A comparative paleolimnological analysis of *Chydorus* exposure to ultraviolet radiation associated with shoreline retrogressive thaw slumping in lakes of the Mackenzie Delta uplands (Northwest Territories, Canada)

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Abstract

Retrogressive thaw slumps, which are a type of landslide disturbance caused by thawing of ice-rich permafrost, are increasing in size, intensity, and frequency in the Arctic because of climate warming. The formation of thaw slumps on lake shorelines in the Mackenzie Delta region (Northwest Territories, Canada) has been shown to increase water clarity, which may increase exposure risk of aquatic biota to potentially harmful ultraviolet (UV) radiation. To test this, we inferred temporal trends in UV exposure for the cladoceran *Chydorus* (Family Chydoridae, Class Branchiopoda) in a slump-affected lake and a neighbouring undisturbed lake by measuring absorbance at UV wavelengths in *Chydorus* subfossil carapaces isolated from lake sediment cores. There was no statistically significant difference in *Chydorus* carapace UV absorbance measures between the slump-affected and the undisturbed lake, despite notable differences in dissolved organic carbon and water clarity. No increase in *Chydorus* UV absorbance measures occurred in the slump-impacted lake following re-initiation of slumping in the ~1990s, but a steady increase in UV absorbance was observed in both lakes since ~1800, independent of slump formation. Overall, the results of this study suggest that retrogressive thaw slumping did not substantially increase *Chydorus* exposure to potentially harmful UV radiation. As benthic taxa, *Chydorus* are likely able to find refuge among the dense macrophyte beds that develop in slump-affected lakes, which would provide shading from UV radiation.

Introduction

Retrogressive thaw slumps are mass wasting features that form when ice-rich permafrost thaws and the ground subsides, coupled to the lateral erosion of sediments downslope. They are visible as amphitheatre-shaped depressions that are common on lake, river, and coastal margins in ice-rich permafrost regions (Burn and Kokelj 2009; Kokelj et al. 2017). They are abundant in the western Canadian Arctic (Lantz and Kokelj 2008), Alaska (Jorgenson et al. 2008), and northern Siberia (Astakhov et al. 1996; Alexanderson et al. 2002). Over the past 50 years, the frequency and intensity of retrogressive thaw slump formation on lake shorelines has increased in the uplands east of the Mackenzie Delta (Northwest Territories), in the western Canadian Arctic, primarily due to climate warming (Lantz and Kokelj 2008; Kokelj et al. 2017). These events have substantial implications for water quality and lake ecosystem functioning (Kokelj et al. 2005; Thienpont et al. 2013; Houben et al. 2016).

Slump-affected lakes in the Mackenzie Delta region typically exhibit higher conductivity, alkalinity, and pH, and lower dissolved organic carbon (DOC) and nutrient (nitrogen and phosphorus) concentrations compared to undisturbed lakes (Kokelj et al. 2009; Thompson et al. 2012; Houben et al. 2016). The erosion of inorganic sediments from slumps, deposited into lakes, binds to DOC and nutrients and scours them from the water column, increasing water clarity as the sediments are deposited to the lake bottom (Kokelj et al. 2005, 2009). Primary production is also reduced in slump-affected lakes compared to undisturbed lakes, likely due to lower nutrient availability (Houben et al. 2016). The higher water clarity may increase the exposure risk of planktonic and benthic organisms to potentially harmful ultraviolet (UV) radiation because UV radiation may penetrate deeper into the water column without sufficient DOC for attenuation (Williamson et al. 1996; Häder et al. 2007).

Arctic lakes experience seasonal fluctuations in annual solar radiation budget. Snow and ice cover persist on lakes for up to 8 months of the year and lakes receive minimal to no solar radiation input. In contrast, lakes experience 24 hours of sunlight during the short summer months. The 24 hours of daylight that Arctic lakes experience during the summer months may act as a potential stressor on planktonic communities and have an overall negative impact on lake ecosystems (Perin & Lean 2004). For example, experiments revealed that *Asplancha* spp., *Ceriodaphnia quadrangula*, and *Bosmina longirostris* are highly sensitive to UV radiation in Arctic lakes, and exposure to UV radiation may play an important role in the spatial distribution and abundance of zooplankton in Arctic lakes of different ages (Williamson et al. 2001).

The depth at which incoming UV radiation can penetrate the water column is largely dependent on the quality and quantity of chromophoric (coloured) DOC (Zagarese and Williamson 2001; Rautio and Korhola 2002). Previous studies have identified a DOC threshold concentration of 5 mg L^{-1}, below which UV radiation is likely to negatively impact aquatic biota (Williamson et al. 1996; Häder et al. 2007). UV radiation has been reported to penetrate several meters deep into the water column of some lakes with DOC concentrations < 2 mg L^{-1} (Schindler 1996). Mackenzie Delta upland lakes impacted by thaw slumps have low DOC, high water clarity, and generally have shallow lake depths (< 5 m). Consequently, the intensification of thaw slumping related to anthropogenic climate warming has the potential to increase the risk of exposure of plankton and benthos to potentially harmful UV radiation through decreases in chromophoric DOC.

Aquatic biota have several physiological and behavioral adaptations to mitigate the impacts of UV exposure. For example, several species of Cladocera (crustacean zooplankton) can increase production of melanin, a photoprotective pigment, in their exoskeletons in response to exposure to UV radiation (Rautio and Tartarotti 2010; Nevalainen et al. 2015a). Cladocerans also leave well-preserved and identifiable remains in lake sediments. Because melanin is chemically inert in cladoceran carapaces, and the degree of melanisation of the carapace is directly related to the intensity of UV exposure, changes in pigment production over time in response to UV exposure can be inferred through spectral absorbance measures (Nevalainen and Rautio 2014; Nevalainen et al. 2015a). This approach has been successfully applied to reconstruct past UV exposure of open-water *Daphnia* and the littoral cladocerans *Alona* and *Chydorus* in high latitude and alpine lakes in response to changes in lake water optics and solar forcings (Rautio and Nevalainen 2013; Nevalainen et al. 2015b; Nevalainen et al. 2018).

In this study, we reconstructed past exposure of cladocerans to UV radiation in paired lakes in the uplands east of the Mackenzie Delta by measuring spectral absorbances of *Chydorus* carapaces in lake sediment cores. One of the lakes was slump-affected and the second was a neighboring undisturbed (reference) lake. *Alona* and *Daphnia* remains were not abundant enough in the sediments to be used as independent proxies of UV exposure. The aim of this study was to determine if thaw slumping increases exposure of *Chydorus* to potentially harmful UV radiation. We hypothesized that: 1) *Chydorus* carapace absorbances will be higher in the slump-affected lake compared to the neighbouring undisturbed lake; and 2) *Chydorus* carapace absorbances will increase following the re-initiation of shoreline retrogressive thaw slumping in the slump-affected lake.

Materials and methods

Study site description

The uplands east of Mackenzie Delta and north of the town of Inuvik (Northwest Territories, Canada) are comprised of the Tuktoyaktuk Coastlands and Anderson Plain physiographic regions (Rampton 1988) and located in the northern Taiga Plains and Tundra Plains ecoregions (Ecosystems Classification Group 2012). The landscape is lake-rich, and terrain is underlain by thick (>100 m) ice-rich continuous permafrost (Burn and Kokelj 2009). The study region spans the transition from the boreal forest to the low-shrub tundra (Lantz et al. 2010), and thermokarst activity is well-documented in the area (Lantz and Kokelj 2008; Kokelj et al. 2017). Mean annual air temperatures at Inuvik are -9.2 °C, and mean annual precipitation is 240.6 mm (Environment Canada). Predicted air temperature increases in the region are among the highest in Canada (Prowse et al. 2009), and this has important implications for the stability of ice-rich permafrost in the region (Lantz and Kokelj 2008; Kokelj et al. 2017). Average annual air temperatures have increased by 3.1°C since 1926 (Lantz et al. 2019).

The Mackenzie Delta region is characterized by numerous small, shallow lakes that have been well-studied in previous investigations into the limnological effects of thaw slumping (Kokelj et al. 2009; Thompson et al. 2012; Houben et al. 2016). We selected a pair of neighbouring study lakes (Lakes 9A and 9B) west of Parsons Lake, located approximately 70 km north of Inuvik (Figure 1). These lakes have been extensively studied over more than 50 years, including repeated sampling of water chemistry, paleolimnological analyses, and remote sensing of thaw slump development (Kokelj et al. 2005; Kokelj et al. 2009; Thompson et al. 2012; Deison et al. 2012; Thienpont et al. 2013; Eickmeyer et al. 2016; Houben et al. 2016; Thienpont et al. 2020). As a result, the slump history of both of the study lakes has been reliably established. Lake 9A is a neighbouring reference lake with no history of thaw slumping (Kokelj et al. 2005; Thienpont et al. 2013; Thienpont et al. 2020). Lake 9B has a shoreline thaw slump with a polycyclic slump history, meaning Lake 9B has experienced multiple episodes of slump initiation, stabilization, and re-initiation over its history (Kokelj et al. 2005; Thienpont et al. 2013; Thienpont et al. 2020). This polycyclic slump history is reflected in geochemical sediment characteristics in gravity cores, where sediments were consistently depleted in organic carbon and enriched in metals and polycyclic aromatic hydrocarbons originating from eroded slumped materials, with no pronounced changes in sediment geochemistry in Lake 9B evident over at least the last several hundred years (Deison et al. 2012; Thienpont et al. 2020). Based on air photo evidence, Lake 9B had small, stable slumps that are older than 1950 (the earliest air photos), and experienced re-initiation of a highly active slump in the 1990's that re-stabilized by 2008 (Thienpont et al. 2013). Diatom assemblages in 9B exhibited similar changes to diatoms in 9A over the last 200 years, although the magnitude of species compositional change was slightly higher in 9B compared to 9A and changes began earlier (Thienpont et al. 2013). The slump on Lake 9B was still stable at the time of sediment coring in 2013 for this study, and at the time of water chemistry sampling in 2017.

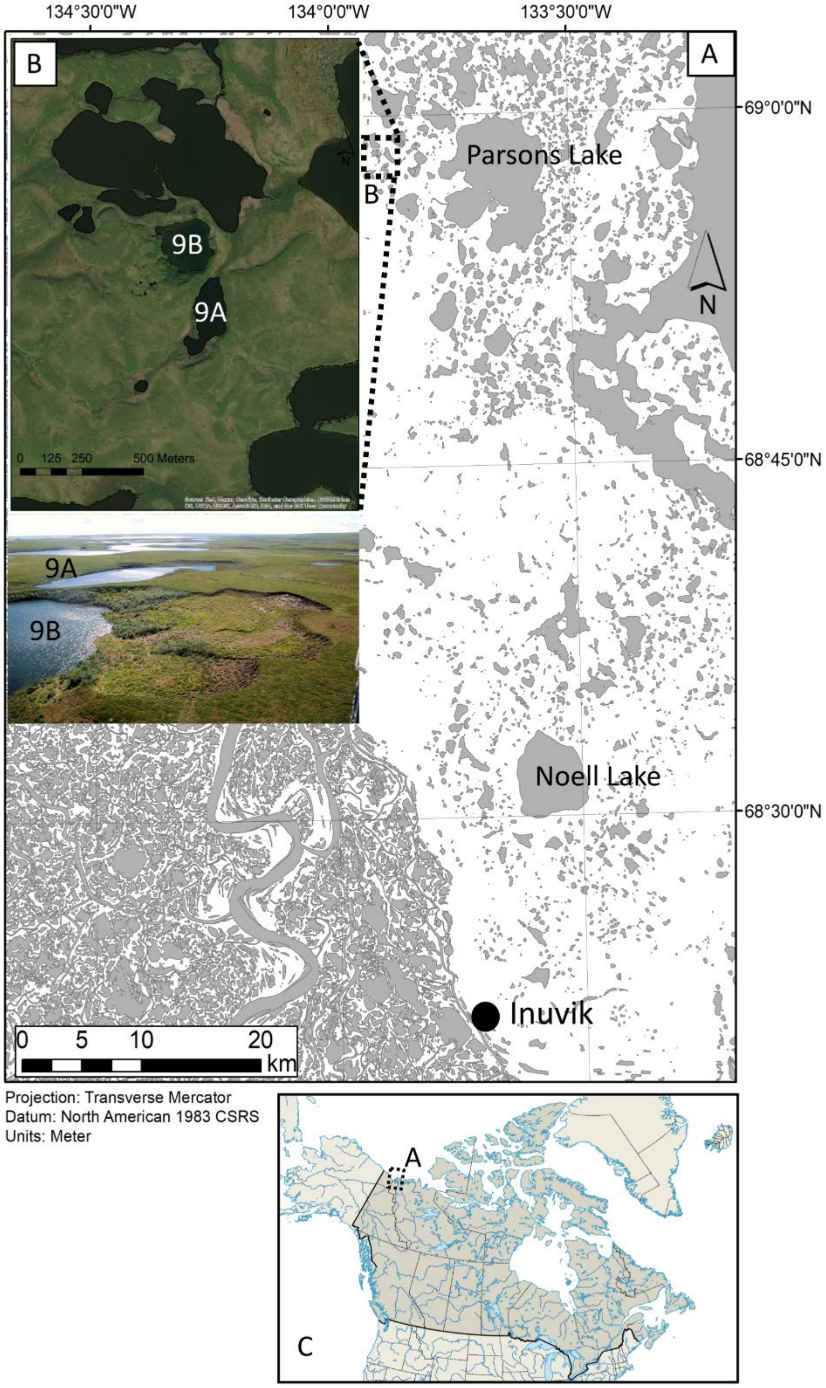

Figure 1: (A) Map of study Lakes 9A and 9B in the Mackenzie Delta region (Northwest Territories, Canada). Inset (A) shows the location of Lakes 9A/B west of Parsons Lake in the Mackenzie Delta region. Inset (B) shows (B) Google Earth images of Lakes 9A and 9B. The photo below inset B provides a visual image of the shoreline retrogressive thaw slump on Lake 9B. (C) The location of the Mackenzie Delta region within Canada.

Field and laboratory methods

Lake sediment cores were collected from Lakes 9A and 9B in July 2013. Sediment cores were collected near the centre of the lake on an inflatable boat using a UWITEC gravity corer with hammer action to penetrate deep into the thick, clay-rich sediment. Sediment cores were sectioned on the same day at 0.5-cm resolution using a modified Glew (1988) vertical extruder and stored frozen at the University of Ottawa (Canada). Lakes were re-sampled for water chemistry in 2017 from the centre of the lake at approximately 50 cm below the water surface, using the pontoons of a helicopter as a sampling platform. Water was collected into sterile polyethylene containers that had been triple rinsed with lake water. Water collected for analysis of dissolved organic carbon and nutrients was filtered within 24 hours using 0.45 µm cellulose acetate filters (diameter 47 mm) and acidified with high purity nitric acid. Water samples were shipped cold to Taiga Environmental Laboratory in Yellowknife (Northwest Territories) within 48 hours of sample collection for water quality analyses. Taiga Environmental Laboratory is accredited by the Canadian Association for Laboratory Accreditation (CALA).

Sediment core chronologies were established for Lakes 9A and 9B based on ^{210}Pb and ^{137}Cs isotopic activities analyzed at the Laboratory for the Analysis of Natural and Synthetic Environmental Toxicants (University of Ottawa) measured using an Ortec high purity germanium gamma spectrometer (Oak Ridge, TN, USA). Certified reference materials obtained from International Atomic Energy Association (Vienna, Austria) were used for efficiency corrections, and results were analyzed using ScienTissiME (Barry's Bay, ON, Canada). ^{137}Cs dating was used to delineate sediment deposited from atmospheric nuclear bomb testing during the 1950's and 1960's (Appleby 2001) to corroborate sediment ages derived from ^{210}Pb activity.

A peak in ^{137}Cs was used as an independent age marker for 1963, when an international ban on atmospheric bomb testing was put in place. An age-depth model was developed, and sedimentation rates were inferred using the constant rate of supply (CRS) model (Appleby and Oldfield 1978).

Chydorus carapaces were extracted from the sediment cores of Lakes 9A/B at 1-cm (9A) and 2-cm (9B) sampling resolution, using methods described in Korosi and Smol (2012). Sampling resolution was determined based on the CRS dating chronology. Approximately 1 g of wet sediment was deflocculated in 100 mL of 10% KOH solution and heated to 70°C on a hotplate for 20 minutes. The sediment mixture was sieved through a 64 µm mesh and rinsed with deionized water before being transferred to a beaker. Approximately 1 mL aliquots from each sub-sample were transferred to a Bogorov chamber where *Chydorus* carapaces were hand-picked with tweezers using a dissection microscope at 25x magnification. We aimed to collect up to 10 carapaces per interval, to ensure we had enough replicates to capture variability in *Chydorus* melanin production (Nevalainen and Rautio 2014), but this was not always possible. Carapaces were transferred to centrifuge tubes (one centrifuge tube per sediment interval), and 3-4 drops of 10% ethanol was added as a preservative, before being shipped to the Nevalainen Laboratory at University of Helsinki (Finland) for UV absorbance measurements.

Chydorus carapace absorbances were measured at UV radiation wavelengths 305 nm (UV-B) and 340 nm (UV-A) using a Shimadzu UV/VIS-2401PC dual-beam spectrophotometer connected to a Shimadzu UV Probe program (Shimadzu Corporation, Kyoto, Japan), following methods outlined in Nevalainen and Rautio (2014). A specialized adapter that was developed specifically for spectral analysis of subfossil cladoceran remains was used to reduce the spectrophotometer beam diameter of the cuvette holder (design described in Nevalainen and

Rautio 2014). Carapaces were individually attached to the adapter with UV-transparent cellophane tape. Carapace absorbances were measured in triplicates for quality assurance and quality control, and the standard error was calculated for each carapace. The mean of the triplicate absorbance measurements was calculated for each carapace. We then calculated the averages of the absorbance values at 340 and 305 to produce a final carapace UV absorbance value (ABS_{UV}).

Statistical Methods

We performed a Wilcoxon Rank Sum Test on pooled ABS_{UV} measures for all *Chydorus* carapaces recovered in the sediment intervals to test for statistically significant differences in *Chydorus* carapace ABS_{UV} measures between Lake 9A and Lake 9B, on the assumption that the known polycyclic slump history of 9B would have resulted in higher water clarity in 9B relative to 9A over the time duration captured by our sediment core. A Wilcoxon Rank Sum Test was used because the results of a Shapiro-Wilk test that showed ABS_{UV} measures were not normally distributed in either 9A or 9B. The Shapiro-Wilk and Wilcoxon Rank Sum Test were both performedusing R Statistical Software (v4.2.1; R Core Team 2022) in RStudio (RStudio Team 2020). A generalized additive mixed model (GAMM) using a gamma error distribution (k = 5) and restricted maximum likelihood was performed to identify if there were any periods of statistically significant change in the combined measured *Chydorus* ABS_{UV} from both lakes 9A and 9B, with estimated ^{210}Pb age as the covariate (Simpson et al. 2018). Lake ID as a factor was included as a random effect (random intercept) in the model, and tested for significant difference using ANOVA (Pedersen et al. 2019). Periods of significant change in the model trend was determined by extracting the first derivates of the fitted GAMM trend. The model was performed in the mgcv (v. 1.8-4.1; Wood 2022) package of R (v. 4.2.1; R Core Team 2022).

Results

Lake water chemistry

Both study lakes had similar lake depths but differed based on DOC concentrations, apparent lake colour, conductivity, total phosphorus, calcium, and total dissolved solids (TDS) (Table 1). Consistent with previous studies on water quality in slump-impacted and reference lakes of the Mackenzie Delta uplands (Kokelj et al. 2009; Thompson et al. 2012; Houben et al. 2016), Lake 9A had higher DOC, phosphorus, and apparent colour, and lower conductivity, calcium, and TDS compared to Lake 9B (Table 1). Water quality in Lake 9A and 9B was within the range of measurements typical of regional reference and slump-affected lakes, respectively (Kokelj et al. 2009; Houben et al. 2016).

Table 1: Lake locations, maximum water depth, and water chemistry based on surface water samples collected in July 2017. Water chemistry variables analyzed are dissolved organic carbon (DOC), apparent colour (Colour), specific conductivity @25°C (Cond), dissolved phosphorus (TP), and calcium (Ca).

Lake ID	Latitude (N)	Longitude (W)	Depth (m)	DOC (mg L^{-1})	Colour (cobalt units)	Cond (µS cm^{-1})	TP (mg L^{-1})	Ca (mg L^{-1})
9A	68°58.072	133°53.875	2.5	20.3	181	44.3	0.019	3.8
9B	68°58.220	133°53.968	2.1	7.4	22	463.0	0.004	55.6

Sediment core chronologies

In Lake 9A, there was a monotonic decline in ^{210}Pb isotopic activity to 12.0 cm, where background ^{210}Pb was reached (Figure 2A). There was a peak in ^{137}Cs isotopic activity in the 3.0-3.5 cm interval, which roughly corresponded with the dates produced by the CRS model that indicated a date of 1953 at a core depth of 3.5 – 4.0 cm. Based on the CRS model, 1943 ± 23 years occurred at a core depth of 4.0-4.5 cm, and below this depth the error in the age estimates from the CRS model increased substantially (Figure 2C). In Lake 9B, ^{210}Pb isotopic activity was lower in magnitude and more variable compared to that of Lake 9A, though it generally declined to background levels at 14.0 cm (Figure 2A). There was a clear peak in ^{137}Cs isotopic activity at a depth of 7.0-7.5 cm indicating ~1963. This is consistent with the CRS model, where 1963 also corresponds to a core depth of approximately 7.0 cm. Based on the CRS model, 1927 ± 11 years occurred at a core depth of 10.0-10.5 cm, and below this depth the error margins of the CRS model increased substantially (Figure 2C).

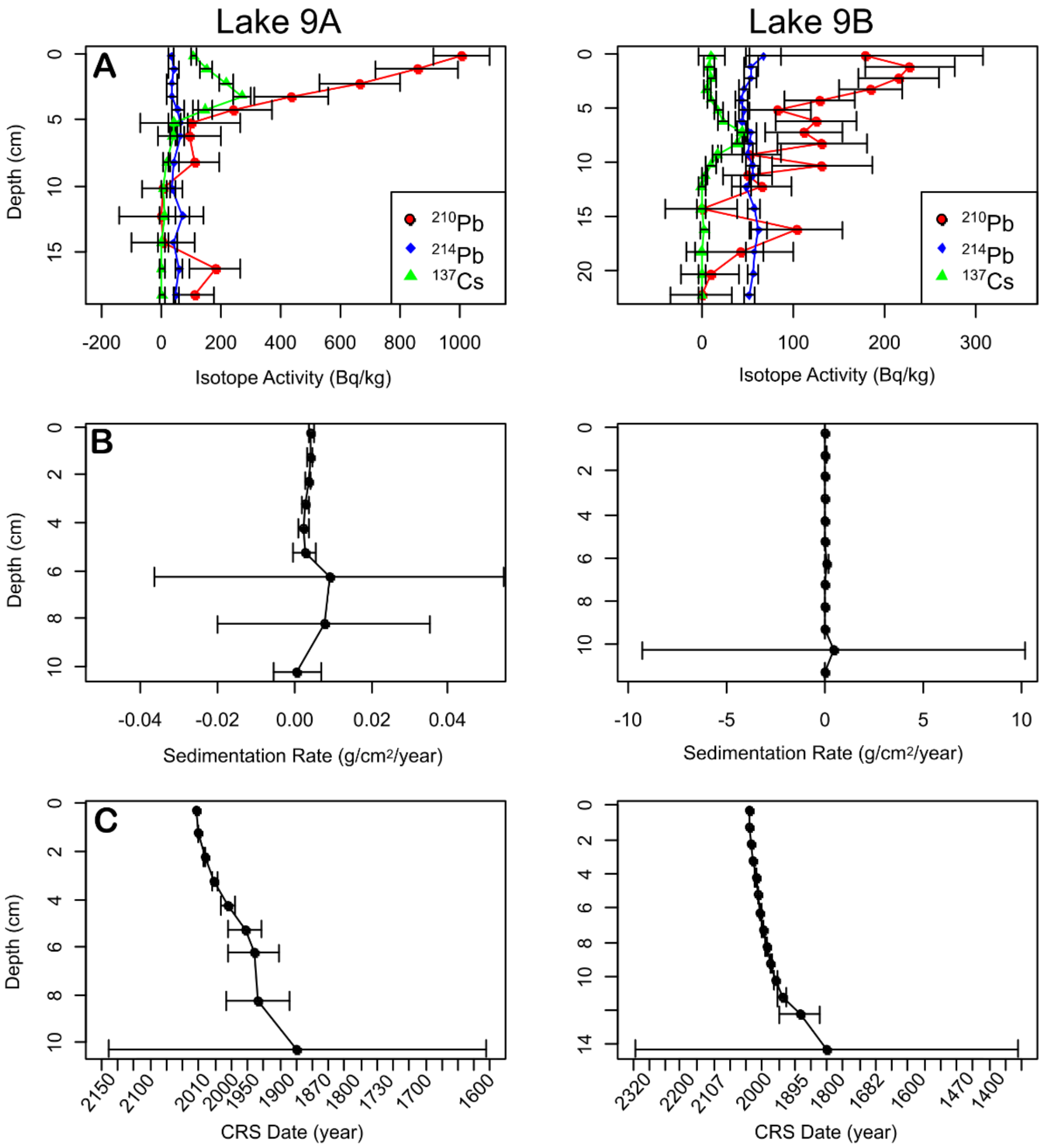

Figure 2 The results of ^{210}Pb dating for Lakes 9A and 9B. (A) Radioisotopic activities for ^{210}Pb, ^{214}Pb, and ^{137}Cs. (B) The sedimentation rate based on ^{210}Pb dating CRS model. (C) Sediment core depth versus date based on the CRS model. Bars represent standard error.

Cladoceran carapace absorbances

There was no significant difference in *Chydorus* carapace absorbance measures between Lake 9A and Lake 9B based on the Wilcoxon Signed Rank Test (W=2395, p=0.48). In Lake 9A, the maximum mean absorbances of individual carapaces were 2.68 at 305 nm and 2.26 at 340 nm, observed at a sediment core depth of 1.0-1.5 cm (Figure 3). The minimum mean absorbances of individual carapaces were 0.41 at 305 nm and 0.38 at 340 nm, found at a sediment core depth of 10.0-10.5 cm (Figure 3). The standard error for individual carapaces (based on triplicate measures) ranged from 0.001-0.375 at 305 nm and 0.002-0.123 at 340 nm. In Lake 9B, the maximum mean absorbances of individual carapaces were 2.79 at 305 nm and 2.32 at 340 nm, both at a sediment core depth of 4.0-4.5 cm (Figure 3). The minimum mean absorbance of individual carapaces was 0.24 at 305 nm and 0.23 at 340 nm, both at a sediment core depth of 12.0-12.5 cm (Figure 3). The standard error for individual carapaces (based on triplicate measures) ranged from 0.002-0.411 at 305 nm and 0.002-0.496 at 340 nm. Only one carapace was recovered in the 10.0-10.5 cm interval, with mean absorbance values of 1.4 and 1.3 at 305 nm and 340 nm, respectively. Several of the *Chydorus* carapaces recovered (especially from Lake 9B) were very small (< 300 μm) and did not fully cover the shutter of the adapter on the Shimadzu UV/VIS-2401PC dual-beam spectrophotometer. This contributed to the high range of variability we recorded for some of our triplicate measures. The combined *Chydorus* carapace ABS_{UV} values exhibited a significant ($p<0.001$), generally linear increase ($R^2_{adj} = 0.605$, deviance explained = 72.5%) from ~1800 to present-day, represented at the surface of the core (Figure 4). Lake ID as a random factor was not significant ($p=0.885$) as determined by ANOVA, indicating the trends in ABS_{UV} were similar between the two lakes.

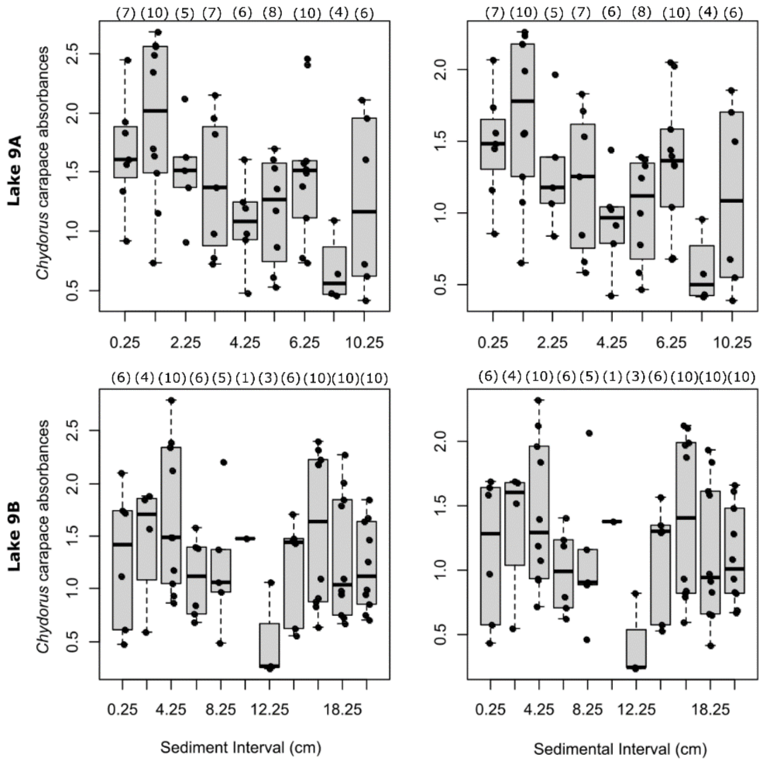

Figure 3 Box and whisker plots comparing the mean of the triplicate absorbance measures for each carapace at 305 nm (left) and 340 nm (right) wavelengths in downcore sediment profiles from Lake 9A and Lake 9B. The numbers in brackets at the top of the plots represent the number of *Chydorus* carapaces recovered from each sediment interval.

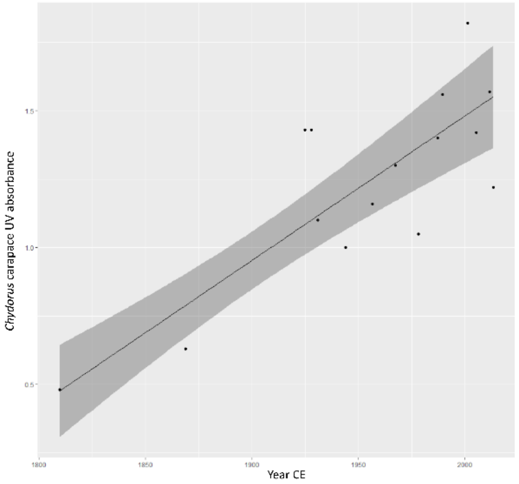

Figure 4: Fitted generalized additive mixed model trend since ~1850 for pooled Chydorus carapace ABSUV in Lake 9A and Lake 9B. The combined Chydorus carapace ABSUV values exhibited a significant ($p<0.001$), generally linear increase from ~1850 to present-day (R2adj = 0.605, deviance explained = 72.5%). . Lake ID as a random factor was not significant ($p=0.885$) as determined by ANOVA. The shaded area represents the 95% confidence interval.

Discussion

The aim of the study was to reconstruct exposure of *Chydorus* to UV radiation wavelengths in two neighboring lakes of the Mackenzie Delta region to determine if shoreline retrogressive thaw slumping increased UV exposure risk. We hypothesized that *Chydorus* carapace absorbances (ABS_{UV}) would be higher in the slump-affected lake compared to the neighbouring undisturbed lake because the slump-affected lake has lower concentrations of DOC and higher water clarity. We also hypothesized that *Chydorus* subfossil melanin content in the slump-affected lake would have increased after ~1990 when the slump re-initiated for the first time since at least 1950 (Thienpont et al. 2013). The data did not support either hypothesis, suggesting that shoreline retrogressive thaw slumping did not increase *Chydorus* exposure to UV radiation.

Chydorus carapace absorbance values at 305 and 340 nm wavelengths in Lakes 9A and 9B were mostly between 1 and 1.5. Similar carapace absorbance measurements have been reported in a subarctic boreal lake with high DOC (approximately 1.5 at 305 nm and 1.2-1.3 at 340 nm), in contrast to the higher absorbances measures reported in an alpine lake with a highly transparent water column (approximately 1.8-2.4 at 305 nm and 1.5-2 at 340 nm) (Nevalainen and Rautio 2014). Collectively, these results indicated *Chydorus* in Lake 9B are not exposed to higher UV radiation. We suggest that the most plausible explanation for this is that *Chydorus* can find physical refuge among macrophytes that provide shading. Access to physical refuges is a key factor influencing the response of littoral taxa to UV radiation, and photoprotective pigmentation and other physiological adaptations have been shown to be used mainly by taxa living in habitats without access to refuges (Vinebrook and Leavitt 1999)

Slump-affected lakes in the Mackenzie Delta region have higher macrophyte biomass because of changes in sediment chemistry and increased light penetration to the benthic zone (Mesquita et al. 2010). *Chydorus* are commonly associated with benthic and littoral substrates, although they do exhibit weak swimming ability that allows them to filter feed in the water column (Frey 1988; Thienpont et al. 2015). *Chydorus* in Lake 9B may be living amongst the dense macrophyte beds that provide shading from UV radiation. Alternatively, DOC concentrations in Lake 9B may have remained high enough to prevent exposure to harmful UV radiation. Previous studies have indicated that UV radiation negatively impacts aquatic biota below a DOC threshold of 5 mg L^{-1} (Williamson et al. 1996; Häder et al. 2007). The DOC concentration in Lake 9B is 7.4 mg L^{-1}, although this is likely composed mainly of non-chromophoric DOC given the high clarity of the lake water (Table 1). Chromophoric DOC is the main UV-absorbing constituent (Gareis et al. 2010).

Lake 9B had small, stable (no longer actively eroding) slumps along its shoreline that had been there since at least 1950, the date of the earliest available aerial imagery, while sediment geochemistry in gravity cores indicates that Lake 9B has likely been impacted by polycyclic thaw slumping for several hundred years (Deison et al. 2012; Thienpont et al. 2020). The slump re-initiated in ~1990 after at least 40 years of stability and was highly active until the early 2000s before stabilizing in 2008 (Thienpont et al. 2013). We did not observe any increase in *Chydorus* carapace ABS_{UV} that would indicate that slump re-initiation increased *Chydorus* exposure to UV radiation. The polycyclic slumping history of Lake 9B (repeated cycles of slump formation, stabilization, and re-initiation) likely results in legacy effects that influence lake ecological responses to slump re-initiation, such as insufficient time for lakes to recover between slump stabilization and re-initiation. The time it takes for lake DOC concentrations to recover following slumping is unknown but is likely on the order of decades (Kokelj et al. 2009). Diatom subfossil assemblage changes support this, as the major changes in diatom occurred in the early 1950s and not upon slump re-initiation in the 1990s, and were similar to diatom changes observed in Lake 9A (Thienpont et al. 2013).

Chydorus carapace ABS_{UV} exhibited a significant liner increase (from ~0.5 to 1.6) since ~1800 in both lakes based on pooled data, independent of slump formation. This could indicate that *Chydorus* exposure to UV radiation increased over this time. The beginning of the increase in *Chydorus* carapace ABS_{UV} pre-dates the onset of diatom assemblage changes indicating lake responses to climate warming, including a decrease in the relative abundance of small benthic *Fragilaria* spp. from ~1970 to 2008 and an increase in chrysophyte scales relative to diatom valves in Lake 9A from ~1990 to 2008 (Thienpont et al. 2013). The increase in *Chydorus* carapace ABS_{UV} could have resulted from several drivers, including decreases in DOC and/or lake water levels, or shifts in habitat usage and spatial distribution of *Chydorus* within the lake. A survey of UV radiation in thermokarst lakes of the Mackenzie Delta region showed approximately 19% and 31% of the water columns were exposed to UV-B and UV-A radiation, respectively, despite high chromophoric DOM concentrations (Gareis et al. 2010), and even small shifts in chromophoric DOM can increase the depth to which UV radiation penetrates the water column (Forsström et al. 2015).

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Competing Interests Statement

The authors declare there are no competing interests.

Author Contributions

BA performed lab work to isolate *Chydorus* carapaces from the sediments, and led the data analysis, interpretation, and writing of the manuscript. LN developed the methodology for absorbance measurements on *Chydorus* carapaces and conducted the spectral analysis. JRT contributed to the conceptual design of the research. JMB and JBK contributed to the conceptual design of the research and funding of the research. All authors contributed to data analysis and interpretation, critically reviewed and revised the manuscript, and approved the final version for publication.

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