Preface to special theme, part 2

Summary of Lake Simcoe's past, present, and future

Michelle E. Palmer[1*], Véronique P. Hiriart-Baer[2], Rebecca L. North[3], and Michael D. Rennie[4]

[1] *Ontario Ministry of the Environment, Environmental Monitoring and Reporting Branch, 125 Resources Rd, Toronto, M9P 3V6, ON, Canada*
[2] *Environment Canada, National Water Research Institute, 867 Lakeshore Rd, PO Box 5050, Burlington, L7R 4A6, ON, Canada*
[3] *University of Saskatchewan, 112 Science Place, Saskatoon, S7N 5E2, SK, Canada*
[4] *Fisheries and Oceans Canada, Freshwater Institute, Experimental Lakes Area, 501 University Crescent, Winnipeg, R3T 2N6, MB, Canada*
** Corresponding author email: michelle.palmer@ontario.ca*
*** All authors contributed equally to this paper.*

Published 29 April 2013

This special section of Inland Waters contains the final installment of a collection of papers on Lake Simcoe, Ontario, Canada. Collectively, the 4 papers in Volume 3, Issue 1 and the 13 papers in the current issue demonstrate the integrative and collaborative monitoring and research efforts underway to protect this large, multi-stressed lake. In the first preface to the special sections (Palmer et al. 2013), we detailed legislative and financial initiatives that have been implemented by the federal and provincial governments to support science in the Lake Simcoe watershed. Here, we summarize the resultant science reported in these special sections and highlight priority areas for future work.

The primary water quality concern in the Lake Simcoe watershed is excess phosphorus (P) loading that promotes the growth of algae and macrophytes, the decomposition of which depletes hypolimnetic dissolved oxygen (DO) and restricts the natural recruitment of lucrative coldwater sportfish (Evans et al. 1996). As such, P and DO are important indicators of ecosystem health in Lake Simcoe (North et al. 2013a). To meet the deepwater DO target of 7 mg L^{-1} needed to sustain coldwater fish populations, total P (TP) loading to Lake Simcoe must be reduced to 44 tonnes yr^{-1} (Young et al. 2011) from the most recent 5 year average of 86 tonnes yr^{-1} (hydrologic years 2005–2009; OMOE and LSRCA 2013). TP loadings were estimated from long-term monitoring of 5 main sources (annual total for 2007–2009 ranged from 71.9 to 115.5 tonnes yr^{-1}): tributaries (47.4–80.6), atmospheric deposition (11.1–20.1), polders (drained wetlands used for agriculture; 5.3–7.2), water pollution control plants (3.7–5.0), and septic systems (4.4; Fig. 1a; OMOE and LSRCA 2013).

Despite extensive efforts to reduce anthropogenic P inputs to the lake (e.g., restrictions on P output from water pollution control plants, prohibition of new point source discharges, P reduction stewardship projects; Winter et al. 2002), TP loadings did not monotonically decrease from 1998 to 2006 (North et al. 2013a) and were relatively high in 2007–2008. However, the high loadings observed in 2007 and 2008 were more likely influenced by hydrology than anthropogenic P sources. Tributary loads, which provide the greatest contribution to TP loads, were particularly high in 2007 and 2008, coinciding with unusually high tributary flow (Fig. 1b); in fact, 2008 was the wettest year since flow records began in 1969 (O'Connor et al. 2013, OMOE and LSRCA 2013). When tributary discharges returned to typical levels in 2009, TP loading dropped to 71.9 tonnes yr^{-1}, similar to the 2002–2006 average load of 72 tonnes yr^{-1} (OMOE et al. 2009). High flow rates in recent years have also been reported for Lake Erie (Joosse and Baker 2011) and Lake Winnipeg (Manitoba) where they were linked to increased in-lake TP concentrations (McCullogh et al. 2012). Climate change modeling in the Lake Simcoe watershed predicts greater winter precipitation and warmer air temperatures resulting in higher winter flows and earlier snowmelt, which could increase TP loading to the lake (Crossman et al. 2013). These results reaffirm the need to continue reducing TP loading to protect Lake Simcoe, particularly in a changing climate.

P reduction requires knowledge of the point and non-point P sources in the Lake Simcoe watershed and has been an on-going area of research, as demonstrated by a number of papers in this collection in Inland Waters. Two

DOI: 10.5268/IW-3.2.622 *Inland Waters* (2013) **3**, pp. 119-124

papers investigated previously understudied P sources: groundwater and internal P loading from lake sediments. In a 2-year survey along ~2 km of the shoreline near Barrie, the largest city in the watershed, Roy and Malenica (2013) found that soluble reactive P in groundwater was elevated compared to lake water. Elevated concentrations of bioavailable nitrogen (N), metals, organic pollutants, and salts were also widespread with at least one contaminant exceeding aquatic life toxicity guidelines in ~50% of samples. These results suggest that urban groundwater may be a source of contaminants, including P, to the lake and sediment-dwelling organisms. In a comparison study of Lake Simcoe to lakes Winnipeg and Ontario (represented by the eutrophic embayment Hamilton Harbour), Loh et al. (2013) determined release rates of P and iron (Fe) during laboratory incubations to facilitate the quantification of internal P and Fe loading from sediments. This work informed a companion study by Nürnberg et al. (2013), which indicates that internal loading may be a substantial source of P to Lake Simcoe. Hiriart-Baer et al. (2013) also compared Lake Simcoe to other large lakes in their investigation of the quantity and quality of dissolved organic matter (DOM) in the lake. They found that dissolved organic carbon concentration in Lake Simcoe, which was higher than in lakes Erie and Ontario, was greater than would be expected based on lake TP and conductivity. Their results suggest the influence of an internal source of DOM in Lake Simcoe.

Non-point P loading from agriculture and construction activities was also addressed in these special issues. Using a modeling approach, Weiss et al. (2013) developed dust response units combining soil type and agricultural land use to characterize crop dust emission in the Lake Simcoe airshed. Their work identified 12 combinations of soil and crop type that account for a total of 85% of crop dust emissions. Mapping of these high priority areas will allow targeted implementation of best management practices to reduce atmospheric deposition of P-laden dust. In a jurisdictional scan, Trenouth et al. (2013) reviewed construction-phase stormwater management approaches and proposed revisions to Ontario's current guidelines. Improved stormwater management will

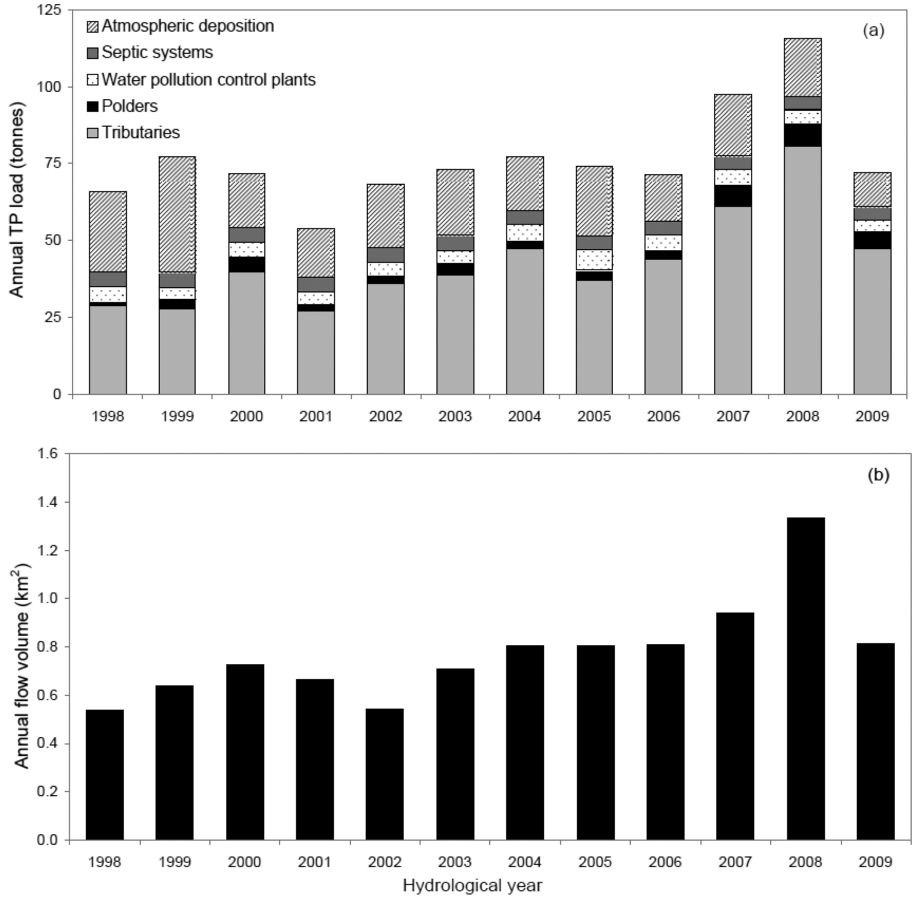

Fig. 1. Annual (a) TP loading from 5 main sources and (b) flow volume for the 1998–2009 hydrological years (1 Jun–31 May) for Lake Simcoe, Canada; adapted from OMOE and LSRCA (2013).

DOI: 10.5268/IW-3.2.622

reduce sediment-bound P export from construction in high urban growth areas like the Lake Simcoe watershed.

Three additional papers in this collection characterized P export from tributaries and modeled the effectiveness of different management strategies in achieving mandated TP reductions. Miles et al. (2013) examined the relationships between land use and the export of different forms of P over an entire hydrological year in the Beaver River catchment, a major inflow to Lake Simcoe. They found that P concentrations varied greatly over time and tended to be positively correlated with agricultural land use but negatively correlated with woodlands and wetlands. However, even at a small spatial scale, relationships were complex and varied depending on the form of P and time period of analysis. P dynamics in the Beaver River were further assessed by Baulch et al. (2013) using the Branched-INCA-P process-based biogeochemical model on data from multiple monitoring stations throughout the catchment. While model performance was moderate, simulations adequately represented spatial differences in P and identified several P export 'hotspots'. The authors also found that P concentrations in ~23% of samples collected in 2010–2011 exceeded provisional water quality thresholds. Jin et al. (2013) extended the application of the INCA-P model to the entire Lake Simcoe watershed and simulated P concentrations in the lake. The modeled effectiveness of various management scenarios on tributary (Baulch et al. 2013) and lake (Jin et al. 2013) P concentrations indicate that extensive, multifaceted point and non-point source control measures are needed to meet TP reduction targets.

While TP loading reductions are critical for the protection of Lake Simcoe, the quality of P inputs is also important (Joosse and Baker 2011). P bioavailability was investigated by North et al. (2013b) who showed that agricultural (specifically, cropland) land use can have a significant effect on the availability of P to algae in tributaries of Lake Simcoe. This work linking nutrient management in the watershed with downstream water quality and impacts on aquatic biota is widely applicable to other systems and improves our understanding of P export from the land to the lake. This integrative approach was exemplified by North et al. (2013a) who compiled numerous datasets to assess long-term trends in parameters from every trophic level in the lake to examine their interaction with P and DO dynamics. As well, a previously untested mechanism for DO depletion in Lake Simcoe was explored by Quinn et al. (2013) who showed that annual production by heterotrophic bacteria was low, suggesting DO demand at lower trophic levels is unlikely to be a major contributor to low hypolimnetic DO. The authors also discussed the influence of water quality and temperature on spatial and seasonal patterns in bacterial activity. Potentially pathogenic bacteria in Lake Simcoe were also examined in this collection of papers. Khan et al. (2013) reported on the prevalence of *Campylobacter* species, which have been linked to human gastrointestinal infections in other areas, at Lake Simcoe beaches over a 2-year period. They found that *Campylobacter* was present infrequently and at concentrations well below infective doses. Study results suggest that fecal contamination in sand and rivers, as well as bird droppings along shorelines, are potential bacterial sources.

Six of the papers in this collection also tackled the pressing issue of aquatic invasive species, specifically the spiny water flea *Bythotrephes longimanus* and dreissenid mussels. Kelly et al. (2013) examined the dynamics of *Bythotrephes*, an invasive zooplankton that may have significant ecosystem-level impacts, in Lake Simcoe. They reported significant bottom-up (prey abundance) and top-down (predation) controls on mean annual *Bythotrephes* abundance. Warm epilimnetic temperatures and increased water clarity were also found to positively influence *Bythotrephes* abundance. Reduced cladoceran abundance coincident with peak *Bythotrephes* abundance suggests this predator has a strong top-down impact on favoured prey. Ongoing monitoring will provide additional insight on the effects of this invasive predator.

Dreissenid mussels were established in the lake by 1996 (Evans et al. 2011), and have caused dramatic changes in other invaded ecosystems (Higgins and Vander Zanden 2010), including increased transparency and reduced nutrient and algal concentrations. Similar patterns following dreissenid establishment in Lake Simcoe (reviewed in North et al. 2013a) warranted investigations for similar potential effects. The nearshore in particular may be affected by dreissenids (Higgins and Vander Zanden 2010), which are most concentrated within the 5–15 m isopleths of the lake (North et al. 2013a). Reviewing existing data, North et al. (2013a) reported a decline in benthic invertebrate density in offshore regions, but an increase in nearshore regions following dreissenid establishment, consistent with recently reported patterns for benthic biomass (Rennie and Evans 2012). An estimated 14-fold increase in the secondary production of nearshore littoral benthos following dreissenid establishment may result from both an increase in benthic-derived production and sestonic production diverted towards littoral zones via dreissenid filtering (Ozersky et al. 2012).

Two papers used spatially-explicit contemporary data to examine dressenid impacts on algal concentrations at nearshore versus offshore sites. Guildford et al. (2013) demonstrated significantly lower indicators of phytoplankton biomass at nearshore sites (those where dreissenids would have direct contact with well-mixed epilimnetic waters) as compared to offshore sites, but found little evidence that nutrient regeneration by dreissenids was sufficient to offset P deficiency in nearshore phytoplankton. Further, the authors presented evidence of photoacclimation of nearshore phytoplankton, which suggests measurements of chlorophyll *a* (Chl-*a*) concentrations may underestimate phytoplankton biomass in the nearshore. Also within the nearshore, Schwalb et al. (2013) found that Chl-*a* concentrations were greater where higher-density aggregations of mussels bordered the offshore region, compared to more nearshore sites with lower mussel densities. They suggested that this was a likely result of onshore water transport (horizontal advection), an observation consistent with recent work by Ozersky et al. (2012) that demonstrated that a major component of increased secondary consumer production at littoral rocky substrates is derived from sestonic resources. Schwalb et al. (2013) suggested thermal stratification may have facilitated near-bottom depletion events (therefore limiting dreissenid densities and growth rates at shallower sites), but that deep Chl-*a* maxima may also play a role in sustaining the peak concentration of dreissenids in the nearshore at intermediate depths. Recent findings from Cossu and Wells (2013) seem to suggest that this region of high mussel density may also exist to take advantage of nutrient resuspension and mixing with nutrient-rich hypolimnetic waters associated with turbulence generated from internal seiches. Further, lower measured Chl-*a* concentrations at nearshore sites (Schwalb et al. 2013) compared to offshore sites may in part reflect a regional effect of photoacclimation (Guildford et al. 2013).

Dreissenid impacts were also assessed using temporal comparisons. Baranowska et al. (2013) examined data from water treatment plant intakes (one of the only sources of long-term nearshore data for Lake Simcoe) and reported significant declines in phytoplankton biomass and Chl-*a* concentrations following dreissenid establishment; these changes were not detected at offshore sites. Importantly, this provides strong support for the above spatial studies that suggested a greater impact of dreissenids in the nearshore for lower trophic levels (i.e., phytoplankton). Further, the authors demonstrated a shift in the timing of peak Chl-*a* concentrations from fall to winter. Changes in the phenology of peak events can have significant effects on the flow of energy through foodwebs (Winder and Schindler 2004); more work is required to determine if such temporal mismatches are occurring in Lake Simcoe.

Profound changes in the nearshore of Lake Simcoe were also detected among organisms occupying higher trophic levels. In this issue, Rennie et al. (2013) used stable isotopes of carbon (C) and N to track the importance of offshore-pelagic versus nearshore-benthic production in zooplankton, benthic invertebrate, and fish communities. While zooplankton isotopic signatures varied seasonally and annually with no clear trend, the degree of change found in both benthic invertebrates and fishes were habitat-dependent. In nearshore areas, C isotopic values of a number of benthic taxa and fishes increased by 3–5‰, indicating a major increase in the contribution of benthic-derived production in the nearshore. In contrast, offshore benthic invertebrates, and pelagic and profundal fishes showed less pronounced changes. Most offshore fishes evaluated showed slight but significant increases in C isotopic values, indicating that the increase in nearshore benthic-derived production was great enough to be integrated at higher trophic positions in offshore consumers.

These special sections are an important venue for the integration of recent and on-going science on Lake Simcoe's airshed, watershed, and the lake itself. Continued excess TP loading to the lake signifies the need to better quantify P sources to inform mitigation actions. The recent focus on non-point sources of nutrient loading to the lake identifies this as an existing research gap, although the papers in these issues are pioneering the way to characterizing these sources. As we develop a better understanding of nutrient sources and hotspots, an evaluation of the efficacy of best management practices is needed. The papers presented here also emphasize the importance of research and monitoring of aquatic invasive species, which appear to be significantly altering the Lake Simcoe ecosystem, particularly in the nearshore areas of the lake. Eutrophication and invasive species are not the only stressors impacting the Lake Simcoe watershed and future work needs to focus on how multiple stressors, including contaminants and climate change, are affecting water quality, biota, and ecosystem services and functions in Lake Simcoe. Given the tremendous degree of interest and a renewed source of funding (LSCUF; Palmer et al. 2013), these areas of research will hopefully be addressed in the next round of projects and through enhanced monitoring programs. Lake Simcoe is well on its way to becoming the most research intensive lake in Canada.

Acknowledgements

We thank Jack Jones, David Hamilton, Janice Faaborg (Inland Waters), and Simon Pawley and Karen Rouen (Freshwater Biological Association) for their continual support of the Lake Simcoe special sections. The authors and reviewers are warmly acknowledged for their contributions to this important and timely collection of papers.

 DOI: 10.5268/IW-3.2.622

Printing of these issues was partially funded by the Ontario Ministry of the Environment.

References

Baranowska KA, North RL, Winter JG, Dillon PJ. 2013. Long-term seasonal effects of dreissenid mussels on phytoplankton in Lake Simcoe, Ontario, Canada. Inland Waters. 3(2):285–296.

Baulch HM, Futter MN, Jin L, Whitehead PG, Woods DT, Dillon PJ, Butterfield DA, Oni SK, Aspden LP, O'Connor EM, et al. 2013. Phosphorus dynamics across intensively monitored subcatchments in the Beaver River. Inland Waters. 3(2):187–206.

Cossu R, Wells MG. 2013. The interaction of large amplitude internal seiches with a shallow sloping lakebed: observations of benthic turbulence in Lake Simcoe, Ontario, Canada. PLoS ONE. 8(3):e57444. doi:10.1371/journal.pone.0057444

Crossman J, Futter MN, Oni SK, Whitehead PG, Jin L, Butterfield D, Baulch HM, Dillon PJ. 2013. Impacts of climate change on hydrology and water quality: Future proofing management strategies in the Lake Simcoe watershed, Canada. J Great Lakes Res. 39:19–32.

Evans DO, Nicholls KH, Allen YC, McMurtry MJ. 1996. Historical land use, phosphorus loading, and loss of fish habitat in Lake Simcoe, Canada. Can J Fish Aquat Sci. 53:194–218.

Evans DO, Skinner A, Allen R, McMurty MJ. 2011. Invasion of zebra mussel, *Dreissena polymorpha*, in Lake Simcoe. J Great Lakes Res. 37(Suppl. 3):36–45.

Guildford SJ, Depew DC, Ozersky T, Hecky RE, Smith REH. 2013. Nearshore-offshore differences in planktonic chlorophyll and phytoplankton nutrient status after dreissenid establishment in a large shallow lake. Inland Waters. 3(2):253–268.

Higgins SN, Vander Zanden MJ. 2010. What a difference a species makes: a meta-analysis of dreissenid mussel impacts on freshwater ecosystems. Ecol Monogr. 80:179–196.

Hiriart-Baer VP, Binding C, Howell TE. 2013. Dissolved organic matter quantity and quality in Lake Simcoe compared to 2 other large lakes in southern Ontario. Inland Waters. 3(2):139–152.

Jin L, Whitehead PG, Baulch HM, Dillon PJ, Butterfied D, Oni SK, Futter MN, Crossman J, O'Connor EM. 2013. Modelling phosphorus in Lake Simcoe and its subcatchments: scenario analysis to assess alternative management strategies. Inland Waters. 3(2):207–220.

Joosse PJ, Baker DB. 2011. Context for re-evaluating agricultural source phosphorus loadings to the Great Lakes. Can J Soil Sci. 91:317–327.

Kelly NE, Young JD, Winter JG, Yan ND. 2013. Dynamics of the invasive spiny water flea, *Bythotrephes longimanus*, in Lake Simcoe, Ontario, Canada. Inland Waters. 3(1):75–92.

Khan IUH, Hill S, Nowak E, Palmer ME, Jarjanazi H, Lee D-Y, Mueller M, Schop R, Weir S, Abbey A-MI, *et al*. 2013. Investigation of the prevalence of thermophilic *Campylobacter* species at Lake Simcoe recreational beaches. Inland Waters. 3(1):93–104.

Loh PS, Molot LA, Nürnberg GK, Watson SB, Ginn B. 2013. Evaluating relationships between phosphorus and iron release across three different water bodies. Inland Waters. 3(1):105–118.

McCullough GK, Page SJ, Hesslein RH, Stainton MP, Kling HJ, Salki AG, Barber DG. 2012. Hydrological forcing of a recent trophic surge in Lake Winnipeg. J Great Lakes Res. 38:95–105.

Miles JJ, Eimers CM, North RL, Dillon PJ. 2013. Spatial distribution and temporal variability in the forms of phosphorus in the Beaver River subwatershed of Lake Simcoe, Ontario, Canada. Inland Waters. 3(2):179–186.

North RL, Barton D, Crowe AS, Dillon PJ, Dolson RML, Evans DO, Ginn BK, Håkanson L, Hawryshyn J, Jarjanazi H, *et al*. 2013a. The state of Lake Simcoe (Ontario, Canada): the effects of multiple stressors on phosphorus and oxygen dynamics. Inland Waters. 3(1):51–74.

North RL, Winter JG, Dillon PJ. 2013b. Nutrient indicators of agricultural impacts in the tributaries of a large lake. Inland Waters. 3(2):221–234.

Nürnberg GK, LaZerte BD, Loh PS, Molot LA. 2013. Quantification of internal phosphorus load in large, partially polymictic and mesotrophic Lake Simcoe, Ontario. J Great Lakes Res.

O'Connor EM, Aspden L, Lembcke D, Young J, Stainsby EA, Lucchese M, Winter JG. 2013. Annual water balances and total phosphorus loads to Lake Simcoe (2007–2009); [cited 15 April 2013]. Available from: http://www.ene.gov.on.ca/environment/en/resources/STDPROD_103494.html

[OMOE and LSRCA] Ontario Ministry of the Environment and Lake Simcoe Region Conservation Authority. 2013. Report on the phosphorus loads to Lake Simcoe 2007-2009; [cited 15 April 2013]. Available from: http://www.ene.gov.on.ca/environment/en/resources/STDPROD_103494.html

[OMOE et al.] Ontario Ministry of the Environment, Ontario Ministry of Natural Resources, and Lake Simcoe Region Conservation Authority. 2009. Lake Simcoe Protection Plan; [cited 15 April 2013]. Available from: http://www.ene.gov.on.ca/environment/en/resources/STD01_076301.html

Ozersky T, Evans DO, Barton D. 2012. Invasive mussels alter the littoral food web of a large lake: stable isotopes reveal drastic shifts in sources and flow of energy. PLoS ONE. 7(12):e51249.

Palmer ME, Hiriart-Baer VP, North RL, Rennie MD. 2013. Toward a better understanding of Lake Simcoe through integrative and collaborative monitoring and research. Inland Waters. 3(1):47–50.

Quinn CJ, North RL, Dillon PJ. 2013. Year-round patterns in bacterial production and biomass in Lake Simcoe, Ontario, Canada: are heterotrophic bacteria a significant contributor to low hypolimnetic oxygen? Inland Waters. 3(2):235–252.

Rennie MD, Evans DO. 2012. Decadal changes in benthic invertebrate biomass and community structure in Lake Simcoe. Freshwat Sci. 31(3):733–749.

Rennie MD, Evans DO, Young JD. 2013. Increased dependence on nearshore benthic resources in the Lake Simcoe ecosystem after dreissenid invasion. Inland Waters. 3(2):297–310.

Roy JW, Malencia A. 2013. Nutrients and toxic contaminants in shallow groundwater along Lake Simcoe urban shorelines. Inland Waters. 3(2):125–138.

Schwalb AN, Bouffard D, Ozersky T, Boegman L, Smith REH. 2013. Impacts of hydrodynamics and benthic communities on phytoplankton distributions in a large, dreissenid-colonized lake (Lake Simcoe, Ontario, Canada). Inland Waters. 3(2):269–284.

Trenouth WR, Gharabaghi B, MacMillan G, Bradford A. 2013. Better management of construction sites to protect inland waters. Inland Waters. 3(2):167–178.

Weiss L, Stainsby EA, Gharabaghi B, Thé J, Winter JG. 2013. Mapping key agricultural sources of dust emissions within the Lake Simcoe airshed. Inland Waters. 3(2):153–166.

Winder M, Schindler DE. 2004. Climate change uncouples trophic interactions in an aquatic ecosystem. Ecology. 85:2100–2106.

Winter JG, Dillon PJ, Futter MN, Nicholls KH, Scheider WA, Scott LD. 2002. Total phosphorus budgets and nitrogen loads: Lake Simcoe, Ontario (1990 to 1998). J Great Lakes Res. 28:301–314.

Young JD, Winter JG, Molot L. 2011. A re-evaluation of the empirical relationships connecting dissolved oxygen and phosphorus loading after dreissenid mussel invasion in Lake Simcoe. J Great Lakes Res. 37:7–14.

 DOI: 10.5268/IW-3.2.622