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Spatiotemporal patterns of water quality in Lake Ontario and their implications for nuisance growth of *Cladophora*

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ABSTRACT

This study, motivated by a resurgence in *Cladophora*, investigates changes in the nutrient environment in the littoral zone of Lake Ontario. We measured nutrient concentrations from 2004 to 2008 at two littoral zone (2–12 m) sites on the north shore of Lake Ontario where *Cladophora* has experienced a resurgence and compared concentrations with data collected in the late 1970s. Spring total phosphorus (TP) and soluble reactive P (SRP) concentrations have significantly declined at these two sites. Furthermore, P loading from the major tributaries to our study sites declined between 1964 and 2008. Upwelling events were not detectably associated with increases in P concentrations at our sites. We conclude that a recent upsurge in nuisance *Cladophora*, at least at these sites, cannot be explained by deteriorating littoral zone water quality in terms of P concentrations or by changes in catchment loading. For additional context, we also examined trends in coastal (14–20 m) and offshore (>50 m) nutrients using Environment Canada epilimnetic surveillance data, 1975–2008. Significant declines in TP and SRP concentrations have occurred in north coast waters, concurrent with declines in the offshore. However, nutrient concentrations, notably spring SRP, have not decreased among south coast stations, potentially reflecting greater coastal entrapment of catchment-derived waters. We infer that EC-monitored north coast stations reflect integrated interannual water quality, while south coast stations are more strongly influenced by catchment loading. The effects of higher nutrient concentrations along the south coast, which co-occur with lower water transparency, on benthic algal growth have yet to be determined.

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Introduction

Accelerating eutrophication of the lower Great Lakes through the 20th century led to noxiously high algal abundance by the 1960s and 1970s, especially in coastal regions. Although allochthonous nutrient loads to the lakes, identified as the primary drivers of eutrophication, were supplied to nearshore areas via point and nonpoint sources, the effects of eutrophication were manifest lake-wide. In offshore areas of Lake Ontario, excessive nutrient concentrations led to frequent and potentially harmful phytoplankton blooms, while in coastal zones, excessive lake-wide nutrient concentrations caused phytoplankton blooms as well as benthic algal blooms, notably an overabundance of nuisance filamentous green macroalga *Cladophora glomerata* (Lean, 1987). Mandated reductions in point-source phosphorus loading to the Great Lakes were underway by 1975 and were successful in reducing Lake Ontario lake-wide spring total P concentrations by more than 1.0 μg L^{-1} $year^{-1}$ (0.032 μM $year^{-1}$) between 1973 and 1982 (Millard et al., 2003; Stevens and Neilson, 1987).

The success of the coordinated binational efforts to reduce eutrophication in the lower Great Lakes has justifiably been touted as one of the best examples of effective environmental stewardship and ecosystem rehabilitation (De Pinto et al., 1986). However, recent evidence has been mounting that benthic algae, particularly *Cladophora*, has again been increasing in the littoral zone of the lower Great Lakes over the past decade (Auer et al., 2010; Higgins et al., 2005, 2008) leading to concerns about changing nutrient conditions in shallow coastal areas.

In contrast to past decades, however, nutrient distribution patterns, especially in the lower Great Lakes, are now potentially affected by the presence of highly abundant suspension feeding bivalves. According to the nearshore shunt hypothesis (Hecky et al., 2004), invasive dreissenid mussels may be focusing nutrients to the benthos by efficiently filtering particles from the water column and redistributing them to the lake

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bottom through excretion of soluble nutrients and production of biodeposits (as feces and pseudofeces). In marine coastal systems, elevated dissolved nutrient concentrations have been measured above mussel beds (Aquilino et al., 2009; Pfister, 2007), and benthic suspension-feeding bivalves have been shown to increase nutrient retention in the benthos (Cloern et al., 2007). Previous work in a littoral zone study site on the north shore of Lake Ontario demonstrated that soluble reactive phosphorus (SRP), regenerated by a defined area of dreissenid mussels, exceeded that supplied directly from Sixteen Mile Creek and, moreover, exceeded the demands for seasonal *Cladophora* growth within that area (Ozersky et al., 2009). The establishment of dense mussel beds also appears to be mediating greater benthic secondary production (Johannsson et al., 2000). The ecosystem effects of dreissenid mussels are expected to be greatest in shallow nearshore areas, where mussels have maximal contact with the euphotic zone and where higher turbulence make particles available to suspension feeders. Before dreissenid mussel establishment, high nearshore nutrient concentrations supported abundant *Cladophora* growth, but there was also high export of suspended nutrients to the offshore, supporting noxious phytoplankton blooms. The nearshore shunt hypothesis predicts there is now continually greater sedimentation of nutrients in the nearshore, facilitated by mussel metabolism, causing persistently reduced suspended nutrient transport from the nearshore to the offshore.

Cladophora growth is expected to be affected by local nutrient supply, which may be influenced by both local and large-scale processes. This study seeks to describe the littoral, coastal, and offshore spatial and temporal trends in nutrient concentrations in Lake Ontario and then to assess if nutrient loads to sites where *Cladophora* is currently thriving have changed over the past four decades. We examined lake-wide, long-term nutrient concentrations monitored by Environment Canada (EC), explicitly exploring differences in water quality between north coast, south coast, and offshore regions of the lake. We looked at phosphorus concentrations, known to limit *Cladophora* growth, as well as inorganic N and suspended chlorophyll concentrations, to gain insight into the potential mechanisms affecting the phosphorus distributions observed. We first compared surface water macronutrient and chlorophyll concentrations in spring and summer between north and south coasts (14–20 m) and offshore (>50 m) zones using records from 1975 to 2008. We then examined littoral zone (2–12 m) macronutrient concentrations at two areas on the north shore, chosen for intensive study because of recent complaints of a *Cladophora* resurgence (Auer et al., 2010; Hecky et al., 2007). We measured nutrient concentrations in Halton region between 2004 and 2006 and in Durham region from 2007 to 2008 (Fig. 1). Historic nutrient data for these two littoral zone locations were available from 1976 to 1979, enabling a direct comparison of changes in nutrient concentrations over time. Finally, to assess the possible role of catchment loading in driving the *Cladophora* resurgence, we quantified the long-term nutrient loadings (1964–2006) from Sixteen Mile Creek (adjacent to the Halton study site) and Duffins Creek (within the Durham study site).

Methods

Lake-wide sampling, Environment Canada Data, 1975–2008

Environment Canada's Great Lakes Surveillance Program has been monitoring water quality since the late 1960s. By 1975, a permanent station pattern was established for Lake Ontario. Ship-based monitoring cruises are conducted to measure physical, chemical, and some limited biological parameters. A subset of sampling stations in Lake Ontario was selected to compare north coast, south coast, and offshore zones (Fig. 1). For this study, all surveillance stations that were less than the 20-m depth contour were defined as "coastal," corresponding to the area where the thermocline, at its deepest autumnal extent, typically intersects with the lake bed (i.e., the coastal boundary layer; Rao and Schwab, 2007). Based on this criterion, there were six north coast stations (Stations 8, 10, 31, 43, 47, and 62) and five south coast stations (Stations 17, 53, 57, 66, and 71), all of which were between depths of 14 and 20 m. A similar number ($n = 6$) of offshore stations, along a transect spanning the length of the lake, was chosen for comparison (Stations 14, 25, 33, 40, 60, and 74). Stations chosen to represent the pelagic "offshore" area were more than 50 m deep. Samples for analysis were collected at 1 m depth, except for chlorophyll (Chl *a*) samples, which were depth-integrated from 2 m above the lake bottom to the surface for coastal stations or from 20 m (i.e., the estimated maximum mixing depth) to the surface for offshore stations. Secchi depth was read with a 30-cm disk.

Environment Canada sampling protocols have been recently compiled (Dove et al., 2009). All laboratory analyses were conducted by the National Laboratory for Environmental Testing (NLET) in Burlington, Ontario. Briefly, total phosphorus (TP) and soluble reactive phosphorus (SRP) were analyzed using the standard molybdate blue method with TP being first digested in a persulphate solution. Data from Lake Ontario from 1971 showed that NO_2^{2-} made up only 0.5% of the

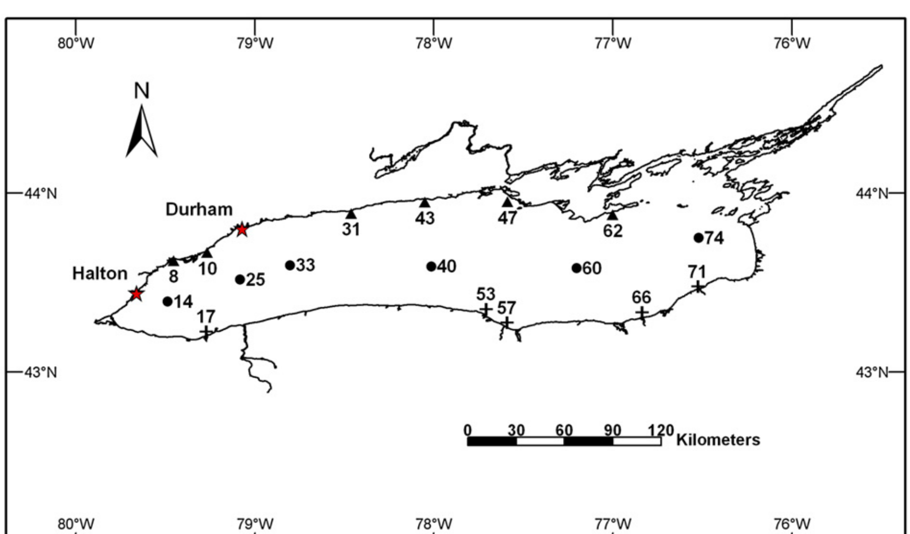

Fig. 1. Lake Ontario survey stations chosen to represent the nutrient conditions of the littoral (2–12 m; Halton and Durham areas), north coast (14–20 m; triangles), south coast (14–20 m; plus signs) and offshore (>50 m; circles) zones. Numbers for coastal and offshore stations are Environment Canada Surveillance Program permanent station numbers.

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