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Community science to the rescue: capturing water quality data during the COVID-19 pandemic

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Abstract

In 2020, the COVID-19 pandemic interrupted all aspects of human activity, including environmental research and monitoring. Despite a lack of laboratory access and other restrictive measures, we adapted an existing community science monitoring program to continue through the summer of 2020. We worked with local community groups to recruit 58 volunteers who collected lake water samples from 60 sites on 16 lakes in south-central Ontario from June to September 2020. We organized drop-off depots and had volunteers freeze samples to monitor nearshore nutrients (phosphorus and nitrogen) and chlorophyll-a. A survey was distributed to volunteers to analyze lake-front property owners' activities during the pandemic. We found spatial patterns in nearshore water quality across the lakes, with sub-watershed development being a significant predictor of nutrients and chlorophyll-a. Additionally, pre-pandemic (2019) and pandemic (2020 and 2021) nutrient concentrations were compared, but there was no clear impact of the pandemic on nearshore nutrient concentrations, despite changes in lake-front property owners activities. Overall, this study demonstrated the ability of community science to provide water quality data on a large spatial scale despite a major societal disruption, providing insight into regional nutrient trends during the first year of the pandemic.

Key words: community science, water quality, nearshore zone, pandemic, nutrients, anthropause

1. Introduction

Environmental monitoring is essential to understanding human impacts on natural ecosystems, and continuity is a key property of successful monitoring programs. Unfortunately, this was not possible when the COVID-19 pandemic hit and impacted almost every aspect of human life, including some unexpected ecological changes. The spring of 2020 brought the "anthropause", a time with drastically constrained human activities, especially regarding industrial activity and travel (Rutz et al. 2020). Headlines that declared pandemic lockdowns were having a positive effect on the environment quickly emerged (Zerefos et al. 2021). In Venice, Italy, the canal bottom was seen for the first time in decades, and several large cities had improvements in air quality (Bherwani et al. 2020; Clifford 2020; He et al. 2020). Although early indications were that the pandemic allowed some environmental renewal, contributing to improved air and water quality, these anecdotal observations do not provide a robust understanding of the pandemic's full environmental impacts (Berman and Ebisu 2020; Hallema et al. 2020; Cooke et al. 2021).

One unfortunate effect of the COVID-19 pandemic was the pausing or cancelling of environmental monitoring programs. In the spring of 2020, much uncertainty surrounding the pandemic and concerns about maintaining social distancing led to a reduction in environmental monitoring (Cooke et al. 2021). The U.S. National Park Service, for example, issued just 37% of its normal amount of research permits (Miller-Rushing et al. 2021), while the Canadian federal government paused all water quality monitoring programs (Zingel 2020). Compared to other locations, Ontario had extended closures during the summer of 2020, and details of the provincial re-opening plan can be found in Howarth et al. (2021). Within Ontario, the Lake Partner Program, a province-wide volunteer-based water quality monitoring program that covers over 550 inland lakes, paused for the summer of 2020 (Dorset Environmental Science Centre 2020). Along with federal and provincial governments, many local conservation authorities could not run their regular monitoring programs as employees were told to work remotely to reduce transmission of COVID-19 (Akinsorotan et al. 2021). This multi-level monitoring shut-down reflected a data gap where thousands of lakes and streams in Ontario were not monitored for water quality during the entire summer of 2020.

The pause in water quality monitoring left gaps in long-term monitoring programs and constrained the ability to measure the immediate impacts of the COVID-19 pandemic on Ontario's lakes. In Ontario, the pandemic led to multiple public health interventions that restricted travel and social interactions, as well as changes in individuals' hygiene habits (i.e., increased hand washing) (Park et al. 2010; Nielsen 2021). These changes improved air quality in many places, and it has recently been found that water quality may have been affected as well (He et al. 2020; Tokatlı and Varol 2021). Although most field monitoring was cancelled in 2020, some researchers used remote sensing to examine turbidity and found it decreased in the Ganga River and Vembanad Lake in India during the lockdown period (Garg et al. 2020; Yunus et al. 2020). Alternatively, in the Meriç-Ergen River Basin in Turkey, turbidity did not change, but there were reductions in metal(loid) levels (Tokatlı and Varol 2021). The reductions in water quality parameters were attributed to reduced effluent from industrial sources and reduced pollution from human activities, such as tourism, in the area. Water consumed by households was also higher, with people staying home and increasing hygienic behaviours, such as hand washing (Kalbusch et al. 2020; Abu-Bakar et al. 2021). In areas with household septic systems, there was the potential for these systems to become overloaded, resulting in poor treatment performance. Excessive septic seepage can lead to increased nutrient concentrations in nearby surface waters (Reay 2004; Oldfield et al. 2020).

One avenue to continue research through laboratory closures was the implementation/expansion of community science monitoring programs. Crimmins et al. (2021) found an increase in community science participation on the most popular community science programs (iNaturalist and eBird) in the spring of 2020 in the United States. However, they found the trends in community science greatly varied by geographic location, with higher participation in urban areas (Crimmins et al. 2021). Although these programs can be useful for biodiversity monitoring, water monitoring, which often requires access to a laboratory, was harder to conduct during the pandemic; the largest community science program in Ontario, the Lake Partner Program, was shut down for the entirety of the spring and summer of 2020 (Dorset Environmental Science Centre 2020). Alternatively, a survey of U.S. and Canadian community science water monitoring program coordinators (Stepenuck and Carr 2022) found that 72% of programs planned to continue through the 2020 field season, despite delays. highlighting the flexibility of community science as a water monitoring tool.

While pandemic restrictions inhibited routine water quality monitoring from occurring in Ontario, Canada, in 2020, we demonstrate that a community science approach could address questions pertaining to lake water quality during a disruption of regular monitoring. As such, we (1) evaluated lake-front residents' behaviours during the early months of strict pandemic measures in 2020, (2) assessed spatial nutrient dynamics across 16 lakes in the Kawartha Lakes region during the most restrictive pandemic year (2020), and (3) compared pandemic nutrient conditions in four Kawartha Lakes during a pre-pandemic (2019) year and pandemic years (2020 and 2021). This study offered the unique opportunity to test if there was a detectable effect of the anthropause in an agriculturally dominated region with high shoreline development. Given that agricultural activities were not affected by pandemic restrictions and more people were residing at lakefront properties during the summer of 2020, we hypothesized that nutrient inputs during the pandemic years would be higher than pre-pandemic years. Overall, we demonstrate that community science monitoring is a flexible tool that has the potential to enhance and, in some cases, replace mandated governmental monitoring work.

2. Materials and methods

2.1. Study site

The Kawartha Lakes region, located in south-central Ontario, is within a 1–2 h drive from the densely populated Greater Toronto Area (GTA) (Fig. 1). Their proximity to the GTA and natural surroundings make the Kawartha Lakes an extremely popular tourist and cottage destination in Ontario (City of Kawartha Lakes 2020). The Kawartha Lakes are also part of the Trent-Severn Waterway (TSW), a National Historic Site of Canada, which connects Georgian Bay to Lake Ontario. Tourism is one of the biggest industries for the City of Kawartha Lakes, with recreational activities on the lakes a major draw for the area, helping to bring in over 1.6 million visitors annually (City of Kawartha Lakes 2020). The Kawartha Lakes watershed is also part of "The Land Between"—a biodiverse ecotone that reflects a geological shift from limestone to granite (Alley 2006). The watersheds of these lakes also have over 55 provincially significant watersheds that provide key ecosystem services (Kawartha Conservation 2023).

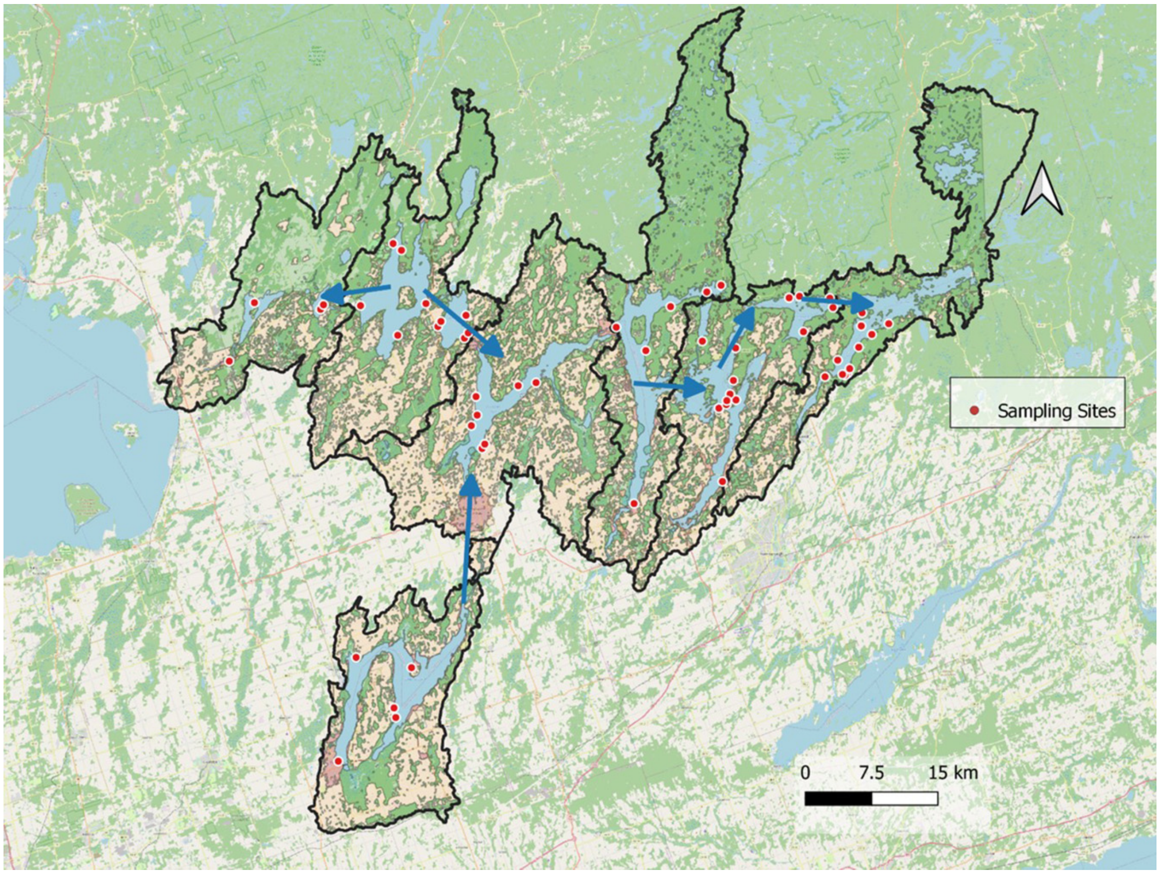
As part of the TSW, the Kawartha Lakes have controlled flow between the lakes through locks and dams. In our study lakes, the flow begins at Balsam Lake, feeds Canal and Mitchell to the west and Cameron to the east, and continues east with Katchewanooka as the final downstream lake in our study area (Fig. 1 and Table S1). Lake Scugog is a headwater lake that flows into Sturgeon, and Sandy Lake is the only study lake not hydrologically connected to the TSW.

2.2. Community science model

Our research group had been conducting research with the local conservation authority, Kawartha Conservation, using community science for several years before the pandemic, with monitoring on five lakes included in this study (Scugog, Balsam, Cameron, Sturgeon, and Pigeon). Through this partnership, we had established a network of lake associations and volunteers to tap into this study; additionally, community science was an ideal approach that could ensure physical distancing during the pandemic years. We contacted a local environmental group, the Kawartha Lake Stewards Association (KLSA), which helped recruit additional volunteers through email and virtual meetings. We also partnered with Curve Lake First Nation, whose traditional lands and waters encompass the Kawartha Lakes region. Five volunteers from Curve Lake First Nation selected sites to monitor across their reserve territory, located between Buckhorn and Chemong Lake. Through partnering with these organizations, we recruited 58 community science volunteers to sample from 60 sites across 16 lakes in the first year of the pandemic (2020). Due to strict physical distancing requirements at this time, volunteers were asked to collect water samples with the provided containers and store them in their freezer until the end of the study period in September 2020.

 FACETS 8: 1–12 (2023) | dx.doi.org/10.1139/facets-2023-0004

Fig. 1. Map of 2020 water sampling sites in 16 Kawartha Lakes. The arrows indicate the direction of water flow through the system, and watersheds are outlined in black. Background map obtained from OpenStreetMap (2022); land-use data received from Kawartha Conservation. Coordinate reference system: WGS84/UTM zone 17 N.



Volunteer training was conducted virtually to ensure the safety of all participants. A training video was created and shared on YouTube, with a direct link sent to all volunteers. Two live virtual follow-up sessions were booked about a week after the release of the recorded video to answer questions and share additional information. Volunteers were also sent a document with visual and written instructions for collecting and storing water samples and recording field observations.

Finally, a vital component of community science research is information dissemination. All volunteers were provided with a final report, which included an overview of the project, a site-specific summary of water quality findings, and descriptions of some waterfront property best management practices and resources. Additionally, Curve Lake First Nation was provided with the site-specific results for all five of their monitoring stations, and with possession of these data, they are in control of using them as they see fit.

2.3. Sample collection

One week before the first sample collection date in 2020, water sampling kits were distributed to volunteers at four pick-up locations that included local marinas and volunteers' homes. Sample kits included eight high-density polyethylene (HDPE) 200 mL specimen containers, gloves, collection instructions, and a field datasheet. Monthly water samples were collected in duplicate by community science volunteers from June to September 2020. Samples were collected on the last Tuesday of the month between 8 and 9 am, for consistency across sites. If volunteers were unable to take the sample at the requested time, they recorded the date and time of their sample collection. Samples were collected by volunteers from their docks at a location where the depth was ~1 m. Volunteers were instructed to fill their two specimen containers to 1 cm from the lid with lake water from approximately 10 cm below the surface. Volunteers were also required to fill out a data collection sheet where they recorded the air and water temperatures at their site, along with any other observations about the weather or water conditions. Once samples were collected, the labelled specimen cups were placed in the volunteers' freezer until sample pick-up in late September. Overall, 227 samples were returned, resulting in a participation rate of 95%.

In 2019, water samples were collected at sites on Scugog, Balsam, Cameron, Sturgeon, and Pigeon lakes, and all of the above lakes were sampled in 2021 at the same sites except for Scugog. In 2019, water sampling kits were delivered directly to the volunteers' homes, and in 2021, the pick-up depots established in 2020 were used to deliver and collect water samples. Sample kits in 2019 and 2021 were distributed monthly and included two acid-washed 1 L HDPE Nalgene bottles, one 100 mL sterile specimen cup, gloves, collection instructions, and a field datasheet. Water samples were collected monthly from June to September, with Scugog, Balsam, and Cameron lake samples collected on a Tuesday and Sturgeon and Pigeon lake samples collected on the following Thursday. Samples were picked up by researchers on the same day they were collected and kept on ice until returned to the laboratory. Aliquots were poured for phosphorus and nitrogen analysis and frozen within 24 h of sample collection.

Precipitation data was retrieved from Kawartha Conservation's monitoring station at Ken Reid Conservation Area, Lindsay. These data were used for all sites as they are centrally located and there are not sufficient weather stations in the region to have coverage by lake or watershed. Total precipitation in the 4 days prior to sample collection was calculated, and the presence/absence of a storm event (>15 mm of precipitation in a 24 h period) was recorded for each sample event.

Land-use analysis was conducted in QGIS (QGIS Development Team 2019). Land-use data based on surveys as recent as 2017 was provided by Kawartha Conservation and classified as water, natural, agricultural, or developed. A provincial digital elevation model was used to delineate drainage basins for each site (Ontario Ministry of Natural Resources and Forestry 2019); quaternary watershed boundaries were determined based on a shapefile from the Ontario Ministry of Natural Resources and Forestry (2021). The percentage of each land-use type was calculated for each drainage basin and watershed and used in subsequent analyses.

2.4. Volunteer survey deployment

With various pandemic-related lockdown measures in place in 2020 and 2021, we wanted to examine if there was an impact of these measures on homeowners' habits. Of particular interest were changes to the number of people and time spent at the lake-front property, habits that impacted septic tank loads, and lake-front property maintenance. Researchers created an anonymous online survey to investigate changes in waterfront property-owner habits. The survey was approved by the Ontario Tech University Research Ethics Board (REB) on 29 May 2020 (Supplementary material, REB# 15910). The survey was sent to all volunteers in July 2020 and asked participants to compare their activities at their lake-front property to the previous year (2019), with follow-up questions asking respondents to specify their activities, such as gardening habits as well as demographic questions. These comparisons were used to analyze trends in lake-front property owner habits before and during the COVID-19 pandemic. When the survey closed in the fall of 2020, there were 45 responses.

2.5. Water sample processing

Frozen samples from 2020 were thawed for analysis upon return to the laboratory in September, and frozen samples from 2019 and 2021 were thawed and analyzed within a month of sample collection. Frozen samples were sent to the SGS Environmental Analytical Laboratory in Lakefield, Ontario (SGS) for nitrogen suite analysis (nitrite, nitrate, ammonia + ammonium, and total Kjeldahl nitrogen). SGS is accredited for environmental tests by the Canadian Association for Laboratory Accreditation Inc. (CALA). Samples were thawed for total phosphorus (TP) and chlorophyll-a (Chla) analysis in the laboratory. TP was determined spectrophotometrically based on a modified ascorbic acid method (Murphy and Riley 1962). Due to the samples being previously frozen in 2020, an Aquafluor handheld fluorometer (Turner Designs, Sunnyvale, CA) was used to estimate relative Chla values. Chla samples collected in 2019 and 2021 were filtered within 24 h of collection and determined spectrophotometrically using a 90% acetone extraction method (Kirkwood et al. 1999). Due to the different methodologies and units used for Chla in 2020 (relative units) and 2019 and 2021 (mg/L), Chla values cannot be directly compared across years.

2.6. Statistical analysis

Statistical analyses were completed using the R program (R Core Team 2023) in RStudio (RStudio Team 2020), and all figures were created using the *ggplot2* package (Wickham 2011). An exploratory data analysis was conducted to identify outliers. Points that fell out of the 1.5 times the interquartile range were examined to determine if there was a sampling error. One site on Lake Scugog that has been monitored previously had extremely elevated TP and TN values that appeared to be due to sampling error and were thus removed from the analysis. TP and Chla were log-transformed due to the non-normal distribution of residuals. Spatial variation was analyzed with a nested analysis of variance (ANOVA) to determine if there were differences between lakes, with Tukey's post hoc test to determine specific differences between lakes. Permutational ANOVA (PERMANOVA) was conducted with *vegan* (Oksanen et al. 2020) based on Bray–Curtis dissimilarity to determine if differences between watersheds were significant. A pairwise post hoc test was performed using the *pairwise.adonis* (Martinez Arbizu 2020) R package. Temporal trends (2019–2021) were examined with a mixed-effect model, with month nested in year as fixed effects and lake as a random effect. Pairwise comparisons across years were conducted with the *emmeans* package (Lenth 2016). Welch's *t*-test was conducted on survey data to determine if there were significant differences between property owners' habits in 2019 and 2020. An unconstrained ordination was conducted on the raw water quality data (2019–2021). First, a detrended correspondence analysis (DCA) was conducted to determine whether the data followed a linear or unimodal response. The standard deviation of the first DCA axis was less than three, and such a principal component analysis (PCA) was conducted with the R package *vegan* (Oksanen et al. 2020).

3. Results

3.1. Community science survey

The survey of lake-front property owner's habits was sent to all 58 community scientists in June 2020, and 78% responded by the deadline. Fifty-seven percent of the respondents were in the 65+ age category, and the average length of

Fig. 2. Stacked bar plot showing participant responses when asked about the age of their septic tank and when it was last pumped out, expressed as percentage of the total response.

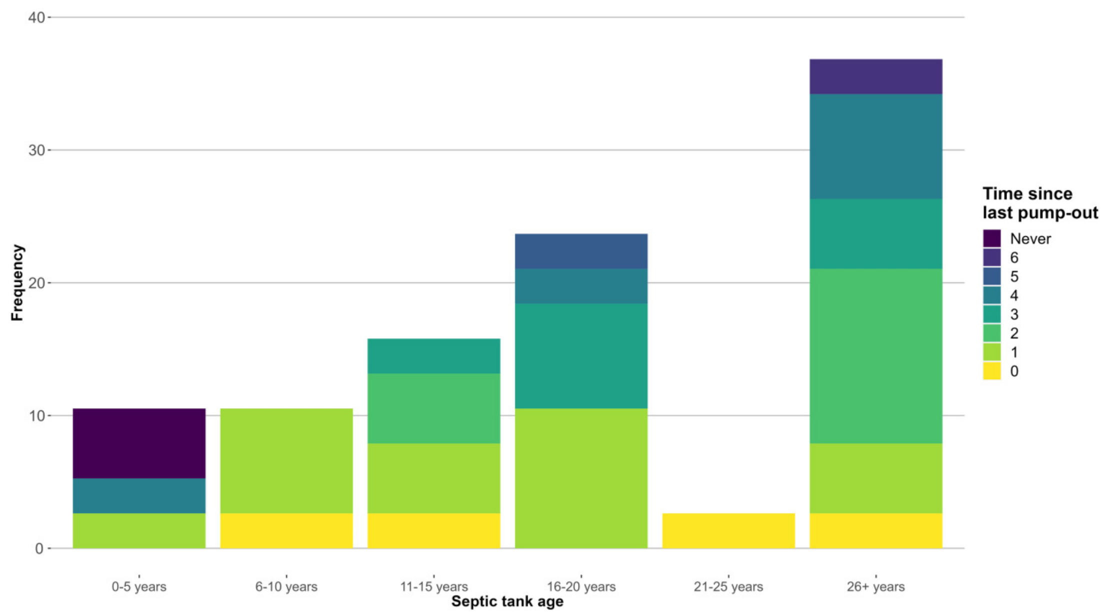
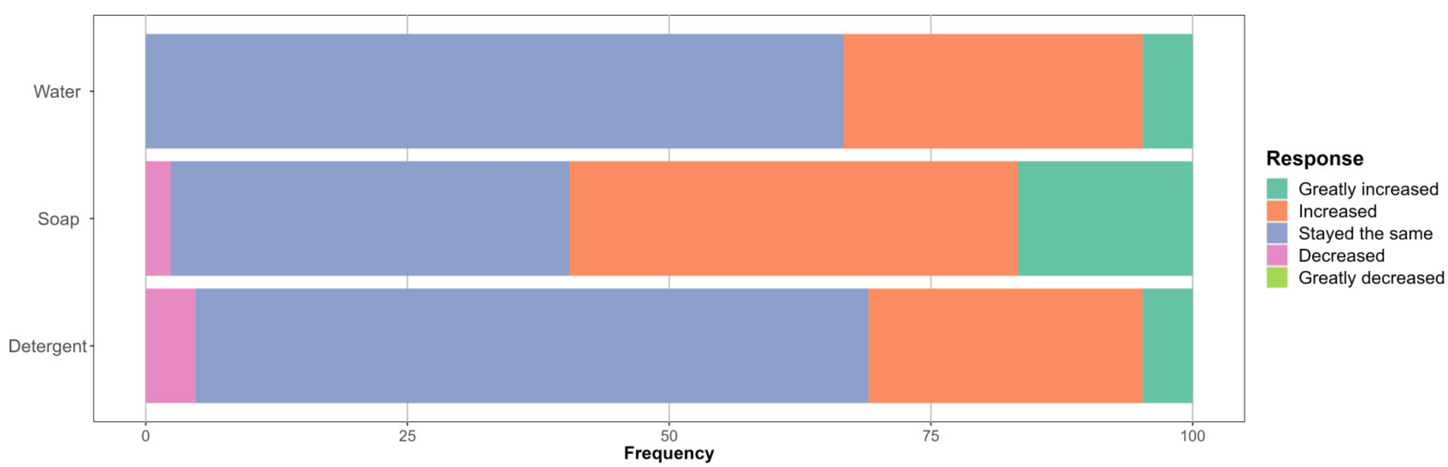


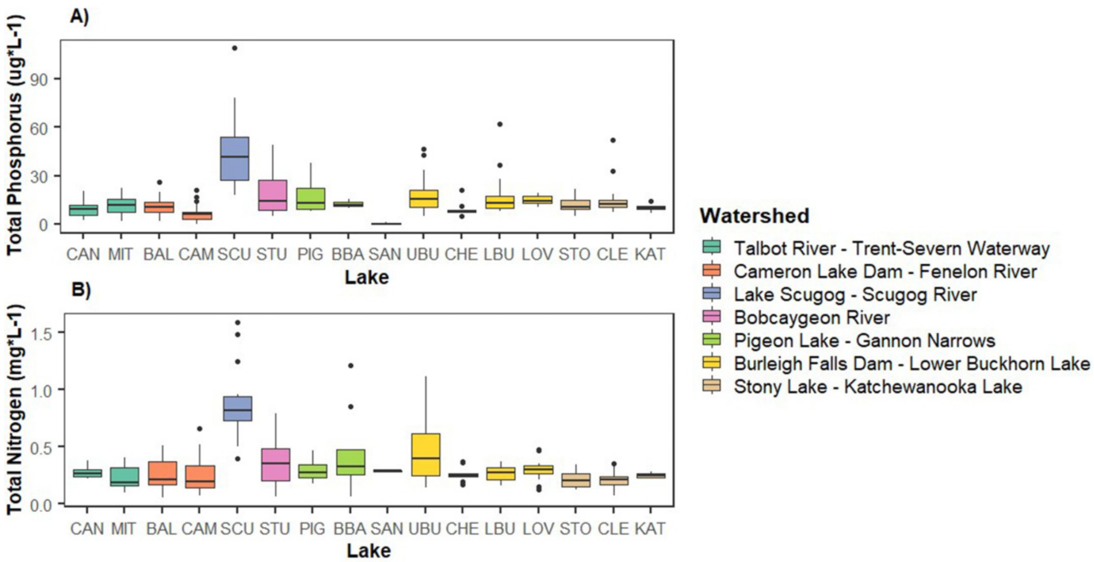
Fig. 3. Stacked bar plot showing participant responses when asked about changes in frequency of their detergent, soap, and water in 2020 compared with 2019, expressed as percentage of total response.



residency at the lake-front property was 25 years. Fifty-seven of respondents identified as male, and 78% completed a degree or diploma beyond high school. Only two respondents indicated that they did not have a septic system. Most septic systems were older, with 63% of respondents with septic systems indicating their system was installed over 15 years ago. Most respondents reported regular septic tank maintenance; 60% of tanks were pumped out within the last 2 years, and only one respondent had not pumped their tank in the previous 5 years (Fig. 2).

When comparing volunteers' habits in the spring of 2020 (pandemic) to 2019 (pre-pandemic), there was no significant difference in the number of days spent at their lake-front residence or the number of people staying at the property, although the average number of guests declined from 5 to 4 (i.e., fewer friends and extended family members at the residence). Habits relating to the use of septic systems shifted between 2019 and 2020, with many respondents indicating they increased their use of detergents, water, and handwashing (Fig. 3). The use of soap had the biggest increase from 2019, with 60% of respondents indicating they increased or greatly increased their use of soap in 2020. Overall, the use of water was reported to have increased by 33% of respondents. Property maintenance habits of lakefront property owners also changed slightly from 2019 to 2020. Forty percent of respondents indicated that they had decreased the amount of time they spent mowing their lawn compared with 2019. Alternatively, time spent gardening increased for 39% of respondents. The amount of fertilizer used on lawns and gardens slightly decreased for 12% of respondents in 2020 (Fig. S1).

Fig. 4. Boxplots of (A) total phosphorus (μg/L) and (B) total nitrogen (mg/L) in each lake, with watershed indicated by box colour.



3.2. Water quality patterns in 2020

Nutrient concentrations across the 16 Kawartha Lakes monitored in 2020 reveal distinct spatial patterns, with higher nutrient concentrations in Lake Scugog and lakes downstream of Lake Scugog (Table 1, Fig. 4). Lake Scugog had a significantly higher TP compared with the rest of the lakes (ANOVA, df = 15, $p < 0.05$). Additionally, TP in Cameron Lake was significantly lower than in Sturgeon, Upper Buckhorn, and Lower Buckhorn lakes; TP in Sandy lake was significantly lower than in Sturgeon lake; and TP in Mitchell lake was significantly greater than in Canal lake (ANOVA, df = 15, $p < 0.05$). PERMANOVA revealed significant differences in water quality profiles between watersheds ($F(6,220) = 11.21$, $p < 0.01$). Specifically, water quality in the Cameron Lake Dam–Fenelon River watershed was significantly different from all other watersheds except the Talbot River–TSW watershed ($p < 0.05$). The water quality in the Lake Scugog—Scugog River watershed was significantly different from all other watersheds ($p < 0.05$).

Proportions of natural, agricultural, and developed land were calculated for the quaternary watersheds and for the sub-watershed draining to each site (Fig. S3). Natural land cover was the most abundant land use/cover type in all the watersheds, except the Lake Scugog—Scugog River and Bobcaygeon River watersheds, where agricultural land use was dominant. Stepwise regressions were run for each water quality parameter and land use. Sub-watershed development was the only predictor selected and was significant for predicting TN, Chla, and TP ($p < 0.05$). The strongest relationship was between TN and development ($p < 0.05$, $R^2 = 0.18$), followed by Chla and development ($p < 0.05$, $R^2 = 0.14$), and TP and development ($p < 0.05$, $R^2 = 0.08$).

3.3. Annual nutrient trends

Phosphorus and nitrogen samples were collected in 2019, 2020, and 2021 in four study lakes (Balsam, Cameron, Sturgeon, and Pigeon). A PCA was conducted to examine nutrient patterns across the three study years (Fig. 5). The first axis explained 34% of the variation in the data and was primarily driven by total organic nitrogen and TP. The second axis explained 26.7% of the variation in the data and was driven by nitrates and nitrites. Ellipses were drawn by year, and all 3 years overlapped and spread along the first axis.

Nutrient concentrations before and during the COVID-19 pandemic were compared with mixed effects models. TP was significantly lower in 2021 than in 2019 and 2020, ammonia/ammonium concentrations were significantly higher in 2019 than in 2020 and 2021, and nitrates were significantly higher in 2021 and 2019 compared to 2020 ($p < 0.05$; Fig. 6). Precipitation and water temperature data were compared across years to examine the potential climate impacts on water quality. Accumulated precipitation in the four days before sample collection was significantly higher in 2021 than in 2019 and 2020 ($p < 0.05$). There were no significant differences in water temperature across the years. We also considered the impact of storm events (>15 mm precipitation) in the week before sample collection and found no significant relationship to any water quality variable.

4. Discussion

4.1. Community science survey

To improve our understanding of the influence of waterfront activity on nearshore water quality, a community science monitoring program and survey were deployed to volunteers in 16 Ontario lakes in 2020. The lake-front property owner survey results indicate that although the number of people and the amount of time spent at lake-front residences did not appreciably change from the pre-pandemic year (2019), there was an increase in detergent use, water use, and handwashing. Initially, we thought that the use of lake-front properties would have been higher in 2020 compared

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Table 1. Mean (standard deviation) nutrient and fluorometer chlorophyll-a values for samples collected from each lake in 2020.

Watershed	Lake	*n*	TP (μg/L)	TN (mg/L)	NH (mg/L)	NO_2 (mg/L)	NO_3 (mg/L)	TKN (mg/L)	Chla (mg/L)
Talbot River–Trent Severn Waterway	Canal	8	9.38 (5.21)	0.28 (0.06)	0.040 (0.017)	0.002 (0.000)	0.004 (0.003)	0.28 (0.06)	1.81 (0.43)
	Mitchell	8	11.60 (6.07)	0.23 (0.11)	0.033 (0.24)	0.002 (0.000)	0.006 (0.004)	0.23 (0.10)	0.96 (0.25)
Cameron Lake Dam–Fenelon River	Balsam	20	10.79 (5.71)	0.25 (0.13)	0.021 (0.004)	0.002 (0.001)	0.008 (0.009)	0.24 (0.13)	1.20 (0.44)
	Cameron	20	6.81 (5.45)	0.24 (0.15)	0.026 (0.020)	0.003 (0.005)	0.010 (0.008)	0.23 (0.14)	0.95 (0.32)
Lake Scugog–Scugog River	Scugog	15	45.90 (24.19)	0.87 (0.30)	0.073 (0.090)	0.002 (0.001)	0.004 (0.002)	0.86 (0.30)	5.27 (5.28)
Bobcaygeon River	Sturgeon	27	19.45 (13.12)	0.34 (0.18)	0.024 (0.009)	0.002 (0.002)	0.016 (0.026)	0.33 (0.18)	1.30 (0.45)
Pigeon Lake–Gannon Narrows	Pigeon	16	16.72 (8.44)	0.29 (0.09)	0.020 (0.000)	0.002 (0.001)	0.014 (0.017)	0.28 (0.08)	1.63 (0.58)
	Big Bald	8	12.21 (1.78)	0.44 (0.37)	0.031 (0.017)	0.002 (0.000)	0.005 (0.004)	0.44 (0.36)	1.31 (0.32)
Burleigh Falls Dam–Lower Buckhorn Lake	Sandy	3	0.29 (0.41)	0.29 (0.00)	0.020 (0.000)	0.002 (0.000)	0.003 (0.000)	0.29 (0.00)	1.79 (0.29)
	Upper Buckhorn	18	18.73 (11.49)	0.45 (0.25)	0.052 (0.030)	0.002 (0.000)	0.005 (0.005)	0.45 (0.24)	1.31 (0.40)
	Chemong	10	9.04 (4.35)	0.26 (0.06)	0.023 (0.009)	0.002 (0.000)	0.005 (0.004)	0.26 (0.06)	1.84 (0.52)
	Lower Buckhorn	15	17.95 (13.98)	0.27 (0.06)	0.023 (0.010)	0.002 (0.000)	0.003 (0.001)	0.27 (0.06)	1.54 (0.75)
	Lovesick	12	14.83 (2.64)	0.30 (0.10)	0.022 (0.006)	0.002 (0.00)	0.0003 (0.001)	0.30 (0.10)	1.66 (0.46)
Stony Lake–Katchewanooka Lake	Stony	16	11.61 (4.13)	0.21 (0.08)	0.020 (0.000)	0.002 (0.000)	0.003 (0.000)	0.21 (0.08)	1.16 (0.28)
	Clear	24	14.52 (9.34)	0.20 (0.07)	0.022 (0.007)	0.002 (0.000)	0.006 (0.006)	0.20 (0.07)	1.32 (0.43)
	Katchewanooka	4	10.11 (2.67)	0.25 (0.02)	0.020 (0.000)	0.002 (0.002)	0.013 (0.008)	0.24 (0.01)	1.37 (0.19)

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Fig. 5. Biplot of principal component analysis axes 1 and 2 with observations from 2019 ($n = 70$), 2020 ($n = 83$), and 2021 ($n = 66$), with ellipses drawn by year representing multivariate normality. The direction and length of the arrow indicate the association with the axes and strength of the driver for each water quality variable. TP, total phosphorus; TON, total organic nitrogen; NH, ammonia/ammonium; NO_2, nitrates; NO_3, nitrates.

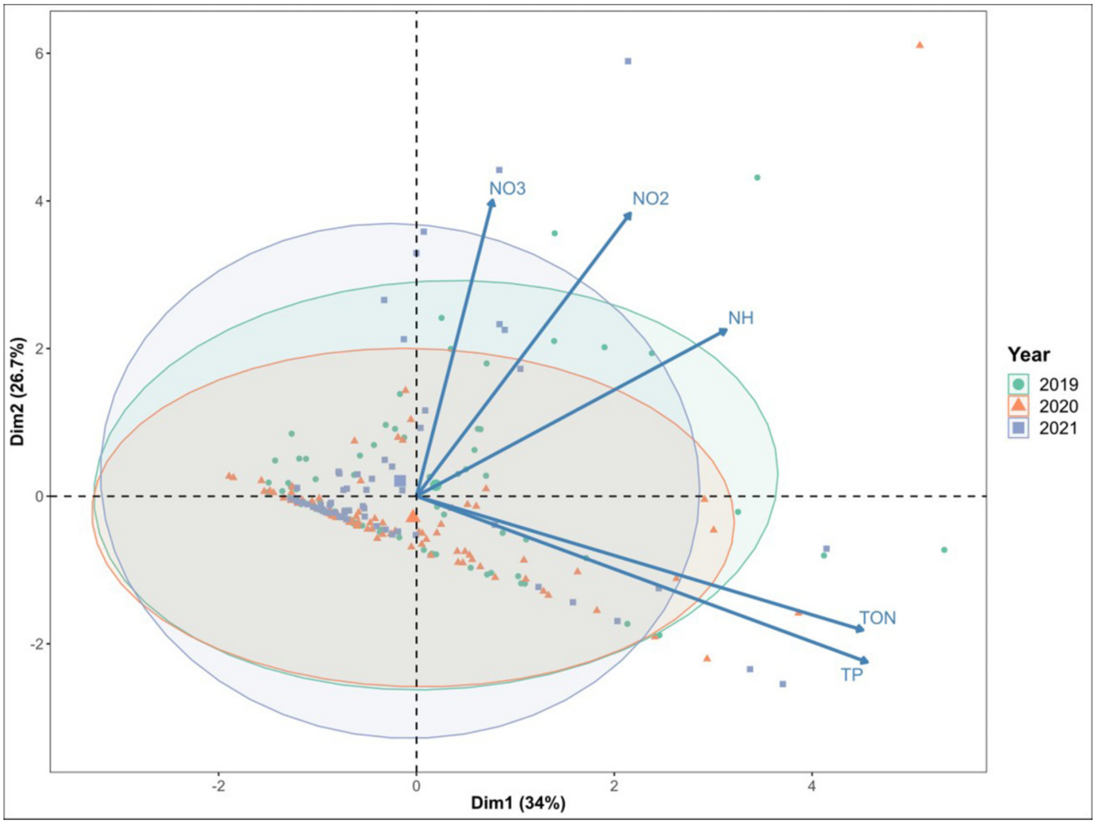
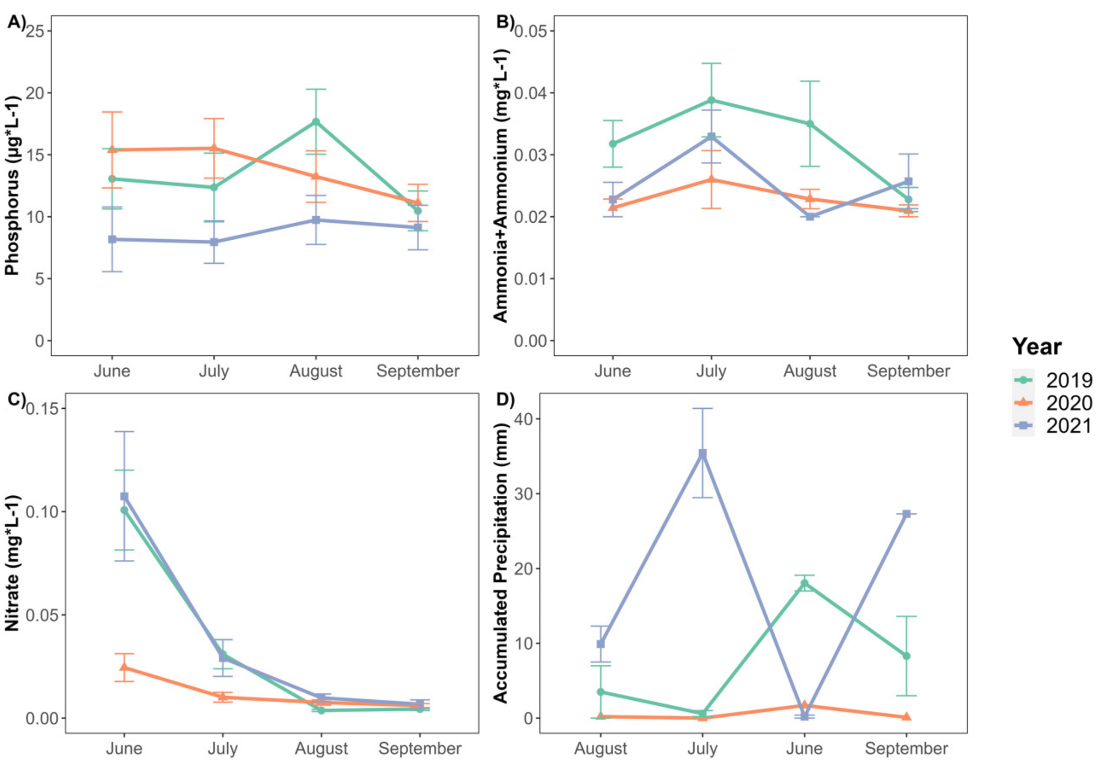


Fig. 6. Line plots with standard error bars of monthly (A) total phosphorus, (B) ammonia/ammonium, (C) nitrates, and (D) accumulated precipitation in the 4 days before sampling for each sampling year from 2019 to 2021 ($n = 219$).



with the pre-pandemic year due to increased local travel within Ontario (Giunta 2020). Though some respondents retreated to their seasonal cottages to minimize exposure to COVID-19 in cities, most respondents were already permanent residents. Thus, the use of lake-front properties did not significantly increase during the first year of the pandemic. The increase in water/hygienic habits related to the COVID-19 pandemic was not surprising, as other studies have found similar changes during health crises (Głąbska et al. 2020; Park et al. 2010). The increase in these habits can incur strain on septic systems (Gray 1995), and combined with the older age of most systems (i.e., most were >25 years old), could result in septic system failure. However, we also found that most septic tanks were regularly maintained, which would reduce the likelihood of contamination of nearby waters (Macintosh et al. 2011). Due to the anonymity of the survey, we could not directly compare septic system use to site-specific water quality results.

4.2. Water quality patterns in 2020

By examining the spatial patterns across the Kawartha Lakes in 2020, we found an impact of watershed land use on lake water quality (PERMANOVA, $p < 0.01$). The water quality in the Lake Scugog watershed was significantly different from the water quality in all other watersheds. Although considered a headwater lake to the TSW, Lake Scugog has both a highly agricultural watershed and high shoreline development. Previous studies have found watershed agricultural activity to be a key factor driving lake nutrient concentrations (Arbuckle and Downing 2001; Zampella et al. 2007). However, examining land use in the Kawartha lakes, we found that only developed land use at the sub-watershed scale had a positive, significant relationship with TN, TP, and Chla, matching previous findings (Fraterrigo and Downing 2008; Howell et al. 2012). Despite the relatively low level of developed land in most of the study watersheds, there was still a detectable negative association with nearshore water quality.

Water from the Cameron Lake Dam–Fenelon River watershed feeds the rest of the study lakes, but its water quality profile was significantly different from every other watershed except the Talbot River–TSW, the only other watershed that is not also fed by Lake Scugog. Lakes in the Cameron Lake Dam–Fenelon River watershed had much lower concentrations of nutrients compared with the lakes downstream of Lake Scugog. This difference in nutrients may indicate an outsize influence of Lake Scugog on downstream lakes in the eastern portion of the TSW. These findings show the importance of a lake's position in a hydrologically connected system for determining nutrient concentrations, which is similar to what previous work has found (Soranno et al. 2015).

4.3. Annual nutrient trends

Nutrient concentrations also varied annually in the four lakes studied from 2019 to 2021. The PCA explained 60.7% of the variation in the data with the first two axes; however, there was a high amount of overlap in the ellipses for each year, indicating there was not much difference in water quality between years. When inter-annual variation in TP, ammonia/ammonium, and nitrates was further explored, some patterns emerged. We hypothesized that there would be a difference in nutrient concentrations between pre-pandemic (2019) and pandemic (2020 and 2021) years due to the notable changes in human behaviour that included increased septic use. Only ammonia/ammonium concentrations followed this pattern, with concentrations significantly higher in 2019 than in 2020 and 2021. In agriculture-dominated watersheds, fertilizer and manure from farming operations are common sources of ammonia/ammonium. However, farming activities did not decline but surged during the pandemic as an essential activity (Statistics Canada 2022). Since we only had data from one pre-pandemic year in this study, we lack the statistical power to confirm whether the lower ammonia/ammonium measured in 2020 and 2021 was an effect of the pandemic.

Precipitation is another important environmental factor to consider when interpreting inter-annual variation in nutrient concentrations, especially storm events, which can drive nutrients from the watershed into lakes. There was an increase in overall precipitation in the days before sample collection in 2021, but only nitrates had a corresponding increase in 2021 (Fig. 6). Fertilizers are a common source of nitrates, and the high levels of agricultural land use in the watersheds may play a role in determining nitrate concentrations. Alternatively, small-scale land use has also been shown to be important for determining nearshore water quality in this region (Smith et al. 2021). Shoreline septic systems and fertilizers used for gardening, combined with more hard surfaces, may be contributing to increased surface runoff of nitrates. Finally, TP had significantly lower concentrations in 2021 than in 2019 and 2020, which was the opposite of precipitation trends. This is an interesting finding since other studies have shown precipitation to be an important driver of phosphorus in surface waters (Fraser et al. 1999; Hart et al. 2004). Overall, the similar phosphorus concentrations between 2019 and 2020 are in line with the community survey results, which indicated no change in the number of people or duration of stay at lake-front properties between 2019 and 2020.

4.4. Community science model

As previously mentioned, due to the closure of research laboratories in the summer of 2020, this study would not have been possible without volunteer community scientists. Furthermore, the dedication of the volunteers in this study resulted in an exceptionally high participation rate of 95% of samples returned. In comparison, other water monitoring studies have much lower participation rates: Freshwater Watch–Toronto reported a participation rate of 24%, and Alabama Water Watch reported a participation rate of 26% (Deutsch and Ruiz-Córdova 2015; Scott and Frost 2017). Even a smaller scale project based in Saskatchewan had a 67% participation rate for six volunteers collecting samples over 4 months (Bos et al. 2019).

It is not clear why the participation rate for this project was so high, although there are two differences between this study and those with lower participation rates: the involvement of local community groups and timing. By working with local environmental community groups, we were able to recruit volunteers who already had an interest in learning about their lake. We made it clear that volunteers would benefit from getting access to study results and information on protecting the health of their lake in a final report. Additionally, as waterfront property homeowners, volunteers had an economic incentive to keep their lake healthy, which may have provided further motivation to participate in the project. The timing of this project, the summer of 2020, also likely impacted the participation rate; many people's work and personal schedules changed during this time. Work schedules changed with some industries closing and others mandating work-from-home, and many recreational activities and travel plans were cancelled due to public-health restrictions, resulting in more time to devote to other activities. It has been found that popular community science programs, like iNaturalist and eBird, experienced increases in participation in the spring of 2020 (Crimmins et al. 2021). However, other studies have found an increase in barriers to community science participation during the pandemic (Lynch and Miller 2023). Although it is not clear whether the timing of this study contributed to the high participation rate, it was designed to keep barriers to access low, with the exception of volunteers needing lakefront access. Organizers worked closely with volunteers to address any potential issues (i.e., access to drop-off depots).

In summary, this study did not detect a significant signal in lake nutrient patterns associated with the COVID-19 pandemic. In effect, the anthropause did not appear to cause a change in nearshore nutrient conditions across the Kawartha Lakes region. The lack of signal from the pandemic indicates that the positive environmental impacts of lockdown measures seen in other studies may be restricted to more densely populated areas, where changes in industrial activity, tourism, and transportation have greater impacts on the environment. In rural areas, like the Kawartha Lakes, consistent agricultural activity and continued domestic tourism (Giunta 2020) resulted in no detectable impact of the pandemic on nearshore water quality. Even though we did not detect an impact of the pandemic on nutrient concentrations, this study serves as a successful example that environmental monitoring can, and should, continue throughout major social disturbances such as pandemics. Community science proved to be an effective monitoring approach due to the dedication of local volunteers and collaboration between regional organizations and university researchers. By monitoring these lakes during the summer of 2020, a large water quality data gap was filled, and new findings about regional nutrient patterns were uncovered. We recommend that lake managers consider developing robust community science programs in their jurisdictions to add built-in resiliency to their annual lake monitoring programs.

Acknowledgements

The authors acknowledge the lands and people of the Mississaugas of Scugog Island First Nation, for whose traditional territory this study was conducted. We are thankful to be welcomed on these lands in friendship. These lands are covered under the Williams Treaties and are the traditional territory of the Mississauga, a branch of the great Anishinaabeg Nation, including Algonquin, Ojibway, Odawa, and Pottawatomi. Thanks to the Kawartha Lake Stewards Association for their help in recruiting volunteers and connecting researchers to the local community. Thanks to Gary Pritchard, who connected us to Curve Lake First Nation, and to all the community scientists for their contributions to this study. Finally, we would like to thank the Ontario Tech University Research Ethics Board (REB) for taking the time to review and provide feedback on the online survey, which they approved on 29 May 2020 (REB# 15910).

Article information

Editor

Irene Gregory-Eaves

History dates

Received: 10 January 2023
Accepted: 7 July 2023
Version of record online: 12 October 2023

Copyright

Data availability

The datasets generated for this study are available upon request.

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Funding information

Funding for this project was provided by a Natural Sciences and Engineering research Council (NSERC) Discovery Grant to AEK (RGPIN 246150).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Supplementary material

Supplementary data are available with the article at https://doi.org/10.1139/facets-2023-0004.

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