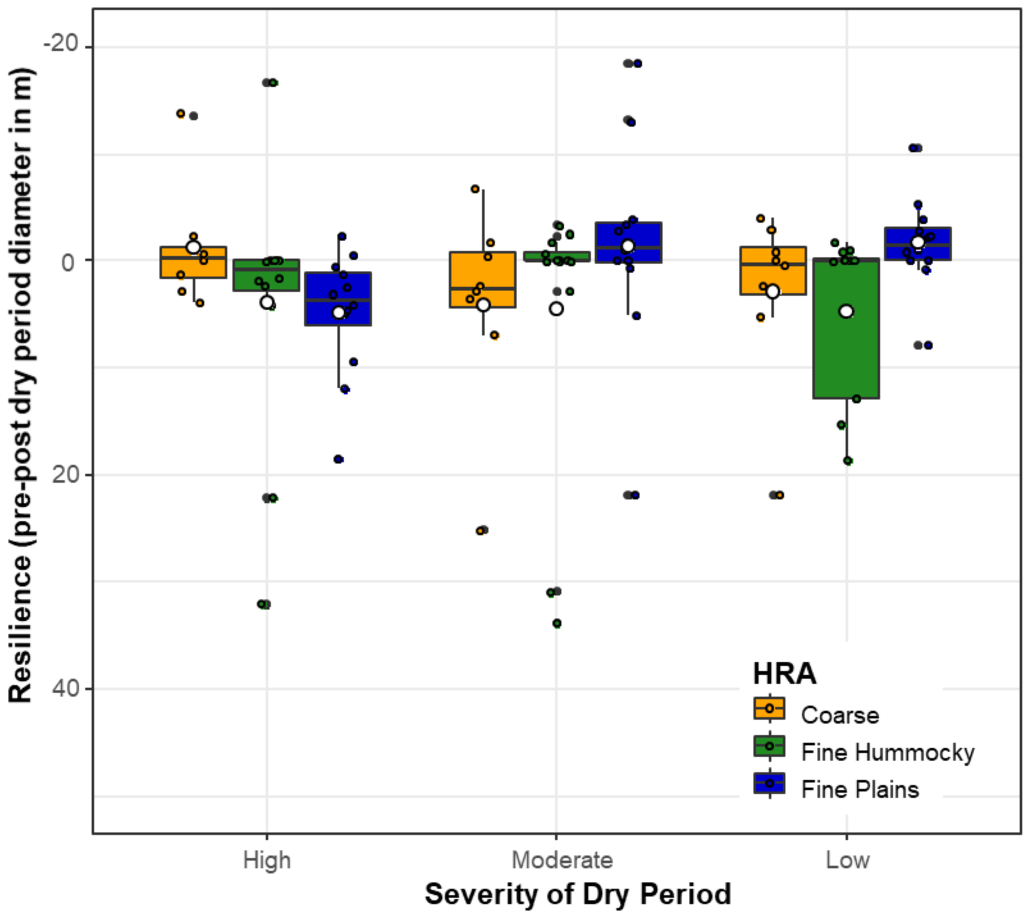


Figure 4.4.10: Boxplots showing the resilience (i.e., pre-post dry period diameter) of lakes grouped by Hydrologic Response Area to dry periods of differing severities. Larger negative departure from 0 m indicates lower resilience to a dry period, whilst positive departure from 0 m indicates an increase in lake diameter beyond pre-dry period extents. White circles indicate the average pre-post dry period diameter for lakes within a HRA responding to a dry period and black horizontal lines represent median pre-post dry period diameter for lakes. Note that median was used due to non normal distributions of change in lake diameter in each HRA.

4.3.4 Controls on resistance, lag time and resilience of lakes in response to dry periods

A multivariate regression tree analysis explained 46% of the variability in resistance, lag time, and resilience of lakes to dry periods (Figure 4.4.11). Proportion of connected wetland in the watershed and lake basin morphology were identified as primary controls on the responses of lakes to dry periods, explaining 40% and 6%, respectively (Figure 4.4.11).

Four lake groups were identified as similar in the multivariate regression tree (Figure 4.4.11). Group 1 lakes exhibited low resistance, resilience, and short lag times and was composed of lakes in fine hummocky regions with low wetland connectivity (<22% in the watershed; Figure 4.4.11). Group 2 exhibited higher resistance and resilience with mostly partial recovery but short lag times between the occurrence of an inter-annual wet-dry periods and open water lake extent response, when compared with Group 1 (Figure 4.4.11). Group 2 lakes were primarily fine-textured lakes with loose substrates, but also included one coarse-textured lake (Lake #17) and were associated with lower wetland connectivity (Lake #111; <50%; Figure 4.4.11). Lake #17 and #111 were also classified as firm substrate (Figure 4.4.11). Both Group 3 and 4 were associated with higher wetland connectivity in the watershed (> 38% in the watershed). However, Group 3 was associated with sloping sided lake basin morphology whilst Group 4 lakes had straight-sided lake basin morphology (Figure 4.4.11). Group 3 lakes exhibited lower resistance than Group 4 lakes, but showed similarly moderate to high resilience when compared with other Group 1 and 2, with Group 4 showing the highest overall resilience and longest lag times (Figure 4.4.11). A fifth group includes lakes that showed limited responses to inter-annual wet-dry periods and were associated with either large watersheds, large relative groundwater contributions, beaver control on hydrology, or a combination of these factors (Figure 4.4.11; A.1.3).

We also calculated the synchronicity of the departure from maximum lake diameter between years within each of the lake groups identified in the multivariate regression tree. The synchronicity of change in lake diameter within groups was generally higher than the overall synchronicity for all 33 study lakes, with exception to Group 2 (*G2 p* (016) < Overall *p* (0.19).

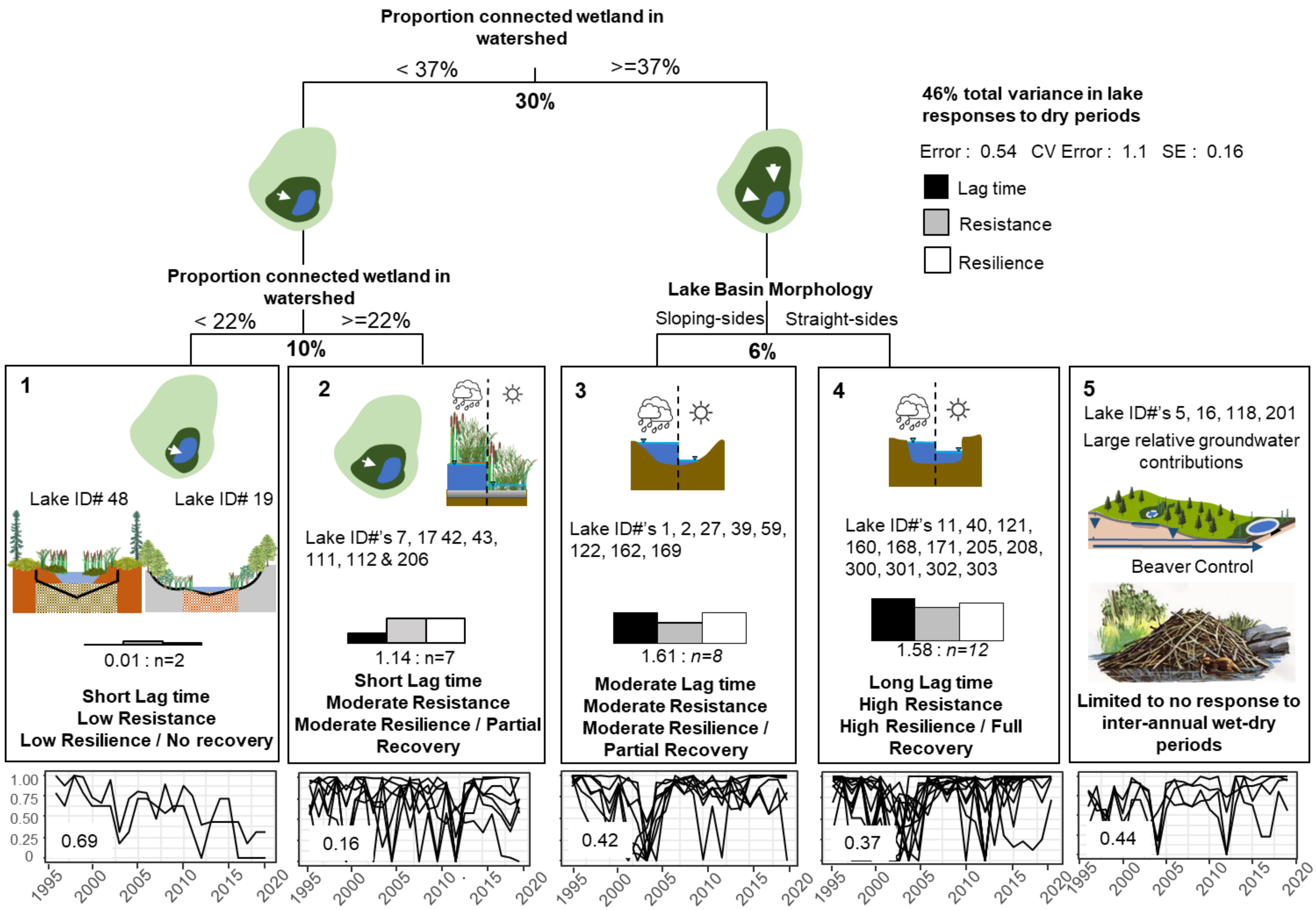

Proportion connected wetland in watershed
< 37%
>=37%
30%
46% total variance in lake responses to dry periods
Error : 0.54 CV Error : 1.1 SE : 0.16
Lag time
Resistance
Resilience
Proportion connected wetland in watershed
< 22%
>=22%
10%
Lake Basin Morphology
Sloping-sides
Straight-sides
6%
1
Lake ID# 48
Lake ID# 19
0.01 : n=2
Short Lag time
Low Resistance
Low Resilience / No recovery
2
Lake ID#'s 7, 17 42, 43, 111, 112 & 206
1.14 : n=7
Short Lag time
Moderate Resistance
Moderate Resilience / Partial Recovery
3
Lake ID#'s 1, 2, 27, 39, 59, 122, 162, 169
1.61 : n=8
Moderate Lag time
Moderate Resistance
Moderate Resilience / Partial Recovery
4
Lake ID#'s 11, 40, 121, 160, 168, 171, 205, 208, 300, 301, 302, 303
1.58 : n=12
Long Lag time
High Resistance
High Resilience / Full Recovery
5
Lake ID#'s 5, 16, 118, 201
Large relative groundwater contributions
Beaver Control
Limited to no response to inter-annual wet-dry periods
1.00
0.75
0.50
0.25
0
0.69
0.16
0.42
0.37
0.44
1995
2000
2005
2010
2015
2020

Figure 4.4.11: Multivariate regression tree showing the primary controls on lake resistance, lag time and resilience to dry periods, and explaining 46% of the total variability in different lake responses. Black lines represent the splitting to create each branch. Bolded values at the split for each branch represents the variability in different lake responses explained by specific explanatory variables. Terminal nodes are represented by rectangles and indicate the groups of lake with similar lag times, resistance, and recovery to dry periods. Bar plots show the similarity between the response variables of lakes within each group. The time series at the bottom of each terminal node shows the lake extent for all lakes in that group from 1996 to 2019 and the synchronicity of lake extents in each group is provided in the bottom left corner.

4.4 Discussion

Our study showed that the contraction and expansion of lakes during and after dry periods varied depending on both lake and watershed attributes, with differences among lakes found with regards to their resistance to change, their lag-times in response to a dry period, and their resilience defined by their ability to recover. We show that variability in resistance, lags, and resilience did not always co-vary, but that different aspects of lake extent response were influenced by specific lake and watershed attributes. For example, HRA influenced the dominance of relative subsurface groundwater and surface flow paths via connected wetland in the watershed, which determined how quickly lake extent responded to dry periods. Furthermore, lake basin morphology (i.e., sloping versus straight-sided lake basins) was an important control on the magnitude of change in lake extent, where sloping sided basins showed greater magnitude of change when compared with straight sided basins. Our study allowed us to develop a conceptual framework to identify lakes that are likely to remain persistent in the landscape under a future climate with more frequent or severe dry periods, those that are likely to fluctuate between alternate stable states, and those that may experience accelerated terrestrialisation in response to inter-annual wet-dry periods. As one of few long-term studies that couples field and remotely-sensed lake responses through time

(Andresen & Lougheed, 2015; Labrecque et al., 2008; Tweed et al., 2009) in a highly heterogeneous landscape, this study provides new insights into the controls on different lake responses to inter-annual wet-dry periods, and can inform robust projections of the future Boreal Plains landscape.

4.4.1 Links between water level and lake extent

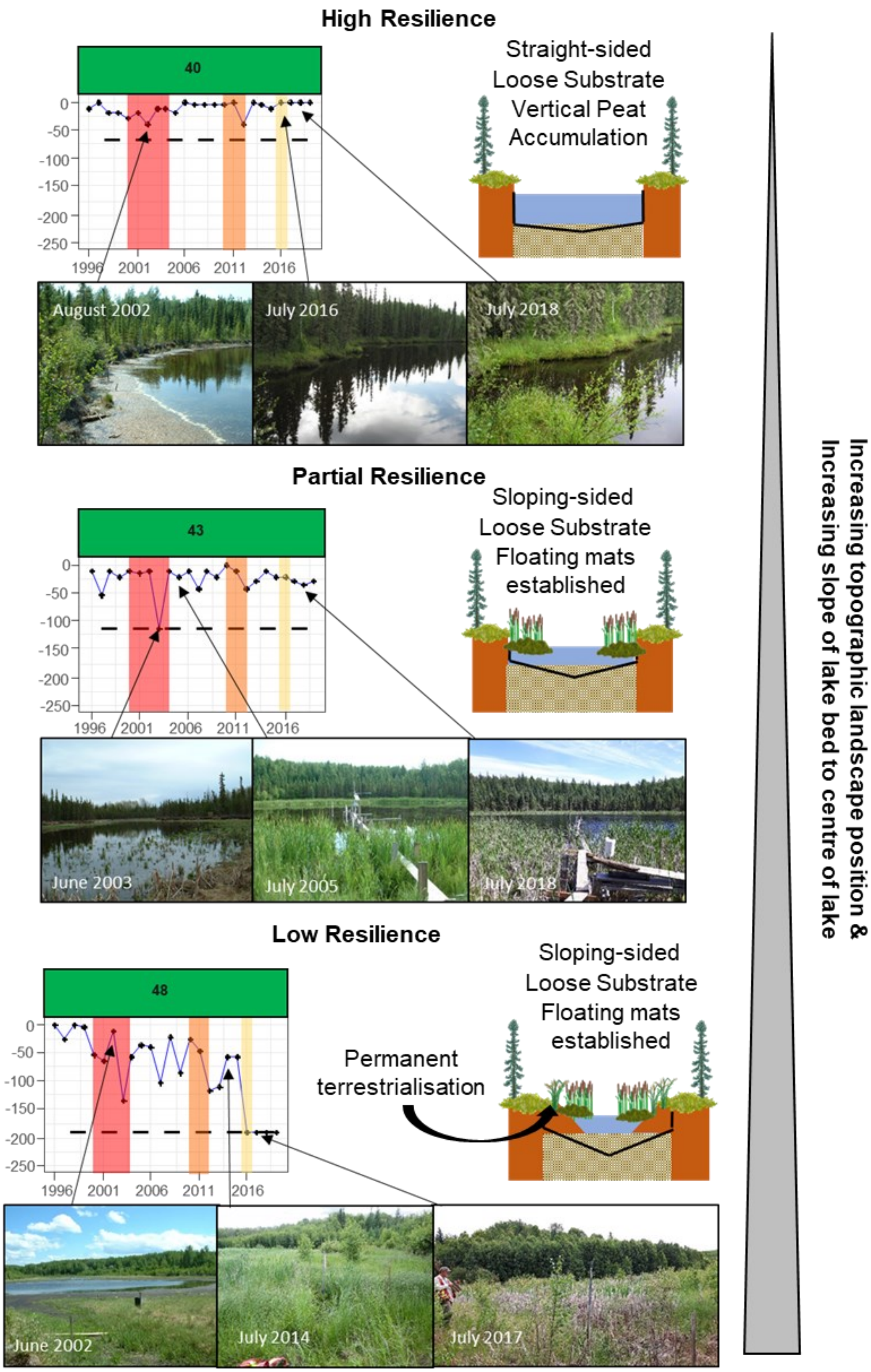
There was variability in the relationship between lake extent and lake water level among the study lakes that can inform us of the processes of terrestrialisation. In our *a-priori* predictions we postulated that key reasons for the variability in relationships between lake water level and lake extent among lakes would include lake basin morphology (i.e., sloping or straight) and lakebed substrate (i.e., loose or firm; Figure 4.4.1). In many lakes, our predictions for the relationship between lake extent and lake water level were correct; however several predictions were not correct, which may be due to the reasons discussed below, or due to issues with using long-term spot water level data, or the resolution of the Global Surface Water Explorer data.

Of the 11 lakes that showed a positive relationship between lake extent and lake water level, three (27%) supported *a-priori* predictions (Table 4.2; Figure 4.4.7) that lake extent contracts with decreasing lake water levels. The positive relationship observed is likely due to individual lake characteristics including sloping basins and firm substrates, where a decrease in lake water level quickly exposes the lake bed (Ireland et al., 2012), then upon rewetting if the lake substrate is firm any vegetation established is flooded out as the vegetation is secured to the lakebed (Figure 4.4.1). The remaining eight lakes showing positive relationships and contradicting predictions are, however, ringed by floating mats with straight sides at the lake edge resulting from floating mat establishment. The lakes may contradict predictions due to the resolution of the Global Surface Water Explorer dataset over-estimating change in lake extent between years, particularly for fine hummocky lakes, which are typically smaller and more susceptible to over-estimation. Furthermore, positive relationships may be present due to changes in the relationship between lake extent and lake water level post-dry period, where lake basins may have been sloping prior to dry periods that initiated floating mat establishment and a transition to straight-sided basins following a dry period. However, from historical photographs, many lakes with positive relationships contradicting predictions showed floating mat establishment already present during the 2000 to 2004 dry period.

There were 13 lakes that showed 'absent' relationships between lake water level and lake extent; however, the responses and processes driving lake responses are likely different. Of the 13 lakes with 'absent' relationships, eight showed minimal contraction of lakes whilst lake water level varied significantly, suggesting the presence of floating vegetation mats that rise and fall with changing water levels. The remaining five lakes showed substantial variability in lake contractions with minimal shifts in lake water level suggesting sloping-sided lakes with benches for deeper portions of the lake that allow for exposure of the lakebed at the lake edge, but minimal changes in lake water level at lake centre.

Of the nine lakes that showed a negative relationship between lake water level and lake extent (Figure 4.4.7), two lakes showed limited change in both lake extent and lake water level, suggesting lakes with limited responses to inter-annual wet-dry periods. One lake with limited responses to inter-annual wet-dry periods was a large lake receiving water from a large upstream lake and the watershed was in a lower topographic landscape position in coarse surficial geology, and thus also receives groundwater contributions, all of which acts to buffer lake extents against the effects of inter-annual wet-dry periods (Winter et al., 2000). The other lake (Lake #40) was in the fine hummocky conditions with a large proportion of peatland in the watershed supplying runoff and also receiving inputs from two upstream lakes that act to maintain lake extents. Furthermore, the fine-textured lake was straight-sided and, although the water level may be dynamic, straight sides resulted in less contraction of the lake during a dry period when compared to sloping-sided lakes (Ireland et al., 2013).

A further seven lakes showed that lakes expanded as lake water levels lowered, three of which were in the fine hummocky locations and have undergone permanent loss in lake extent, which resulted in a new smaller lake extent. Two of the three lakes (Lake #43 & 48) were located near the fine hummocky lake with limited responses to dry periods (Lake #40); however, they showed vast differences in lake extent responses to dry periods (Figure 4.4.12). A steeper slope towards the centre of Lake 48 likely resulted in greater exposure of the lakebed for the establishment of vegetation during the high severity dry period, from which the lake was unable to recover (Figure 4.4.12). Furthermore, Lake 48 is in the highest topographic landscape positions of the three which supplies Lake 43, and then Lake 40. In Lake 43, a lower topographic landscape position, more gradual slope and deep loose sediments allowed for vegetation to establish during the high severity dry period but also maintained enough moisture that the vegetation was able to float as a mat upon rewetting (Figure 4.4.12).



High Resilience
40
Straight-sided
Loose Substrate
Vertical Peat
Accumulation
August 2002
July 2016
July 2018
Partial Resilience
43
Sloping-sided
Loose Substrate
Floating mats
established
June 2003
July 2005
July 2018
Low Resilience
48
Sloping-sided
Loose Substrate
Floating mats
established
Permanent
terrestrialisation
June 2002
July 2014
July 2017
Increasing topographic landscape position &
Increasing slope of lake bed to centre of lake

Figure 4.4.12: A case study to support the influence of lake basin morphology on differences in resilience of lakes located in the same HRA to the same dry periods. The time series panels represent change in lake extent from 1996 to 2019, whilst the photos below represent specific timestamps during the time series. The conceptual model on the right side of each panel proposes reasoning for the differences in resilience among seemingly similar lakes to the same dry period. Orange indicates depth of peat, yellow indicates the depth of loose substrate, and blue represents depth of water in each lake. Vegetation symbols that extend out into the lake indicate the presence of floating vegetation mats.

The remaining five lakes with negative relationships between lake water level and lake extent likely have controls outside the scope of inter-annual wet-dry periods on lake responses (i.e. beaver control (Lake ID # 118), extensive peatland increasing runoff to lakes (Lake ID # 122, 168 & 303) and or groundwater connectivity (Lake ID # 17) or issues associated with data quality from the Global Surface Water Explorer.

4.4.2 Watershed and lake influences on responses to dry periods

There were often links between resistance, lags, and resilience, but there were instances where these responses co-varied and different aspects of the lake extent responses (i.e. resistance, lag-time, and resilience) were independently influenced by lake and watershed attributes, such as wetland connectivity and lake basin morphology. Below, we explore the potential connections between the resistance, lag times, and resilience of the lake groups identified with different lake and landscape attributes.

4.4.2.1 Resistance

More severe droughts led overall to greater reduction in lake extent (i.e., impacts of the dry period exceeded the resistance of lakes). However, lakes in different settings had different resistance thresholds at which terrestrial-aquatic linkages between watershed water sources and lakes would shut down and hydrologically disconnect at which lakes would start to contract. Group 4 lakes had the highest resistance threshold and were predominantly fine-textured lakes with straight-sided basins and extensive wetland connectivity. Higher resistance thresholds to dry periods in Group 4 lakes were likely due to larger storage in the lake basin and slow release of water received from surrounding wetlands. The stable water level and straight-sided lake basin reduce the amount of exposed lake sediment in most dry periods, which prevents colonization by plants and thus of terrestrialisation. (Ireland et al. 2012). However, the high-severity dry period from 2000 to 2004 did exceed the resistance of many fine plains lakes, leading to substantial lake contractions as even the surrounding wetlands stopped supplying water to the lakes. Peatlands have been found to show high resistance to dry periods in boreal and northern temperate regions due to a set of hydrological negative feedbacks that regulate water losses in peatlands when under stress (e.g. during dry periods; Geris et al., 2015; Kettridge & Waddington, 2014). We found that fine plains lakes' low and moderate dry periods did not exceed the resistance of fine plains lakes due to the continued delivery of water from peatlands (Plach et al., 2016). However, a severe dry period was able to interrupt terrestrial-aquatic linkages between lakes and peatlands in the fine plains, resulting in large reductions in lake extent.

The high severity dry period also exceeded the resistance of many fine hummocky lakes. Group 1 and 2 lakes were primarily fine-textured hummocky lakes with lower proportions of connected wetland in the watershed and showed the least resistance to dry periods because of limited surface inputs from adjacent peatlands and a lack of inputs from upland forests during dry periods. Thus, during dry periods a change to the water balance can expose larger areas of the lakebed (Ireland et al., 2012). Given the smaller size of the fine hummocky lakes than fine plains lakes, relative to the total lake area fine hummocky lakes may exhibit more contraction than fine plains lakes, but in absolute meters fine plains lakes had more total shoreline exposed.

The resistance threshold of coarse lakes was generally not exceeded, regardless of dry period severity. Coarse lakes likely showed a higher resistance threshold to dry periods due to the dominance of subsurface flow paths through materials with high hydraulic conductivities (Hokanson et al., 2019; Ireson et al. 2015; Smerdon et al., 2005; Winter, 2001). Regional subsurface flow paths in coarse-textured lakes are less responsive to inter-annual wet-dry periods (Winter et al., 2000), which contrasts the surface flow paths primarily relied on in lakes in fine-textured plains and hummocky watersheds (Devito et al., 2017; Hokanson et al., 2019; Plach et al., 2016).

4.4.2.2 Lag times

Lag times were longest in watersheds with greater wetland connectivity (Group 3 and 4), likely due to the runoff generating function of wetlands to lakes, specifically peatlands with shallow water tables (Devito et al., 2005, 2017; Thompson et al., 2015), and the generally low topographic landscape positions of lakes with expansive connected wetlands in the watershed. Together, properties of peatlands allow for terrestrial-aquatic linkages to be maintained with the release of water through the acrotelm during dry periods up until a certain threshold (See 4.4.4 Resistance), thus delaying the realisation of dry periods in lake extent responses (Kettridge & Waddington, 2014; Ingram, 1978; Thompson et al., 2017). However, as the water table drops down into peat layers with lower hydraulic conductivity (i.e., just above the catotelm), the volume of water received by lakes is reduced until the water table drops into the catotelm, effectively shutting down terrestrial-aquatic linkages (Ingram, 1978; Morris et al., 2011). Lakes located in higher landscape positions and/or with lower proportions of connected peatland in the watershed typically showed shorter lag times, due to limited local surface flow path connections which are largely reliant on precipitation causing lakes to respond rapidly to inter-annual wet-dry periods (Devito et al., 2017; Winter et al., 2000). However, lag times for Groups 1, 2 and 3 were all relatively short when compared to Group 4, which may have large variability in lake volume in response to dry periods, but due to the straight-sided morphology, this lake basin morphology does not lead to contraction of lake extent.

We also show that in coarse-textured watersheds, topographic landscape position can be a determinant of lag time between response of lake extent to dry-periods. However, topographic landscape position is auto correlated with wetland connectivity, where in low topographic positions the groundwater table is more likely to intersect the ground surface facilitating the development and maintenance of wetlands in low positions in coarse watersheds. Furthermore, in coarse-textured lakes the high degree of subsurface contributions at low topographic landscape positions can extend lag times further by limiting and delaying the influence of inter-annual wet-dry periods on lake extent responses (Hokanson et al., 2019; Ireson et al. 2015; Smerdon et al., 2008; Winter, 2001; Winter et al., 2000).

Finally, we identified four lakes that either did not fit the general spatial patterns or had limited to no response to inter-annual wet-dry periods. Three of these lakes have large relative groundwater contributions, which may extend the realisation of inter-annual wet-dry periods in lake extent beyond the five-year lag-times assessed in this study. Furthermore, all four lakes experience beaver control, rather than beaver presence, where beavers appear to be controlling the hydrology of the lake to a larger extent compared to other lakes where beavers may be present but do not appear to be changing the hydrology dramatically, which may be masking any influence of inter-annual wet-dry periods on lake extent.

4.4.2.3 Resilience

Lake resilience, i.e. the ability to recover to pre-drought lake area, was categorised into three types; poor, partial, and full resilience. Only two lakes were found to have poor resilience, i.e. dry periods were likely to have accelerated or kick-started terrestrialisation and pushed these lakes into a new state (Group 1). Group 1 lakes were in fine hummocky watersheds with low wetland connectivity and different combinations lake basin morphologies with the ability to drain and allow for vegetation establishment. Together, the lake and landscape attributes of these lakes suggest that during a high severity dry period (2000 to 2004), lake extent decreased and kick started long-term terrestrialisation processes and the the establishment of new stable states. With each successive dry period, it appears that Group 1 lakes continue to decrease in lake extent with the establishment of vegetation and another stable state, which exists until the next dry period.

We found that lakes showing moderate resilience to dry periods (Group 2 and 3) were generally either associated with loose substrates and sloping-sided lake basin morphology, or a combination of both. An allogenic model of floating mat initiation and episodic expansion proposed by Ireland et al. (2012) broadly supports our findings of low resilience in loose substrate lakes (Group 2). This conceptual model of floating mat initiation and expansion states that during dry periods water level is lowered, thereby exposing lake sediments to colonization by vegetation. Upon rewetting of lakes, loosely rooted mats of vegetation are able to detach from the lake bed and float, which creates a hydrologically stable substrate for further colonization of vegetation and vertical peat accumulation from which the lake is unlikely to recover, thus leading to lower resilience and only partial recovery to pre-dry period extents (Ireland et al., 2012; Warner et al., 1989). Two Group 2 lakes (Lake ID # 17 & 111) had firm substrates yet were grouped with primarily loose substrate lakes, which can be attributed to reed growth in these lakes that Global

Surface Water Explorer likely classifies as terrestrial even though there is water inundation. Group 3 lakes had sloping-sided basins and more extensive wetland connectivity, where larger water level changes occur due to their lower storage volume, thus exposing larger areas of substrate for terrestrialisation processes and resulting in lower resilience (Ireland et al. 2012). Several of the lakes in Group 2 and 3 had both loose substrate and sloping-sided lake attributes; therefore, combining and possibly amplifying the effects of these lake attributes on the resilience and partial recoveries of lake extent.

Group 4 lakes had high wetland connectivity and straight-sided lake basin morphology, and the highest resilience. Expansive connected wetlands likely maintained surface water contributions to lakes during dry periods and straight-sides limited large water table fluctuations, thus promoting high resilience in Group 4 lakes.

4.5 Conclusion

In Boreal Plains lakes differences in the contraction and expansion lake extent during and after dry periods were found to be dependent on watershed attributes including surficial geology and wetland connectivity, in addition to individual lake basin morphologies. In sub-humid, Boreal Plains regions, water is often seen as plentiful due to a high density of lakes and extensive wetlands. However, as the climate warms, lakes are predicted to be a diminishing water resource in the Boreal Plains (Thompson et al., 2017). This study provides new insights into the controls on lake resistance to dry periods, lag-times in response to a dry period, and resilience defined by an ability to recover to pre-dry period extents. Our study suggests that isolated lakes, with lower proportions of connected wetland in the watershed and lake beds that slope towards the lake centre with shallower depths of loose sediment are most susceptible to long-term terrestrialisation processes. These small, isolated lakes likely do not represent a large proportion of the total lake area in the region, but harbour abundant waterfowl populations and offer important sites for carbon cycling (Chp. 2 & 3). In contrast, lakes that are well connected to the watershed with expansive peatlands and/or subsurface connectivity and straight-sided lake basins are likely to be less susceptible to long-term terrestrialisation processes. However, lakes with extensive wetland connectivity, typically found in the fine plains, showed very large lake contractions showing that there are important thresholds that may cause irreversible contractions in fine plains lakes if the climate changes further with more extreme and prolonged dry periods. Coarse-textured lakes, generally most-valued for recreational and provisioning services, were least susceptible to terrestrialisation processes; however, their stability in the landscape could diminish with long-term shifts in inter-annual wet-dry periods that influence groundwater discharge to coarse lakes. As one of few long-term studies that couples field and remotely sensed lake responses through time (Andresen & Lougheed, 2015; Labrecque et al., 2008; Tweed et al., 2009), this study can aid watershed managers and decision makers in identifying the types of lakes that will be most vulnerable to disappearing in response to an increasingly changing climate.

5.0 Synthesis, Conclusions, and Directions for Future Research

As climate change causes widespread changes to the timing and extent of hydrologic connectivity in the watershed, the functioning and presence of lakes will also change with cascading effects to valuable ecosystem services. This research developed a conceptual framework of how spatial and inter-annual variability in hydrologic connectivity across watersheds influences lake DOC characteristics (concentration and composition) and persistence of lake extent in the Canadian Boreal Plains ecozone. The results broadly reveal that Boreal Plains lakes:

(1) Have large spatial variability in lake DOC characteristics, but also large inter-annual variability in DOC characteristics that is ecologically significant and tied to inter-annual wet-dry periods.

(2) Receive most of their DOC from peatlands, but that within-lake processes of autochthonous DOC production and photochemical DOC degradation are responsible for a majority of the spatial and inter-annual variability in lake DOC characteristics.

(3) Expand and contract in response to inter-annual wet-dry periods based on an interaction between lake basin morphology and lake-wetland connectivity, suggesting vulnerability to future terrestrialisation.

Taken collectively, the findings in this thesis indicate that the attributes of lake watersheds are key for understanding spatial and inter-annual variability in lake water chemistry and available water supplies to lakes, specifically DOC characteristics, and lake extent. We show that different surficial geologies forming distinct hydrologic response areas across the Boreal Plains are important controls on the hydrologic connectivity of individual lakes to surface and subsurface flow paths, and thus the source water chemistry and quantity reaching lakes, with implications for lake DOC characteristics and open water lake extent. We found that differences in the dominance of surface versus subsurface flow paths across different lake watershed surficial geologies and the prevalence of peatlands in the watershed were the primary controls on lake DOC characteristics and lake extent, and create large spatial variability in these lake responses. However, we also identified large inter-annual variability in lake DOC characteristics and extent, also related to hydrologic connectivity of different flow paths, but lake DOC characteristics were also strongly influenced by lake water residence time which varied both spatially across HRAs and with inter-annual wet-dry periods. Thus, a framework founded on differences in the hydrologic connectivity of HRAs developed in this thesis, is key to understanding spatial variability in lake responses of DOC characteristics and extent, in addition to their sensitivity to wet-dry periods. By creating a largely generalizable framework that uses universally applicable processes, the concepts presented in this thesis can be used by communities through to government agencies in different hydrogeomorphology settings to identify lakes that will be most sensitive to climate change and implications for ecosystem services, such as habitat, drinking water provision, recreation, and global carbon cycling.

Isolated lakes with low wetland connectivity in fine hummocky watersheds were most sensitive to both changes to lake DOC characteristics and open water lake extent. High sensitivity of these isolated lakes to inter-annual wet-dry periods was attributed to dominance of local surface flow paths, extended lake water residence times, and interactions between lake basin morphology and lakebed substrate. Many of these small, isolated lakes in fine hummocky surficial geology have persisted in the landscape for thousands of years, and although likely do not represent a large proportion of the total lake area in the Boreal Plains, offer an important habitat for abundant waterfowl populations and are also important for carbon cycling. However, with unprecedented climate change, these lakes could shift out of the bounds of their natural cycles, and we could see dramatic increases in within-lake processing of aromatic-DOC, in addition to accelerated rates of terrestrialisation as lake water residence times extend, and the shut-down of terrestrial-aquatic linkages becomes more frequent. Alternatively, accelerated terrestrialisation and thus an increase in available carbon sources could counter the effects of extended lake water residence times on within-lake processing of aromatic-DOC.

Fine plains lakes that were well connected to the watershed with expansive peatlands and typically straight-sided lake basins due to peat accumulation showed moderate sensitivity to changes in lake DOC characteristics and low sensitivity to changes in lake extent. However very large lake contractions were observed during severe dry periods, even though the majority of lakes returned to previous extents, thus showing that there are important thresholds that may cause irreversible contractions in fine plains lakes if the climate changes further with more extreme and prolonged dry periods. Future climate change could also have implications for changes in lake DOC characteristics as the interruption of terrestrial-aquatic linkages could extend lake water residence times from relatively moderate to long, with increased opportunity for within-lake processing.

The least change in lake DOC characteristics and lake extent was typically observed in coarse lakes that are dominated by continuous subsurface flows and are thus less sensitive to inter-annual wet-dry periods. However, although coarse lakes were least susceptible to change, we also observed the lowest DOC concentrations and least aromaticity of DOC in these lakes. With the potential for long-term shifts in climate that may influence regional groundwater sources and thus discharge to coarse lakes, we could expect longer water residence times with increased potential for within-lake processing of DOC that may have more dramatic implications for lake ecosystem functions in this HRA due to already low concentrations of DOC. Furthermore, this research cannot project how stable coarse lake extents will remain if changes to regional and intermediate groundwater sources occur.

Integration of the processes influencing lake DOC characteristics and lake extent with existing knowledge of hydrologic connectivity across the Boreal Plains constitutes an important step in our understanding of spatial and inter-annual variability in different lake responses. Furthermore, development of a novel conceptual model relating hydrologic connectivity of the watershed to lake DOC characteristics (concentration and composition) and presence of lakes through space and time is critical to forecasting potential impacts to lake ecosystem services, especially under a changing climate. Yet there remain unanswered questions, for which further research is needed.

Although, the framework in this thesis was developed through a Boreal Plains lens, the processes identified in each study could be tested in other regions including wetter climates to test whether our theories hold and in similar northern regions with low relief, and thick heterogeneous surficial geology deposits (e.g., Western Siberia, Central Europe, the Baltic States and Northern China). Thus, the processes identified in the Boreal Plains may be tested or compared in regions with different characteristics to holistically understand the influence of hydrologic connectivity on lake DOC characteristics and extent, where ecosystems experience the same processes, but the role played by different processes ranges among ecosystems with different characteristics.

In chapter 2, large spatial and inter-annual variability in lake water quality of the Boreal Plains is shown. Field data collection for this study contributed to an already established long-term dataset, thereby allowing the results to span inter-annual wet-dry periods from 2012 to 2019. However, the inter-annual wet-dry periods in this study were relative to one another, and no years experienced a truly wet hydrologic year, such as that of 1997. Thus, in a wet hydrologic year the conceptual model proposed for relating hydrologic connectivity and lake DOC characteristics across a Boreal Plains landscape and through time may differ. Dilution effects are proposed explanations for observed DOC concentration responses in Boreal Plains lakes. However, according to fill and spill hypotheses, in a wet hydrologic year the water table could intersect the aromatic-DOC rich Leaf Fibric Humic layer of forests (Aikenhead-Peterson et al., 2003), thereby mobilising a previously untapped source of DOC and allowing for this source of carbon to be flushed into lakes. This hypothesis is anticipated to apply to fine-textured hummocky lakes, where in most years, their large water storage capacity is not overcome (Devito et al., 2017; Redding & Devito, 2008), but could result in aromatic-rich DOC spikes in fine-textured hummocky lakes during hydrologic wet years. In a fine-plains setting, an alternative to DOC flushing during hydrologically wet years would be dilution and thus lower DOC concentrations and aromaticity during wet years as the water table intersects the fibric acrotelm with low DOC and aromaticity from fresh plant litter. Thus, continued data collection would meet current research needs for long-term datasets, and allow us to test the proposed alternative conceptual model under more extreme wet-dry periods, which would help validate the conceptual model and improve its application in a changing climate where extreme weather is expected.

Both chapters 2 and 3 revealed the important influence of lake water residence time on the spatial and inter-annual variability of Boreal Plains lake DOC characteristics. The lc-excess of lakes was used as a proxy for lake water residence time. However, using lc-excess means that comparing lake water residence times among surficial geologies is cautioned. Due to the flow-through nature of coarse-textured lakes, the lc-excess signature in a downstream lake could actually reflect evaporative enrichment that occurred in headwater lakes, suggesting lake water residence time is longer than actual lake water residence time (Hokanson et al., in revision).

Therefore, quantification of lake water residence time using stable isotopes (Gibson et al., 2002) and/or using volume and inflow or outflow rates would help to directly compare differences between lakes and relate to lake DOC characteristics rather than infer from relative differences. Quantifying lake water residence time would also allow for better comparison with other boreal regions that have quantified lake water residence time and would help constrain the influence of lake water residence time on lake DOC characteristics across the boreal.

In chapter 3, through an end-member mixing model analysis, we show that within-lake processes significantly alter the DOC characteristics of terrestrial sources reaching lakes, and highlight variability in said alterations through space and time. Although this study showed relative differences in the extent of change to DOC quantity and quality of terrestrial sources to lakes, assumptions in the end-member mixing model resulted in conservative estimates and did not account for autochthonous DOC produced in lakes. Furthermore, autochthonous DOC production proved to be an important consideration for the balance of DOC lost and gained in Boreal Plains lake ecosystems. Measurements of ^{13}C-DOC and/or fluorescence analysis to quantify total input of DOC from autochthonous production (Bade et al., 2007) would help eliminate some assumptions in the end-member mixing model and would allow comparisons of absolute values with other boreal regions, rather than focussing on relative differences within a region. Comparisons of the existing end-member mixing model results, and results which account for autochthonous DOC would compliment this chapter and if similar, validate the relative differences between modelled and observed DOC and A_{254} among lakes.

In chapter 4, we show large inter-annual variability in open water lake extent among lakes, with several lakes exhibiting long-term losses in lake extent. We coupled remotely sensed data from the Global Surface Water Explorer and field measurements to quantify lake extent. However, the Global Surface Water Explorer used 30x30 m Landsat imagery, which for small lakes characteristic of fine hummocky watersheds likely had poorer relative precision of changes to lake extent. To better assess the long-term losses in lake extent, differences in lake area pre- and post-dry period should be quantified by georectifying and digitizing open water extent of the same lake, particularly for small lakes that cannot be accurately assessed using Global Surface Water Explorer and would allow for representation of varying sized lakes.

While Chapter 4 was able to identify changes to lake extent and lake water level and the relationship between both, infilling of lakes and depth of loose sediments (gyttja) was not explicitly measured even though we know these lakes are infilling (Squires et al., 2008) and this process will play an important role in the terrestrialisation of Boreal Plains lakes. Here, gyttja is nutrient-rich loose sediment holding onto water with a gel-like consistency. In chapter 4 we suggest that lakes with shallow sloping basins and shallower gyttja depths are able to drain and terrestrialise when edges of the lake bed are exposed. However, lakes with deep gyttja are infilling through time, yet whether this increases susceptibility to terrestrialisation is unknown. On one hand increasing gyttja depth makes lakes shallower and thus more likely to dry out with rapid establishment of vegetation due to its high nutrient concentration during a dry period. Alternatively, during a dry period, gyttja may be exposed and dry out resulting in compression of the sediment acting to reset the lake depth upon rewetting, thus decreasing susceptibility to terrestrialisation and enabling a lake to maintain its depth. Given the variability in production of autochthonous DOC identified Boreal Plains lakes available for sedimentation from chapter 2, and the likely high variability in flocculation of terrestrially-derived DOC, rates of infilling gyttja are likely to vary across Boreal Plains lakes and should be examined in the future to test the proposed alternate hypotheses and compliment this research as to which lakes have higher susceptibility to terrestrialisation processes.

To summarize, this thesis analyzed both spatial and inter-annual variability of lake DOC characteristics and lake extent at a landscape scale across the Boreal Plains. In these studies, watershed and lake attributes including surficial geology, wetland connectivity, lake water residence time and lake basin morphology were identified as the key controls determining the sensitivity of lake DOC characteristics and lake extent to inter-annual wet-dry periods. The framework presented in this thesis can be used to predict which lakes on the Boreal Plains and in other regions may experience the most rapid changes in lake function with future climate change. Together, these findings illustrate broader impacts of how lake ecosystem functions respond to climate differently under different hydrologic, geomorphic, and geologic conditions which can be applied and tested in other regions to reach unified understandings of ecosystem processes that act on a continuum within different landscapes.

Bibliography

Ågren, A., Buffam, I., Berggren, M., Bishop, K., Jansson, M., & Laudon, H. (2008). Dissolved organic carbon characteristics in boreal streams in a forest-wetland gradient during the transition between winter and summer. Journal of Geophysical Research: *Biogeosciences,* 113(G3).

Aitkenhead-Peterson, J.A., McDowell, W.H., & Neff, J.C. (2003). Sources, production, and regulation of allochthonous dissolved organic matter inputs to surface waters. In *Aquatic Ecosystems* (pp. 25-70).

Alberta Environment, 1999. Surface Water Quality Guidelines for Use in Alberta. Science and Standards Branch, Environmental Assurance Division, Edmonton, AB.

Alberta Wildfire, 2020. Historical Wildfire Perimeter Data: 1931 – 2019. available at: https://wildfire.alberta.ca/resources/historical-data/spatial-wildfire-data.aspx, (last access: 7 October 2020).

Algesten, G., Sobek, S., Bergström, A. K., Ågren, A., Tranvik, L. J., & Jansson, M. (2004). Role of lakes for organic carbon cycling in the boreal zone. *Global change biology*, 10(1), 141-147.

Anas, M. M., Scott, K. A., & Wissel, B. (2015). Carbon budgets of boreal lakes: state of knowledge, challenges, and implications. *Environmental Reviews*, 23(3), 275-287.

Andresen, C. G., & Lougheed, V. L. (2015). Disappearing Arctic tundra ponds: Fine-scale analysis of surface hydrology in drained thaw lake basins over a 65 year period (1948–2013). *Journal of Geophysical Research: Biogeosciences*, *120*(3), 466-479.

Arvola, L., Äijälä, C., & Leppäranta, M. (2016). CDOM concentrations of large Finnish lakes relative to their landscape properties. *Hydrobiologia*, *780*(1), 37-46.

Backlund, P. (1992). Degradation of aquatic humic material by ultraviolet light. *Chemosphere*, 25(12), 1869-1878.

Bade, D. L., Carpenter, S. R., Cole, J. J., Pace, M. L., Kritzberg, E., Van de Bogert, M. C., ... & McKnight, D. M. (2007). Sources and fates of dissolved organic carbon in lakes as determined by whole-lake carbon isotope additions. *Biogeochemistry*, 84(2), 115-129.

Barton, K., & Barton, M. K. (2015). Package 'MuMIn'. Version, 1, 18.

Battin, T. J., Luyssaert, S., Kaplan, L. A., Aufdenkampe, A. K., Richter, A., & Tranvik, L. J. (2009). The boundless carbon cycle. *Nature Geoscience*, *2*(9), 598-600.

Bayley, S. E., Creed, I. F., Sass, G. Z., & Wong, A. S. (2007). Frequent regime shifts in trophic states in shallow lakes on the Boreal Plain: Alternative" unstable" states? *Limnology and Oceanography*, 52(5), 2002-2012.

Benner, R., & Kaiser, K. (2011). Biological and photochemical transformations of amino acids and lignin phenols in riverine dissolved organic matter. *Biogeochemistry*, *102*(1), 209-222.

Berggren, M., Laudon, H., & Jansson, M. (2009). Aging of allochthonous organic carbon regulates bacterial production in unproductive boreal lakes. *Limnology and Oceanography*, 54(4), 1333-1342.

Bertilsson, S. & Jones, J.B. (2003). Supply of dissolved organic matter to aquatic ecosystems: autochthonous sources. In *Aquatic Ecosystems* (pp. 3-24).

Bertilsson, S., & Tranvik, L. J. (2000). Photochemical transformation of dissolved organic matter in lakes. *Limnology and Oceanography*, 45(4), 753-762.

Björk, S. (2010). The evolution of lakes and wetlands. In *Restoration of Lakes, Streams, Floodplains, and Bogs in Europe* (pp. 25-35). Springer, Dordrecht.

Blenckner, T. (2005). A conceptual model of climate-related effects on lake ecosystems. *Hydrobiologia*, *533*(1), 1-14.

Blöschl, G., Bierkens, M. F., Chambel, A., Cudennec, C., Destouni, G., Fiori, A., ... & Renner, M. (2019). Twenty-three unsolved problems in hydrology (UPH)–a community perspective. *Hydrological sciences journal*, *64*(10), 1141-1158.

Bridge S., Johnson E. 2000. Geomorphic principles of terrain organization and vegetation gradients. Journal of Vegetation Science 11: 57-70. DOI: 10.2307/3236776

Brown, J., Ferrians Jr, O. J., Heginbottom, J. A., & Melnikov, E. S. (1997). *Circum-Arctic map of permafrost and ground-ice conditions* (p. 45). Reston, VA: US Geological Survey.

Brown, S. M., Petrone, R. M., Mendoza, C., & Devito, K. J. (2010). Surface vegetation controls on evapotranspiration from a sub-humid Western Boreal Plain wetland. *Hydrological Processes: An International Journal*, 24(8), 1072-1085.

Canadian Council on Ecological Areas (2014). Ecozones of Canada, https://www.ccea.org/Downloads/shapefiles/CA_ecozones_1M_v5_final_map%20v20140213.pdf

Carignan, R., D'Arcy, P., & Lamontagne, S. (2000). Comparative impacts of fire and forest harvesting on water quality in Boreal Shield lakes. *Canadian Journal of Fisheries and Aquatic Sciences*, 57(S2), 105-117.

Carignan, R., Planas, D., & Vis, C. (2000). Planktonic production and respiration in oligotrophic Shield lakes. *Limnology and Oceanography*, 45(1), 189-199.

Carrera-Hernández, J. J., Mendoza, C. A., Devito, K. J., Petrone, R. M., & Smerdon, B. D. (2011). Effects of aspen harvesting on groundwater recharge and water table dynamics in a subhumid climate. *Water Resources Research*, *47*(5).

Catalán, N., Marcé, R., Kothawala, D. N., & Tranvik, L. J. (2016). Organic carbon decomposition rates controlled by water retention time across inland waters. *Nature Geoscience*, 9(7), 501-504.

Chambers, J. M. (1992). Linear models. Chapter 4 of Statistical Models in S eds J. M. Chambers and T. J. Hastie, Wadsworth & Brooks/Cole.

Cobbaert, D., Wong, A. S., & Bayley, S. E. (2015). Resistance to drought affects persistence of alternative regimes in shallow lakes of the Boreal Plains (Alberta, Canada). *Freshwater biology*, 60(10), 2084-2099.

Cole, J. J., Pace, M. L., Carpenter, S. R., & Kitchell, J. F. (2000). Persistence of net heterotrophy in lakes during nutrient addition and food web manipulations. *Limnology and oceanography*, 45(8), 1718-1730.

Cole, J. J., Prairie, Y. T., Caraco, N. F., McDowell, W. H., Tranvik, L. J., Striegl, R. G., ... & Melack, J. (2007). Plumbing the global carbon cycle: integrating inland waters into the terrestrial carbon budget. *Ecosystems*, 10(1), 172-185.

Couture, S., Houle, D., & Gagnon, C. (2012). Increases of dissolved organic carbon in temperate and boreal lakes in Quebec, Canada. *Environmental Science and Pollution Research*, 19(2), 361-371.

Craig, H., Gordon, L. I., & Horibe, Y. (1963). Isotopic exchange effects in the evaporation of water: 1. Low-temperature experimental results. *Journal of Geophysical Research*, 68(17), 5079-5087.

Curtis, P. J., & Adams, H. E. (1995). Dissolved organic matter quantity and quality from freshwater and saltwater lakes in east-central Alberta. *Biogeochemistry*, 30(1), 59-76.

Curtis, P. J., & Schindler, D. W. (1997). Hydrologic control of dissolved organic matter in low-order Precambrian Shield lakes. Biogeochemistry, 36(1), 125-138.

Daggett, C. T., Saros, J. E., Lafrancois, B. M., Simon, K. S., & Amirbahman, A. (2015). Effects of increased concentrations of inorganic nitrogen and dissolved organic matter on phytoplankton in boreal lakes with differing nutrient limitation patterns. *Aquatic Sciences*, *77*(3), 511-521.

D'Arcy, P., & Carignan, R. (1997). Influence of catchment topography on water chemistry in southeastern Quebec Shield lakes. *Canadian Journal of Fisheries and Aquatic Sciences*, 54(10), 2215-2227.

De'Ath, G. (2002). Multivariate regression trees: a new technique for modeling species–environment relationships. *Ecology*, *83*(4), 1105-1117.

Devito, K., Creed, I., Gan, T., Mendoza, C., Petrone, R., Silins, U., & Smerdon, B. (2005). A framework for broad-scale classification of hydrologic response units on the Boreal Plain: is topography the last thing to consider? *Hydrological Processes: An International Journal*, 19(8), 1705-1714.

Devito, K. J., Creed, I. F., Rothwell, R. L., & Prepas, E. E. (2000). Landscape controls on phosphorus loading to boreal lakes: implications for the potential impacts of forest harvesting. *Canadian Journal of Fisheries and Aquatic Sciences*, 57(10), 1977-1984.

Devito, K. J., Hokanson, K. J., Moore, P. A., Kettridge, N., Anderson, A. E., Chasmer, L., ... & Peters, D. L. (2017). Landscape controls on long-term runoff in subhumid heterogeneous Boreal Plains catchments. *Hydrological processes*, 31(15), 2737-2751.

Devito, K., Mendoza, C., & Qualizza, C. (2012). Conceptualizing water movement in the Boreal Plains. Implications for watershed reconstruction. Synthesis report prepared for the Canadian Oil Sands Network for Research and Development, Environmental and Reclamation Research Group. 164 p.

Devito, K. J., Mendoza, C., Petrone, R. M., Kettridge, N., & Waddington, J. M. (2016). Utikuma Region Study Area (URSA)–part 1: hydrogeological and ecohydrological studies (HEAD). *The Forestry Chronicle*, 92(1), 57-61.

Devito, K. J., & Dillon, P. J. (1993). Importance of runoff and winter anoxia to the P and N dynamics of a beaver pond. *Canadian Journal of Fisheries and Aquatic Sciences*, 50(10), 2222-2234.

de Wit, H. A., Couture, R. M., Jackson-Blake, L., Futter, M. N., Valinia, S., Austnes, K., ... & Lin, Y. (2018). Pipes or chimneys? For carbon cycling in small boreal lakes, precipitation matters most. *Limnology and Oceanography Letters*, 3(3), 275-284.

Dillon, P. J., & Molot, L. A. (1997). Effect of landscape form on export of dissolved organic carbon, iron, and phosphorus from forested stream catchments. *Water Resources Research*, 33(11), 2591-2600.

Diodato, N., Higgins, S., Bellocchi, G., Fiorillo, F., Romano, N., & Guadagno, F. M. (2016). Hydro-climatic forcing of dissolved organic carbon in two boreal lakes of Canada. *Science of the Total Environment*, 571, 50-58.

Duarte, C. M., & Prairie, Y. T. (2005). Prevalence of heterotrophy and atmospheric CO 2 emissions from aquatic ecosystems. *Ecosystems*, 8(7), 862-870.

Ducks Unlimited Canada, 2011. Enhanced wetland classification inferred products users guide version 1.0.

EcoRegions Working Group: Ecoclimatic Regions of Canada, First Approximation, Ecological Land Classification Series, No 23, 119 pp., Environment Canada, Ottawa, 1989.

Ejarque, E., Khan, S., Steniczka, G., Schelker, J., Kainz, M. J., & Battin, T. J. (2018). Climate-induced hydrological variation controls the transformation of dissolved organic matter in a subalpine lake. *Limnology and Oceanography*, 63(3), 1355-1371.

Emelko, M.B., Silins, U., Bladon, K.D. and Stone, M., 2011. Implications of land disturbance on drinking water treatability in a changing climate: Demonstrating the need for “source water supply and protection” strategies. *Water Research*, 45(2), pp.461-472.

Engstrom, D. R. (1987). Influence of vegetation and hydrology on the humus budgets of Labrador lakes. *Canadian Journal of Fisheries and Aquatic Sciences*, *44*(7), 1306-1314.

Erlandsson, M., Futter, M. N., Kothawala, D. N., & Köhler, S. J. (2012). Variability in spectral absorbance metrics across boreal lake waters. *Journal of Environmental Monitoring*, 14(10), 2643-2652.

Evans, C. D., Futter, M. N., Moldan, F., Valinia, S., Frogbrook, Z., & Kothawala, D. N. (2017). Variability in organic carbon reactivity across lake residence time and trophic gradients. *Nature Geoscience*, 10(11), 832-835.

Fenton, M. M., Paulen, R. C., and Pawlowicz, J. G.: Surficial geology of the Lubicon Lake area, Alberta (NTS 84B/SW), Alberta Geological Survey, Edmonton, 2003.

Ferland, M. E., Prairie, Y. T., Teodoru, C., & del Giorgio, P. A. (2014). Linking organic carbon sedimentation, burial efficiency, and long-term accumulation in boreal lakes. *Journal of Geophysical Research: Biogeosciences*, *119*(5), 836-847.

Ferone, J. M., & Devito, K. J. (2004). Shallow groundwater–surface water interactions in pond–peatland complexes along a Boreal Plains topographic gradient. *Journal of Hydrology*, 292(1-4), 75-95.

Gaudig, G., Couwenberg, J., & Joosten, H. (2006). Peat accumulation in kettle holes: bottom up or top down. *Mires and Peat*, 1(6), 1-16.

Geological Survey of Canada, "A" Series Map 1880A, 1995, 1 sheet, https://doi.org/10.4095/205040 (Open Access)

Geological Survey of Canada, Canadian Geoscience Map 195, 2014, 1 sheet, https://doi.org/10.4095/295462

Geris, J., Tetzlaff, D., & Soulsby, C. (2015). Resistance and resilience to droughts: hydropedological controls on catchment storage and run-off response. *Hydrological Processes*, *29*(21), 4579-4593.

Gibbs, R. J. (1970). Mechanisms controlling world water chemistry. *Science*, 170(3962), 1088-1090.

Gibson, J. J., Birks, S. J., Yi, Y., & Vitt, D. (2015). Runoff to boreal lakes linked to land cover, watershed morphology and permafrost thaw: a 9-year isotope mass balance assessment. *Hydrological Processes*, *29*(18), 3848-3861.

Government of Alberta, 2010. Facts about water in Alberta. available at: https://open.alberta.ca/dataset/1832cd36-bbeb-4997-ae81-67d3eedfcfe5/resource/18a9d64bbad8-413a-8c63-77a548ec9d88/download/4888138-2010-facts-about-water-in-alberta-2010-12.pdf, (last access: 9 February 2021).

Guillemette, F., McCallister, S. L., & del Giorgio, P. A. (2013). Differentiating the degradation dynamics of algal and terrestrial carbon within complex natural dissolved organic carbon in temperate lakes. *Journal of Geophysical Research: Biogeosciences*, *118*(3), 963-973.

Hall, B. D., Hesslein, R. H., Emmerton, C. A., Higgins, S. N., Ramlal, P., & Paterson, M. J. (2019). Multidecadal carbon sequestration in a headwater boreal lake. *Limnology and Oceanography*, *64*(S1), S150-S165.

Hamon, W. R. (1963). Estimating potential evapotranspiration. *Transactions of the American Society of Civil Engineers*, *128*(1), 324-338.

Hansen, A. M., Kraus, T. E., Pellerin, B. A., Fleck, J. A., Downing, B. D., & Bergamaschi, B. A. (2016). Optical properties of dissolved organic matter (DOM): Effects of biological and photolytic degradation. *Limnology and oceanography*, *61*(3), 1015-1032.

Hanson, P. C., Bade, D. L., Carpenter, S. R., & Kratz, T. K. (2003). Lake metabolism: Relationships with dissolved organic carbon and phosphorus. *Limnology and Oceanography*, *48*(3), 1112-1119.

Hanson, P. C., Pollard, A. I., Bade, D. L., Predick, K., Carpenter, S. R., & Foley, J. A. (2004). A model of carbon evasion and sedimentation in temperate lakes. *Global Change Biology*, *10*(8), 1285-1298.

Hastie, A., Lauerwald, R., Weyhenmeyer, G., Sobek, S., Verpoorter, C., & Regnier, P. (2018). CO 2 evasion from boreal lakes: revised estimate, drivers of spatial variability, and future projections. *Global change biology*, *24*(2), 711-728.

Hayashi, M., & Van der Kamp, G. (2000). Simple equations to represent the volume–area–depth relations of shallow wetlands in small topographic depressions. *Journal of hydrology*, 237(1-2), 74-85.

Health Canada, (2019). Guidance on Natural Organic Matter in Drinking Water.

Hillman, G. R., Feng, J. C., Feng, C. C., & Wang, Y. (2004). Effects of catchment characteristics and disturbances on storage and export of dissolved organic carbon in a boreal headwater stream. *Canadian Journal of Fisheries and Aquatic Sciences*, 61(8), 1447-1460.

Hokanson, K. J., Mendoza, C. A., & Devito, K. J. (2019). Interactions Between Regional Climate, Surficial Geology, and Topography: Characterizing Shallow Groundwater Systems in Subhumid, Low-Relief Landscapes. *Water Resources Research*, 55(1), 284-297.

Hokanson, K. J., Peterson, E. S., Devito, K. J., & Mendoza, C. A. (2020). Forestland-peatland hydrologic connectivity in water-limited environments: hydraulic gradients often oppose topography. *Environmental Research Letters*, 15(3), 034021.

Hokanson K.J., Rostron B.J., Devito K.J., Hopkinson C., Mendoza C.A. Landscape controls of surface water-groundwater interactions on shallow outwash lakes: Long-term groundwater signal overrides interannual variability due to evaporative effects. In revision at *Hydrogeology*.

Holecek, G. (1988). Storage-effective drainage (SED) runoff model. *Journal of hydrology*, 98(3-4), 295-314.

Houle, D., Khadra, M., Marty, C., & Couture, S. (2020). Influence of hydro-morphologic variables of forested catchments on the increase in DOC concentration in 36 temperate lakes of eastern Canada. *Science of the Total Environment*, 747, 141539.

Hudson, J. J., Dillon, P. J., & Somers, K. M. (2003). Long-term patterns in dissolved organic carbon in boreal lakes: the role of incident radiation, precipitation, air temperature, southern oscillation and acid deposition. Hydrology and Earth System Sciences Discussions, European Geosciences Union, 7, (3), pp.390-398. ffhal-00304787

Hutchinson, G.B. 1957. A Treatise on Limnology. Volume 1. Geography, Physics, and Chemistry. John Wiley & Sons, Inc. New York.

Ingram, H. A. P. (1978). Soil layers in mires: function and terminology. *Journal of Soil Science*, 29(2), 224-227.

Ireland, A. W., & Booth, R. K. (2011). Hydroclimatic variability drives episodic expansion of a floating peat mat in a North American kettlehole basin. *Ecology*, *92*(1), 11-18.

Ireland, A. W., Booth, R. K., Hotchkiss, S. C., & Schmitz, J. E. (2012). Drought as a trigger for rapid state shifts in kettle ecosystems: implications for ecosystem responses to climate change. *Wetlands*, *32*(6), 989-1000.

Ireson, A. M., Barr, A. G., Johnstone, J. F., Mamet, S. D., Van der Kamp, G., Whitfield, C. J., ... & Chun, K. P. (2015). The changing water cycle: the Boreal Plains ecozone of Western Canada. *Wiley Interdisciplinary Reviews: Water*, 2(5), 505-521.

Jane, S. F., Winslow, L. A., Remucal, C. K., & Rose, K. C. (2017). Long-term trends and synchrony in dissolved organic matter characteristics in Wisconsin, USA, lakes: Quality, not quantity, is highly sensitive to climate. *Journal of Geophysical Research: Biogeosciences*, 122(3), 546-561.

Jencso, K. G., & McGlynn, B. L. (2011). Hierarchical controls on runoff generation: Topographically driven hydrologic connectivity, geology, and vegetation. *Water Resources Research*, *47*(11).

Jonsson, A., Algesten, G., Bergström, A. K., Bishop, K., Sobek, S., Tranvik, L. J., & Jansson, M. (2007). Integrating aquatic carbon fluxes in a boreal catchment carbon budget. *Journal of Hydrology*, *334*(1-2), 141-150.

Jonsson, A., Karlsson, J., & Jansson, M. (2003). Sources of carbon dioxide supersaturation in clearwater and humic lakes in northern Sweden. *Ecosystems*, 224-235.

Kalbitz, K., & Geyer, S. (2002). Different effects of peat degradation on dissolved organic carbon and nitrogen. *Organic Geochemistry*, *33*(3), 319-326.

Kalbitz, K., Schmerwitz, J., Schwesig, D., & Matzner, E. (2003). Biodegradation of soil-derived dissolved organic matter as related to its properties. *Geoderma*, 113(3-4), 273-291.

Kang, H., Kwon, M. J., Kim, S., Lee, S., Jones, T. G., Johncock, A. C., ... & Freeman, C. (2018). Biologically driven DOC release from peatlands during recovery from acidification. Nature communications, 9(1), 1-7.

Karlsson, J., Byström, P., Ask, J., Ask, P., Persson, L., & Jansson, M. (2009). Light limitation of nutrient-poor lake ecosystems. *Nature*, 460(7254), 506-509.

Kassambara, A., & Mundt, F. (2017). Package 'factoextra'. *Extract and visualize the results of multivariate data analyses*, *76*.

Kettridge, N., & Waddington, J. M. (2014). Towards quantifying the negative feedback regulation of peatland evaporation to drought. *Hydrological Processes*, *28*(11), 3728-3740.

Kellerman, A. M., Dittmar, T., Kothawala, D. N., & Tranvik, L. J. (2014). Chemodiversity of dissolved organic matter in lakes driven by climate and hydrology. *Nature communications*, *5*(1), 1-8.

Kirchman, D. L., Suzuki, Y., Garside, C., & Ducklow, H. W. (1991). High turnover rates of dissolved organic carbon during a spring phytoplankton bloom. *Nature*, *352*(6336), 612-614.

Klein, E., Berg, E. E., & Dial, R. (2005). Wetland drying and succession across the Kenai Peninsula Lowlands, south-central Alaska. *Canadian Journal of Forest Research*, *35*(8), 1931-1941.

Koehler, B., Von Wachenfeldt, E., Kothawala, D., & Tranvik, L. J. (2012). Reactivity continuum of dissolved organic carbon decomposition in lake water. *Journal of Geophysical Research: Biogeosciences*, *117*(G1).

Kolka, R., Weishampel, P., & Fröberg, M. (2008). Measurement and importance of dissolved organic carbon. In: *Field measurements for forest carbon monitoring* (pp. 171-176). Springer, Dordrecht.

Kortelainen, P. (1993). Content of total organic carbon in Finnish lakes and its relationship to catchment characteristics. *Canadian Journal of Fisheries and Aquatic Sciences*, 50(7), 1477-1483.

Kothawala, D. N., Stedmon, C. A., Müller, R. A., Weyhenmeyer, G. A., Köhler, S. J., & Tranvik, L. J. (2014). Controls of dissolved organic matter quality: Evidence from a large-scale boreal lake survey. *Global change biology*, 20(4), 1101-1114.

Kratz, T. K., Soranno, P. A., Baines, S. B., Benson, B. J., Magnuson, J. J., Frost, T. M., & Lathrop, R. C. (1998). Interannual synchronous dynamics in north temperate lakes in Wisconsin, USA. *Management of lakes and reservoirs during global climate change*, 42, 273-287.

Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. B. (2015). Package 'lmertest'. R package version, 2(0).

Labrecque, S., Lacelle, D., Duguay, C. R., Lauriol, B., & Hawkings, J. (2009). Contemporary (1951-2001) evolution of lakes in the Old Crow Basin, Northern Yukon, Canada: Remote sensing, numerical modeling, and stable isotope analysis. *Arctic*, 225-238.

Landwehr, J. M., & Coplen, T. B. (2006, February). Line-conditioned excess: a new method for characterizing stable hydrogen and oxygen isotope ratios in hydrologic systems. In International conference on isotopes in environmental studies (pp. 132-135). Vienna: IAEA.

Laudon, H., Berggren, M., Ågren, A., Buffam, I., Bishop, K., Grabs, T., ... & Köhler, S. (2011). Patterns and dynamics of dissolved organic carbon (DOC) in boreal streams: the role of processes, connectivity, and scaling. *Ecosystems*, *14*(6), 880-893.

Lemmen, D. S., Warren, F. J., Lacroix, J., & Bush, E. (2008). From Impacts to Adaptation. Government of Canada.

Li, M., del Giorgio, P. A., Parkes, A. H., & Prairie, Y. T. (2015). The relative influence of topography and land cover on inorganic and organic carbon exports from catchments in southern Quebec, Canada. *Journal of Geophysical Research: Biogeosciences*, 120(12), 2562-2578.

Mattsson, T., Kortelainen, P., & Räike, A. (2005). Export of DOM from boreal catchments: Impacts of land use cover and climate. *Biogeochemistry*, 76(2), 373-394.

McEachern, P., Prepas, E. E., Gibson, J. J., & Dinsmore, W. P. (2000). Forest fire induced impacts on phosphorus, nitrogen, and chlorophyll a concentrations in boreal subarctic lakes of northern Alberta. *Canadian Journal of Fisheries and Aquatic Sciences*, 57(S2), 73-81.

Magnuson, J. J., Benson, B. J., & Kratz, T. K. (1990). Temporal coherence in the limnology of a suite of lakes in Wisconsin, USA. *Freshwater Biology*, 23(1), 145-159.

Mattsson, T., Kortelainen, P., & Räike, A. (2005). Export of DOM from boreal catchments: impacts of land use cover and climate. *Biogeochemistry*, 76(2), 373-394.

McNamara, J. P., Tetzlaff, D., Bishop, K., Soulsby, C., Seyfried, M., Peters, N. E., ... & Hooper, R. (2011). Storage as a metric of catchment comparison. *Hydrological Processes*, *25*(21), 3364-3371.

Mitsch, W. J., & Gosselink, J. G. (2015). Wetlands.

Molot, L. A., & Dillon, P. J. (1997). Photolytic regulation of dissolved organic carbon in northern lakes. *Global Biogeochemical Cycles*, *11*(3), 357-365.

Montgomery J, Brisco B, Chasmer L, Devito K, Cobbaert D, Hopkinson C. SAR and Lidar Temporal Data Fusion Approaches to Boreal Wetland Ecosystem Monitoring. *Remote Sensing*. 2019; 11(2):161. https://doi.org/10.3390/rs11020161

Moran, M. A., & Zepp, R. G. (1997). Role of photoreactions in the formation of biologically labile compounds from dissolved organic matter. *Limnology and oceanography*, *42*(6), 1307-1316.

Morris, D. P., & Hargreaves, B. R. (1997). The role of photochemical degradation of dissolved organic carbon in regulating the UV transparency of three lakes on the Pocono Plateau. *Limnology and Oceanography*, *42*(2), 239-249.

Morris, P. J., Waddington, J. M., Benscoter, B. W., & Turetsky, M. R. (2011). Conceptual frameworks in peatland ecohydrology: looking beyond the two-layered (acrotelm–catotelm) model. *Ecohydrology,* 4(1), 1-11.

Mueller, K. K., Fortin, C., & Campbell, P. G. (2012). Spatial variation in the optical properties of dissolved organic matter (DOM) in lakes on the Canadian Precambrian shield and links to watershed characteristics. *Aquatic geochemistry*, 18(1), 21-44.

Mwale, D., Gan, T. Y., Devito, K., Mendoza, C., Silins, U., & Petrone, R. (2009). Precipitation variability and its relationship to hydrologic variability in Alberta. *Hydrological Processes: An International Journal*, 23(21), 3040-3056.

Natural Resources Canada (NRC) (2016). Canadian Digital Elevation Model. Government of Canada, Natural Resources Canada, Map Information Branch.

Nippgen, F., McGlynn, B. L., Marshall, L. A., & Emanuel, R. E. (2011). Landscape structure and climate influences on hydrologic response. *Water Resources Research*, *47*(12).

Nürnberg, G. K., & Shaw, M. (1999). Productivity of clear and humic lakes: nutrients, phytoplankton, bacteria. *Hydrobiologia*, 382(1-3), 97-112.

Nguyen, M. L., Westerhoff, P., Baker, L., Hu, Q., Esparza-Soto, M., & Sommerfeld, M. (2005). Characteristics and reactivity of algae-produced dissolved organic carbon. *Journal of Environmental Engineering*, 131(11), 1574-1582.

Olefeldt, D., Devito, K. J., & Turetsky, M. R. (2013). Sources and fate of terrestrial dissolved organic carbon in lakes of a Boreal Plains region recently affected by wildfire. *Biogeosciences*, 10(10), 6247-6265.

Pace, M. L., & Cole, J. J. (2002). Synchronous variation of dissolved organic carbon and color in lakes. *Limnology and Oceanography*, 47(2), 333-342.

Pace, M. L., Reche, I., Cole, J. J., Fernández-Barbero, A., Mazuecos, I. P., & Prairie, Y. T. (2012). pH change induces shifts in the size and light absorption of dissolved organic matter. *Biogeochemistry*, 108(1), 109-118.

Pachauri, R. K., Allen, M. R., Barros, V. R., Broome, J., Cramer, W., Christ, R., ... & Dubash, N. K. (2014). Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change (p. 151). Ipcc.

Partanen, S., & Luoto, M. (2006). Environmental determinants of littoral paludification in boreal lakes. *Limnologica*, *36*(2), 98-109.

Pekel, Jean-François, Andrew Cottam, Noel Gorelick, and Alan S. Belward. "High-resolution mapping of global surface water and its long-term changes." *Nature* 540, no. 7633 (2016): 418-422.

Peltomaa, E., Ojala, A., Holopainen, A. L., & Salonen, K. (2013). Changes in phytoplankton in a boreal lake during a 14-year period.

Perales, K. M., Hein, C. L., Lottig, N. R., & Vander Zanden, M. J. (2020). Lake water level response to drought in a lake-rich region explained by lake and landscape characteristics. *Canadian Journal of Fisheries and Aquatic Sciences*, *77*(11), 1836-1845.

Peuravuori, J., & Pihlaja, K. (2007). Characterization of freshwater humic matter. *Handbook of water analysis*, *2*.

Pinel-Alloul, B., Prepas, E., Planas, D., Steedman, R., & Charette, T. (2002). Watershed impacts of logging and wildfire: case studies in Canada. *Lake and Reservoir Management*, 18(4), 307-318.

Plach, J. M., Ferone, J. M., Gibbons, Z., Smerdon, B. D., Mertens, A., Mendoza, C. A., ... & Devito, K. J. (2016). Influence of glacial landform hydrology on phosphorus budgets of shallow lakes on the Boreal Plain, Canada. *Journal of Hydrology*, 535, 191-203.

Poulin, B. A., Ryan, J. N., & Aiken, G. R. (2014). Effects of iron on optical properties of dissolved organic matter. *Environmental science & technology*, 48(17), 10098-10106.

Prairie, Y. T. (2008). Carbocentric limnology: looking back, looking forward. *Canadian Journal of Fisheries and Aquatic Sciences*. 65(3): 543-548. https://doi.org/10.1139/f08-011

Prairie, Y. T., Bird, D. F., & Cole, J. J. (2002). The summer metabolic balance in the epilimnion of southeastern Quebec lakes. *Limnology and Oceanography*, 47(1), 316-321.

Qualls, R.G. and Haines, B.L., 1992. Biodegradability of dissolved organic matter in forest throughfall, soil solution, and stream water. *Soil Science Society of America Journal*, 56(2), pp.578-586.

Rantakari, M., Kortelainen, P., Vuorenmaa, J., Mannio, J., & Forsius, M. (2004). Finnish lake survey: the role of catchment attributes in determining nitrogen, phosphorus, and organic carbon concentrations. *Water, Air and Soil Pollution: Focus*, 4(2-3), 683-699.

Redding, T. E., & Devito, K. J. (2008). Lateral flow thresholds for aspen forested hillslopes on the Western Boreal Plain, Alberta, Canada. *Hydrological Processes*, 22(21), 4287-4300.

Redding, T., & Devito, K. (2010). Mechanisms and pathways of lateral flow on aspen-forested, Luvisolic soils, Western Boreal Plains, Alberta, Canada. *Hydrological processes*, 24(21), 2995-3010.

Redding, T., & Devito, K. (2011). Aspect and soil textural controls on snowmelt runoff on forested Boreal Plain hillslopes. *Hydrology Research*, 42(4), 250-267.

Riordan, B., Verbyla, D., & McGuire, A. D. (2006). Shrinking ponds in subarctic Alaska based on 1950–2002 remotely sensed images. *Journal of Geophysical Research: Biogeosciences*, *111*(G4).

Ritson, J. P., Graham, N. J. D., Templeton, M. R., Clark, J. M., Gough, R., & Freeman, C. (2014). The impact of climate change on the treatability of dissolved organic matter (DOM) in upland water supplies: a UK perspective. *Science of the Total Environment*, 473, 714-730.

Roach, J., Griffith, B., Verbyla, D., & Jones, J. (2011). Mechanisms influencing changes in lake area in Alaskan boreal forest. *Global Change Biology*, *17*(8), 2567-2583.

Rover, J., Ji, L., Wylie, B. K., & Tieszen, L. L. (2012). Establishing water body areal extent trends in interior Alaska from multi-temporal Landsat data. *Remote Sensing Letters*, *3*(7), 595-604.

Sakamoto, Y., Ishiguro, M., & Kitagawa, G. (1986). Akaike information criterion statistics. Dordrecht, The Netherlands: D. Reidel, 81.

Sass, G. Z., & Creed, I. F. (2008). Characterizing hydrodynamics on boreal landscapes using archived synthetic aperture radar imagery. *Hydrological Processes: An International Journal*, 22(11), 1687-1699.

Sass, G. Z., Creed, I. F., Bayley, S. E., & Devito, K. J. (2008). Interannual variability in trophic status of shallow lakes on the Boreal Plain: Is there a climate signal?. *Water Resources Research*, 44(8).

Schiff, S., Aravena, R., Mewhinney, E., Elgood, R., Warner, B., Dillon, P., & Trumbore, S. (1998). Precambrian shield wetlands: hydrologic control of the sources and export of dissolved organic matter. *Climatic Change*, *40*(2), 167-188.

Schindler, D. W., Bayley, S. E., Curtis, P. J., Parker, B. R., Stainton, M. P., & Kelly, C. A. (1992). Natural and man-caused factors affecting the abundance and cycling of dissolved organic substances in precambrian shield lakes. In *Dissolved organic matter in lacustrine ecosystems* (pp. 1-21). Springer, Dordrecht.

Schindler, D. W., Curtis, P. J., Bayley, S. E., Parker, B. R., Beaty, K. G., & Stainton, M. P. (1997). Climate-induced changes in the dissolved organic carbon budgets of boreal lakes. *Biogeochemistry*, 36(1), 9-28.

Schneider, R. R. (2013). Alberta's natural subregions under a changing climate: past, present, and future.

Seekell, D. A., Lapierre, J. F., Ask, J., Bergström, A. K., Deininger, A., Rodríguez, P., & Karlsson, J. (2015). The influence of dissolved organic carbon on primary production in northern lakes. *Limnology and Oceanography*, 60(4), 1276-1285.

Sepp, M., Kõiv, T., Nõges, P., & Nõges, T. (2019). The role of catchment soils and land cover on dissolved organic matter (DOM) properties in temperate lakes. *Journal of Hydrology*, 570, 281-291.

Smerdon, B. D., Devito, K. J., & Mendoza, C. A. (2005). Interaction of groundwater and shallow lakes on outwash sediments in the sub-humid Boreal Plains of Canada. *Journal of Hydrology*, 314(1-4), 246-262.

Smerdon, B. D., Mendoza, C. A., & Devito, K. J. (2008). Influence of subhumid climate and water table depth on groundwater recharge in shallow outwash aquifers. *Water Resources Research*, 44(8).

Smith, L. C., Sheng, Y., MacDonald, G. M., & Hinzman, L. D. (2005). Disappearing arctic lakes. *Science*, *308*(5727), 1429-1429.

Sobek, S., Algesten, G., Bergström, A. K., Jansson, M., & Tranvik, L. J. (2003). The catchment and climate regulation of pCO2 in boreal lakes. *Global Change Biology*, 9(4), 630-641.

Sobek, S., Tranvik, L. J., Prairie, Y. T., Kortelainen, P., & Cole, J. J. (2007). Patterns and regulation of dissolved organic carbon: An analysis of 7,500 widely distributed lakes. *Limnology and Oceanography*, 52(3), 1208-1219.

Soil Classification Working Group (2001). Soils of Canada. Agriculture and Agri-food Canada, Research Branch. Scale 1:6 500 000 map.

Solomon, C. T., Jones, S. E., Weidel, B. C., Buffam, I., Fork, M. L., Karlsson, J., ... & Saros, J. E. (2015). Ecosystem consequences of changing inputs of terrestrial dissolved organic matter to lakes: current knowledge and future challenges. *Ecosystems*, 18(3), 376-389.

Søndergaard, M., & Middelboe, M. (1995). A cross-system analysis of labile dissolved organic carbon. *Marine ecology progress series. Oldendorf*, *118*(1), 283-294.

Spence, C. (2010). A paradigm shift in hydrology: Storage thresholds across scales influence catchment runoff generation. *Geography Compass*, 4(7), 819-833.

Spiess, A. N., & Spiess, M. A. N. (2018). Package ‘qpcR’.

Sprenger, M., Tetzlaff, D., Tunaley, C., Dick, J., & Soulsby, C. (2017). Evaporation fractionation in a peatland drainage network affects stream water isotope composition. *Water Resources Research*, 53(1), 851-866.

Squires, Margaret M., David Mazzucchi, and Kevin J. Devito. "Carbon burial and infill rates in small Western Boreal lakes: physical factors affecting carbon storage." *Canadian Journal of Fisheries and Aquatic Sciences* 63.4 (2006): 711-720.

Strome, D. J., & Miller, M. C. (1978). Photolytic changes in dissolved humic substances: With 3 figures and 2 tables in the text. *Internationale Vereinigung für theoretische und angewandte Limnologie: Verhandlungen*, *20*(2), 1248-1254.

Therneau, T. M., Atkinson, B., Ripley, B., Oksanen, J., & De’ath, G. (2004). The mvpart package. *Multivariate partitioning*.

Thompson, C., Mendoza, C. A., & Devito, K. J. (2017). Potential influence of climate change on ecosystems within the Boreal Plains of Alberta. *Hydrological Processes*, 31(11), 2110-2124.

Thompson, C., Mendoza, C. A., Devito, K. J., & Petrone, R. M. (2015). Climatic controls on groundwater–surface water interactions within the Boreal Plains of Alberta: Field observations and numerical simulations. *Journal of Hydrology*, 527, 734-746.

Thurman, E.M., 2012. Organic geochemistry of natural waters (Vol. 2). Springer Science & Business Media.

Toming, K., Kutser, T., Tuvikene, L., Viik, M., & Nõges, T. (2016). Dissolved organic carbon and its potential predictors in eutrophic lakes. Water research, 102, 32-40.

Toth, J. (1963). A theoretical analysis of groundwater flow in small drainage basins. *Journal of geophysical research*, *68*(16), 4795-4812.

Tóth, J. (1999). Groundwater as a geologic agent: an overview of the causes, processes, and manifestations. *Hydrogeology journal*, *7*(1), 1-14.

Tranvik, L. J. (1988). Availability of dissolved organic carbon for planktonic bacteria in oligotrophic lakes of differing humic content. *Microbial Ecology*, 16(3), 311-322.

Tranvik, L. J. (1998). Degradation of dissolved organic matter in humic waters by bacteria. In *Aquatic humic substances* (pp. 259-283). Springer, Berlin, Heidelberg.

Tranvik, L. J., Downing, J. A., Cotner, J. B., Loiselle, S. A., Striegl, R. G., Ballatore, T. J., ... & Kortelainen, P. L. (2009). Lakes and reservoirs as regulators of carbon cycling and climate. *Limnology and Oceanography*, 54(6part2), 2298-2314.

Tranvik, L. J., & Jansson, M. (2002). Terrestrial export of organic carbon. *Nature*, 415(6874), 861-862.

Tranvik, L., & Kokalj, S. (1998). Decreased biodegradability of algal DOC due to interactive effects of UV radiation and humic matter. *Aquatic Microbial Ecology*, 14(3), 301-307.

Tranvik, L. J., Olofsson, H., & Bertilsson, S. (1999). Photochemical effects on bacterial degradation of dissolved organic matter in lake water. In *Microbial Biosystems: New Frontiers, Proceedings of the 8th International Symposium on Microbial Ecology* (pp. 193-200). Atlantic Canada Society for Microbial Ecology Halifax, Canada.

Tweed, S., Leblanc, M., & Cartwright, I. (2009). Groundwater–surface water interaction and the impact of a multi-year drought on lakes conditions in South-East Australia. *Journal of Hydrology*, *379*(1-2), 41-53.

Vachon, D., Prairie, Y. T., Guillemette, F., & Del Giorgio, P. A. (2017). Modeling allochthonous dissolved organic carbon mineralization under variable hydrologic regimes in boreal lakes. *Ecosystems*, 20(4), 781-795.

van der Velde Y., Lyon S.W., Destouni G. 2013. Data-driven regionalization of river discharges and emergent land cover-evapotranspiration relationships across Sweden. *Journal of Geophysical Research-Atmospheres.* 118: 2576-87. DOI: 10.1002/jgrd.50224.

Venables, W. N., & Ripley, B. D. (2002). Modern Applied Statistics With S., 4th edn.(Springer-Verlag: New York.).

von Wachenfeldt, E., & Tranvik, L. J. (2008). Sedimentation in boreal lakes—the role of flocculation of allochthonous dissolved organic matter in the water column. *Ecosystems*, *11*(5), 803-814.

Waddington, J.M., Morris, P.J., Kettridge, N., Granath, G., Thompson, D.K. and Moore, P.A., 2015. Hydrological feedbacks in northern peatlands. *Ecohydrology*, 8(1), pp.113-127.

Warner, B. G., Kubiw, H. J., & Hanf, K. I. (1989). An anthropogenic cause for quaking mire formation in southwestern Ontario. *Nature*, *340*(6232), 380-384.

Warner, K. A., & Saros, J. E. (2019). Variable responses of dissolved organic carbon to precipitation events in boreal drinking water lakes. *Water Research*, 156, 315-326.

Webb, J. R., Santos, I. R., Maher, D. T., & Finlay, K. (2019). The importance of aquatic carbon fluxes in net ecosystem carbon budgets: a catchment-scale review. *Ecosystems*, 22(3), 508-527.

Webster, K. E., Soranno, P. A., Cheruvelil, K. S., Bremigan, M. T., Downing, J. A., Vaux, P. D., ... & Connor, J. (2008). An empirical evaluation of the nutrient-color paradigm for lakes. *Limnology and Oceanography*, 53(3), 1137-1148.

Weishaar, J. L., Aiken, G. R., Bergamaschi, B. A., Fram, M. S., Fujii, R., & Mopper, K. (2003). Evaluation of specific ultraviolet absorbance as an indicator of the chemical composition and reactivity of dissolved organic carbon. *Environmental Science & Technology*, 37(20), 4702-4708.

Weyhenmeyer, G. A., Fröberg, M., Karltun, E., Khalili, M., Kothawala, D., Temnerud, J., & Tranvik, L. J. (2012). Selective decay of terrestrial organic carbon during transport from land to sea. *Global Change Biology*, 18(1), 349-355.

Wetzel, R. G. (2001). *Limnology: lake and river ecosystems*. gulf professional publishing.

Wickland, K. P., Neff, J. C., & Aiken, G. R. (2007). Dissolved organic carbon in Alaskan boreal forest: Sources, chemical characteristics, and biodegradability. *Ecosystems*, 10(8), 1323-1340.

Wilkinson, G. N. and Rogers, C. E. (1973). Symbolic descriptions of factorial models for analysis of variance. *Applied Statistics*, 22, 392--399. 10.2307/2346786.

Williamson, C. E., Overholt, E. P., Pilla, R. M., Leach, T. H., Brentrup, J. A., Knoll, L. B., ... & Moeller, R. E. (2015). Ecological consequences of long-term browning in lakes. *Scientific Reports*, 5, 18666.

Williamson, C. E., Saros, J. E., Vincent, W. F., & Smol, J. P. (2009). Lakes and reservoirs as sentinels, integrators, and regulators of climate change. *Limnology and Oceanography*, 54(6part2), 2273-2282.

Winter, T. C. (2001). The concept of hydrologic landscapes 1. JAWRA Journal of the American *Water Resources Association*, 37(2), 335-349.

Wong, L. S., Hashim, R., & Ali, F. H. (2009). A review on hydraulic conductivity and compressibility of peat. *Journal of Applied Sciences*, *9*(18), 3207-3218.

Yoshikawa, K., & Hinzman, L. D. (2003). Shrinking thermokarst ponds and groundwater dynamics in discontinuous permafrost near Council, Alaska. *Permafrost and Periglacial Processes*, *14*(2), 151-160.

Zhang, J., Hudson, J., Neal, R., Sereda, J., Clair, T., Turner, M., ... & Hesslein, R. (2010). Long-term patterns of dissolved organic carbon in lakes across eastern Canada: Evidence of a pronounced climate effect. *Limnology and Oceanography*, 55(1), 30-42.

6.0 Appendices

A1: Supporting Information for Data Chapter 1

Table A.1.1: Summary of annual lake year precipitation values (Pann), departure from average precipitation (DMP), 1-year and 3-year cumulative departure from long-term average precipitation (CDMP; 423 mm), and long-term potential evapotranspiration (519 mm) to precipitation ratios (PET:P) which correspond to wet, mesic or dry weather pattern classifications.

Lake Year	Pann (cm)	DMP (cm)	1-Year CDMP (cm)	3-Year CDMP (cm)	PET:P	Classification
1994 - 1995	407	-16	-16	-171	1.27	Dry
1995 - 1996	527	103	87	-27	0.99	Mesic
1996 - 1997	546	123	210	165	0.95	Mesic
1997 - 1998	428	4	214	185	1.21	Dry
1998 - 1999	359	-64	150	18	1.45	Dry
1999 - 2000	348	-75	75	-180	1.49	Dry
2000 - 2001	384	-39	35	-223	1.35	Dry
2001 - 2002	214	-209	-174	-368	2.43	Dry
2002 - 2003	394	-29	-203	-323	1.32	Dry
2003 - 2004	356	-68	-271	-351	1.46	Dry
2004 - 2005	550	126	-145	-16	0.94	Mesic
2005 - 2006	413	-10	-155	4	1.26	Dry
2006 - 2007	591	167	13	239	0.88	Mesic
2007 - 2008	437	14	27	126	1.19	Dry
2008 - 2009	490	66	93	203	1.06	Mesic
2009 - 2010	246	-177	-84	-142	2.11	Dry
2010 - 2011	427	3	-81	-152	1.22	Dry
2011 - 2012	464	41	-40	-178	1.12	Mesic
2012 - 2013	542	118	78	118	0.96	Mesic
2013 - 2014	422	-2	77	113	1.23	Dry
2014 - 2015	324	-100	-23	-28	1.60	Dry
2015 - 2016	456	33	10	-113	1.14	Mesic
2016 - 2017	450	26	36	-85	1.15	Dry
2017 - 2018	468	44	81	59	1.11	Mesic
2018 - 2019	343	-81	0	-55	1.51	Dry

Table A.1.2: Cumulative precipitation of precipitation scenarios (1-month, 12-month and 24-month prior to sampling) throughout the study period (2012 – 2019).

	Cumulative Precipitation (mm)		
Year	**1-month**	**12-month**	**24-month**
2012	107.50	464.25	886.28
2013	123.75	541.80	982.80
2014	48.16	421.57	950.62
2015	25.00	323.66	737.73
2016	93.75	456.30	778.46
2017	76.00	449.60	904.65
2018	138.00	467.70	918.55
2019	67.25	342.65	785.35

Table A.1.3: Lake and landscape attributes for the 34 study lakes at URSA.

Lake #	A (m^2)	P (m)	D (cm)	V (m^3)	RE (%)	CA (m^2)	CA:A	WA (m^2)	CAW (m^2)	% WA	% FA	HRA	% CO	% HM	% CP	BCWA (m^2)	HA (m^2)	Avg [DOC] (mg C L-1)	Avg SUVA (L C m-1)	Avg EC (µS)	Avg lc (‰)
1	112090	3114	271	157510	22.48	15912271	141.96	11000012	10810140	69	30	CO	86.57	13.43	0.00	4453573	0	10.25	1.93	143.63	-16.41
2	2466945	6828	491	505908	4.52	95444990	38.69	54804339	53015254	57	40	CO	72.25	27.75	0.00	34335427	898360	15.61	1.90	174.38	-17.60
5	3240144	13139	333	974064	4.97	90559288	27.95	50548602	48921022	56	41	CO	74.28	25.72	0.00	34234228	898219	16.49	2.24	132.14	-15.21
7	28671	762	184	80799	69.16	632350	22.06	220645	203699	35	61	HM	24.13	75.87	0.00	0	0	23.98	2.68	122.00	-26.70
11	7118	323	152	28062	73.34	129472	18.19	70253	70253	54	40	HM	13.35	86.65	0.00	0	0	34.30	2.74	158.38	-28.18
15	485	93	40	1330	77.21	77928	160.68	29246	29246	38	62	HM	100.00	0.00	0.00	0	0	37.17	3.94	92.68	-9.80
16	399257	2889	210	190220	8.41	1852940	4.64	607116	542883	33	46	CO	100.00	0.00	0.00	299807	0	20.04	1.55	213.29	-23.59
17	930713	6291	550	360563	25.12	4718789	5.07	1586712	1516224	34	47	CO	100.00	0.00	0.00	0	0	18.50	1.21	153.38	-26.30
19	11179	492	188	5967	42.74	295189	26.41	54582	47406	18	78	HM	100.00	0.00	0.00	0	0	17.49	3.06	91.29	-27.53
27	67743	1234	89	715034	84.98	436515	6.44	181361	181361	42	43	HM	31.71	68.29	0.00	0	0	29.04	2.39	92.29	-29.49
39	63994	1414	259	24767	82.19	2760538	43.14	1179506	1161998	43	55	HM	0.00	100.00	0.00	0	0	19.36	2.10	229.14	-26.85
40	7725	341	105	7391	94.81	82182	10.64	43169	43169	53	38	HM	0.00	100.00	0.00	0	0	46.26	2.66	243.00	-24.90
42	14037	485	230	6169	89.22	303315	21.61	93358	91317	31	65	HM	0.00	100.00	0.00	0	0	23.00	3.08	73.59	-32.06
43	12773	623	48	17544	96.42	274136	21.46	76108	64153	28	68	HM	0.00	100.00	0.00	0	0	35.29	2.96	133.20	-26.19
48	49779	1356	17	84968	97	798440	16.04	218351	177869	27	66	HM	0.00	100.00	0.00	0	0	34.00	2.90	158.13	-28.43
59	240951	2273	159	905429	72.25	1674675	6.95	934714	934714	56	30	CP	0.00	38.28	61.72	836659	0	31.71	2.75	128.14	-19.70
111	58463	1262	208	130602	95.56	463452	7.93	166327	156541	36	51	HM	0.00	100.00	0.00	147160	0	27.51	2.61	250.38	-22.49
112	48472	1125	181	140466	61.92	6052994	124.88	2680744	2026174	44	55	HM	0.00	90.56	9.44	2185850	488920	37.51	3.18	246.71	-11.56
118	50625	951	147	229508	55.63	444833	8.79	268357	262421	60	28	HM	0.00	54.88	45.12	242163	0	35.63	3.02	127.71	-21.90
121	84474	1051	170	50244	38.79	563027	6.67	478553	478553	85	0	CP	0.00	0.00	100.00	477567	0	40.71	2.92	180.00	-20.50
122	89710	1215	149	60452	43.7	373987	4.17	140745	140745	38	38	HM	0.00	58.21	41.79	139609	0	39.70	2.15	247.86	-25.11
160	301008	2026	-	-	15.26	2751476	9.14	1824575	1824575	66	23	CP	0.00	0.00	100.00	1063152	0	46.91	2.79	227.43	-18.46
162	896944	4239	215	421070	11.35	3092438	3.45	1458348	1458348	47	24	CP	0.00	0.00	100.00	1376222	19045	39.54	1.91	445.13	-20.53
168	139540	1550	183	400305	62.33	18486283	132.48	13328400	13186862	72	27	CP	0.00	0.04	99.96	8545424	51276	44.41	2.74	310.14	-17.95
169	3211537	8859	244	1348503	71.22	16409541	5.11	8715486	8634378	53	27	CP	0.00	0.04	99.96	7264942	16409541	43.36	2.08	351.88	-20.02
171	108320	1255	100	926105	62.33	823504	7.60	632979	632979	77	10	CP	0.00	0.00	100.00	533468	0	47.20	3.08	172.40	-18.58
201	391153	2617	306	437913	26.91	720999	1.84	158116	158116	22	24	CO	100.00	0.00	0.00	88645	0	16.89	1.73	177.71	-22.37
205	208632	1682	116	1517644	81.78	2672777	12.81	1615773	1615773	60	32	CP	0.00	0.24	99.76	1590061	0	32.69	3.74	140.75	-15.75
206	147312	2117	336	140545	50.92	1834926	12.46	624327	484819	34	58	CO	58.60	41.40	0.00	247332	0	19.38	2.06	190.50	-25.33
208	37142	726	176	114361	26.91	178668	4.81	106591	106591	60	20	CO	100.00	0.00	0.00	70841	0	19.59	2.51	104.57	-22.91
300	146485	1446	115	964807	74.86	980778	6.70	818712	818712	83	2	CP	0.00	0.00	100.00	0	0	49.39	2.82	185.75	-21.46
301	2451950	6559	312	2649076	27.42	21738065	8.87	13270682	12304842	61	28	CP	0.00	0.15	99.85	0	0	37.09	2.40	287.57	-18.73
302	232881	1846	201	558687	41.9	1340844	5.76	1003726	1003726	75	8	CP	0.00	0.00	100.00	0	0	44.04	2.70	101.89	-19.15
303	257278	2035	168	860918	38.33	4984826	19.38	4063186	4063186	82	13	CP	0.00	0.00	100.00	0	0	32.20	3.26	78.29	-18.82

Note. *Lake area (A), lake perimeter (P), lake depth (D), lake volume (V), relative elevation (RE), watershed area (CA), watershed area : lake area (CA:A), total wetland area (WA), connected wetland area (CWA), % total wetland area in watershed (% WA), % total forest area in watershed (% FA), % watershed comprised of coarse outwash (% CO), % watershed comprised of hummocky moraine (% HM), % watershed comprised of clay plains (% CP), burned connected wetland area (BCAW), harvest area (HA), average DOC concentration (Avg [DOC]), average SUVA254 (Avg SUVA), average electrical conductivity (Avg EC), average lc-excess (Avg lc).*

Table A.1.4: Descriptive statistics of A Spatial (long-term average), and B Inter-annual variability (standard deviation of each lakes measurements from 2012-2019) of lake characteristics (DOC concentration, $SUVA_{254}$, lake depth, lc-excess and EC).

	(A) Spatial Variability (Averages)						(B) Inter-annual Variability (SDs)					
	Min	Max	Avg	Std. Dev	Avg CV (%)	*p*	Min	Max	Avg	Std. Dev	Avg CV (%)	*p*
DOC (mg C L^{-1})												
Coarse Outwash *n* =8	10.25	20.04	17.09	3.19	11.71		1.02	2.64	1.86	0.56	10.94	
Hummocky Moraine *n* = 14	17.48	46.25	31.44	8.29	13.83	5.4E-08*	1.34	9.35	4.09	2.11	12.91	1.34E-02*
Clay Plains *n* = 12	31.71	49.39	40.77	6.18	9.14		2.14	5.75	3.49	1.12	8.54	
$SUVA_{254}$ (L mg C m-1)												
Coarse Outwash *n* = 8	1.21	2.51	1.89	0.4	11.37		0.12	0.30	0.20	0.06	10.61	
Hummocky Moraine *n* = 14	2.1	3.94	2.82	0.47	11.47	1.58E-04*	0.12	0.43	0.30	0.09	10.70	8.58E-03*
Clay Plains *n* = 12	1.91	3.74	2.77	0.49	15.40		0.16	0.48	0.34	0.10	12.03	
Lake Depth (m)												
Coarse Outwash *n* = 8	1.72	5.69	2.01	1.09			0.12	0.30	0.17	0.06		
Hummocky Moraine *n* = 14	0.40	2.61	1.47	0.52	-	6.51E-05*	0.08	0.27	0.14	0.05	-	0.48
Clay Plains *n* = 12	1.08	3.11	1.75	0.50			0.09	0.25	0.14	0.05		
lc-excess (‰)												
Coarse Outwash *n* = 8	-16.41	-26.30	-21.21	4.22			2.15	4.02	3.19	0.57		
Hummocky Moraine *n* = 14	-9.80	-32.06	-24.37	6.37	-	0.03*	2.36	11.26	6.05	2.26	-	7.82E-04*
Clay Plains *n* = 12	-15.75	-21.46	-19.14	1.48			2.83	5.94	3.98	0.98		
EC (µS)												
Coarse Outwash *n* = 8	104.6	213.3	161.2	34.7			16.8	71.3	33.0	15.5		
Hummocky Moraine *n* = 14	73.6	250.4	161.9	67.7	-	0.40	10.9	96.5	42.4	23.8	-	0.34
Clay Plains *n* = 12	101.9	445.1	217.5	110.6			12.2	126.9	51.0	31.5		

*Note. Results shown include minimum (Min) and maximum (Max) values, average, standard deviation (St.Dev) and the p-value (p) from an ANOVA to test differences between Hydrologic Response Areas (HRAs). Average coefficient of variation (CV) for lakes in each HRA is also included for lake DOC concentration and SUVA254. An * indicates the significance of each ANOVA ($p < 0.05$).*

Table A.1.5: Synchrony analyses results for A [DOC], B SUVA254, C lc-excess, D EC and E lake depth. Each value represents the Pearson *r* coefficient between a lake pair.

A - Synchrony Analysis for 34 lake pairs - [DOC]

	1	11	111	112	118	121	122	15	16	160	162	168	169	17	171	19	2	201	205	206	208	27	300	301	302	303	39	40	42	43	48	5	59	7
1		0.56	-0.03	-0.08	-0.01	-0.35	-0.67	0.00	-0.05	0.46	-0.19	-0.07	-0.74	0.32	-0.59	0.47	0.11	0.05	-0.15	0.17	0.39	-0.31	-0.27	-0.32	-0.52	-0.04	0.17	0.48	0.37	0.54	-0.01	0.59	-0.16	-0.03
11			0.38	0.01	0.29	0.10	0.06	-0.15	-0.02	0.28	0.44	-0.18	-0.55	0.46	-0.41	0.88	0.72	0.43	-0.28	0.35	0.71	-0.15	0.16	-0.14	-0.20	0.13	0.29	0.97	0.83	0.84	0.50	0.74	0.37	0.70
111				0.72	0.84	0.83	0.42	-0.11	0.26	0.58	0.41	0.42	0.11	0.41	0.47	0.35	0.87	0.81	0.68	0.77	0.56	0.78	0.77	0.59	-0.24	0.20	0.89	0.69	0.47	0.77	0.27	0.53	0.67	0.45
112					0.37	0.36	-0.01	0.17	-0.36	0.62	-0.21	0.69	-0.08	-0.17	0.35	-0.24	0.41	0.35	0.82	0.21	0.18	0.61	0.35	0.56	-0.17	0.23	0.50	0.37	0.38	0.61	-0.43	0.57	0.26	-0.21
118						0.91	0.45	-0.36	0.57	0.31	0.59	0.31	0.36	0.59	0.60	0.42	0.72	0.90	0.61	0.94	0.63	0.65	0.94	0.67	0.00	0.30	0.88	0.52	0.18	0.63	0.41	0.27	0.80	0.52
121							0.69	-0.24	0.61	0.18	0.62	0.26	0.53	0.45	0.70	0.29	0.69	0.78	0.57	0.85	0.39	0.81	0.93	0.60	0.01	0.13	0.81	0.48	0.05	0.48	0.47	0.02	0.72	0.56
122								-0.57	0.50	-0.36	0.82	-0.15	0.68	0.39	0.63	0.20	0.54	0.52	0.02	0.33	0.29	0.35	0.56	0.40	0.29	0.18	0.21	-0.01	0.13	-0.15	0.67	-0.26	0.64	0.70
15									-0.79	0.39	-0.95	0.25	-0.50	-0.79	-0.51	-0.21	-0.39	-0.68	0.01	-0.20	-0.73	0.30	-0.25	-0.53	-0.27	-0.55	0.01	0.52	-0.28	0.33	-0.76	0.00	-0.74	-0.83
16										-0.07	0.73	-0.40	0.62	0.92	0.49	0.46	0.32	0.61	0.09	0.65	0.47	0.40	0.45	0.23	-0.17	-0.12	0.49	0.10	-0.28	0.01	0.80	-0.37	0.53	0.54
160											-0.34	0.13	-0.44	0.18	-0.26	0.28	0.39	0.28	0.55	0.39	0.08	0.52	0.04	-0.06	-0.80	-0.54	0.69	0.79	0.33	0.96	-0.13	0.66	0.03	-0.11
162												-0.24	0.45	0.72	0.45	0.57	0.66	0.71	-0.13	0.54	0.69	0.09	0.60	0.37	0.24	0.37	0.30	0.15	0.34	0.01	0.86	-0.02	0.77	0.89
168													-0.06	-0.42	0.39	-0.43	0.07	0.05	0.65	0.20	0.06	0.45	0.43	0.50	0.14	0.55	0.30	0.12	-0.04	0.35	-0.57	0.20	0.00	-0.31
169														0.23	0.84	-0.31	-0.04	0.35	0.30	0.19	-0.03	0.28	0.47	0.60	0.47	0.17	0.08	-0.49	-0.45	-0.44	0.25	-0.61	0.49	0.10
17															0.24	0.67	0.61	0.78	0.02	0.64	0.72	0.09	0.35	0.24	-0.28	0.04	0.52	0.35	0.35	0.30	0.79	0.21	0.66	0.63
171																-0.33	0.23	0.55	0.63	0.39	0.24	0.51	0.68	0.86	0.35	0.48	0.36	-0.26	-0.19	-0.11	0.10	-0.28	0.60	0.09
19																	0.69	0.51	-0.32	0.57	0.60	0.00	0.26	-0.22	-0.29	-0.16	0.43	0.85	0.54	0.64	0.76	0.45	0.41	0.82
2																		0.81	0.25	0.70	0.74	0.48	0.62	0.33	-0.26	0.17	0.72	0.76	0.72	0.70	0.61	0.59	0.70	0.78
201																			0.49	0.79	0.81	0.44	0.77	0.69	-0.02	0.32	0.76	0.45	0.46	0.56	0.53	0.42	0.94	0.60
205																				0.46	0.13	0.73	0.57	0.75	-0.08	0.20	0.66	0.25	-0.04	0.59	-0.36	0.26	0.39	-0.28
206																					0.55	0.65	0.83	0.40	-0.24	0.07	0.92	0.68	0.11	0.69	0.51	0.22	0.61	0.56
208																						-0.03	0.49	0.49	0.04	0.59	0.44	0.47	0.72	0.61	0.48	0.61	0.77	0.61
27																							0.65	0.38	-0.35	-0.18	0.81	0.75	-0.11	0.76	0.08	0.03	0.27	0.13
300																								0.71	0.26	0.39	0.73	0.39	0.06	0.48	0.32	0.09	0.76	0.50
301																									0.42	0.66	0.41	-0.13	0.12	0.17	-0.07	0.15	0.76	0.04
302																										0.60	-0.44	-0.61	-0.17	-0.47	-0.15	-0.29	0.30	0.02
303																											-0.07	-0.32	0.29	-0.09	-0.12	0.20	0.44	0.10
39																												0.79	0.20	0.85	0.31	0.39	0.53	0.36
40																													0.61	0.91	0.35	0.68	0.22	0.54
42																														0.63	0.27	0.85	0.43	0.48
43																															0.06	0.86	0.35	0.29
48																																-0.07	0.50	0.90
5																																	0.32	0.16
59																																		0.61
7																																		

B - Synchrony Analysis for 34 lake pairs - $SUVA_{254}$

	1	11	111	112	118	121	122	15	16	160	162	168	169	17	171	19	2	201	205	206	208	27	300	301	302	303	39	40	42	43	48	5	59	7
1		0.70	0.79	0.42	0.73	0.63	0.71	0.53	0.92	0.63	0.84	0.76	0.85	0.88	0.43	0.42	0.81	0.70	0.72	0.77	0.83	0.69	0.26	0.21	0.90	0.61	0.94	0.75	0.78	0.86	0.36	0.66	0.54	0.60
11			0.94	0.89	0.94	0.95	0.88	0.43	0.66	0.99	0.92	0.92	0.81	0.54	0.69	0.86	0.84	0.46	0.93	0.36	0.75	0.70	0.60	0.69	0.51	0.63	0.83	0.95	0.91	0.68	0.86	0.82	0.90	0.87
111				0.81	0.93	0.89	0.93	0.41	0.75	0.91	0.94	0.96	0.80	0.60	0.81	0.66	0.90	0.40	0.99	0.60	0.71	0.65	0.44	0.65	0.60	0.55	0.93	0.94	0.94	0.78	0.68	0.88	0.92	0.75
112					0.76	0.77	0.78	-0.09	0.32	0.91	0.80	0.83	0.60	0.25	0.74	0.85	0.60	0.04	0.82	0.06	0.58	0.74	0.45	0.77	0.20	0.40	0.58	0.86	0.69	0.48	0.82	0.61	0.90	0.79
118						0.98	0.92	0.66	0.67	0.95	0.87	0.93	0.72	0.53	0.75	0.73	0.93	0.47	0.92	0.49	0.67	0.55	0.69	0.68	0.67	0.71	0.88	0.96	0.88	0.68	0.83	0.80	0.81	0.67
121							0.87	0.67	0.63	0.97	0.81	0.86	0.69	0.44	0.68	0.78	0.90	0.50	0.88	0.40	0.61	0.48	0.77	0.72	0.56	0.72	0.81	0.92	0.89	0.61	0.88	0.82	0.82	0.72
122								0.42	0.55	0.85	0.85	0.90	0.60	0.47	0.85	0.56	0.94	0.30	0.92	0.59	0.71	0.63	0.54	0.77	0.55	0.66	0.84	0.87	0.83	0.83	0.75	0.77	0.84	0.63
15									0.55	0.35	0.27	0.39	0.31	0.31	0.19	0.23	0.67	0.61	0.35	0.51	0.13	-0.12	0.85	0.24	0.81	0.91	0.59	0.45	0.53	0.19	0.40	0.36	0.18	0.05
16										0.59	0.76	0.65	0.92	0.91	0.23	0.46	0.76	0.84	0.69	0.77	0.78	0.62	0.19	0.03	0.79	0.47	0.90	0.65	0.85	0.75	0.29	0.81	0.51	0.69
160											0.88	0.89	0.79	0.48	0.70	0.96	0.82	0.40	0.91	0.19	0.73	0.85	0.66	0.72	0.49	0.63	0.77	0.96	0.88	0.57	0.88	0.76	0.89	0.89
162												0.95	0.90	0.76	0.67	0.74	0.80	0.46	0.91	0.48	0.85	0.80	0.33	0.46	0.64	0.48	0.90	0.93	0.83	0.75	0.67	0.76	0.79	0.80
168													0.78	0.61	0.84	0.71	0.83	0.30	0.96	0.48	0.69	0.69	0.43	0.59	0.62	0.50	0.90	0.96	0.83	0.65	0.69	0.74	0.84	0.67
169														0.88	0.34	0.71	0.65	0.70	0.75	0.44	0.83	0.70	0.23	0.16	0.68	0.39	0.84	0.82	0.80	0.69	0.51	0.75	0.63	0.83
17															0.17	0.37	0.57	0.74	0.55	0.59	0.82	0.58	-0.01	-0.15	0.78	0.28	0.78	0.59	0.58	0.71	0.23	0.56	0.30	0.54
171																0.39	0.70	-0.16	0.85	0.43	0.31	0.41	0.35	0.77	0.29	0.33	0.66	0.77	0.63	0.47	0.53	0.58	0.81	0.33
19																	0.49	0.35	0.65	-0.13	0.59	0.65	0.60	0.50	0.34	0.47	0.52	0.88	0.63	0.34	0.86	0.52	0.68	0.83
2																		0.56	0.86	0.73	0.70	0.51	0.62	0.65	0.76	0.78	0.91	0.85	0.89	0.89	0.69	0.82	0.74	0.59
201																			0.32	0.50	0.63	0.27	0.36	-0.08	0.68	0.56	0.60	0.39	0.60	0.58	0.31	0.56	0.17	0.54
205																				0.55	0.64	0.58	0.42	0.67	0.51	0.46	0.89	0.93	0.91	0.70	0.68	0.88	0.92	0.70
206																					0.45	0.23	0.08	0.21	0.72	0.44	0.76	0.32	0.64	0.84	0.01	0.62	0.39	0.20
208																						0.84	0.22	0.25	0.66	0.52	0.74	0.75	0.66	0.91	0.58	0.60	0.52	0.78
27																							0.18	0.37	0.61	0.46	0.60	0.90	0.54	0.83	0.52	0.36	0.59	0.75
300																								0.66	0.40	0.85	0.39	0.58	0.52	0.20	0.78	0.36	0.44	0.36
301																									0.03	0.59	0.41	0.62	0.62	0.43	0.74	0.54	0.81	0.48
302																										0.69	0.84	0.65	0.59	0.63	0.26	0.39	0.26	0.35
303																											0.60	0.62	0.63	0.62	0.65	0.42	0.45	0.45
39																												0.87	0.89	0.81	0.51	0.81	0.72	0.62
40																													0.86	0.61	0.76	0.70	0.84	0.79
42																														0.79	0.65	0.94	0.88	0.80
43																															0.42	0.74	0.61	0.69
48																																0.58	0.69	0.71
5																																	0.83	0.74
59																																		0.78
7																																		

C - Synchrony Analysis for 34 lake pairs - lc-excess

	1	11	111	112	118	121	122	15	16	160	162	168	169	17	171	19	2	201	205	206	208	27	300	301	302	303	39	40	42	43	48	5	59	7
1		0.97	0.99	0.87	0.72	0.91	0.87	0.20	0.88	0.99	0.85	0.98	0.95	0.88	0.76	0.90	0.90	0.96	0.98	0.83	0.86	0.54	0.72	0.89	0.94	0.95	0.87	0.91	0.88	0.87	0.75	0.98	0.87	0.93
11			0.97	0.87	0.81	0.92	0.84	0.15	0.93	0.94	0.91	0.99	0.95	0.90	0.83	0.94	0.87	0.93	0.95	0.71	0.88	0.64	0.77	0.85	0.96	0.95	0.82	0.95	0.90	0.91	0.76	0.93	0.95	0.97
111				0.90	0.75	0.92	0.87	0.26	0.88	0.99	0.82	0.96	0.91	0.86	0.75	0.93	0.85	0.94	0.98	0.84	0.83	0.52	0.72	0.91	0.95	0.95	0.87	0.89	0.87	0.86	0.77	0.97	0.89	0.90
112					0.63	0.82	0.85	0.24	0.81	0.88	0.72	0.84	0.78	0.73	0.79	0.85	0.63	0.76	0.86	0.66	0.74	0.54	0.75	0.82	0.82	0.94	0.71	0.80	0.74	0.73	0.77	0.80	0.83	0.83
118						0.72	0.67	-0.02	0.79	0.69	0.73	0.76	0.69	0.71	0.75	0.83	0.60	0.70	0.65	0.53	0.65	0.55	0.53	0.69	0.83	0.68	0.66	0.70	0.79	0.83	0.76	0.71	0.83	0.89
121							0.93	0.23	0.92	0.98	0.89	0.90	0.83	0.68	0.84	0.96	0.74	0.85	0.94	0.59	0.90	0.71	0.91	0.95	0.96	0.94	0.79	0.93	0.82	0.88	0.85	0.83	0.77	0.86
122								-0.16	0.90	0.97	0.82	0.83	0.74	0.64	0.84	0.91	0.67	0.91	0.86	0.71	0.98	0.73	0.86	0.93	0.93	0.93	0.87	0.88	0.84	0.88	0.88	0.79	0.78	0.80
15									-0.26	-0.17	-0.17	0.20	0.21	-0.06	-0.12	0.03	-0.01	-0.09	0.35	-0.23	-0.43	-0.63	0.06	0.47	0.00	0.07	-0.27	-0.09	-0.32	-0.35	0.34	0.15	-0.01	-0.03
16										0.94	0.93	0.89	0.82	0.81	0.86	0.96	0.78	0.88	0.86	0.66	0.95	0.85	0.84	0.81	0.97	0.94	0.87	0.96	0.96	0.98	0.74	0.83	0.90	0.95
160											0.90	0.95	0.89	0.77	0.90	0.95	0.81	0.93	0.98	0.78	0.95	0.91	0.97	0.95	0.97	0.98	0.85	0.95	0.85	0.90	0.86	0.96	0.84	0.90
162												0.91	0.90	0.80	0.91	0.86	0.84	0.84	0.83	0.52	0.97	0.84	0.85	0.76	0.90	0.89	0.72	0.98	0.85	0.93	0.72	0.77	0.78	0.95
168													0.98	0.91	0.82	0.89	0.92	0.95	0.96	0.73	0.87	0.58	0.74	0.86	0.93	0.93	0.80	0.94	0.86	0.88	0.75	0.95	0.89	0.95
169														0.92	0.79	0.80	0.95	0.93	0.92	0.69	0.84	0.53	0.67	0.78	0.86	0.87	0.73	0.91	0.80	0.83	0.67	0.92	0.79	0.93
17															0.65	0.75	0.93	0.95	0.81	0.79	0.76	0.50	0.48	0.60	0.80	0.80	0.78	0.82	0.87	0.83	0.48	0.92	0.89	0.93
171																0.82	0.62	0.68	0.73	0.41	0.85	0.80	0.86	0.78	0.83	0.86	0.59	0.88	0.72	0.83	0.87	0.63	0.81	0.83
19																	0.71	0.86	0.90	0.70	0.88	0.73	0.84	0.89	0.98	0.94	0.85	0.91	0.91	0.93	0.81	0.85	0.90	0.89
2																		0.93	0.85	0.78	0.79	0.49	0.53	0.67	0.81	0.78	0.80	0.85	0.83	0.82	0.49	0.92	0.70	0.90
201																			0.89	0.93	0.92	0.51	0.61	0.87	0.93	0.89	0.96	0.88	0.93	0.92	0.75	0.96	0.82	0.95
205																				0.74	0.82	0.53	0.78	0.91	0.93	0.94	0.82	0.90	0.82	0.82	0.73	0.94	0.79	0.92
206																					0.69	0.25	0.24	0.65	0.76	0.69	0.92	0.59	0.81	0.71	0.48	0.90	0.67	0.66
208																						0.79	0.82	0.86	0.93	0.91	0.89	0.97	0.90	0.96	0.82	0.78	0.75	0.95
27																							0.83	0.53	0.72	0.72	0.59	0.82	0.73	0.82	0.55	0.43	0.45	0.74
300																								0.82	0.82	0.87	0.59	0.88	0.66	0.76	0.76	0.57	0.48	0.78
301																									0.91	0.89	0.76	0.82	0.72	0.78	0.92	0.81	0.67	0.74
302																										0.94	0.89	0.94	0.93	0.96	0.82	0.90	0.90	0.91
303																											0.83	0.95	0.87	0.89	0.79	0.87	0.91	0.94
39																												0.80	0.95	0.90	0.61	0.89	0.74	0.80
40																													0.88	0.94	0.72	0.84	0.83	0.97
42																														0.97	0.63	0.88	0.88	0.92
43																															0.72	0.84	0.86	0.94
48																																0.64	0.62	0.63
5																																	0.84	0.88
59																																		0.92
7																																		

D - Synchrony Analysis for 34 lake pairs - EC

	1	11	111	112	118	121	122	15	16	160	162	168	169	17	171	19	2	201	205	206	208	27	300	301	302	303	39	40	42	43	48	5	59	7
1		-0.13	-0.14	-0.31	0.15	0.19	-0.43	-0.59	-0.16	-0.02	-0.38	-0.08	0.25	-0.44	-0.06	0.12	-0.84	0.51	-0.40	0.88	0.67	-0.16	-0.13	-0.59	-0.36	0.36	0.12	0.74	-0.42	-0.33	0.31	-0.33	0.22	-0.20
11			-0.21	0.34	0.09	-0.34	-0.12	0.91	-0.32	0.55	0.34	0.93	0.39	0.28	0.90	0.51	-0.09	-0.49	0.27	0.05	-0.16	0.51	-0.33	0.81	-0.33	0.45	0.36	-0.06	0.74	-0.04	0.60	0.41	0.45	0.79
111				-0.21	0.39	-0.02	0.57	-0.30	0.28	0.01	-0.26	-0.36	0.14	-0.07	-0.53	-0.89	0.40	0.11	0.10	-0.24	-0.01	-0.85	0.49	-0.40	0.30	-0.48	-0.21	-0.50	-0.61	-0.79	-0.59	0.65	-0.42	-0.43
112					-0.33	-0.88	0.22	0.48	0.44	0.11	0.79	0.59	-0.84	0.91	-0.40	0.39	-0.09	0.20	-0.28	0.03	0.08	0.11	0.19	0.08	-0.28	-0.09	0.21	-0.17	0.24	0.22	0.37	-0.41	0.60	0.07
118						-0.01	0.67	-0.15	-0.14	0.22	-0.51	-0.26	0.06	-0.37	0.00	-0.24	0.15	-0.14	-0.21	0.10	-0.32	-0.49	-0.40	-0.19	-0.11	-0.36	-0.05	-0.15	-0.36	-0.34	-0.53	0.31	-0.44	-0.34
121							-0.30	-0.22	-0.12	-0.03	-0.53	-0.26	0.57	-0.86	0.06	-0.28	0.12	-0.33	0.37	0.00	-0.16	0.15	-0.07	0.03	0.37	0.28	0.06	0.20	-0.14	0.00	-0.26	0.20	-0.56	0.30
122								-0.10	0.43	0.18	0.05	-0.46	-0.44	0.01	-0.41	-0.47	0.69	-0.03	0.05	-0.58	-0.66	-0.60	0.06	-0.17	0.37	-0.82	-0.22	-0.76	-0.39	-0.10	-0.72	0.44	-0.28	-0.41
15									-0.55	0.65	0.55	0.91	0.30	0.35	0.81	0.59	0.34	-0.73	0.70	-0.43	-0.49	0.81	-0.40	0.96	-0.35	0.71	0.95	-0.45	0.93	0.24	0.52	0.44	0.30	0.92
16										0.63	0.62	-0.42	-0.23	-0.03	-0.45	-0.73	0.38	0.26	0.49	0.10	-0.34	-0.30	0.79	-0.35	0.69	-0.23	0.24	-0.63	-0.56	-0.40	-0.30	0.07	0.28	-0.21
160											0.49	0.63	0.29	-0.13	0.93	0.15	0.10	-0.56	0.67	0.48	-0.52	0.46	0.05	0.44	0.09	0.63	0.86	-0.46	0.06	-0.36	0.08	0.49	0.26	0.48
162												0.42	-0.23	0.57	0.36	0.24	0.13	-0.07	0.40	0.01	-0.21	0.33	0.44	0.34	0.19	0.19	0.35	-0.41	0.23	0.11	0.39	-0.05	0.75	0.59
168													0.41	0.35	0.84	0.61	-0.24	-0.45	0.27	0.09	0.06	0.79	-0.26	0.81	-0.36	0.79	0.49	0.13	0.86	0.08	0.80	0.26	0.55	0.91
169														-0.61	0.62	-0.16	-0.01	-0.23	0.62	0.21	-0.04	0.21	0.06	0.33	0.29	0.39	-0.08	0.02	0.27	-0.42	0.25	0.65	0.03	0.74
17															-0.12	0.34	-0.03	0.05	-0.30	-0.26	0.19	0.19	0.07	0.21	-0.38	-0.11	-0.03	-0.14	0.44	0.24	0.32	-0.23	0.42	-0.10
171																0.64	-0.01	-0.48	0.84	0.02	-0.47	0.69	-0.47	0.99	0.06	0.94	-0.32	-0.16	0.67	0.15	0.68	0.38	0.44	0.97
19																	-0.51	-0.19	-0.29	0.13	0.14	0.83	-0.67	0.52	-0.63	0.65	0.51	0.53	0.85	0.68	0.72	-0.52	0.47	0.48
2																		-0.39	0.57	-0.85	-0.81	-0.20	0.28	0.27	0.70	-0.59	-0.23	-0.89	0.03	0.04	-0.64	0.54	-0.44	0.02
201																			-0.43	0.33	0.63	-0.82	0.41	-0.84	0.08	-0.75	-0.59	0.19	-0.64	-0.21	0.10	-0.49	0.42	-0.63
205																				-0.31	-0.58	0.25	0.45	0.50	0.75	0.20	0.09	-0.60	0.22	-0.18	0.01	0.66	0.10	0.64
206																					0.56	0.09	0.02	-0.48	-0.42	0.78	0.53	0.65	-0.37	-0.73	0.40	-0.57	0.44	-0.04
208																						-0.07	0.07	-0.48	-0.51	0.28	-0.14	0.71	-0.09	-0.21	0.48	-0.42	0.33	-0.27
27																							-0.34	0.77	-0.37	0.92	0.85	0.32	0.73	0.57	0.54	0.05	0.13	0.75
300																								-0.38	0.67	-0.28	-0.10	-0.51	-0.42	-0.50	-0.13	0.24	0.26	-0.19
301																									-0.09	0.60	0.47	-0.15	0.92	0.41	0.41	0.36	0.13	0.93
302																										-0.38	-0.29	-0.70	-0.34	-0.17	-0.40	0.38	-0.09	0.03
303																											0.88	0.53	0.47	0.05	0.62	0.04	0.25	0.70
39																												0.17	0.08	-0.10	0.09	0.00	-0.19	0.63
40																													0.08	0.21	0.47	-0.58	0.08	-0.02
42																														0.67	0.60	0.46	0.22	0.80
43																															0.18	-0.60	0.00	0.17
48																																-0.23	0.81	0.64
5																																	-0.25	0.38
59																																		0.43
7																																		

E - Synchrony Analysis for 34 lake pairs - Lake Depth

	1	11	111	112	118	121	122	15	16	160	162	168	169	17	171	19	2	201	205	206	208	27	300	301	302	303	39	40	42	43	48	5	59	7
1		0.97	0.99	0.87	0.72	0.91	0.87	0.20	0.88	0.99	0.85	0.98	0.95	0.88	0.76	0.90	0.90	0.96	0.98	0.83	0.86	0.54	0.72	0.89	0.94	0.95	0.87	0.91	0.88	0.87	0.75	0.98	0.87	0.93
11			0.97	0.87	0.81	0.92	0.84	0.15	0.93	0.94	0.91	0.99	0.95	0.90	0.83	0.94	0.87	0.93	0.95	0.71	0.88	0.64	0.77	0.85	0.96	0.95	0.82	0.95	0.90	0.91	0.76	0.93	0.95	0.97
111				0.90	0.75	0.92	0.87	0.26	0.88	0.99	0.82	0.96	0.91	0.86	0.75	0.93	0.85	0.94	0.98	0.84	0.83	0.52	0.72	0.91	0.95	0.95	0.87	0.89	0.87	0.86	0.77	0.97	0.89	0.90
112					0.63	0.82	0.85	0.24	0.81	0.88	0.72	0.84	0.78	0.73	0.79	0.85	0.63	0.76	0.86	0.66	0.74	0.54	0.75	0.82	0.82	0.94	0.71	0.80	0.74	0.73	0.77	0.80	0.83	0.83
118						0.72	0.67	-0.02	0.79	0.69	0.73	0.76	0.69	0.71	0.75	0.83	0.60	0.70	0.65	0.53	0.65	0.55	0.53	0.69	0.83	0.68	0.66	0.70	0.79	0.83	0.76	0.71	0.83	0.89
121							0.93	0.23	0.92	0.98	0.89	0.90	0.83	0.68	0.84	0.96	0.74	0.85	0.94	0.59	0.90	0.71	0.91	0.95	0.96	0.94	0.79	0.93	0.82	0.88	0.85	0.83	0.77	0.86
122								-0.16	0.90	0.97	0.82	0.83	0.74	0.64	0.84	0.91	0.67	0.91	0.86	0.71	0.98	0.73	0.86	0.93	0.93	0.93	0.87	0.88	0.84	0.88	0.88	0.79	0.78	0.80
15									-0.26	-0.17	-0.17	0.20	0.21	-0.06	-0.12	0.03	-0.01	-0.09	0.35	-0.23	-0.43	-0.63	0.06	0.47	0.00	0.07	-0.27	-0.09	-0.32	-0.35	0.34	0.15	-0.01	-0.03
16										0.94	0.93	0.89	0.82	0.81	0.86	0.96	0.78	0.88	0.86	0.66	0.95	0.85	0.84	0.81	0.97	0.94	0.87	0.96	0.96	0.98	0.74	0.83	0.90	0.95
160											0.90	0.95	0.89	0.77	0.90	0.95	0.81	0.93	0.98	0.78	0.95	0.91	0.97	0.95	0.97	0.98	0.85	0.95	0.85	0.90	0.86	0.96	0.84	0.90
162												0.91	0.90	0.80	0.91	0.86	0.84	0.84	0.83	0.52	0.97	0.84	0.85	0.76	0.90	0.89	0.72	0.98	0.85	0.93	0.72	0.77	0.78	0.95
168													0.98	0.91	0.82	0.89	0.92	0.95	0.96	0.73	0.87	0.58	0.74	0.86	0.93	0.93	0.80	0.94	0.86	0.88	0.75	0.95	0.89	0.95
169														0.92	0.79	0.80	0.95	0.93	0.92	0.69	0.84	0.53	0.67	0.78	0.86	0.87	0.73	0.91	0.80	0.83	0.67	0.92	0.79	0.93
17															0.65	0.75	0.93	0.95	0.81	0.79	0.76	0.50	0.48	0.60	0.80	0.80	0.78	0.82	0.87	0.83	0.48	0.92	0.89	0.93
171																0.82	0.62	0.68	0.73	0.41	0.85	0.80	0.86	0.78	0.83	0.86	0.59	0.88	0.72	0.83	0.87	0.63	0.81	0.83
19																	0.71	0.86	0.90	0.70	0.88	0.73	0.84	0.89	0.98	0.94	0.85	0.91	0.91	0.93	0.81	0.85	0.90	0.89
2																		0.93	0.85	0.78	0.79	0.49	0.53	0.67	0.81	0.78	0.80	0.85	0.83	0.82	0.49	0.92	0.70	0.90
201																			0.89	0.93	0.92	0.51	0.61	0.87	0.93	0.89	0.96	0.88	0.93	0.92	0.75	0.96	0.82	0.95
205																				0.74	0.82	0.53	0.78	0.91	0.93	0.94	0.82	0.90	0.82	0.82	0.73	0.94	0.79	0.92
206																					0.69	0.25	0.24	0.65	0.76	0.69	0.92	0.59	0.81	0.71	0.48	0.90	0.67	0.66
208																						0.79	0.82	0.86	0.93	0.91	0.89	0.97	0.90	0.96	0.82	0.78	0.75	0.95
27																							0.83	0.53	0.72	0.72	0.59	0.82	0.73	0.82	0.55	0.43	0.45	0.74
300																								0.82	0.82	0.87	0.59	0.88	0.66	0.76	0.76	0.57	0.48	0.78
301																									0.91	0.89	0.76	0.82	0.72	0.78	0.92	0.81	0.67	0.74
302																										0.94	0.89	0.94	0.93	0.96	0.82	0.90	0.90	0.91
303																											0.83	0.95	0.87	0.89	0.79	0.87	0.91	0.94
39																												0.80	0.95	0.90	0.61	0.89	0.74	0.80
40																													0.88	0.94	0.72	0.84	0.83	0.97
42																														0.97	0.63	0.88	0.88	0.92
43																															0.72	0.84	0.86	0.94
48																																0.64	0.62	0.63
5																																	0.84	0.88
59																																		0.92
7																																		

Table A.1.6: Statistical results of relationships between DOC characteristics (DOC concentration & $SUVA_{254}$) with different precipitation scenarios (1-month, 12-month and 24-month).

DOC Characteristic	Cumulative Precipitation (mm)	HRA	Pearson R (*r*)	*p*-value
[DOC]	1-month	Coarse Outwash	-0.67	0.07
		Hummocky Moraine	-0.57	0.14
		Clay Plains	-0.13	0.76
	12-month	Coarse Outwash	-0.32	0.44
		Hummocky Moraine	-0.33	0.43
		Clay Plains	0.14	0.73
	24-month	Coarse Outwash	-0.31	0.45
		Hummocky Moraine	-0.31	0.46
		Clay Plains	-0.34	0.40
$SUVA_{254}$	1-month	Coarse Outwash	0.10	0.81
		Hummocky Moraine	0.53	0.18
		Clay Plains	0.39	0.34
	12-month	Coarse Outwash	0.29	0.48
		Hummocky Moraine	0.66	0.07
		Clay Plains	0.55	0.15
	24-month	Coarse Outwash	0.82	0.01
		Hummocky Moraine	0.90	0.00
		Clay Plains	0.77	0.03

A2: Supplementary Information for Chapter 3

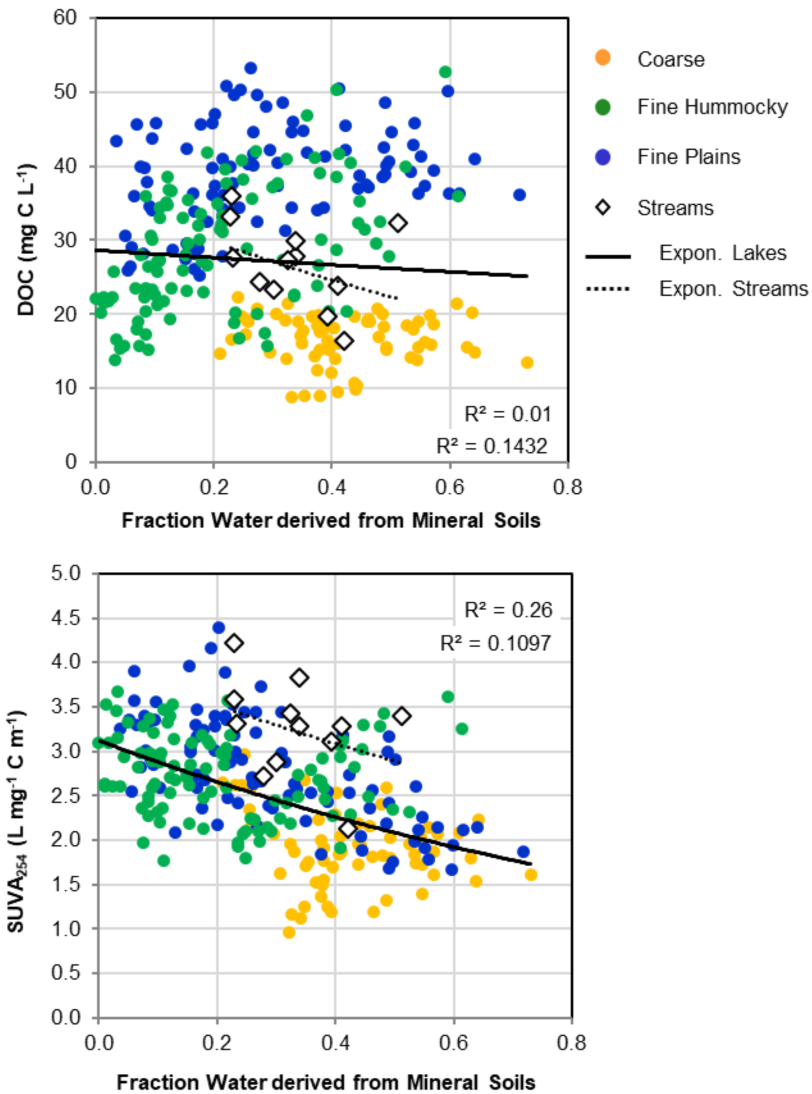


Figure A.2.1: Relationship between fractional contributions of water derived from mineral soils and DOC concentration (top panel) and $SUVA_{254}$ (bottom panel). The fraction if water remaining is represents the fractional contribution of peatland water to lakes.

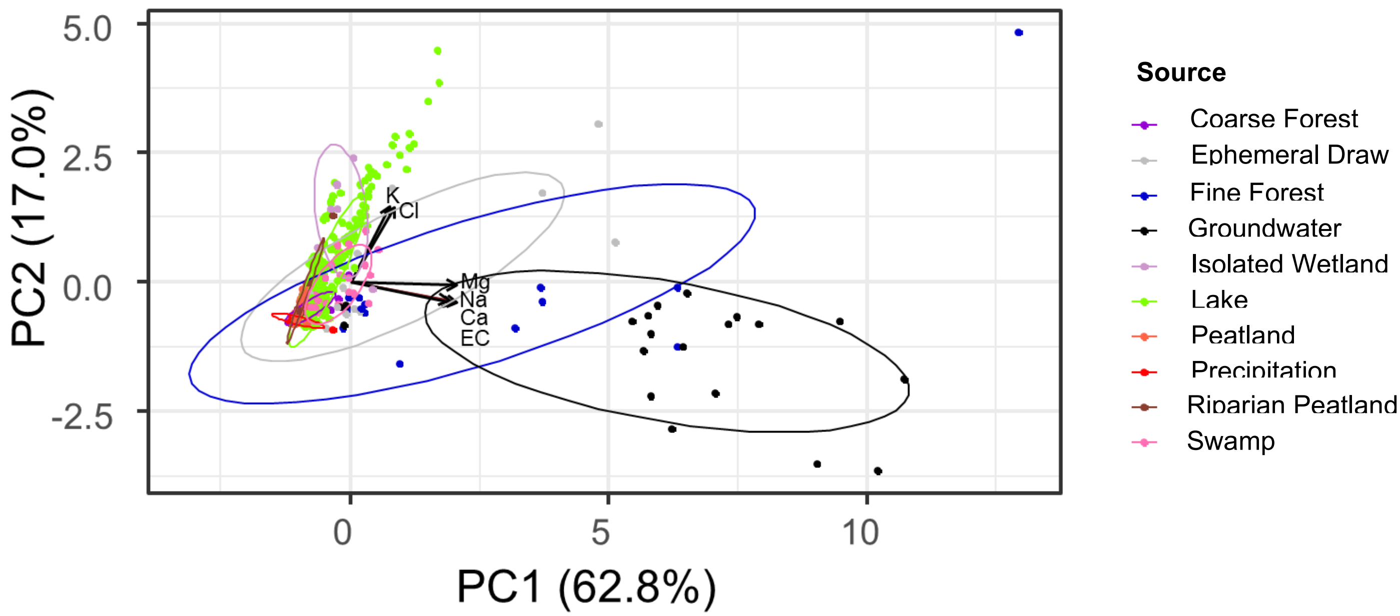


Figure A.2.2: Identifying water quality parameter to be used as a conservative tracer in a two end-member separation hydrologic mixing model using a principal component analysis.

Table A.2.3: Results from a two-sample t-test (*p*-values) to identify significant differences in water chemistry between (a) coarse and fine-textured mineral shallow forest and deeper groundwater sources; (b) coarse and fine-textured organic peatland sources for justification of end-member values used in the hydrological mixing model. Italicized *p*-values indicate significant differences ($p < 0.05$).

Forest / Groundwater		Fine				
		DOC	A254	SUVA	MgCa	EC
Coarse	DOC	0.15				
	A254		*8.00E-07*			
	SUVA			*0.04*		
	MgCa				*7.00E-05*	
	EC					*0.02*
Peatland		**Fine**				
		DOC	A254	SUVA	MgCa	EC
Coarse	DOC	0.27				
	A254		0.17			
	SUVA			0.16		
	MgCa				0.47	
	EC					0.39

Table A.2.4: Results from a two sample *t*-test (*p*-values) to identify significant differences in DOC characteristics of end-members between spring freshet and summer for justification of adjustment of end-member values used in the hydrological mixing model. Italicized *p*-values indicate significant differences ($p < 0.05$).

Peatland		**Spring Freshet**		
		DOC	**A_{254}**	**$SUVA_{254}$**
Summer	**DOC**	*1.20E-05*		
	A_{254}		*8.52E-05*	
	$SUVA_{254}$			3.10E-01
Forest / Groundwater		**Spring Freshet**		
		DOC	**A_{254}**	**$SUVA_{254}$**
Summer	**DOC**	0.3		
	A_{254}		---	
	$SUVA_{254}$			---

Table A.2.5: Results from a two-sample *t*-test (*p*-values) to identify significant differences in DOC characteristics between (a) fine and coarse-textured peatlands; (b) shallow and deep portions of peatlands in coarse-textured watersheds; and (c) shallow and deep portions of peatlands in fine-textured watersheds. Italicized *p*-values indicate significant differences ($p < 0.05$).

(a) Peatland		Fine		
Coarse		**DOC**	**A254**	**SUVA**
	DOC	0.27		
	A254		0.17	
	SUVA			0.16

(b) Coarse Peatland		Deep		
Shallow		**DOC**	**A254**	**SUVA**
	DOC	*1.21E-04*		
	A254		*1.57E-03*	
	SUVA			0.06

(c) Fine Peatland		Deep		
Shallow		**DOC**	**A254**	**SUVA**
	DOC	*1.50E-04*		
	A254		*1.62E-03*	
	SUVA			0.2

Table A.2.6: Results from a two-sample *t*-test (*p*-values) to identify significant differences in water chemistry between (a) coarse-textured organic peatland, mineral shallow forest and deeper groundwater sources; and (b) fine-textured organic peatland, mineral shallow forest and deeper groundwater sources. Italicized *p*-values indicate significant differences ($p < 0.05$).

(a)		Forest					Groundwater				
		Coarse-textured									
		DOC	A254	SUVA	MgCa	EC	DOC	A254	SUVA	MgCa	EC
Peatland	DOC	*3.30E-06*					*2.90E-12*				
	A254		*4.00E-04*					*1.30E-03*			
	SUVA			*2.00E-05*					*5.00E-05*		
	MgCa				*1.20E-09*					*1.70E-05*	
	EC					*8.30E-06*					*7.70E-06*
(b)		Fine-textured									
		DOC	A254	SUVA	MgCa	EC	DOC	A254	SUVA	MgCa	EC
Peatland	DOC	*4.00E-09*					*8.00E-14*				
	A254		*7.00E-11*					*5.00E-17*			
	SUVA			*3.00E-04*					*1.00E-08*		
	MgCa				*4.20E-08*					*6.00E-31*	
	EC					*4.30E-08*					*1.20E-08*

Table A.2.7: Results from a two-sample *t*-test (*p*-values) to identify significant differences in MgCa and EC between (a) coarse-textured mineral shallow forest and deeper groundwater; and (b) fine-textured mineral shallow forest and deeper groundwater. Italicized *p*-values indicate significant differences ($p < 0.05$).

(a) Coarse-textured		**Groundwater**	
Forest		**MgCa**	**EC**
	MgCa	0.24	
	EC		0.43
(b) Fine-textured		**Groundwater**	
Forest		**MgCa**	**EC**
	MgCa	*6.00E-24*	
	EC		*8.00E-06*

A3: Supplementary Information for Chapter 4

Table A.3.1: Shoreline index values for each of the study lakes, calculated according to Hutchinson (1957) methodology.

Lake ID	Shoreline Development Index
1	2.62
2	1.47
5	2.22
7	1.27
11	1.02
15	1.19
16	1.27
17	1.91
19	1.20
27	1.33
39	0.98
40	1.09
42	1.16
43	1.56
48	1.71
59	1.31
111	1.47
112	1.44
118	1.59
121	1.02
122	1.15
160	1.04
162	1.26
168	1.16
169	1.43
171	1.07
201	1.17
205	1.04
206	1.80
208	1.06
300	1.07
301	1.18
302	1.08
303	1.13

Table A.3.2: Pearson correlation coefficients between lake diameter and cumulative departure from mean precipitation calculated across five different cumulative departure from mean (CDM) precipitation scenarios.

Lake ID	CDM 1	CDM 2	CDM 3	CDM 4	CDM 5	Order
Coarse-textured						
HRA sub-unit						
206	***0.36***	0.10	0.05	-0.11	-0.2	High Landscape Position
201	-0.19	-0.37	-0.31	-0.38	-0.4	
208	0.12	0.23	***0.47***	0.43	0.43	Low Landscape Position
HRA sub-unit						
17	***0.43***	0.12	0.1	0.09	0.07	High Landscape Position
1	0.32	0.54	***0.63***	0.48	0.52	
16	-0.14	-0.14	0.01	-0.11	-0.51	
5	-0.23	-0.42	-0.39	-0.5	-0.51	
2	0.13	0.39	0.56	0.64	***0.65***	Low Landscape Position
Fine-textured						
121	0.23	0.34	***0.44***	0.37	0.34	High wetland connectivity
300	0.39	0.36	0.53	0.68	***0.7***	
303	0.26	0.42	0.52	0.65	***0.7***	
171	0.21	0.21	0.26	0.37	***0.44***	
302	0.04	0.03	0.14	0.16	***0.18***	
168	-0.13	0.12	***0.31***	***0.31***	0.26	
160	0.23	0.48	0.58	***0.63***	***0.63***	
205	0.19	0.57	0.62	0.66	***0.67***	
118	-0.16	-0.16	-0.04	-0.03	-0.06	
301	0.38	0.3	0.47	0.61	***0.69***	
59	***0.56***	0.34	0.42	0.43	0.53	
11	-0.24	***0.25***	0.15	0.02	0.06	
169	0.34	0.52	***0.68***	0.66	0.66	
40	-0.13	0.14	***0.25***	0.14	0.09	
162	0.34	0.21	0.4	0.44	***0.5***	
39	0.17	0.08	0.22	0.33	***0.38***	
27	-0.57	***0.27***	0.24	0.16	0.10	
122	0.24	0.45	0.55	0.63	***0.72***	
111	***0.38***	-0.06	0.10	0.20	0.17	
112	-0.17	-0.04	0.13	0.08	0.03	
7	***0.33***	0.082	0.28	0.23	0.21	
42	0.16	0.15	***0.25***	0.18	0.2	
43	0.01	-0.07	0.05	0.03	0.02	
48	***0.49***	0.14	0.21	0.28	0.26	
19	***0.61***	0.36	0.53	0.55	0.53	Low wetland connectivity

Note: Coarse-textured lakes are ordered by landscape position in different HRA sub-units, and fine-textured lakes are ordered by the proportion of wetland in each lake watershed. Bold italicised numbers highlight the strongest relationship between CDMP and lake diameter to infer the lag time between lake diameter and wet-dry periods. Lakes that are shaded grey did not show any relationships between lake diameter and the CDM scenarios used in this analysis.

Table A.3.3: Spatial variability in contraction and expansion of lake diameter from 1996 to 2019 (expressed as 2 standard deviations of the departure from maximum lake diameter) among HRAs.

	Spatial Variability 2SD of the departure from maximum lake diameter					
	Absolute (m)			Relative (%)		
	Average	Min	Max	Average	Min	Max
Coarse *n=8*	27.14[a]	4.96	52.55	6.32[a]	0.53	19.25
Fine Hummocky *n=13*	37.09[a]	5.76	127.83	24.39[b]	4.10	66.76
Fine Plains *n=12*	121.11[b]	24.46	370.96	13.03[ab]	4.51	27.63
p-value	*0.003*			*0.007*		

Note: A Kruskal Wallis test was used to identify significant differences in the spatial variability of lake diameter among HRAs, and to identify which HRAs are different we used a pairwise Wilcox test. Lower case letters in that are not in common between different HRAs indicates a significant difference ($p < 0.05$).

Table A.3.4: Spatial variability in contraction of lake diameter among HRAs in response to high, moderate and low severity dry periods (expressed as departure from maximum lake extent prior to each dry period).

Change in Lake Diameter (relative to maximum)	Absolute Lake Diameter (m)			Relative Lake Diameter (%)		
	Coarse	Fine Hummocky	Fine Plains	Coarse	Fine Hummocky	Fine Plains
	High Severity					
Median	-39.11[a]	-48.75[a]	-115.59[b]	3.28[a]	26.79[b]	20.63[ab]
SD	25.53	41.42	244.15	12.31	31.08	15.62
Maximum	-83.43	-132.86	-782.90	0.88	5.84	2.56
Minimum	-7.87	-6.21	-13.90	32.18	100.00	53.70
p-value		*0.01**			*0.03**	
	Moderate Severity					
Median	-22.42	-31.81	-32.32	1.64[a]	24.28[bc]	5.94[ac]
SD	29.76	36.15	73.39	12.71	26.91	7.50
Maximum	-97.02	-115.80	-279.33	0.75	2.73	1.80
Minimum	-8.35	-6.21	-13.97	35.55	87.56	28.96
p-value		*0.46*			*0.01**	
	Low Severity					
Median	-5.28	-1.59	-0.76	0.88	16.06	1.16
SD	9.27	53.01	12.60	1.02	31.12	2.21
Maximum	-24.04	-191.49	-38.25	0.00	0.00	0.00
Minimum	0.00	0.00	0.00	2.99	100.00	6.37
p-value		*0.66*			*0.57*	

Note: A Kruskal Wallis test was used to identify significant differences in the spatial variability of lake diameter contraction responses to different dry periods among HRAs, and to identify which HRAs are different we used a pairwise Wilcox test. Lower case letters in that are not in common between different HRAs indicates a significant difference ($p < 0.05$).

Table A.3.5: Synchrony analyses results for time series of open water lake extent for each lake group identified in the multivariate regression tree A Group 1, B Group 2, C Group 3, D Group 4, E Group 5, and F All Lakes. Each value represents the Pearson *r* coefficient between a lake pair. Average synchronicity of each group is provided in the bottom right of each table.

A - Synchrony analysis for Group 1 lakes		
	19	**48**
19		0.69
48		
	Average	0.69

B Synchrony analysis for Group 2 lakes							
	7	**17**	**42**	**43**	**111**	**112**	**206**
7		0.34	0.25	0.24	0.57	0.36	0.34
17			-0.08	-0.05	0.29	-0.30	-0.29
42				-0.17	0.29	0.36	0.38
43					0.21	0.06	0.03
111						0.08	-0.07
112							0.51
206							
						Average	0.16

C Synchrony analysis for Group 3 lakes								
	1	**2**	**27**	**39**	**59**	**122**	**162**	**169**
1		0.52	0.34	0.33	0.34	0.69	0.49	0.78
2			0.64	0.50	0.11	0.70	0.45	0.66
27				0.22	-0.27	0.55	0.14	0.40
39					0.05	0.43	0.45	0.52
59						0.18	0.30	0.27
122							0.50	0.79
162								0.81
169								
							Average	0.42

D Synchrony analysis for Group 4 lakes												
	11	**40**	**121**	**160**	**168**	**171**	**205**	**208**	**300**	**301**	**302**	**303**
11		0.68	0.40	0.32	0.45	0.34	0.48	0.34	0.30	0.06	-0.11	0.24
40			0.56	0.55	0.75	0.25	0.55	0.41	0.53	0.19	0.02	0.46
121				0.08	0.57	0.08	0.42	0.51	0.48	0.22	0.25	0.12
160					0.19	0.62	0.74	0.38	0.59	0.59	-0.18	0.88
168						0.01	0.34	0.41	0.41	0.08	0.12	0.21
171							0.60	0.11	0.53	0.44	-0.27	0.71
205								0.53	0.76	0.65	-0.20	0.81
208									0.56	0.60	-0.15	0.31
300										0.86	0.09	0.77
301											-0.04	0.76
302												-0.19
303												
											Average	0.37

E Synchrony analysis for Group 5 lakes				
	5	**16**	**118**	**201**
5		0.24	0.23	0.19
16			0.54	0.66
118				0.79
201				
		Average		0.44

F Synchrony analysis for All lakes

	1	2	5	7	11	16	17	19	27	39	40	42	43	48	59	111	112	118	121	122	160	162	168	169	171	201	205	206	208	300	301	302	303
1		0.52	0.30	0.43	0.65	0.45	-0.26	0.23	0.34	0.33	0.56	0.28	0.12	-0.20	0.34	0.12	0.46	0.36	0.54	0.69	0.57	0.49	0.35	0.78	0.46	0.43	0.61	0.39	0.61	0.68	0.62	0.09	0.57
2			0.31	0.02	0.42	0.13	-0.34	-0.02	0.64	0.50	0.51	-0.14	0.17	-0.15	0.11	0.08	0.19	0.53	0.35	0.70	0.61	0.45	0.31	0.66	0.28	0.52	0.73	0.28	0.59	0.71	0.63	-0.08	0.59
5				0.48	0.48	0.24	0.00	0.29	0.13	0.09	0.39	0.09	0.22	0.23	0.11	0.12	0.29	0.23	0.51	0.13	-0.06	-0.02	0.38	0.28	-0.23	0.19	0.19	0.60	0.27	0.11	-0.05	0.23	-0.11
7					0.24	0.41	0.34	0.63	-0.35	0.08	0.22	0.25	0.24	0.50	0.28	0.57	0.36	0.11	0.58	0.06	-0.09	0.16	0.46	0.32	-0.08	0.10	0.03	0.34	0.22	0.22	0.07	0.55	-0.09
11						0.35	-0.28	-0.11	0.53	0.11	0.68	0.28	0.14	-0.27	-0.04	-0.11	0.39	0.20	0.40	0.46	0.32	-0.08	0.45	0.36	0.34	0.24	0.48	0.71	0.34	0.30	0.06	-0.11	0.24
16							-0.19	0.21	0.03	0.19	0.36	0.29	0.00	-0.19	-0.03	0.17	0.58	0.54	0.52	0.22	0.03	0.47	0.39	0.49	-0.01	0.66	0.10	0.52	0.62	0.33	0.26	0.20	-0.04
17								0.56	-0.66	-0.27	-0.44	-0.08	-0.05	0.68	0.52	0.29	-0.30	-0.52	-0.07	-0.49	-0.38	-0.23	-0.25	-0.31	-0.29	-0.35	-0.40	-0.29	-0.37	-0.41	-0.43	0.54	-0.50
19									-0.43	-0.14	-0.10	-0.04	0.45	0.69	0.47	0.39	-0.05	-0.19	0.47	0.10	0.00	0.19	-0.03	0.31	0.08	-0.06	0.11	-0.02	0.08	0.14	0.12	0.49	-0.05
27										0.22	0.56	-0.02	0.03	-0.59	-0.27	-0.47	0.29	0.55	0.11	0.55	0.54	0.14	0.38	0.40	0.25	0.42	0.63	0.48	0.48	0.34	0.28	-0.51	0.46
39											0.32	0.43	-0.15	-0.24	0.05	0.31	0.40	0.56	0.25	0.43	0.13	0.45	0.41	0.52	0.13	0.50	0.41	0.21	0.52	0.68	0.55	0.07	0.33
40												0.28	-0.05	-0.37	-0.07	0.10	0.36	0.48	0.56	0.49	0.55	0.05	0.75	0.42	0.25	0.25	0.55	0.77	0.41	0.53	0.19	0.02	0.46
42													-0.17	-0.25	-0.03	0.29	0.36	0.16	0.40	0.09	-0.24	-0.12	0.44	0.09	0.05	0.02	0.04	0.38	0.21	0.21	-0.03	0.07	-0.09
43														0.43	0.01	0.21	0.06	-0.11	0.34	0.35	-0.03	-0.11	-0.02	0.15	0.30	-0.12	0.30	0.03	-0.05	0.28	0.20	-0.08	0.15
48															0.43	0.42	-0.25	-0.40	0.03	-0.20	-0.23	-0.10	-0.19	-0.10	-0.10	-0.32	-0.15	-0.27	-0.26	-0.14	-0.13	0.37	-0.23
59																0.26	-0.16	-0.05	0.03	0.18	0.21	0.30	-0.13	0.27	0.09	0.03	0.15	-0.20	0.06	0.21	0.27	0.27	0.17
111																	0.08	0.01	0.31	0.08	-0.08	0.05	0.25	0.04	0.04	-0.09	-0.05	-0.07	-0.07	0.44	0.23	0.64	0.05
112																		0.60	0.43	0.19	0.01	0.32	0.52	0.46	-0.10	0.62	0.18	0.51	0.69	0.34	0.25	0.04	0.03
118																			0.35	0.44	0.28	0.60	0.64	0.63	-0.09	0.79	0.39	0.52	0.79	0.54	0.53	-0.14	0.30
121																				0.39	0.08	0.15	0.57	0.53	0.08	0.28	0.42	0.60	0.51	0.48	0.22	0.25	0.12
122																					0.72	0.50	0.29	0.79	0.65	0.43	0.93	0.20	0.54	0.85	0.81	-0.16	0.85
160																						0.44	0.19	0.57	0.62	0.27	0.74	0.09	0.38	0.59	0.59	-0.18	0.88
162																							0.01	0.81	0.13	0.77	0.38	-0.07	0.75	0.54	0.81	0.01	0.42
168																								0.33	0.01	0.29	0.34	0.81	0.41	0.41	0.08	0.12	0.21
169																									0.33	0.71	0.75	0.32	0.86	0.75	0.81	-0.03	0.59
171																										-0.01	0.60	-0.02	0.11	0.53	0.44	-0.27	0.71
201																											0.39	0.33	0.87	0.47	0.54	-0.06	0.19
205																												0.28	0.53	0.76	0.65	-0.20	0.81
206																													0.45	0.19	-0.12	-0.08	-0.02
208																														0.56	0.60	-0.15	0.31
300																															0.86	0.09	0.77
301																																-0.04	0.76
302																																	-0.19
303																																	
																																Average	0.24