Revisiting the influence of top-down and bottom-up pressures on Wa hia hé:ta (yellow perch *Perca flavescens* Mitchill, 1814) population dynamics in Kaniatarowanenneh (the Upper St. Lawrence River): Implications for collaborative research

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Abstract

Kaniatarowanenneh (St. Lawrence River) is the outflow of one of the world's largest freshwater ecosystems and its ecological health has implications for resource management. The population dynamics of an ecologically and economically important fish, the Wa hia hé:ta, Mohawk for yellow perch (*Perca flavescens* Mitchill, 1814), are considered by including data that extends to the past century to redress temporal gaps in comparative literature. We found both a significant top-down effect from piscivorous fish as well as a significant bottom-up effect related to total phosphorus on yellow perch relative abundance in the Lake Ontario-Upper St. Lawrence system. Regarding the bottom-up effect, the current state of yellow perch reflects the population size prior to cultural eutrophication (pre-1940s/50s) likely responding to the re-oligotrophication of the system. These findings emphasize the importance of considering historical records in fish population dynamics research to incorporate shifting population baselines into fisheries management. The study also demonstrates the need for collaborative approaches that bring critical new insights and multivocality.

Keywords: fisheries, shifting baseline syndrome, nutrients, predator-prey, Great Lakes

Résumé

Kaniatarowanenneh (fleuve Saint-Laurent) est l'exutoire de l'un des plus grands écosystèmes d'eau douce du monde et sa santé écologique a des implications pour la gestion des ressources. La dynamique de la population d'un poisson important sur le plan écologique et économique, Wa hia hé:ta (perchaude ou *Perca flavescens* Mitchill, 1814 en mohawk), est examinée en incluant des données qui remontent au siècle dernier afin de combler les lacunes temporelles dans la littérature comparative. Nous avons constaté un effet *top-down* significatif des poissons piscivores, ainsi qu'un effet *bottom-up* significatif lié au phosphore total sur l'abondance relative de la perchaude dans le système du lac Ontario et du haut Saint-Laurent. Concernant l'effet *bottom-up*, l'état actuel de la perchaude reflète la taille de la population avant l'eutrophisation culturelle (avant les années 1940 et 1950) et répond probablement à la réoligotrophisation du système. Ces résultats soulignent l'importance de prendre en compte les données historiques dans la recherche sur la dynamique des populations de poissons afin d'intégrer les changements dans la population de référence dans la gestion des pêches. L'étude démontre également le besoin d'approches collaboratives qui apportent de nouvelles perspectives critiques et de la plurivocité.

Mots clés : pêcheries, syndrome de changement de base de référence, nutriments, prédateurs-proies, Grands Lacs

Introduction

In the Great Lakes-St. Lawrence system, community engagement is considered necessary for the future health of the basin (Krantzberg et al. 2014). In 2018, the St. Lawrence River Institute of Environmental Sciences in partnership with the Mohawk Council of Akwesasne's Environment Program began pursuing answers to community-driven questions about the health of Kaniatarowanenneh (the Upper St. Lawrence River). This initiative, called the “Great River Rapport” (https://riverrapport.ca/), is a collaborative project that engages community members, both Indigenous and Non-Indigenous, and their knowledges to contribute to the understanding of the health of the river. Community consultations from 2018 to 2020 culminated in yellow perch *Perca flavescens* Mitchill, 1814 populations being selected as one of 35 ecological indicators for further research. For Indigenous People, the Wa hia hé:ta or yellow perch are recognised as a being with agency that carry important roles and responsibilities to the Kanienkehaka and were identified as a species of concern in Kaniatarowanenneh through engagement with local communities. Indeed, yellow perch populations have declined in regions of the Upper St. Lawrence River over the past 50 years (e.g., the Thousand Islands, Resseguie and Gordon 2020a). Declines have also been reported in other areas of the Great Lakes (e.g., Lake Huron, Fielder 2008; Lake Michigan, Marsden and Robillard 2004). These temporal declines are concerning because yellow perch hold ecological, cultural, and economic importance in the region.

As of 2020, the species is the most abundant pelagic fish, the most targeted and harvested species fished recreationally, and contributes the highest biomass of all species caught commercially in Kaniatarowanenneh (OMNRF 2019; OMNRF 2021). These fish are associated with vegetated shorelines throughout the growing season, which provide cover and suitable spawning habitat for the species (Krieger et al. 1983; Brown et al. 2009). Yellow perch are voracious consumers of lower trophic prey (Brown et al. 2009). Their diets can vary ontogenically with a switch from zooplankton to benthic macroinvertebrates and fish when reaching larger size ranges (Scott and Crossman 1973; Brown et al. 2009). Yellow perch are major prey of walleye *Sander vitreus* Mitchill, 1818 and other piscivorous fish including smallmouth bass *Micropterus dolomieu* Lacepède, 1802 and northern pike *Esox lucius* Linnaeus, 1758 in the Great Lakes (Scott and Crossman 1973; Hoyle et al. 2017; Pothoven et al. 2017). They are also major prey of piscivorous birds such as the double-crested cormorant *Phalacrocorax auritus* Lesson, 1831 (Johnson et al. 2015), osprey *Pandion haliaetus* Linnaeus, 1758 (Dunstan 1974) and bald eagle *Haliaeetus leucocephalus* Linnaeus, 1766 (Van Daele and Van Daele 1980). Yellow perch therefore play an integral role in supporting Great Lakes-St. Lawrence food webs but continue to be subjected to multiple anthropogenic pressures.

Based on the biological and physicochemical characteristics of the Lake Ontario system (i.e., relatively species rich and warm water), theoretically, the food webs should be regulated by both bottom-up and top-down pressures (Frank et al. 2007). However, a previous study of Lake Ontario found no evidence of bottom-up controls and only limited evidence of top-down controls, but this study did not include yellow perch and was temporally limited to ~ a decade of data (Bunnell et al. 2014). There are several potential factors that may be contributing to yellow perch declines in the Lake Ontario-St. Lawrence system, including competition (e.g., with round goby *Neogobius melanostomus* Pallas, 1814, Duncan et al. 2011), predation from species such as double-crested cormorants (Burnett 2002), land use changes and dynamics in productivity

(Hudon et al. 2011; Giacomazzo et al. 2020), as well as shoreline hardening and overharvesting (Mailhot et al. 2015; Magnan 2020). While some studies have investigated the potential drivers of yellow perch declines in other regions of the Great Lakes (e.g., see Marsden and Robillard 2004; Fielder 2008), no research to our knowledge has focused on the specific declines recorded in the Lake Ontario-Upper St. Lawrence River interface. It is important to understand how the above-mentioned factors affect yellow perch populations given the sensitivity of this species in the river. For instance, a large fluvial lake in the lower reaches of Kaniatarowanenneh, Lake Saint-Pierre, has experienced a collapse of yellow perch stocks, thought to have been caused by changes in nutrient inputs from tributaries and overharvesting (Hudon et al. 2011; Mailhot et al. 2015; Magnan 2020). A complete moratorium of the yellow perch fisheries has been in place since 2012 in Lake Saint-Pierre to attempt to recover stocks but has unfortunately been unsuccessful to date as the current population size no longer supports sustainable recruitment rates (Hudon et al. 2011; Maillot et al 2015; Magnan 2020).

In Kaniatarowanenneh, long-term monitoring of fish communities was initiated in 1977 by the New York State Department of Environmental Conservation (NYSDEC) in the American portion of the Thousand Islands through a standardized annual gillnetting program (Resseguie and Gordon 2020a). In the 1980s, this program was expanded to monitor Canadian portions of the Upper St. Lawrence River (Resseguie and Gordon 2020b) along with additional gillnetting programs for the region initiated by the governments of Ontario (Ministry of Natural Resources and Forestry, OMNRF 2021) and Quebec (Ministère des Forêts, de la Faune et des Parcs, La Violette et al. 2003). The establishment of these long-term monitoring programs allowed for a better characterization of yellow perch population trends including the declines over the past several decades (e.g., 1977-2020, Resseguie and Gordon 2020a) and such data have been used to inform fisheries management decisions for the region.

In fisheries management, emphasis is often put on harvesting as a major anthropogenic force driving fish stocks, although the need for more holistic frameworks have been identified (Piczak et al. 2022). Specifically, incorporating historic information into present models would improve our understanding of the impact of fisheries on population stocks (Pauly 1995). The failure to do so often leads to misevaluations of what is a desirable state of the natural environment leading to ineffective management, contributing to shifting baseline syndrome which is often seen in fisheries (Soga and Gaston 2018). Through the 20th century, the Great Lakes experienced extensive cultural eutrophication (the excess of nutrients in a water body derived from anthropogenic activity); the fish monitoring programs in Lake Ontario and the Upper St. Lawrence River were initiated near the height of this phenomenon (i.e., in the 1970s; Schelske 1991). No research to date has assessed yellow perch population dynamics pre-1970s in the Lake Ontario-St. Lawrence River system. Commercial fishing records for the region do extend beyond fishery-independent assessments and while they can only be used as a proxy for population abundance trends (Pope et al. 2010), they have the advantage of dating estimates back to the early 1900s (Baldwin et al. 2018).

We drew on community concerns related to yellow perch population dynamics to determine the research questions of this project and the efforts to understand the datasets were a direct result of extensive consultation with diverse partners, including data providers, academics, government agencies, First Nations organisations and community members as well as local non-Indigenous community members. The goal of this study was to determine the state and drivers of yellow perch populations in the Lake Ontario-Upper St. Lawrence system through time. To reach this goal, we: (1) determined if commercial harvests data can be used as a proxy for yellow perch relative abundance, and (2) evaluated the impact of top-down (e.g., piscivorous predators) vs. bottom-up (e.g., total phosphorus) pressures on yellow perch populations at both historical and contemporary time frames. This paper is a first step to show the importance of extending the timeframe to include historic data to provide new insights into the health of Kaniatarowanenneh. We open a discussion on the need to conduct ecological research 'in a good way' (Reid et al. 2023) by engaging local and Indigenous community perspectives with their connection to the land and their deep and long knowledge to provide additional context to the scientific data currently considered in resource management.

Methods

Lake Ontario-St. Lawrence system

The Great Lakes-St. Lawrence system is one of the world's largest freshwater ecosystems, representing ~ 20% of the world's surface freshwater. More than 30 million people live along its shores, resulting in dramatic alterations to the system (Wuebbles et al. 2019). Lake Ontario is the smallest of the Great Lakes by area measuring 18 960 km^2 and has a drainage area of just over 60 000 km^2 (Theberge 1989). At Kingston (ON), Lake Ontario drains into Kaniatarowanenneh, the main natural outflow of the system. The Upper St. Lawrence River, between Kingston and Cornwall (ON), is approximately 180 km long and has a long-term average discharge of ~ 6 800 m^3/s (Lefaivre et al. 2016). Water quality conditions (in particular total phosphorus) in the main channel of the river are largely dominated by the influence of Lake

Ontario in the upper reaches (Farrell et al. 2010). Our data were derived from the Lake Ontario and Upper St. Lawrence River (Thousand Islands) portions of the system.

Gillnetting data

The catch per unit effort (CPUE) for our response variable, yellow perch, along with an indicator of top-down pressure, a piscivorous fish index, were collected through governmental index gillnetting programs. The piscivorous index represented the sum of walleye, northern pike and smallmouth bass CPUE to represent the top-down effect. These species were selected because they represent major yellow perch predators and detailed catch data were available. Yellow perch and the piscivorous fish index CPUE from 1977 to 2020 were obtained from the New York State Department of Environmental Conservation (NYSDEC) long-term fish monitoring dataset. NYSDEC initiated the long-term biomonitoring program in 1977 to track changes in fish communities in the American waters of the Thousand Islands (which is directly adjacent to the outflow of Lake Ontario) as part of their *Warmwater Fisheries Assessment* (Resseguie and Gordon 2020a). Every year between late-July and early-August, the NYSDEC deployed multi-panel gillnets measuring 61 m long by 2.4 m high, with mesh sizes of 38, 51, 64, 76, 89, 102, 127, and 152 mm, parallel to the shore at fixed locations. 16 gillnets were deployed annually from 1977-2020; additional gillnets were added to the sampling protocol in later years (1982), but we chose to exclusively use the data from the 16 original nets to ensure that there was no impact/bias of sampling location and unbalanced sampling design on the data (Fig. 1). In 2004, multifilament gillnets were updated to monofilament gillnets, and prior multifilament yellow perch catch data were corrected by a factor of 1.35 to account for these changes in gillnetting gear. The correction factor was derived from a paired net comparison (deploying both multi- and mono-filament nets at sites) that determined the extent of the discrepancy in gear on all fish species caught, in which there was a need to correct yellow perch CPUE, but no need to correct walleye, northern pike or smallmouth bass CPUE (Resseguie and Gordon 2020a). Approximately half of the gillnets were deployed in depths ranging from 3-10 m and the other half were deployed in deeper waters with depths ranging from 10.1-18.3 m. The CPUE was expressed as the number of yellow perch or the sum of walleye, northern pike and smallmouth bass (piscivorous fish index) caught per net night (Resseguie and Gordon 2020a).

Historic commercial harvests

The biomass (in lbs) of yellow perch commercial harvests for Lake Ontario and the Upper St. Lawrence River was obtained from 1913-2015 from Baldwin et al. (2018) (Fig. 2). The commercial harvests of piscivorous fish predators were used to assess the potential effect of top-down pressures on yellow perch commercial harvests. It combined both walleye (1918-2015) and northern pike (1913-2015) harvests obtained from Baldwin et al. (2018). Open-access data were available from the Lake Ontario-Upper St. Lawrence system in its entirety and could not be parsed out into different sections thus we treated the data source for the whole system (Baldwin et al. 2018).

Commercial harvests were from Lake Ontario and the New York waters of the St. Lawrence River from 1913 – 1941 and harvests from the Ontario waters of the St. Lawrence River were added for the years 1941 – 2015. Therefore, data from Lake Ontario and the Ontario and New York waters of the St. Lawrence River (which extend to the beginning of Lake St. Francis) were included in the analysis. Data originating from the Quebec portions of the Upper St. Lawrence River were not available therefore not included in this study. The commercial harvests data were rounded to the nearest thousand lbs (see Baldwin et al. 2018). The associated fishing effort data were not readily available for this dataset.

Total phosphorus (TP)

Both contemporary and historic total phosphorus data were obtained to describe the nutrient status of the system through time. To test the relationship between more contemporary total phosphorus concentrations and annual gillnetting data, we used the total phosphorus data from 1977-2019 collected by the Ontario Ministry of the Environment, Conservation and Parks (MECP 2020). Data included weekly total phosphorus concentrations (μg/L) from the head of the St. Lawrence River, measured at a depth of 10.5 m at the Kingston – King Street Water Treatment Plant (44.22211, -76.50279), directly upstream from the gillnet locations (Fig. 1). Measurements were not collected in the years 2013 and 2014, therefore these years were not included in the analyses. We calculated average July-August total phosphorus concentrations to match the yellow perch gillnet sampling periods (also sampled in July and August).

To test for temporal historic relationships, we used the estimated historic lake water total phosphorus concentrations for Lake Ontario derived from the sediment-inferred total phosphorus (SI-TP) model for the period 1913 to 1977 calculated by Moyle and Boyle (2021). The model was applied to a sediment phosphorus profile taken from the Rochester basin of Lake Ontario (Fig. 1, core G32; Schelske et al. 1988) using a site-specific apparent settling velocity (v=19; Chapra and Dolan 2012) to calculate the phosphorus retention coefficient (R_P). Moyle and Boyle (2021) calculated lake-wide total phosphorus concentrations by scaling the sediment core mass accumulation rates to an estimated basin-wide phosphorus burial rate from Kemp and Harper (1976). Based on the core dating, total phosphorus concentrations were estimated for intervals of

1-18 years (Moyle and Boyle 2021). Moyle and Boyle (2021) coupled the SI-TP data with published mean annual surface water monitoring data for the region collected from 1978-2010 by Chapra and Dolan (2012).

Analyses

All statistical analyses were computed in R (v. 4.2.2, R Core Team 2021) and RStudio (v. 2022.12.0, RStudio Team 2021).

Generalized Additive Models (GAMs) are widely used and represent a flexible regression-based method that relates response variables to predictors using smooth functions (Wood 2017). GAMs are appropriate statistical analyses to model non-linear trends in time series data (Simpson 2018). GAMs were used to 1) determine if commercial harvests data can be used as a proxy for yellow perch CPUE, and 2) determine the effect of piscivorous fish predators (i.e., top-down pressure) and total phosphorus (i.e., bottom-up pressure) on both yellow perch CPUE and yellow perch commercial harvests. GAMs were performed using the *mgcv* package v1.8-41 (Wood 2011). For objective 1, yellow perch CPUE was included as the response variable and the GAM included a thin plate spine for the yellow perch commercial harvests, a Duchon spline for the spatial effect of gillnet location, and a random smooth intercept to account for the year effect. For objective 2, two models were built following a similar framework but at different timescales. To assess the trends over more recent years (1977-2020), the first model included the yellow perch CPUE as the response variable. The thin plate spline was used for the piscivorous fish index CPUE and the contemporary total phosphorus for which modelled top-down and bottom-up pressures, respectively. Latitude and longitude smooth interactions using a Duchon spline was included in the model to account for the spatial effect of the gillnet location, and a random intercept smooth for year was applied to generalize the effect over time. The second model assessed the trends over a historical time scale. It included the yellow perch commercial harvests as the response variable and included a thin spline for the piscivorous fish predator commercial harvests and the historical total phosphorus, and a tensor product interaction to account for the explanatory variables' interaction.

A Tweedie error distribution was applied to all GAMs to account for the left-skewed distribution of the response variable. Maximum basis functions (k) were assessed using the gam.check function while model diagnostics were validated with the appraise function of the *gratia* package. All diagnostic plots suggest normality and homoscedasticity of the residuals (Figs. S1-S3). The absence of temporal autocorrelation was verified using the acf and pacf functions of the model residuals from the *stats* package (Figs. S4-S6). GAMs were visualized using the *mgcViz* package v0.1.9 (Fasiolo et al. 2018)

Results

For objective 1, there was a significant relationship between yellow perch commercial harvests and CPUE in the Lake Ontario-Upper St. Lawrence system (Table 1). There was a positive nearly 1:1 ratio between yellow perch CPUE and yellow perch commercial harvests up until harvests exceeded ~700 000 lbs per year, which then had a negative effect on yellow perch CPUE (occurring in ~10% of years from 1913 to 2010) (Fig. 3). For objective 2, both timescales (contemporary and historic) showed a significant effect of bottom-up and top-down pressures on yellow perch CPUE and commercial harvests (Tables 2, 3). From 1977-2020, the piscivorous fish index had a significant negative effect on yellow perch CPUE when the index reached ~ 20 CPUE (Fig. 4B). The same negative trend was detected at the historical timescale; the piscivorous fish predator commercial harvests displayed a negative relationship with the yellow perch commercial harvests (Fig. 5B). From 1977-2020, total phosphorus had a linear positive effect on yellow perch CPUE in the Thousand Islands (Upper St. Lawrence River) up to an approximate threshold of 20 μg/L, in which yellow perch CPUE plateaued (Fig. 4A). A similar trend was detected at the historical timescale from 1913-2010 where total phosphorus had a significant positive effect on yellow perch commercial harvests up to a threshold of approximately 15 μg/L after which a negative effect was detected (Fig. 5A). However, at high total phosphorus levels, the null effect was included in the confidence interval (Fig. 5A).

Discussion

We examined the driving factors influencing the population sizes of an ecologically, culturally and economically important fish in the Lake Ontario-Upper St. Lawrence system, the Wa hia hé:ta (yellow perch). We found evidence of both top-down predator-derived regulation (i.e., piscivorous fish) and bottom-up nutrient-derived regulation (i.e., total phosphorus) on yellow perch relative abundance in the system (Tables 2, 3, Figs. 4, 5). These findings align well with the theoretical framework developed by Frank et al. (2007), which hypothesized a mix of top-down and bottom-up pressures influencing food webs based on the characteristics of the Lake Ontario-St. Lawrence system. Our findings are however different from a study that found no evidence of top-down predator-derived regulation (i.e., biomass of piscivorous fish) or nutrient-derived bottom-up regulation (i.e., total phosphorus) on Lake Ontario food webs (Bunnell et al. 2014). However, the authors hypothesized that this was due to a lack of analysis of more historical data prior to 1998 (Bunnell et al. 2014). Our study also found some evidence of top-down controls related to the commercial harvesting of yellow perch in the system when a certain threshold (> 700 000 lbs) was reached (Fig. 3), but this extreme pressure was not common (occurring ~10 % of years). Our results indicate that historic commercial harvests data of the Lake Ontario-Upper St. Lawrence River may be used as a proxy for yellow perch relative abundance of the Thousand Islands section of the Upper St. Lawrence River, given the positive linear relationship between CPUE and harvests (up until 700 000 lbs harvested) from 1977-2015 (Fig. 3). We recognize that these relationships should be interpreted with caution as they relate data from different spatial scales, with the commercial harvests data originating from the entire Lake Ontario-Upper St. Lawrence River while the gillnetting monitoring data were restricted to the Thousand Islands section of the river. We also cannot conclude if there was a relationship between the gillnetting data and the commercial harvests data prior to the initiation of the gillnetting biomonitoring program specifically. However, we found an overall similar response of yellow perch gillnetting CPUE and yellow perch commercial harvests to predator-abundance and TP, which suggests that they do indeed follow similar trends through time in relation to the drivers (Figs. 4, 5).

We found a negative relationship between the number/biomass of piscivorous fish and yellow perch (Figs. 4B, 5B). Predation can contribute considerably to the overall mortality of larval and juvenile fishes (Hartman and Margraf 1993; Zhang et al. 2018). For example, in a large lake in New York (Oneida Lake), walleye consumed between 48-58% of ages 0-1 yellow perch (Van de Valk et al. 1999). In addition, yellow perch contributed between 1-31% of the diets of walleye in Lake Huron (Pothoven et al. 2017). Our results oppose those found in Bunnell et al. (2014) who found a bottom-up effect of prey fish abundance on piscivore biomass. However, Bunnell et al. (2014) did not include yellow perch and their predatory fish were salmonids (i.e., Lake Trout *Salvelinus namaycush* Walbaum in Artedi, 1792 and Chinook

Salmon *Oncorhynchus tshawytscha* Walbaum in Artedi, 1792) (Bunnell et al. 2014), which could explain some of the inconsistencies between our results. We found both top-down and bottom-up effects on the yellow perch (Tables 2, 3).

In the Lake Ontario-St. Lawrence system, our findings indicate total phosphorus as one of the main driving factors affecting yellow perch relative abundance over the study period. The decline in the yellow perch populations was part of the concerns raised by Akwesasne community members that also informed and shared their perspective on the identified drivers. The century-long commercial harvests data allowed us to uniquely demonstrate that current yellow perch populations likely reflect the population sizes that existed prior to cultural eutrophication, as we suspect as a response to the re-oligotrophication of the system (Figs. 2, 3, S7). The system has experienced considerable changes in productivity over the past century. Early trophic history of Lake Ontario, determined through paleolimnological records, indicate a meso-oligotrophic system between 1800 and mid-1900 in the early phases of European settlement, with moderate increases in total phosphorus after ca. 1850 from runoff and erosion due to land clearing (Schelske 1991). However, between the 1940s and the 1970s, records indicate a period of exponential anthropogenic nutrient enrichment (Schelske 1991) associated with increasing human population size around the basin and related impacts, such as the clearing of land associated with agricultural activities, the installation of domestic sewer systems, and the introduction of phosphate-based detergents (Chapra 1977). This period of increasing nutrient input to the lake shifted the system from meso-oligotrophic to meso-eutrophic (Fig. S7). Due to the degradation of water quality from the eutrophication of Lake Ontario as well as the other Great Lakes, a binational agreement between the USA and Canada (termed “The Great Lakes Water Quality Agreement”) was signed in 1972 to reduce phosphorus inputs in the Great Lakes.

Pelagic phosphorus targets originally established by the agreement were met in the 1980s across the Great Lakes (Hecky and DePinto 2020). Total phosphorus appears to have now decreased to levels lower than the historic estimates for Lake Ontario (Fig. S7, Moyle and Boyle 2021), likely due to the invasion of *dreissenid* mussels and associated effects of trapping nutrients in benthic areas, termed "benthification" (Hecky et al. 2004; Farrell et al. 2010; Mayer et al. 2014). The resulting shift in the trophic state of Lake Ontario and consequently, the Upper St. Lawrence River, has significantly impacted the ecology of the system, thus reshaping the biological carrying capacity of the river.

The relationship between total phosphorus and yellow perch population size is likely indirect and related to increased productivity of the system with higher nutrient levels. Productivity has been shown to affect the habitat quality (i.e., submerged aquatic vegetation and food sources) of yellow perch in Kaniatarowanenneh (Farrell et al. 2010; Hudon et al. 2011; Giacomazzo et al. 2020). Links between productivity and higher trophic levels have been previously established in Lake Saint-Pierre, a fluvial lake of the St. Lawrence River that is downstream of our study area (Hudon et al. 2011; Giacomazzo et al. 2020). Total phosphorus in Lake Saint-Pierre was positively associated with higher abundances of submerged aquatic vegetation, which were causally linked to higher yellow perch CPUE (Giacomazzo et al. 2020). Lower abundances of submerged aquatic vegetation have been hypothesized to decrease yellow perch survival (e.g., reduced shelter, predator-prey interactions, Giacomazzo et al. 2020). Significantly lower yellow perch biomass was found in sections of Lake Saint-Pierre with low total phosphorus and four times less macrophyte biomass than the mouths of nearby nutrient-rich tributaries (Hudon et al. 2011). In addition, invertebrate biomass was nine times lower at the oligotrophic sites compared to mesotrophic tributary mouths in Lake Saint-Pierre, with significantly less abundant gastropods, littoral zooplankton, oligochaetes and insects (Hudon et al. 2011). Summer zooplankton density also decreased with total phosphorus in the Thousand Islands region of the river from the 1970s-2000s (Farrell et al. 2010). Invertebrates (including zooplankton and benthic macroinvertebrates) are important food items for young-of-the-year (YOY) yellow perch (Brown et al. 2009). YOY yellow perch that do not reach a certain minimum size by the end of their first growing season are more likely to suffer size-selective mortality during winter (Post and Evans 1989). In our study, we found a positive relationship between total phosphorus and yellow perch CPUE (Fig. 4A). The effect of total phosphorus on yellow perch relative abundance plateaued when total phosphorus was > 20 µg/L, which is considered a eutrophic state in this system (based on the estimates from Chapra and Dobson 1981 for the Great Lakes). Eutrophication can have negative impacts on fish production through shifts in invertebrate communities leading to food limitations for the yellow perch (Hayward and Margraf 1987; Schaeffer et al 2000; Vander Zanden and Vadeboncoeur 2002).

Our analysis of commercial harvests and biomonitoring data demonstrated that the Upper St. Lawrence River has experienced baseline shifts in yellow perch stocks. Biomonitoring programs to assess fish communities in the Upper St. Lawrence River began in 1977 (Resseguie and Gordon 2020a). Prior to this period, exponential nutrient enrichment occurred throughout the basin and coincided with a period of peak yellow perch population size. Yellow perch populations have since declined considerably. Hence, the gillnet biomonitoring programs only captured the post nutrient-derived elevated carrying capacity and subsequent decline, therefore, are not representative of the more historic state of the Lake Ontario-Upper St. Lawrence system. Based on the historic commercial fishery harvests data, yellow perch populations have shifted in tandem with the trophic state of the system over the past century, but with a lag in time for nutrients to affect higher trophic levels (Figs. 2, 5A, S7). This assessment highlights the importance of understanding the variability in baseline carrying capacity in relation to trophic state to ensure sustainable fishery practice.

Failure to incorporate historic knowledge into contemporary models can lead to shifting baseline syndrome, which has been observed in fisheries across the globe (Pauly 1995; Soga and Gaston 2018). Evidence of shifting baseline syndrome is seen through an altered perception of the condition of the environment between generations (also referred to as "environmental generational amnesia" Kahn 2002) (for examples see Katikiro 2014; Sáenz-Arryo et al. 2005). Three main reasons have been identified to be causing the shifting baseline syndrome: (1) lack of data (including historic data dating back > 1 generation), (2) loss of interaction with nature, and (3) lack of familiarity with the environment (Soga and Gaston 2018). A European study has shown that most biomonitoring programs were initiated in the late 20th century, failing to capture the full extent of anthropogenic impacts to the natural system (Mihoub et al. 2017). This was also the case for the Upper St. Lawrence River, with gillnet biomonitoring programs starting in the 1970s-1990s (La Violette et al. 2003; Resseguie and Gordon 2020a; b; OMNRF 2021), which was within the height of many anthropogenic pressures to the system (i.e., cultural eutrophication). Our results demonstrate that the carrying capacity of yellow perch in the system has shifted twice over the past century, likely driven by bottom-up regulation (once due to cultural eutrophication and once due to re-oligotrophication). In 1984, the government of Ontario implemented the individual transferable quota system for commercial fisheries in the province, which allowed commercial harvests to be more readily tracked (Taylor et al. 2012). Based on available data, between 1993 and 2020, the commercial yellow perch quotas in the Upper St. Lawrence River have either been consistent (Thousand Islands [zones 1-5, 2-5], OMNRF 2021) or have increased over time (Lake St. Francis [zone 1-7], OMNRF 2021), despite the significant decrease in productivity to the system which, as shown in this paper, was associated with a reduction in the yellow perch carrying capacity. Constant or increased quotas/harvests coupled with environmental change reducing fishery stocks leads to production overharvests (harvests exceed biomass production in a given year) (Embke et al. 2019). Further research is needed in the Upper St. Lawrence River to investigate the effects of production overharvests in the region and potentially adjust fishery models accordingly.

Changes have been made to the recreational fisheries of the Upper St. Lawrence River, for example, in 2004 a catch limit was set for the Ontario portion of the river of 25-50 yellow perch per day, depending on the licence type (i.e., either conservation or sport fishing licence) (OMNRF 2004). However, yellow perch mortality rates associated with the recreational fishery still greatly outweigh that of the commercial fishery in parts of the Upper St. Lawrence River (e.g., Lake St. Francis, OMNRF 2021). Changes in fisheries management to incorporate shifting baselines are critical at this time given the known sensitivity of the yellow perch stocks to nutrients and overharvesting in the river (as seen by the population decline further downstream in Lake Saint-Pierre, Mailhot et al. 2015). In this study, we identified the historic baseline population for yellow perch in the Lake Ontario-Upper St. Lawrence system which reflects a population estimate closer to the present relative abundance of yellow perch in the river (Fig. 2). We encourage the incorporation of this baseline into the fisheries management of the region. These data do not exist in most locales and do not exist prior to European settlement, thus other methods to incorporate historic information are needed to allow adaptive fisheries management.

Implications for collaborative research along Kaniatarowanenneh (the St. Lawrence River)

This paper is an example of the type of research questions we can address using a reflexive and collaborative framework. The project forms part of a larger initiative which highlighted Wa hia hé:ta (yellow perch) population dynamics in Kaniatarowanenneh as of concern following extensive collaborations with rightsholders and stakeholders. Participation of collaborators throughout the analysis and interpretation of the data were central to the scientific findings. To address the questions raised through this collaborative approach, we relied on a variety of data sources, including historic data from sediment cores, commercial fisheries and biomonitoring programs. Despite various challenges in bringing disparate datasets together, the findings from this study demonstrate the benefits that can be realized from commitments to such endeavours, for important fish species, such as, in this case, yellow perch.

The standardization of biomonitoring programs across Kaniatarowanenneh would greatly benefit the region and reduce the current challenges of analyzing and interpreting the data across a spatial scale where data collection methods differ. Developing infrastructure for collaboration that is sustainable and “supportive” (meaningful relationship building) would advance the scientific programs along Kaniatarowanenneh. Collaborative structures must include Indigenous Communities and build meaningful relationships to avoid the hyper-mystification of Indigenous Identity and Knowledge. Such knowledge systems manifest in a variety of forms and pathways, that are both conceptual and tangible, and include a non-linear understanding of deep time. An approach of this nature can ensure that data gaps are filled and limited historical data are expanded upon, with input from communities that have long and meaningful cultural connections to the landscape.

Future research for this initiative will include studying the ecological connectivity of all aspects of Kaniatarowanenneh and contribute to the wellbeing of the Great River into the future.

We will work towards the development of methods that reflect the Kaswentha (Two-Row Wampum) teachings, which is a peace treaty between the Haudenosaunee and Dutch and reflects their mutual commitment to respecting each other's autonomy in perpetuity (Ransom and Ettenger 2001). The objective is not to subsume the two paradigms into each other. Instead, it is meant to inform our collaborative efforts and how these can improve the products of our different knowledge systems answering complex questions. This includes understanding how fish are connected to the land (e.g., shoreline hardening and agricultural runoff), birds (e.g., cormorants and eagles), invasive species (e.g., round goby, zebra mussels *Dreissena polymorpha* Pallas, 1771 and quagga mussels *Dreissena bugensis* Andrusov, 1897), and other aspects of the ecosystem, including communities of People, and how they will adapt to the challenges these present, along with challenges such as climate change.

The language to traverse these communications across paradigms has yet to be created, but the conversation is occurring and requires research, such as the current study, to show the potentiality and value embedded in this labour. We recommend developing a research framework that would benefit from local knowledges which have the potential to provide unique and important historical perspectives to protect Kaniatarowanenneh in the future.

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Competing Interests

The authors declare there are no competing interests.

Data Availability

Commercial fisheries data (Baldwin et al. 2018): http://www.glfc.org/great-lakes-databases.php

Annual total phosphorus data (MECP): https://data.ontario.ca/dataset/lake-water-quality-at-drinking-water-intakes

All other data was retrieved from data requests to authors

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Figure Captions

Fig. 1. The Lake Ontario-Upper St. Lawrence River (Thousand Islands) locations of the gillnet (n=16) surveys sampled by the New York State Department of Environmental Conservation (NYSDEC; Resseguie and Gordon 2020a), surface water total phosphorus measurements (sampled at the Kingston Intake centre, MECP 2020) and the sediment core location G32 (Schelske 1988) used to model historic total phosphorus concentrations (Moyle and Boyle 2021). Map created with ArcGIS Pro (v. 2.9.2) and World Light Gray Canvas Map (ESRI et al. 2021), projection NAD83.

Fig. 2. Yellow perch commercial harvests of Lake Ontario and the Upper St. Lawrence River (Ontario and New York waters) from 1913-2015. Data obtained from Baldwin et al. (2018).

Fig. 3. Generalized additive model (GAM) assessing the partial effect of yellow perch commercial harvests (x 1000 lbs) on the yellow perch relative abundance (CPUE), while accounting for spatial effect of gillnet location and the random effect of year. Shaded area indicates the 95% confidence interval, dashed line represents the null effect, and the rug plot (ticks on the x axis) are the observations of the predictor variables.

Fig. 4. Generalized additive model (GAM) assessing the effect of A) total phosphorus (TP; μg/L) and B) piscivorous fish (walleye, northern pike and smallmouth bass CPUE) on the yellow perch abundance (CPUE) while accounting for the random effect of year and the spatial effect of

gillnet location. Shaded area indicates 95% confidence interval, dashed line represents the null effect, and the rug plot (ticks on the x axis) are the observations of the predictor variables.

Fig. 5. Generalized additive model (GAM) assessing the effect of A) historical total phosphorus (TP; µg/L), and B) the effect of piscivorous predator commercial harvests (PPCH, x 1000 lbs) on the yellow perch commercial harvests (x 1000 lbs) while accounting for the interaction between historical total phosphorus and piscivorous predator commercial harvests. Shaded area indicates 95% confidence interval, dashed line represents the null effect, and the rug plot (ticks on the x axis) are the observations of the predictor variables.

Table 1. Statistical summary of the generalized additive model (GAM) of the effect Yellow Perch commercial harvest (x 1000 lbs) on the Yellow Perch relative abundance (CPUE) while accounting for the random effect of year, and the spatial effect of gillnet location. edf indicates the estimated degrees of freedom and Ref.df represents the residual degrees of freedom. Significant parametric (A) and partial effects (B) are indicated by *p*-values <0.05.

A. parametric coefficients	**Estimate**	**Standard Error**	**t-value**	***p*-value**
(Intercept)	2.70	0.05	54.41	<0.0001
B. smooth terms	**edf**	**Ref.df**	**F-value**	***p*-value**
s(Harvest)	3.01	3.34	16.50	<0.0001
s(Year)	20.62	37	1.34	<0.0001
s(Longitude, Latitude)	13.20	15	13.27	<0.0001
R^2-adjusted	**0.30**			
Deviance explained	**37.5**			

Table 2. Statistical summary of the generalized additive model (GAM) of the effect of total phosphorus (TP, μg/L) and piscivorous fish (Walleye, Northern Pike and Smallmouth Bass CPUE) on the Yellow Perch abundance (CPUE) while accounting for the random effect of year, and the spatial effect of net location. Edf indicates the estimated degree of freedom and Ref.df represents the residual degree of freedom. Significant parametric (A) and partial effects (B) are indicated by *p*-value <0.05.

A. parametric coefficients	**Estimate**	**Standard Error**	**t-value**	***p*-value**
(Intercept)	2.68	0.06	48.22	<0.0001
B. smooth terms	**edf**	**Ref.df**	**F-value**	***p*-value**
s(TP)	2.34	2.45	15.43	<0.0001
s(Piscivorous fish)	1.00	1.00	5.27	0.022
s(Year)	25.66	39.00	2.04	<0.0001
s(Longitude, Latitude)	12.91	15.00	13.15	<0.0001
R^2-adjusted	**0.30**			
Deviance explained	**37.9**			

Table 3. Statistical summary of the generalized additive model (GAM) of the effect of historical total phosphorus (TP, µg/L) and piscivorous predator commercial harvests (Walleye and Northern Pike, x1000lbs) on the Yellow Perch commercial harvests (x1000 lbs) while accounting for the interaction between historical total phosphorus and piscivorous predator commercial harvests (PPCH). Edf indicates the estimated degree of freedom and Ref.df represents the residual degree of freedom. Significant parametric (A) and partial effects (B) are indicated by *p*-value <0.05.

A. parametric coefficients	**Estimate**	**Standard Error**	**t-value**	***p*-value**
(Intercept)	5.80	0.08	74.03	<0.0001
B. smooth terms	**edf**	**Ref.df**	**F-value**	***p*-value**
s(TP)	3.54	3.84	12.61	<0.0001
s(PPCH)	1.88	2.26	25.66	<0.0001
ti(TP, PPCH)	2.84	3.69	2.47	0.0512
R^2-adjusted	**0.67**			
Deviance explained	**75.1**			

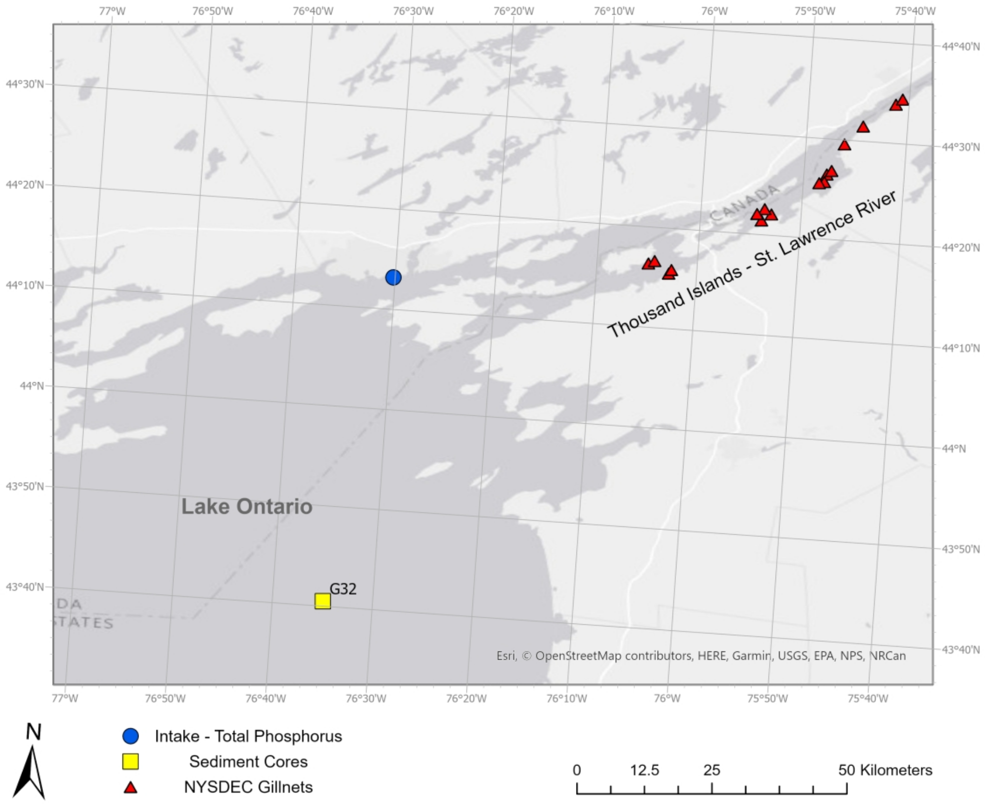

Fig. 1. The Lake Ontario-Upper St. Lawrence River (Thousand Islands) locations of the gillnet (n=16) surveys sampled by the New York State Department of Environmental Conservation (NYSDEC; Resseguie and Gordon 2020a), surface water total phosphorus measurements (sampled at the Kingston Intake centre, MECP 2020) and the sediment core location G32 (Schelske 1988) used to model historic total phosphorus concentrations (Moyle and Boyle 2021). Map created with ArcGIS Pro (v. 2.9.2) and World Light Gray Canvas Map (ESRI et al. 2021), projection NAD83.

228x190mm (400 x 400 DPI)

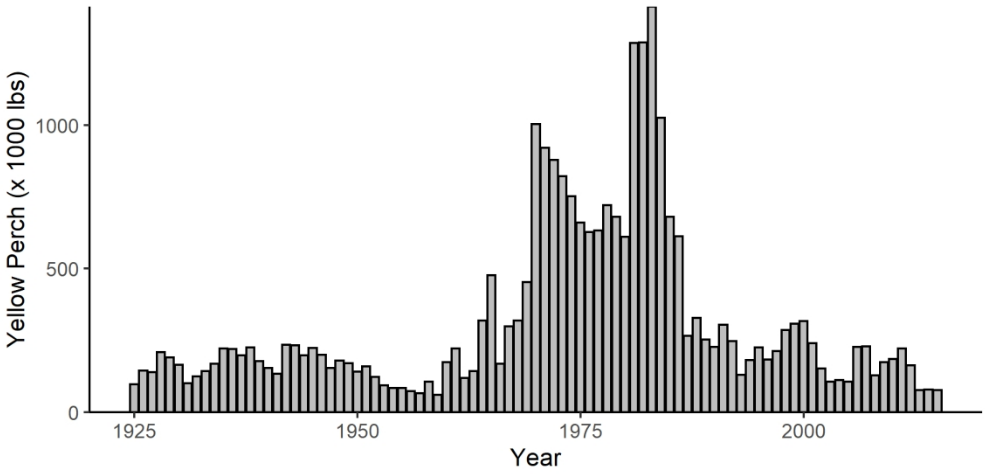

Fig. 2. Yellow perch commercial harvests of Lake Ontario and the Upper St. Lawrence River (Ontario and New York waters) from 1913-2015. Data obtained from Baldwin et al. (2018).

408x197mm (118 x 118 DPI)

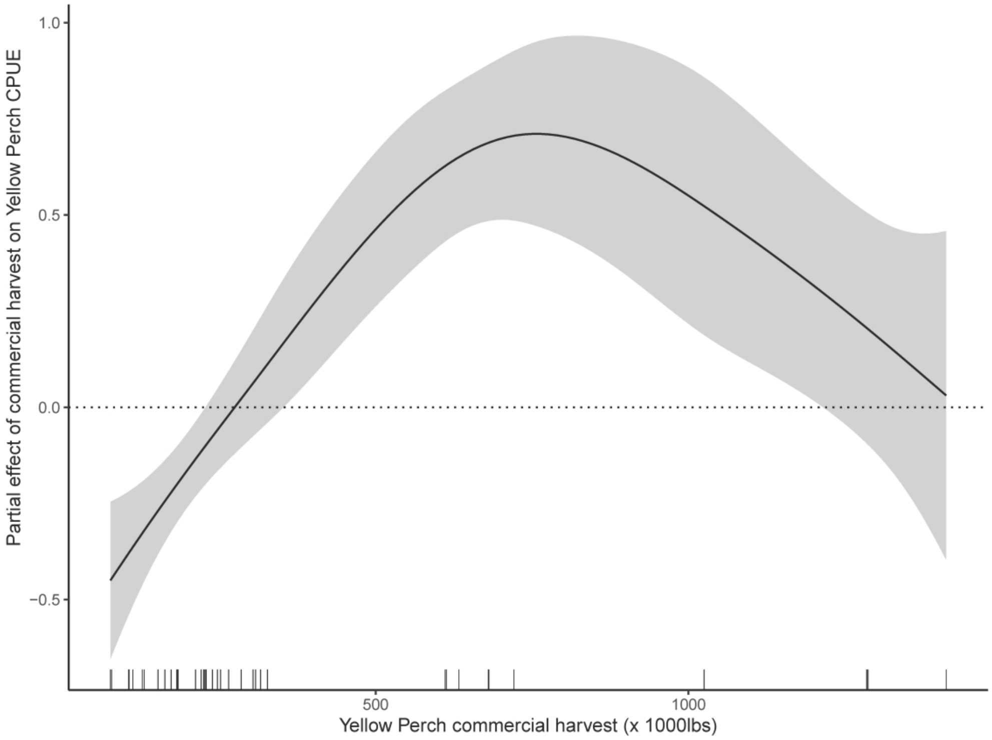

Fig. 3. Generalized additive model (GAM) assessing the partial effect of yellow perch commercial harvests (x 1000 lbs) on the yellow perch relative abundance (CPUE), while accounting for spatial effect of gillnet location and the random effect of year. Shaded area indicates the 95% confidence interval, dashed line represents the null effect, and the rug plot (ticks on the x axis) are the observations of the predictor variables.

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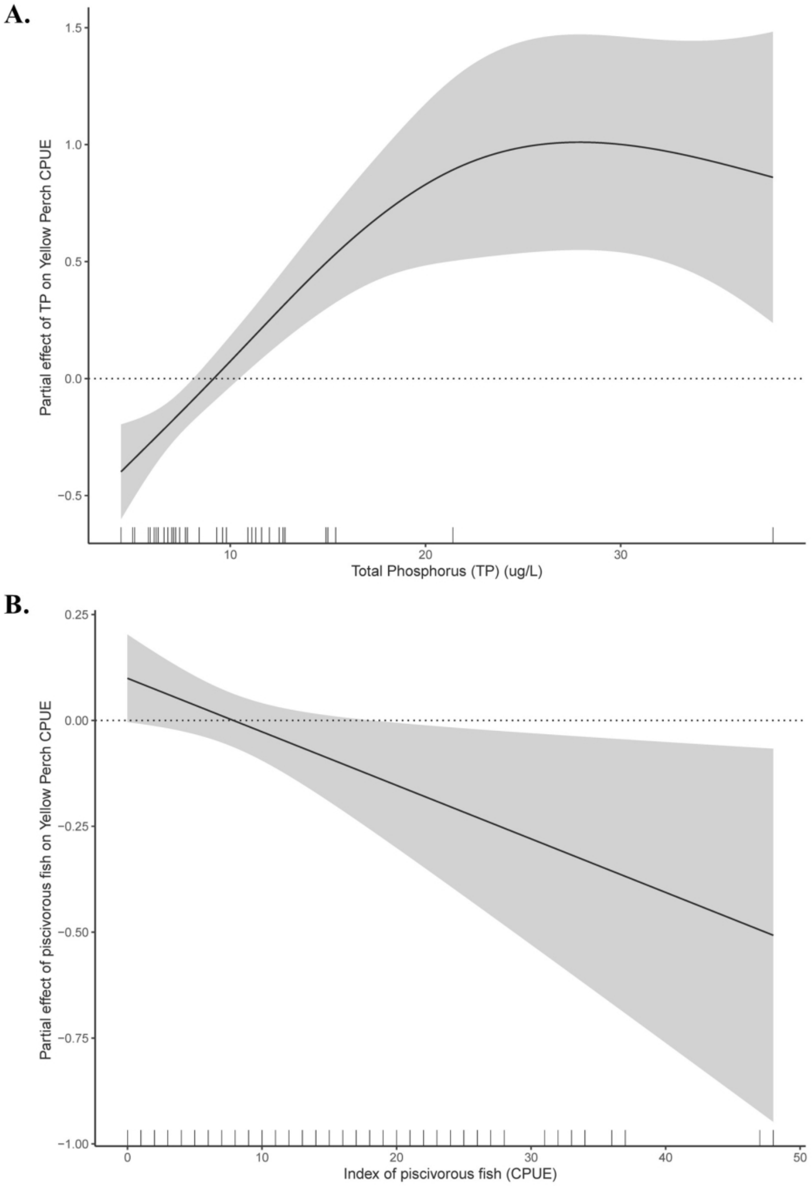

Fig. 4. Generalized additive model (GAM) assessing the effect of A) total phosphorus (TP; µg/L) and B) piscivorous fish (walleye, northern pike and smallmouth bass CPUE) on the yellow perch abundance (CPUE) while accounting for the random effect of year and the spatial effect of gillnet location. Shaded area indicates 95% confidence interval, dashed line represents the null effect, and the rug plot (ticks on the x axis) are the observations of the predictor variables.

126x184mm (330 x 330 DPI)

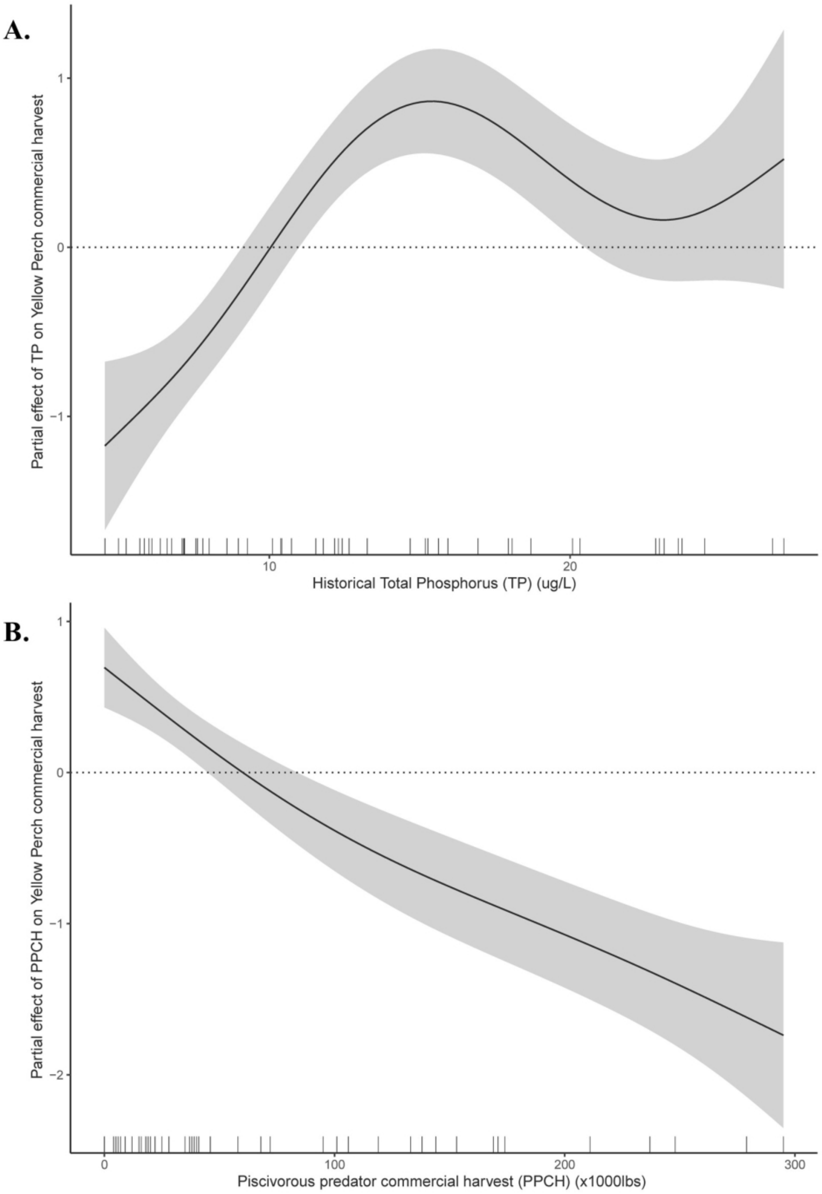

Fig. 5. Generalized additive model (GAM) assessing the effect of A) historical total phosphorus (TP; µg/L), and B) the effect of piscivorous predator commercial harvests (PPCH, x 1000 lbs) on the yellow perch commercial harvests (x 1000 lbs) while accounting for the interaction between historical total phosphorus and piscivorous predator commercial harvests. Shaded area indicates 95% confidence interval, dashed line represents the null effect, and the rug plot (ticks on the x axis) are the observations of the predictor variables.

125x179mm (330 x 330 DPI)