Multi-year isoscapes of lake water balances across a dynamic northern freshwater delta

Casey R. Remmer[1], Laura K. Neary[1], Mitchell L. Kay[1], Brent B. Wolfe[2], Roland I. Hall[1]

[1]Department of Biology, University of Waterloo,
Waterloo, Ontario, N2L 3G1, Canada

[2]Department of Geography and Environmental Studies, Wilfrid Laurier University,
Waterloo, Ontario, N2L 3C5, Canada

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Corresponding author:
Casey Remmer
Department of Biology
University of Waterloo
200 University Avenue West
Waterloo ON N2L 3G1 Canada
crremmer@uwaterloo.ca
https://orcid.org/0000-0003-2626-3012

Key Points

- Tracking status and trends in water balance of remote lake-rich landscapes is challenging but needed to inform stewardship decisions.
- Isotope-derived E/I ratios during 2015-2019 distinguish roles of evaporation and flooding on lakes in the Peace vs Athabasca deltas.
- The study approach and design provide a foundation for ongoing isotope-based hydrological monitoring required by Parks Canada.

Abstract

Sustainable approaches are needed to track status and trends of lake water balances in complex, remote freshwater landscapes. Here we use water isotope composition measured at ~60 lakes and 9 river sites three times during the 2015-2019 ice-free seasons at the internationally recognized Peace-Athabasca Delta (Canada) to characterize temporal and spatial patterns in lake water balances and influential hydrological processes. Calculation of evaporation-to-inflow ratios using a coupled-isotope tracer approach, employment of generalized additive models and geospatial 'isoscapes' identified areas vulnerable to mid-summer evaporative lake-level drawdown and areas more resilient due to replenishment by river floodwaters during spring ice-jams and the open-water season. The former largely defines the northern, relic Peace sector whereas the latter typifies the more active floodplain environment of the southern Athabasca sector. Ability to capture the marked temporal and spatial heterogeneity in lake water balances serves as a foundation for ongoing isotope-based hydrological monitoring.

Plain Language Summary

The Peace-Athabasca Delta in northern Alberta, Canada, is a globally recognized floodplain landscape that provides important freshwater resources and habitat to people and wildlife. Concerns about water level drawdown have recently prompted need for a lake monitoring program. Due to its remote location and dynamic nature, however, it is difficult to monitor lake water balances and what causes them to change. Here we use measurements of lake water isotope composition at ~60 lakes and 9 river sites three times during the spring, summer and fall of 2015-2019 to reveal patterns in lake water balance over time and space, and the roles of evaporation and river flooding. We identified areas where lakes are more vulnerable to water

loss due to summer evaporation and areas that are more resilient due to receiving river floodwater. We propose that our approach can form the foundation of ongoing hydrological monitoring.

1.0 Introduction

Shallow lakes and wetlands are abundant in northern landscapes where they provide invaluable habitat for migratory waterfowl and other wildlife, and serve as a global store of freshwater. Increasingly, cumulative effects of climate change and other stressors are threatening the integrity and existence of these water bodies. Unprecedented declines in lake area and abundance during recent decades have been observed in Siberia (Smith et al., 2005), the Canadian Arctic (Bouchard et al., 2013; Carroll et al., 2011; Smol & Douglas, 2007) and Alaska (Riordan et al., 2006). Even small shifts in meteorological conditions and hydrological processes can result in cascading ecological changes, with dire consequences for ecosystems, wildlife and traditional resource users (e.g., Chavez-Ramirez & Wehtje, 2011; Huot et al., 2019; Prowse et al., 2006; Schindler & Donahue, 2006; Schindler & Smol, 2006; Smol et al., 2005). Thus, monitoring of hydrological processes and their influence on freshwater availability in northern landscapes is needed as a measure of ecosystem integrity and services.

At the Peace-Athabasca Delta (PAD), located in northern Alberta, Canada, declining lake levels are a focal concern that has persisted for decades (e.g., MCFN, 2014; PADPG, 1973) and has been variably attributed to the effects of river regulation, climate change and natural deltaic processes (e.g., Beltaos, 2014; Kay et al., 2019; Prowse and Conly, 2002; Wolfe et al., 2012). Regardless of cause, reduction in freshwater abundance has had consequences for wildlife (Straka et al., 2018; Ward et al., 2018, 2019) and access to traditional territories (MCFN, 2014; Vaninni & Vaninni, 2019). The PAD is a large (6000 km^2) lake-rich landscape recognized as a Ramsar Wetland of International Importance and contributed to the listing of Wood Buffalo National Park (WBNP) as a UNESCO World Heritage Site. Given the importance of water in this landscape, improved monitoring of hydrological processes and their influence on lakes is essential to inform ecosystem stewardship decisions and is recognized as a priority recommendation and action by federal and international agencies (WBNP, 2019; WHC/IUCN, 2017). However, the complexity of the PAD and its numerous lakes, which are variably influenced by river floodwater, snowmelt, rainfall and evaporation over a range of temporal and spatial scales (Prowse & Conly, 2002; Wolfe et al., 2007), present significant challenges to design effective hydrological monitoring approaches.

Prior water isotope tracer studies in the PAD have demonstrated their value for capturing snapshots of water balance for a season or year (Remmer et al., 2018; Wiklund et al., 2012; Wolfe et al., 2007, 2008b) and the extent and magnitude of ice-jam floods (Remmer et al., 2020). Here we use water isotope compositions measured at ~60 lakes and 9 river sites during spring, summer and fall of a 5-year period (2015-2019) to assess the influence of meteorological conditions and hydrological processes on spatial variation of lake water balances over seasonal, inter-annual and multi-annual time scales. Integration of an isotope-mass balance model and geospatial analysis allowed development of 'isoscapes' (*sensu* Bowen & Revenaugh, 2003) for effective visualization of areas where lakes are most influenced by evaporative water loss and river flooding, two prominent hydrological processes that drive delta lake water balances.

2.0 Methods

2.1 Study Area

Lakes of the PAD are situated mainly within two distinct sectors, which are known to be broadly differentiated by the relative roles of hydrological processes that influence lake water balances (Figure 1; Wolfe et al., 2007). The northern Peace sector, a relic delta, is fed by the Peace River during episodic high-water events that cause flow reversals in distributaries.

Consequently, lakes in this sector are strongly influenced by evaporation, except during infrequent ice-jam flood events on the Peace River that cause widespread flooding. The southern Athabasca sector, fed by the Athabasca River, contains more active deltaic environments. Here, lakes span a broad gradient of influence from river floodwaters during both the spring (due to ice-jams) and summer open-water season, while lakes in more elevated areas are dominated by evaporation. Three large lakes (Claire, Mamawi, Richardson) occupy central and southern locations of the PAD and continuously receive river through-flow.

2.2 Sampling for Water Isotope Composition

Surface water samples were collected from 57-60 lakes and 9 river sites spanning the two main sectors of the PAD three times during the ice-free seasons of five consecutive years, 2015-2019 (Figure 1; see S1 of the Supporting Information). To capture and compare the effects of hydrological processes (i.e., snowmelt, spring ice-jam flooding, open-water flooding, evaporation and rainfall), samples were consistently collected during two to three-week intervals in the spring (May), summer (July) and fall (September) of each year. An exception occurred in 2016 when the Fort McMurray (Alberta) regional wildfire delayed our spring sample collection by three weeks (June). Samples were collected mid-lake (or mid-channel) from a depth of ~10 cm and stored in sealed 30 ml high-density polyethylene bottles. Lake water isotope compositions were measured by Off-Axis Integrated Cavity Output Spectroscopy (O-AICOS) at the University of Waterloo – Environmental Isotope Laboratory (UW-EIL). Isotope compositions are expressed as δ-values, representing deviations in per mil (‰) from Vienna Standard Mean Ocean Water (VSMOW) such that $\delta\text{-sample} = [(R_{sample}/R_{VSMOW}) - 1] \times 10^3$, where R is the $^{18}O/^{16}O$ or $^{2}H/^{1}H$ ratio in the sample and VSMOW. Results of $\delta^{18}O$ and $\delta^{2}H$

analyses are normalized to -55.5‰ and -428‰, respectively, for Standard Light Antarctic Precipitation (Coplen, 1996). Analytical uncertainties are ±0.2‰ for $\delta^{18}O$ and ±0.8‰ for $\delta^{2}H$. In-situ measurements of specific conductivity were obtained using a YSI ProDSS sonde. Field observations were recorded at the time of sampling for each lake.

2.3 Water Balance Derivation and Analysis

Evaporation-to-inflow ratios (E/I), an informative water-balance metric, were calculated from the lake water isotope compositions using a coupled-isotope tracer method (Yi et al., 2008) and an isotopic framework representing average meteorological conditions during 2015-2019 (see S2 of the Supporting Information). This approach to isotope-mass balance modelling systematically accounts for varying input water isotope compositions in the calculation of E/I ratios, which are evident in the scatter of lake water isotope compositions about the predicted Local Evaporation Line (LEL; see S3 of Supporting Information). Consistent with other studies (MacDonald et al., 2017; Remmer et al., 2018), we set E/I ratios to 1.5 for lakes experiencing very strong non-steady-state conditions. Time series of E/I ratios were visualized as generalized additive models (GAMs) for each sector and year using RStudio v1.2.5001 (Rstudio Team, 2019), and the ggplot2 v.3.2.1 (Wickham, 2016) and mgcv v.1.8.28 (Wood, 2017) packages. Spatial interpolations of E/I ratios were presented as isoscapes for all 15 sampling campaigns by ordinary kriging using ArcMap 10.7.1 software because Moran's I was significant ($p < 0.05$, see S4 of Supporting Information). Lakes that received river floodwaters during the spring, which we assume to be the result of ice-jams as directly observed in 2018 (Remmer et al., 2020), and the open-water season were identified using lake water isotope compositions, specific conductivity and field observations following the approach of Remmer et al. (2020) (See S3 of

Supporting Information). The extent of river floodwaters was delineated on the isoscapes by inverse distance weighting using ArcMap 10.7.1 software.

3.0 Results

3.1 Meteorological Conditions (2015-2019)

Air temperature did not vary substantially among years and did not differ measurably from the 1981-2010 climate normal, while precipitation records show notable variation with respect to the 1981-2010 climate normal (Figure 2). Snowfall (precipitation during November to March) was below normal during all five years. Rainfall (precipitation during May to September) was below normal in the spring (April, May) and early to mid-summer (June, July) of each year, except for July 2015 and June 2018. Late summer and early fall (August, September) rainfall was below normal in 2015 and 2018, and above normal in 2016 and 2019.

3.2 Trends in Lake Evaporation-to-Inflow Ratios (2015-2019)

E/I ratios for the lakes vary substantially across the sampling periods and sectors, ranging from near zero to beyond terminal basin isotopic steady-state (i.e., E/I > 1; Figure 3). GAM-defined trendlines in E/I ratios display patterns reflecting broad similarities and differences in hydrological processes influencing lakes in the Peace and Athabasca sectors of the delta. During each sampling year, trendlines indicate higher E/I ratios (i.e., more intense evaporation) in lakes of the Peace sector than the Athabasca sector, consistent with the relic deltaic environment of the former. For three of the five years (2015, 2016, 2019), Peace and Athabasca E/I trendline patterns are similar, but offset, rising from spring to summer then declining in the fall. The increase in E/I ratios from spring to summer is generally steeper in the Peace sector than the

Athabasca sector and can be attributed to strong influence of evaporation and absence of open-water flooding in the Peace sector. Parallel declines in the trendline from the summer to fall during 2016 and 2019 in both sectors are due to rainfall, with additional contributions from open-water flooding in the Athabasca sector in 2019 (also see below and Figure 4).

Distinct differences in seasonal trendline patterns for lakes in the Peace and Athabasca sectors occur during 2017 and 2018. In 2017, the E/I trendline rises rapidly in the Peace sector during the open-water season to values >1 and remains high in the fall. In the Athabasca sector, the trendline rises less rapidly between spring and summer and continues to rise steadily in the fall. In 2018, E/I trendlines are also not parallel. E/I ratios rise in lakes of the Peace sector for the entire open-water season, whereas the trendline for the Athabasca sector lakes shows a small rise and then a decline from summer to fall. Differences in the spring-to-summer E/I trendlines during these two years is due to spring ice-jam flooding in the Athabasca sector, which was extensive in 2018 (Remmer et al., 2020). High E/I ratios in the Athabasca sector during summer and fall of 2017 reflect the evaporative response of lakes during a year without open-water flooding (also see below and Figure 4). This is in contrast to 2018, when E/I ratios decline in lakes of the Athabasca sector during the fall due to open-water flooding (also see below and Figure 4).

3.3 Isoscapes of Lake Evaporation-to-Inflow Ratios

Additional insight into spatial variation and influence of key hydrological processes on lake water balance, including evaporation and river flooding, can be gleaned from E/I isoscapes for the 15 sampling intervals (Figure 4). Regions where E/I ratios exceed 1 are noteworthy as they indicate where evaporation is greater than inflow, resulting in lake-level drawdown. These regions tend to include the central and northwestern Peace sector and the southwestern Athabasca sector (summer 2015, spring and summer 2016, summer and fall 2017, summer 2019). High E/I ratios in the northwestern portion of the Peace sector in 2016 are consistent with wildfires near this area prior to and during the sampling period. High E/I ratios across much of the Peace sector and the southwestern Athabasca sector during summer and fall 2017 align with field observations of lake desiccation.

Also delineated on Figure 4 is floodwater extent, an important source of water to lakes which offsets water loss by evaporation and produces low E/I ratios. Based on consideration of lake water isotope composition and specific conductivity in relation to river isotope composition and specific conductivity, as well as field observations, we identified flooding during 8 of 15 sampling campaigns. This includes ice-jam flooding during spring of 2017-2019, open-water flooding during summer of 2017-2019, which remained detectable during fall of the latter two years. Ice-jam flooding in 2017 and 2019 was limited to lakes in the central Athabasca sector and along the Athabasca River. In contrast, ice-jam flooding in 2018 was widespread and encompassed most of the Athabasca sector and a few lakes in the central Peace sector (Figure 4; Remmer et al., 2020). Open-water flooding also varied in extent, but was generally restricted to the central Athabasca sector and some lakes farther east along the Athabasca River.

4.0 Discussion and Conclusions

Analysis of >1000 samples for water isotope composition collected during 15 field sampling campaigns from 2015-2019 in the Peace-Athabasca Delta (PAD) provide exceptional insight into hydrological processes influencing lake water balances across this dynamic floodplain landscape. Quantification of evaporation-to-inflow (E/I) ratios, summarized using generalized additive models (GAMs) and depicted as isoscapes, provides a useful approach to delineate patterns of lake water balance over time and space and their underlying causes. Our study captured two years with no river flooding (2015, 2016), three years with river flooding (2017-2019), and striking E/I responses to absence and occurrence of this key hydrological process and to variation in meteorological conditions.

Results show that evaporative water loss is greatest in the summer and persists in the central and northwestern Peace and southwestern Athabasca portions of the PAD, consistent with recent observations and concerns (IEC, 2018; MCFN, 2014). This highlights the vulnerability of lakes in the relic Peace sector and an elevated portion of the Athabasca sector to lake-level drawdown and desiccation, especially with anticipated further declines in the frequency of ice-jam flooding, longer ice-free seasons leading to increased evaporation and reduced snowmelt runoff (Schindler & Smol, 2006; Wolfe et al., 2008a). Indeed, all five years of our study were characterized by below normal snowfall, perhaps signifying a shift to reduction in supply of this source of water to lakes in the PAD. However, influence of rainfall lowered E/I ratios during the fall of some years (2016, 2019). Results align with a long-term trend of increasing evaporative influence on lakes in the Peace sector and greater resilience of lakes to the effects of evaporation in much of the Athabasca sector (Remmer et al., 2018; Wolfe et al., 2008a, 2020).

Clearly, the main source of lake water replenishment is river floodwaters, as revealed by low E/I ratios in lakes within the areas delineated in Figure 4. Analysis of water isotope compositions and specific conductivity, supplemented by field observations, identified a major ice-jam flood event (spring 2018), as well as more localized spring ice-jam flooding (2017, 2019) and open-water flooding (2017-2019). Both ice-jam and open-water flooding occurred almost exclusively in the Athabasca sector and preferentially along the Athabasca-Embarras-Mamawi corridor owing to the Embarras Breakthrough, a natural river avulsion that occurred in 1982 and has had profound influence on hydrological trajectories of lakes across the Athabasca sector (Kay et al., 2019). While spring ice-jam flooding has long been known to be an important hydrological process for replenishing high-elevation (perched) lakes (Prowse & Lalonde, 1996), open-water flooding in the Athabasca sector evidently is also a major contributor to maintaining lake water balances in this part of the PAD, despite not being widely recognized (IEC, 2018). Results further substantiate that the two sectors of the delta largely function as distinctly different landscapes. The elevation of the Peace River is lower than the delta, thus it bypasses the Peace sector except during episodic ice-jam flood events. In contrast, the Athabasca River flows directly into and through the Athabasca sector, branching into several distributaries which supply water to low-lying lakes during both the spring (ice-jam) and open-water seasons.

An important feature of our extensive data set is the marked seasonal, interannual and spatial variability in E/I ratios and hydrological processes that influence lake water balances. Northern freshwater landscapes are both uniquely vulnerable to climate change and other stressors, and due to logistical and funding constraints are often lacking in comprehensive monitoring required to track and anticipate hydrological change (Canadian Polar Commission, 2014; Mallory et al., 2018; Prowse et al., 2006). Effectiveness of water isotope tracers permitted assessment of lake water balances at temporal and spatial scales essential for capturing the exceptional hydrological heterogeneity of lakes in the PAD. We envision that our five-year isotope-based hydrological study provides the foundation of a comprehensive aquatic ecosystem monitoring program for lakes of the PAD, serves as a pivotal contribution to execution of the federal government's Action Plan (WBNP, 2019), and demonstrates the value of the approach for other dynamic, difficult-to-access lake-rich landscapes.

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References

Beltaos, S. (2014). Comparing the impacts of regulation and climate on ice-jam flooding of the Peace-Athabasca Delta. *Cold Regions Science and Technology*, *108*, 49–58. https://doi.org/10.1016/j.coldregions.2014.08.006

Bouchard, F., Turner, K. W., MacDonald, L. A., Deakin, C., White, H., Farquharson, N., et al. (2013). Vulnerability of shallow subarctic lakes to evaporate and desiccate when snowmelt runoff is low. *Geophysical Resource Letters*, *40*, 6112–6117. https://doi.org/10.1002/2013GL058635

Bowen, G. J., & Revenaugh, J. (2003). Interpolating the isotopic composition of modern meteoric precipitation. *Water Resources Research, 39*, 1299. https://doi.org/10.1029/2003WR002086

Bowen, G. J. (2016). The Online Isotopes in Precipitation Calculator, version 2.2. Accessible at http://www.waterisotopes.org

Carroll, M. L., Townshend, J. R. G., DiMiceli, C. M., Loboda, T., & Sohlberg, R. A. (2011). Shrinking lakes of the Arctic: Spatial relationships and trajectory of change. *Geophysical Resource Letters*, *38*, L20406. https://doi.org/10.1029/2011GL049427

Chavez-Ramirez, F., & Wehtje, W. (2011). Potential impact of climate change scenarios on Whooping Crane life history. *Wetlands*, *32*, 11–20. https://doi.org/10.1007/s13157-011-0250-z

Coplen, T. B. (1996). New guidelines for reporting stable hydrogen, carbon, and oxygen isotope-ratio data. *Geochimica et Cosmochimica Acta, 60*, 3359–3360. https://doi.org/10.1016/0016-7037(96)00263-3

Craig, H., & Gordon, L. I. (1965). Deuterium and oxygen 18 variations in the ocean and the marine atmosphere, p. 9–130. In E. Tongiorgi [Ed.], *Stable Isotopes in Oceanographic Studies and Paleotemperatures*. Laboratorio di Geologia Nucleare, Pisa: Italy.

Edwards, T. W. D., Wolfe, B. B., Gibson, J. J., &. Hammarlund, D. (2004). Use of water isotope tracers in high latitude hydrology and paleolimnology, p. 187–207. In R. Pienitz, M. S. V. Douglas, and J. P. Smol [Eds.], *Long-Term Environmental Change in Arctic and Antarctic Lakes*. Dordrecht, Netherlands: Springer.

Gibson J. J., & Edwards, T. W. D. (2002). Regional water balance trends and evaporation-transpiration partitioning from a stable isotope survey of lakes in northern Canada. *Global Biogeochemical Cycles*, *16*, 1–9. https://doi.org/10.1029/2001GB001839

Gibson J. J., Edwards, T. W. D., & Prowse, T. D. (1999). Pan-derived isotopic composition of atmospheric water vapour and its variability in northern Canada. *Journal of Hydrology*, *217*, 55–74. https://doi.org/10.1016/S0022-1694(99)00015-3

Gonfiantini, R. (1986). Environmental isotopes in lake studies, p. 113–168. In Fritz, P., & Fontes, J. C. [Eds.], *Handbook of Environmental Isotope Geochemistry*, Volume 2. New York: Elsevier.

Horita J., & Wesolowski, D. (1994). Liquid-vapour fractionation of oxygen and hydrogen isotopes of water from the freezing to the critical temperature. *Geochimica et Cosmochimica Acta*, *58*, 3425–3497. https://doi.org/10.1016/0016-7037(94)90096-5

Huot, Y., Brown, C. A., Potvin, G., Antoniades, D., Baulch, H. M., Beisner, B. E., et al. (2019). The NSERC Canadian Lake Pulse Network: A national assessment of lake health providing science for water management in a changing climate. *Science of the Total Environment*, *695*, 133668. https://doi.org/10.1016/j.scitotenv.2019.133668

IAEA/WMO. (2015). Global Network of Isotopes in Precipitation. *The GNIP Database*. Accessible at: https://nucleus.iaea.org/wiser.

Independent Environment Consultants (IEC). (2018). Strategic environmental assessment of Wood Buffalo National Park World Heritage Site. Volume 1, Milestone 3 – Final SEA Report. Independent Environment Consultants (IEC), Markham, Ontario.

Kay, M. L., Wiklund, J. A., Remmer, C. R., Neary, L. K., Brown, K., MacDonald, E., et al. (2019). Bi-directional hydrological changes in perched basins of the Athabasca Delta (Canada) in recent decades caused by natural processes. *Environmental Research Communications, 1*, 081001. https://doi.org/10.1088/2515-7620/ab37e7

MacDonald, L. A., Wolfe, B. B., Turner, K. W., Anderson, L., Arp, C. D., Birks, S. J., et al. (2017). A synthesis of thermokarst lake water balance in high-latitude regions of North America from isotope tracers. *Arctic Science*, *3*, 118-149. https://doi.org/10.1139/as-2016-0019

Mallory, M. L., Gilchrist, H. G., Janssen, M., Major, H. L., Merkel, F., Provencher, J. F., & Strøm, H. (2018). Financial costs of conducting science in the Arctic: examples from seabird research. *Arctic Science*, *4*, 624–633. https://doi.org/10.1139/as-2017-0019

MCFN. (2014). Petition to The World Heritage Committee Requesting Inclusion of Wood Buffalo National Park on the List of World Heritage in Danger. Mikisew Cree First Nation.

PADPG. (1973). Peace–Athabasca Delta Project, technical report and appendices, *Volume 1: Hydrological Investigations, Volume 2: Ecological investigations*. Peace-Athabasca Delta Project Group, Delta Implementation Committee, Governments of Alberta, Saskatchewan and Canada.

Pietroniro, A., Prowse, T. D., & Peters, D. L. (1999). Hydrologic assessment of an inland freshwater delta using multi-temporal satellite remote sensing. *Hydrological Processes*, *13*, 2483–2498. https://doi.org/10.1002/(SICI)1099-1085(199911)13:16<2483::AID-HYP934>3.0.CO;2-9

Prowse, T.D., & Lalonde, V. (1996). Open-water and ice-jam flooding of a northern delta. *Nordic Hydrology*, *27*, 85–100. https://doi.org/10.2166/nh.1996.0021

Prowse, T. D., & Conly, F. M. (2002). A review of hydroecological results of the Northern River Basins Study, Canada. Part 2. Peace–Athabasca Delta. *River Research and Applications*, *18*, 447–460. https://doi.org/10.1002/rra.682

Prowse, T. D., Beltaos, S., Gardner, J. T., Gibson, J. J., Granger, R. J., & Leconte, R. (2006). Climate change, flow regulation and land-use effects on the hydrology of the Peace-Athabasca-Slave system: findings from the Northern Rivers Ecosystem Initiative. *Environmental Monitoring and Assessment*, *113*, 167–197. https://doi.org/10.1007/s10661-005-9080-x

R Core Team (2019). R: A language and environment for statistical computing. R

Remmer C. R.**,** Owca, T., Neary, L., Wiklund, J. A., Kay, M., Wolfe, B. B., & Hall, R. I. (2020). Delineating extent and magnitude of river flooding to lakes across a northern delta using water isotope tracers. *Hydrological Processes*, *34*, 303-320. https://doi.org/10.1002/hyp.13585

Remmer, C. R., Klemt, W. H., Wolfe, B. B., & Hall, R. I. (2018). Inconsequential effects of flooding in 2014 on lakes in the Peace-Athabasca Delta. *Limnology and Oceanography*, *63*, 1502–1518. https://doi.org/10.1002/lno.10787

Riordan, B., Verbyla, D., & McGuire, A.D. (2006). Shrinking ponds in subarctic Alaska based on 1950–2002 remotely sensed images. *Journal of Geophysical Research, 111*, G04002. https://doi.org/10.1029/2005JG000150

Schindler D. W., & Smol, J. P. (2006). Cumulative effects of climate warming and other human activities on freshwaters of arctic and subarctic North America. *Ambio, 35*, 160–168. https://doi.org/10.1579/0044-7447(2006)35[160:CEOCWA]2.0.CO;2

Schindler, D. W., & Donahue, W. F. (2006). An impending water crisis in Canada's western prairie provinces. *Proceedings of the National Academy of Sciences of the United States of America, 103*, 7210–7216. https://doi.org/10.1073/pnas.0601568103

Smith, L. C., Sheng, Y., MacDonald, G. M., & Hinzman, L. D. (2005). Disappearing Arctic lakes. *Science, 308*, 1429. https://doi.org/10.1126/science.1108142

Smol J. P., & Douglas, M. S. V. (2007). Crossing the final ecological threshold in high Arctic ponds. *Proceedings of the National Academy of Sciences of the United States of America*, *104*, 12395–12397. https://doi.org/10.1073/pnas.0702777104

Smol, J. P., Wolfe, A. P., Birks, H. J. B., Douglas, M. S. V., Jones, V. J., Korhola, A., et. al. (2005). Climate-driven regime shifts in the biological communities of Arctic lakes. *Proceedings of the National Academy of Sciences of the United States of America*, *102*, 4397–4402. https://doi.org/10.1073/pnas.0500245102

Straka, J., Antoine, A., Bruno, R., Campbell, D., Campbell, R., Campbell, R., et al. (2018). "We Used to Say Rats Fell from the Sky After a Flood:" Temporary Recovery of Muskrat Following Ice Jams in the Peace-Athabasca Delta. *Arctic, 71,* 218–228. https://doi.org/10.14430/arctic4714

Thornthwaite, C.W. (1948). An approach toward a rational classification of climate. *Geographical Review*, *38*, 55–94. https://doi.org/10.2307/210739

Vannini, P., & Vannini, A. (2019). The exhaustion of Wood Buffalo National Park: Mikisew Cree First Nation experiences and perspectives. *International Review of Qualitative Research, 12*, 278–303. https://doi.org/10.1525/irqr.2019.12.3.278

Ward, E. M., & Gorelick, S. M. (2018). Drying drives decline in muskrat population in the Peace-Athabasca Delta, Canada. *Environmental Research Letters*, *13*, 124026. https://doi.org/10.1088/1748-9326/aaf0ec

Ward, E. M., Wysong, K., & Gorelick, S. M. (2020). Drying landscape and interannual herbivory-driven habitat degradation control semiaquatic mammal population dynamics. *Ecohydrology*, *13*, e2169. https://doi.org/10.1002/eco.2169

Wood Buffalo National Park (WBNP). (2019). World Heritage Site Action Plan. *Parks Canada*. https://www.pc.gc.ca/en/pn-np/nt/woodbuffalo/info/action.

WHC/IUCN. (2017). Reactive monitoring mission to Wood Buffalo National Park, Canada; mission report, March 2017. *United Nations Educational, Scientific and Cultural Organization*. Accessible at http://whc.unesco.org/en/documents/156893.

Wickham, H. (2016). ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag, New York.

Wiklund, J. A., Hall, R. I., & Wolfe, B. B. (2012). Timescales of hydrolimnological change in floodplain lakes of the Peace-Athabasca Delta, northern Alberta, Canada. *Ecohydrology, 5*, 351–367. https://doi.org/10.1002/eco.226

Wolfe, B. B., Hall, R. I., Edwards, T. W. D., Jarvis, S. R., Sinnatamby, R. N., Yi, Y., & Johnston, J. W. (2008a). Climate-driven shifts in quantity and seasonality of river discharge over the past 1000 years from the hydrographic apex of North America. *Geophysical Research Letters*, *35*, L24402. https://doi.org/10.1029/2008GL036125

Wolfe, B. B., Hall, R. I., Edwards, T. W. D., Vardy, S. R., Falcone, M. D., Sjunneskog, C., et al. (2008b). Hydroecological responses of the Athabasca Delta, Canada, to changes in river flow and climate during the 20th century. *Ecohydrology, 1*, 131–148. https://doi.org/10.1002/eco.13

Wolfe, B. B., Hall, R. I., Edwards, T. W. D., & Johnston, J. W. (2012). Developing temporal hydroecological perspectives to inform stewardship of a northern floodplain landscape subject to multiple stressors: Paleolimnological investigations of the Peace-Athabasca Delta. *Environmental Reviews, 20*, 191–210. https://doi.org/10.1139/a2012-008

Wolfe, B. B., Hall, R. I., Wiklund, J. A., and Kay, M. L. 2020. Past variation in Lower Peace River ice-jam flood frequency. *Environmental Reviews* (in press). https://doi.org/10.1139/er-2019-0047

Wolfe, B. B., Karst-Riddoch, T. L., Hall, R. I., Edwards, T. W. D., English, M. C., Palmini, R. & Vardy, S. R. (2007). Classification of hydrologic regimes of northern floodplain basins (Peace-Athabasca Delta, Canada) from analysis of stable isotopes ($\delta^{18}O$, $\delta^{2}H$) and water chemistry. *Hydrological Processes, 21*, 151–168. https://doi.org/10.1002/hyp.6229

Wood, S. N. (2017). Generalized Additive Models: An Introduction with R (2nd edition). Chapman and Hall/CRC.

Yi, Y., Brock, B. E., Falcone, M. D., Wolfe, B. B., & Edwards, T. W. D. (2008). A coupled isotope tracer method to characterize input water to lakes. *Journal of Hydrology, 350*, 1–13. https://doi.org/10.1016/j.jhydrol.2007.11.008

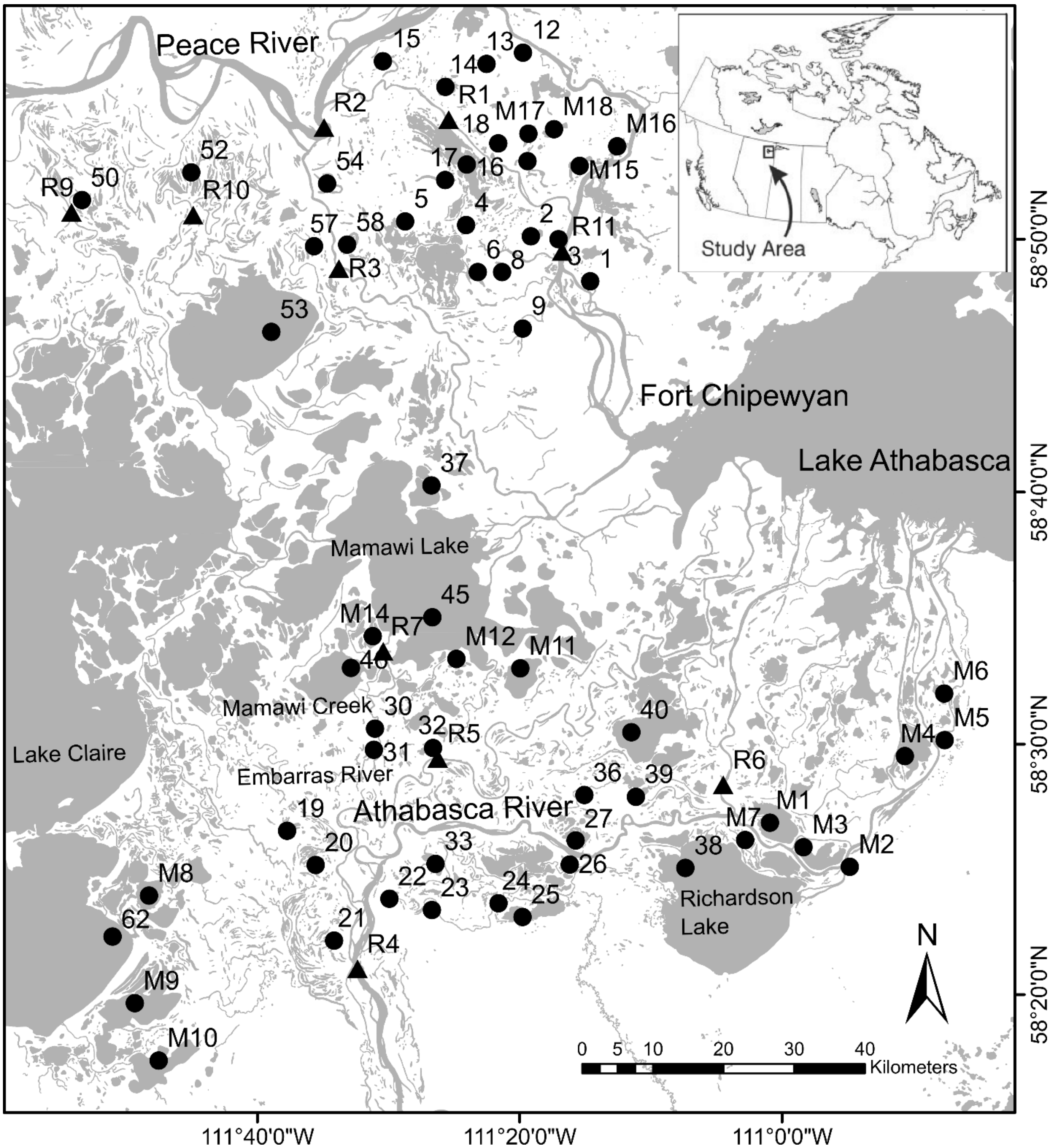
Figure Captions

Figure 1. Location of the Peace-Athabasca Delta with lake (circles) and river (triangles) sampling locations.

Figure 2. Precipitation and air temperature for Fort Chipewyan, Alberta (and Fort Smith, NWT – see 2016 precipitation) during 2015-2019 and 30-year (1981-2010) climate normals (https://climate.weather.gc.ca/climate_normals/).

Figure 3. Generalized additive models (GAMs) capturing seasonal trends (as lines) in the evaporation-to-inflow (E/I) ratios of lakes (symbols) in the Peace (yellow) and Athabasca (blue) sectors of the Peace-Athabasca Delta. Shaded areas represent the 95% confidence interval of the trendline. The data are binned by month.

Figure 4. 'Isoscapes' displaying spatial interpolation of lake evaporation-to-inflow (E/I) ratios across the Peace-Athabasca Delta during spring, summer and fall of the five-year period 2015-2019. Black dashed lines represent flood extent while white dashed lines represent areas with E/I > 1 (i.e., net evaporative drawdown).



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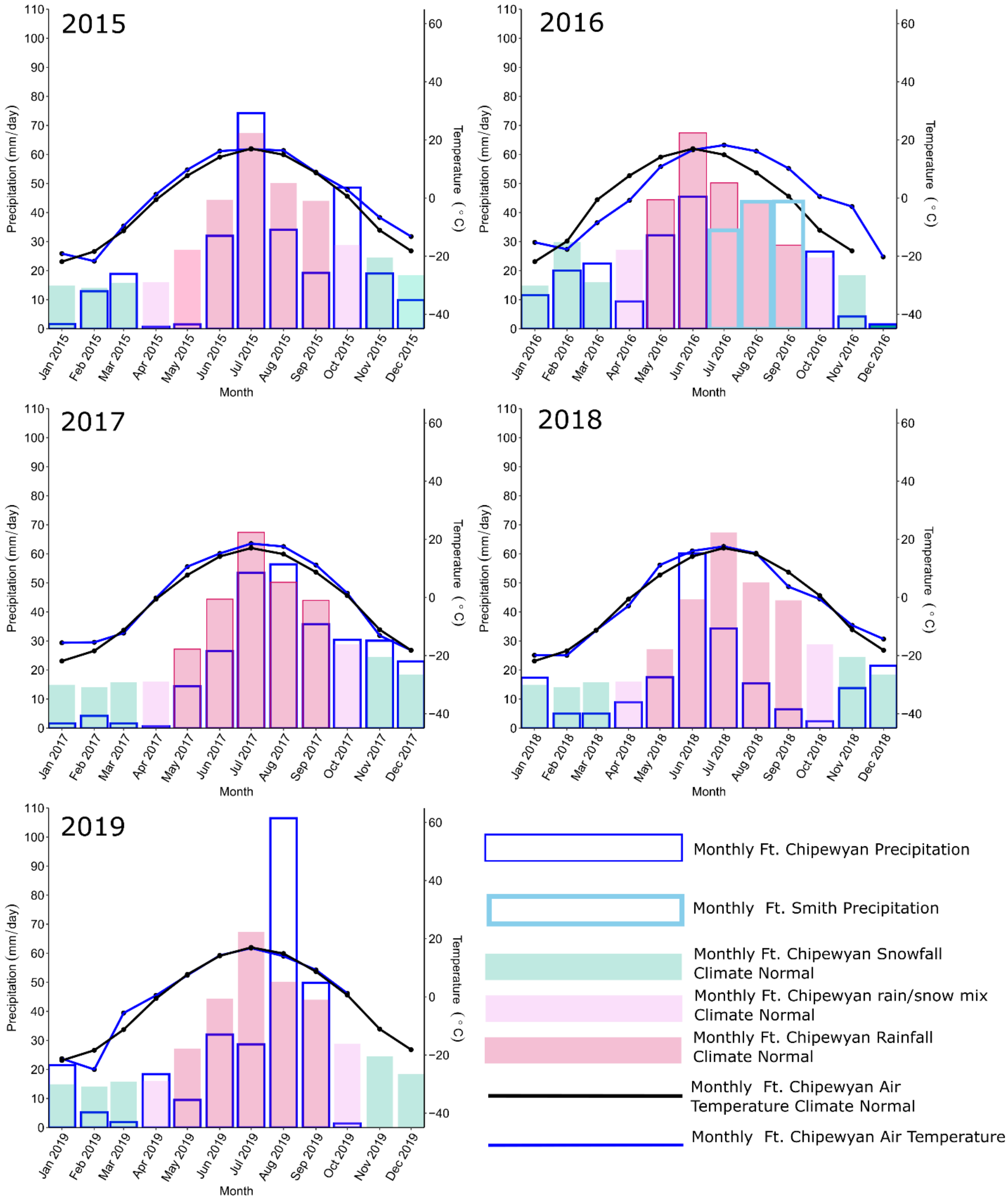

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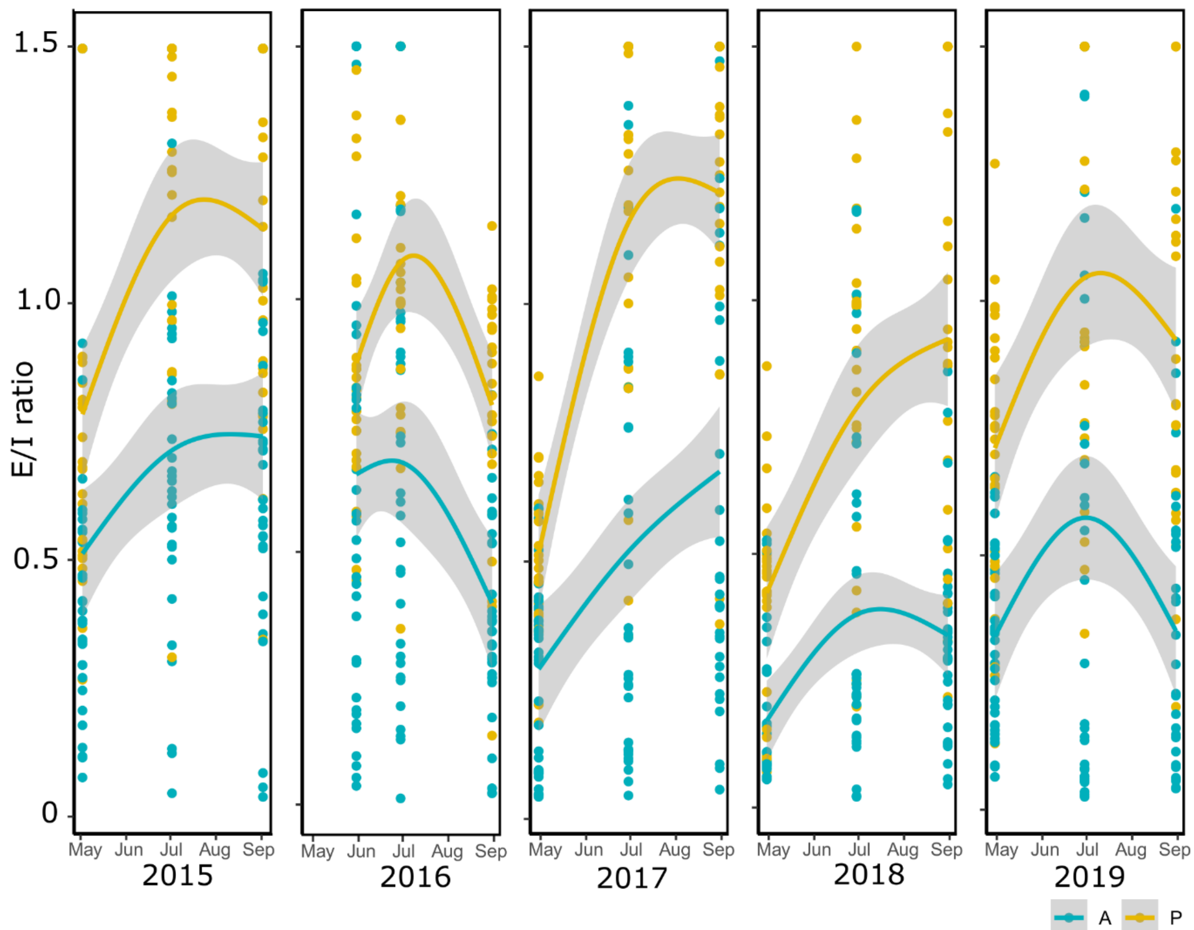

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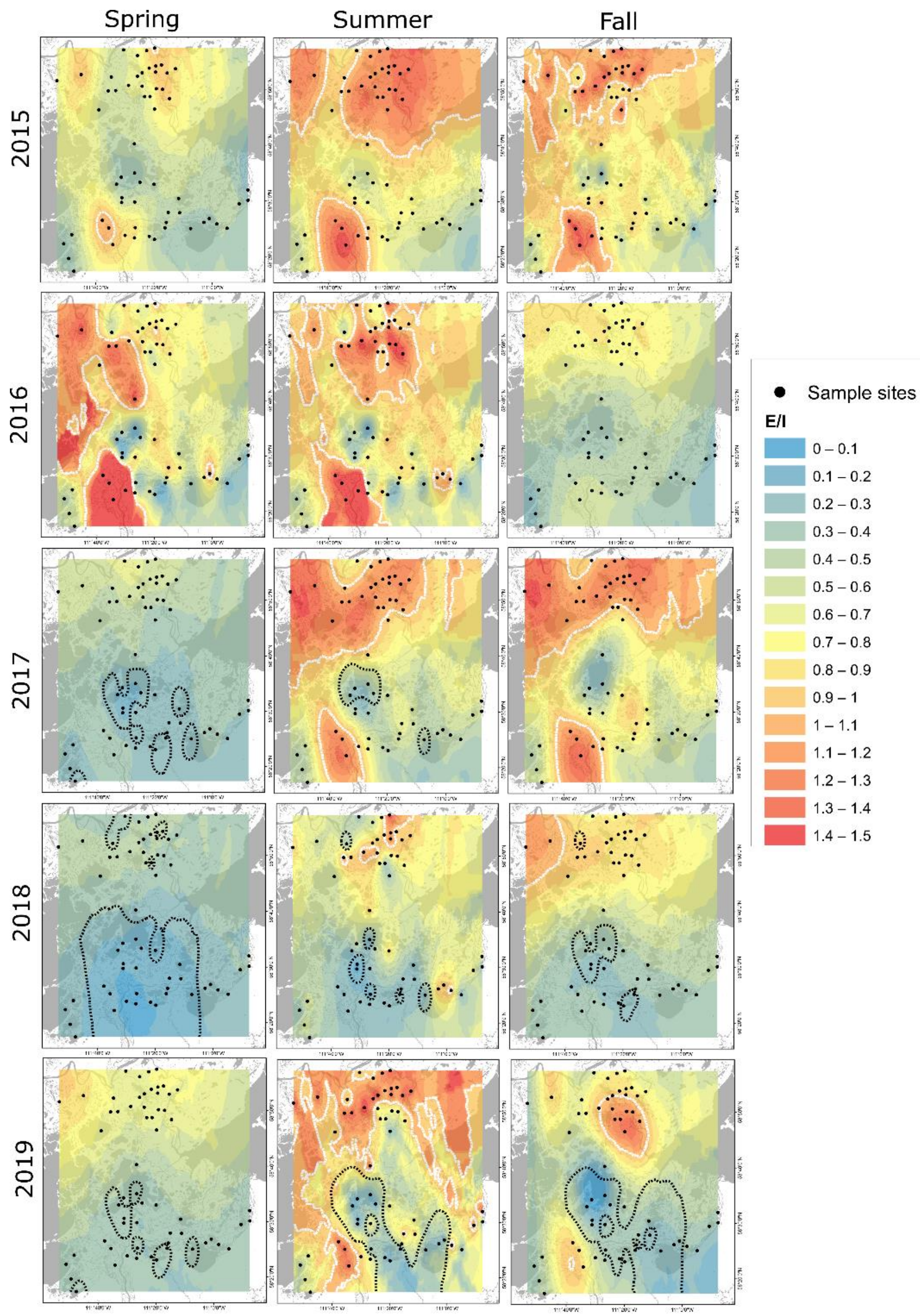

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