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Paleolimnological proxies reveal continued eutrophication issues in the St. Lawrence River Area of Concern

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ABSTRACT

Recent surface-water surveys suggest that high nutrient concentrations and nuisance algae remain issues in the St. Lawrence River Area of Concern (AOC) at Cornwall, Ontario, specifically in the tributaries and nearshore zones of Lake St. Francis (LSF). In particular, it is unclear whether management actions designed to reduce nutrient inputs, first implemented in the 1990s as part of the Remedial Action Plan for the AOC, have reduced algal production or influenced assemblage composition. To address this issue, a paleolimnological approach was used to provide a historical context for the present-day nutrient concentrations and to quantify the extent of change in water quality in LSF since the early 1990s. A sediment core was collected near the north shore of LSF and was examined for changes in the concentrations and compositions of fossil diatoms and pigments, as well as stable isotope ($\delta^{15}N$ and $\delta^{13}C$) values. Analyses of diatom and pigment concentrations indicated that overall algal abundance has risen in the last few decades, including trends of increasing occurrences of potentially toxic cyanobacteria, despite ongoing remediation efforts. Temporal patterns of stable isotope signatures in the core suggest a steady increase in nutrient influx since the mid-20th century, with the post-1990 increase in algal production likely attributable to recent inputs associated with land-use changes in local contributing watersheds. These patterns suggest that the AOC delisting goals for the LSF tributaries will not be reached without a drastic change in land management practices.

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Introduction

Within the Laurentian Great Lakes Basin, 43 Areas of Concern (AOCs) have been identified by the International Joint Commission as regions that have experienced environmental degradation as a result of biological, chemical, or physical changes in the aquatic ecosystem (Dreier et al., 1997; International Joint Commission, 2003a). The St. Lawrence River near Cornwall, ON, and Massena, NY, is the easternmost AOC where environmental issues arose from intensive industrial and agricultural activities, habitat loss and degradation, as well as from hydrodynamic changes from anthropogenic modifications to the waterway such as the construction of the St. Lawrence Seaway (Anderson et al., 1992). Two Remedial Action Plans (RAPs) were developed for the St. Lawrence River AOC at Cornwall and Massena, serving to identify and remediate beneficial use impairments (BUIs; International Joint Commission, 2012) in the Canadian and U.S. portions of the AOC, respectively. Within the Canadian section of the AOC, many of the identified environmental stressors have been mitigated through regulations and local action, including reductions in the concentrations of harmful bacteria, improved management of fish populations, and restrictions on industrial discharges to the waterway (Environment Canada and Ontario Ministry of the Environment, 2010). However, three BUIs remain impaired in this AOC, including eutrophication and the presence of undesirable algae (e.g., toxic cyanobacterial blooms), a problematic issue in the nearshore zones and tributaries of the fluvial lake known as Lake St. Francis (LSF; Environment Canada and Ontario Ministry of the Environment, 2010).

Increased nutrient loadings from the LSF watersheds, faulty septic systems in nearshore communities, changes to the hydraulics of the system from seaway construction, and climate change have all been suggested as contributing sources of the nuisance eutrophication and algal blooms in the AOC (Anderson et al., 1992; The St. Lawrence River (Cornwall) RAP Team, 1995). Although only 5% of the water in LSF originates in its tributaries (Anderson et al., 1992), the large proportion of agricultural land in the contributing watersheds could disproportionately affect nutrient loadings to LSF and impair water quality in

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nearshore areas. Remediation goals for eutrophication in the AOC originally included mean summer tributary and nearshore total phosphorus (TP) concentrations ≤30 μg/L and no eutrophication-related fish kills (Dreier et al., 1997). The targets for TP concentration in the tributaries were updated in 2009 to reflect proportional goals based on the amount of agricultural activity in each watershed, ranging from 35 to 60 μg/L (AECOM Canada Ltd., 2009; J. Ridal, pers. comm.). The TP target for the main body of LSF, beyond the 2-m isopleth, remains at 20 μg/L and is not currently considered impaired.

Since the early 1990s, efforts to reduce eutrophication in LSF have primarily targeted nutrients emanating from local farms and those from the city of Cornwall. Actions have included tributary restoration programs (including tree planting along tributary banks and fencing to restrict cattle access to streams), upgrades to septic systems, reductions in agricultural runoff through the Nutrient Management Act (2002), upgrades to the city of Cornwall wastewater treatment plant, and reductions in the number of combined sewers in the city of Cornwall (Environment Canada and Ontario Ministry of the Environment, 2010). Unfortunately, monitoring of the water-quality and ecological responses to these actions has been limited, hampering the ability to assess potential eutrophication declines in LSF. Monitoring data for both TP and algal abundance and community structure are sparse prior to the last decade (Pilon and Chrétien, 1991; Reavie et al., 1998; Richman et al., 1997), and it remains unclear if and how algal communities in the tributaries and nearshore zones of LSF have responded to remedial actions.

Provided that the sediment has remained relatively undisturbed, paleolimnological approaches can be applied to LSF to examine how algal assemblages have responded to the implementation of the RAP, and how those communities have changed over time. Previous paleolimnological characterisations of the eastern end of LSF, collected in the early 1990s, suggested that diatom communities responded to the known period of eutrophication in the Great Lakes in the mid-20th century, and additionally responded to well-documented macrophyte growth in the region (Reavie et al., 1998). However, less is known about historical changes in other groups of primary producers, including potentially toxin-producing cyanobacteria such as *Anabaena* and *Microcystis* (Carmichael, 2001), occurrences of which have been reported in this region in recent years (Bramburger, 2014; Waller et al., 2016). Paleolimnological techniques have been successfully applied to other AOCs (e.g., Alexson et al., 2017; Dixit et al., 1998), providing valuable information to stakeholders regarding historical environmental changes to the impacted systems.

The objective of the current study is to assess the degree to which the abundance and composition of algal communities in the nearshore areas of LSF have changed since the implementation of the RAP in the early-1990s. Although some surface-water sampling has been conducted in recent years, the response of algal assemblages to actions implemented as part of the RAP has not been examined, despite ongoing concerns regarding high nutrient concentrations and algal blooms in the AOC, including occurrences of toxin-producing cyanobacteria (Bramburger, 2014; Environment Canada and Ontario Ministry of the Environment, 2010; Savard et al., 2013, 2015). To address this issue, we quantified sedimentary concentrations of photosynthetic pigments known to reliably indicate historical changes in abundances of primary producers (Hall et al., 1999; Leavitt and Findlay, 1994), fossil diatom assemblages to infer past environmental conditions along the impacted northern shore of LSF (Battarbee et al., 2002; Reavie and Edlund, 2010), and carbon (C) stable isotopes to evaluate temporal changes in production and C sources (Hodell and Schelske, 1998; Savage et al., 2010). In addition, stable isotopes of nitrogen (N) were used to infer historical changes in nutrient sources arising from changes in aquatic production (N_2 fixation), agriculture within the watershed, or regional urban development (Bunting et al., 2016; Leavitt et al., 2006). These proxies can be used to provide a comprehensive overview of changes to algal abundance, production, and composition, suitable to evaluate water quality status. This information is valuable to the St. Lawrence River AOC, as beneficial uses must be restored to all 14 BUIs prior to delisting (International Joint Commission, 2012), including reductions in symptoms of eutrophication and the presence of undesirable algae.

Methods

Study area

The St. Lawrence River at Cornwall, Ontario, Canada, marks the eastern end of the international section of the waterway and is located just downstream of the Moses-Saunders Power Dam. East of the city of Cornwall, the river widens into Lake St. Francis for 50 km before narrowing again as it passes around Grande-Île, near Salaberry-de-Valleyfield, Quebec (Fig. 1a). Lake St. Francis covers approximately 233 km^2, with a mean depth of 6 m (maximum 26 m), short hydraulic residence time (3 days) and a total volume of 2.8 km^3 (Anderson et al., 1992; Fortin et al., 1994). Water level is controlled in this portion of the St. Lawrence River by the Moses-Saunders Power Dam upstream and the Coteau works and Beauharnois hydroelectric generating station downstream (Anderson et al., 1992). Water levels in the St. Lawrence River are regulated by the International Joint Commission to stabilise Lake Ontario and to ensure adequate capacity for navigation, hydroelectric power generation, and flood control (Yee et al., 1990). In LSF, Hydro Quebec manages the downstream discharge through the Beauharnois dam such that water level variation is typically <20 cm (Morin and Leclerc, 1998). Approximately 95% of the flow in LSF comes from Lake Ontario, with the remainder originating from tributaries on the north and south shores (Anderson et al., 1992). Little mixing occurs across the main shipping channel, which divides the north and south portions of LSF, each of which is differently influenced by local inflow tributaries (International Joint Commission, 2003b). As a result, the main channel and the flows north and south thereof can be considered to be three distinct water bodies (Dreier et al., 1997). On the northern shore, nine Ontario watersheds drain into LSF, the largest of which, the Raisin River watershed, covers over 500 km^2 (Fig. 1b, c). Across the northern watersheds, the dominant agricultural products are corn and soybeans, accounting for 15% and 14% of land use, respectively, with other dominant land cover including forest (43%), pasture and forages (15%), and urban and developed areas (8%; 2015 annual crop inventory data from Agriculture and Agri-Food Canada, 2016, http://open.canada.ca/data/en/dataset/3688e7d9-7520-42bd-a3eb-8854b685fef3, accessed 25 July 2017).

In the deep, fast-flowing channels of the river, sedimentation does not reliably occur (Carignan and Lorrain, 2000), making the collection of a sediment core representative of past conditions unlikely from deeper sites. Several areas in LSF also have been disturbed previously by dredging activities when the shipping channel was created as part of the construction of the St. Lawrence Seaway in the 1950s (Morin and Leclerc, 1998); such areas were avoided for the current study to ensure a continuous, undisturbed sedimentary record. In the AOC, five sedimentation basins have been described (Lorrain et al., 1993), two of which are on the northern side of the main channel of the St. Lawrence River and are likely to be influenced by flows from the northern tributaries. Sediment cores with reliable, continuous dating profiles have previously been collected from both of these basins (Carignan and Lorrain, 2000). The more westerly of these two basins, located just east of Lancaster, Ontario, is in a portion of the river that has seen extensive water-quality monitoring take place since 2010 (Bramburger, 2014; Savard et al., 2013, 2015). Both the availability of recent monitoring data and the known sedimentation characteristics of the basin influenced the selection of this site for sample collection.

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