The rapid eutrophication of Lake Winnipeg: Greening under global change

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A B S T R A C T

Nuisance blooms of heterocystous Cyanobacteria in Lake Winnipeg have nearly doubled in size since the mid 1990s. The increases are the result of a recent rapid increase in loading and concentration of phosphorus. The rapid increase in phosphorus is largely the result of two factors. The first factor is the result of rapidly increased livestock production and use of synthetic fertilizer in the Red River Valley, with smaller contributions of phosphorus from the city of Winnipeg and other human development in the Red and Winnipeg river basins. The second factor is the increased frequency and intensity of spring floods in the Red River watershed in recent years, which have greatly enhanced the transfer of phosphorus from the landscape to the lake, as well as slower increases in nitrogen. Because the low ratio of nitrogen to phosphorus in the increased inputs favors nitrogen fixing species of Cyanobacteria, these nuisance forms account for most of the increase in phytoplankton. Recovery of the lake will require reducing both agricultural and major urban sources of phosphorus and, if possible, the frequency and intensity of flooding in the Red River watershed. Flooding will be increasingly difficult to control if modeled predictions for increased precipitation under climate warming materialize. Even with targeted reductions in phosphorus inputs of 50% and measures to control flooding, recovery of the lake is expected to be slow because of phosphorus recycled from sediments and the climatic sensitivity of this shallow lake and the flooding of the Red River.

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Introduction

Between 1990 and 2000 the phosphorus concentration of Lake Winnipeg doubled (McCullough et al., 2012) and algal blooms, dominated by nitrogen fixing Cyanobacteria, proliferated (Kling et al., 2011). Although much of the lake's catchment had been converted to agriculture and the human population had been slowly increasing over the previous century, the rapid eutrophication late in the 20th century was unforeseen, and how to reverse it is controversial. In recent years, several other great lakes such as tropical Lake Victoria (Hecky et al., 2010) and lakes Huron and Michigan (Evans et al., 2011) have also undergone rapid, unpredicted changes in trophic condition, as a result of changing inputs of nutrients and invasive species, causing concern for their long term sustainable use. Significant changes in nutrient concentrations in these large lakes have occurred in less than a decade, clearly illustrating that lake size alone provides little protection to lake condition. Such rapid changes challenge
aquatic science for explanation. The papers in this volume, many generated through major federal and provincial studies that responded to public concern about the future of Lake Winnipeg, illustrate many changes to the lake following the rapid eutrophication since the early 1990s. Here, we synthesize the findings of some of these studies and other recent research to assess the relative contributions of sewage, land use change and climatic variability to the rapid eutrophication, and to identify possible actions that might reverse the recent eutrophication of Lake Winnipeg.

When one of us (DWS) first studied Lake Winnipeg in 1969 as part of a team of scientists from the now defunct Fisheries Research Board of Canada (FRBC), the lake was already moderately eutrophic, (summarized by Brunskill, 1973; and in unpublished data reports), and biologically altered from the initial observations on the lake in the 1920s (Bajkov, 1934; Patalas and Salki, 1992). At the time, we deduced that the Red River watershed was yielding more nutrients than it had under pristine conditions, because most of the basin had been transformed from long grass prairie to agricultural land within the 20th century, but it was not clear how much the nutrient input had increased over natural background.

Unfortunately, following the demise of the FRBC in the 1970s and despite the construction in 1977 of a control structure which controls the lake level and the outflow of the lake for hydroelectric purposes, little research attention was paid to Lake Winnipeg (Fig. 1; McCullough et al., 2012), resulting in a long hiatus in real time observation. When surveys were resumed in the early 1990s, it first appeared that the lake had changed very little in the intervening two decades. However, rapid increases in nutrient inputs and associated symptoms of increasing eutrophication began to occur by the mid-1990s.

Paleolimnological studies using nutrient concentrations and algal remains in lake sediments have filled in the early history of the lake and provide a baseline against which to evaluate the recent observed changes since the early 1990s. These paleolimnological studies concluded that, like many lakes of the western prairies, Lake Winnipeg was mildly eutrophic in its natural state (Bunting et al., 2011; Kling, 1998; Kling et al., 2011; Mayer et al., 2006) as a consequence of phosphorus-rich soils in the western and southern parts of the lake’s catchment. Increasing clearing of the basin for agriculture and inputs of synthetic fertilizers and manure during the 20th century and a slowly increasing human population caused a slow increase in the lake’s phytoplankton abundance over time. However, eutrophication increased very rapidly after the mid-1990s (Armstrong and McCullough, 2011; Kling et al., 2011; Figs. 2 and 3) as the result of the combination of factors reviewed below.

**Changes to the watershed of Lake Winnipeg**

Since the mid 20th century, several large reservoirs have been built on the Saskatchewan River, which was once the largest source of water to the lake (Fig. 1). The river drains a large, semi-arid area of Alberta and Saskatchewan. The reservoirs serve as traps for nutrients and silt, as well as sites of increased evaporation. The Saskatchewan watershed had warmed over 2 °C since the mid 20th century, mostly in winter and spring. The watershed has shown a strong trend to less precipitation, less snow, and earlier spring melts than it once had...

(Dibike et al., 2012; Schindler and Donahue, 2006). This combination of changes has resulted in the river delivering less water, less silt, and less nutrient to Lake Winnipeg than in earlier times, despite the development of agriculture in the watershed. In contrast, the Red and Winnipeg rivers have increased in flow during the same period. The watershed of the former has been slowly drained and water storage modified, with over 50% of the wetlands eliminated in the US part of the watershed. The runoff:precipitation ratio in recent years is almost threefold greater than in the early 20th century (Ehsanzadeh et al., 2011). The Winnipeg River has shown slower increases in nutrients, as a result of similar land-use changes plus riparian development along the river and on upstream Lake of the Woods. However, the Winnipeg River catchment is still largely wooded, and several reservoirs on the river act as phosphorus sinks.

Increasing nutrient sources

Expansion and intensification of agriculture in the 20th century have been rapid in the southern part of the Lake Winnipeg catchment, in both Canada and the USA. Slow increases in the use of synthetic fertilizers and recent rapid increases in livestock wastes are well known sources of nutrients to watercourses, and most of the tributaries to the Red River that have been studied show increasing phosphorus and nitrogen (Jones and Armstrong, 2001; Yates et al., 2012). Of particular relevance to the rapid recent deterioration of the lake’s condition since the mid-1990s is the great increase in livestock (primarily pigs; Fig. 2) in the Lake Winnipeg basin, especially following the repeal of the Western Grain Transportation Act in 1995. With the long-term subsidy for transporting grain to coastal terminals removed, farmers turned to feeding grain crops to livestock locally as a way to increase profits. The number of pigs in Manitoba increased greatly between 1995 and 2006, primarily in the southern part of the province. The maximum number of pigs in the province reached 3.0 million head in 2006. A single sow averages nine pigs per litter, so the same year total annual pig production reached 9.1 million head, mostly for export. The population declined after that to around 2,600,000 head in 2007 (Brewin et al., 2007) with production decreasing to 8,000,000 head by 2010. Pig production has since decreased by about 10% (Honey, 2011).

Much of the associated manure produced, including 7000 tonnes of phosphorus per year (Brewin et al., 2007), was spread on agricultural lands in the southern Lake Winnipeg basin. There has also been an expansion in cattle, with the most recent population statistics showing over 1.6 million animals in the province (Fig. 2). As a rule of thumb, one adult hog or cow contributes the equivalent (measured as excretion of phosphorus, the primary nutrient of concern in eutrophication, Schindler and Vallentyne, 2008) of ten humans (Chambers et al., 2001). Use of synthetic fertilizer has also increased, contributing to the problem (Fig. 2).

In contrast, human wastes are a relatively small part of the nutrient input to Lake Winnipeg. The population of Manitoba has increased very slowly during the 20th century (Fig. 2). The city of Winnipeg, accounting for approximately one-half of the provincial population, adds about 5% of the total phosphorus load to the lake, while all other point sources are estimated to contribute about 4% (LWSB, Lake Winnipeg Stewardship Board, 2006). The sparse human population of rural subcatchments in southern Manitoba contributes only about 1% of the nutrient load (Yates et al., 2012). About 50% of the phosphorus in the Red River is known to originate from the US side of the border. Despite the relatively sparse human population, the total animal plus human excrement in the Lake Winnipeg Basin in Manitoba is equivalent to a human population of almost 50 million. Much of this growth in animal populations and waste in the Lake Winnipeg watershed happened in the catchment of the Red River and that of its major tributary, the Assiniboine River, especially since the mid 1990s (Fig. 2; Armstrong and McCullough, 2011; LWSB, Lake Winnipeg Stewardship Board, 2006).

Crop fertilization, with both animal manure and synthetic fertilizers, has increased (Fig. 2), causing increased concentrations of phosphorus and nitrogen in the soils of regions of intense agriculture. Yields of phosphorus to surface water now correlate well with livestock density and land in crop production in the Lake Winnipeg basin (Salvano et al., 2009). Fertilizer applications are generally indexed to the nitrogen requirements of the crops that farmers are attempting to grow. Consequently, the increasing use of animal manure as fertilizer results in

![Fig. 2. Time series of selected watershed and nutrient input parameters shown with measured mean midsummer phytoplankton biomass (gray circles). Data are for the Manitoba portion of the Lake Winnipeg watershed. Sources: population—Statistics Canada; cattle—Honey (2011); pigs—Honey (2010); fertilizer—Korol (2002) (1972–2002), CFIS (2011) (2003–06); phytoplankton—H. Kling (McCullough et al., 2012).](image)

![Fig. 3. Measured (black diamonds) and modeled (heavy black line) mean midsummer phosphorus in Lake Winnipeg shown with measured mean midsummer phytoplankton biomass (gray circles). Discharge of Red River is shown as the moving average of the previous 3 years. Sources: phosphorus and phytoplankton—McCullough et al. (2012); discharge—HYDAT (Environment Canada).](image)
excess phosphorus being applied, because the ratio of nitrogen to phosphorus in manure is typically about 3:1 by weight, whereas the growth of terrestrial plants harvested is 16:1 or more. Some agricultural regions are known to be so phosphorus saturated that soils are predicted to leak excess phosphorus for many decades, even if its application is controlled now (Carpenter, 2005).

Changes from conventional tillage to conservation tillage have also caused increases in the runoff of soluble phosphorus relative to nitrogen on the Canadian prairies (Tieszen et al., 2010). Under conservation tillage, which reduces soil erosion, more of the applied and available phosphorus is left on the soil surface where it can be readily mobilized in runoff events. The change to low tillage agriculture in rich agricultural catchments in the Laurentian Great Lakes basin has also decreased losses of particulate phosphorus, but has increased runoff of soluble phosphorus which is the form most readily available to phytoplankton. This process has been identified as a reason for the recent recurrence of coastal eutrophication in the lower Great Lakes, following two decades of recovery following the elimination of point sources of phosphorus (Jooosse and Baker, 2011). The flat terrain of the Red River watershed does not allow higher runoff to generate much increase in particulate phosphorus, and as much as 80% of the phosphorus carried in small tributaries from the watershed is in soluble form. Even in the mainstem of the Red River, near its mouth, half of the phosphorus load remains in dissolved form. Of the particulate load, half is in forms (organic and non-apatitic inorganic) that are biologically reactive, so that nearly three-quarters of the load is readily available to phytoplankton (McCullough et al., 2012).

Overall, inputs of phosphorus to the lake have increased four times more rapidly than inputs of nitrogen. Between 1994 and 2007, phosphorus inputs increased 71%, an average of 5.1% per year. During the same period, nitrogen input (including estimated fixation) only increased by 18%, or 1.3%/y (Armstrong and McCullough, 2011). The nitrogen from the Red River has a high δ15N, which is usually regarded as evidence for significant inputs of animal or human waste (Vander Zanden et al., 2005), but the progressive decline of δ15N in fish from south to north in the lake (Hobson et al., 2012) suggests that fixation is adding substantially to the loading of N as water moves through the lake. In 2003 and 2004, nitrogen fixation averaged 10% of the annual nitrogen loading to the lake, almost threefold greater than Winnipeg sewage (LWSB, Lake Winnipeg Stewardship Board, 2006).

The δ15N of nitrate in summer is also lower than in spring nitrate, which is consistent with a strong influence of nitrogen fixation (with δ15N = 0) in both basins as the cyanobacteria bloom in summer. The higher availability of radiant energy in the more transparent northern basin of Lake Winnipeg likely also favors higher N fixation and lighter N isotopic signatures in nitrogen compounds as observed in Lake Victoria (East Africa) where primary productivity and nitrogen fixation are both limited by light availability in the mixed layer (Hecky et al., 2010).

The low N:P ratio in the rapidly increasing nutrient load has resulted in rapid increases in nitrogen-fixing Cyanobacteria in Lake Winnipeg (Kling et al., 2011; LWSB, Lake Winnipeg Stewardship Board, 2006), as found in other studies (Schindler, 1977; Smith, 1983). Decreasing δ15N in sediments of Lac la Biche during the 20th century were interpreted as meaning increased nitrogen fixation (Schindler et al., 2008b) and similar changes have probably occurred in Lake Winnipeg. The proportion of phytoplankton that is Cyanobacteria has increased from 56% in 1969 to over 80% in the past few years (McCullough et al., 2012). In Lake Winnipeg, nitrogen-fixing species have been responsible for most of the increases in phytoplankton biomass in the last four decades (Kling, 1998; Kling et al., 2011).

In summary, sources of nutrients, especially phosphorus, to Lake Winnipeg have increased greatly since the mid 1990s, and increases in phytoplankton follow closely (Fig. 2). Nitrogen fixing Cyanobacteria have increased more than other taxa, as expected due to declining N:P ratio in loading. In this respect, the story of Lake Winnipeg is rather similar to those of lakes in many other areas impacted by anthropogenic activities.

Climate change and basin modification as amplifiers of nutrient loading

The amplification of increased nutrient availability by increased hydrological loading due to spring flooding has given Lake Winnipeg a unique “double whammy” in recent years. This dynamic, climate-related aspect of nutrient loading distinguishes Lake Winnipeg from more familiar cases of point source eutrophication, e.g. by sewage treatment plants that deliver nutrients from human wastes at relatively constant rates over time. While long-term trends show declining precipitation throughout much of the Canadian part of the Lake Winnipeg basin (Dibike et al., 2012), precipitation in the Red River Valley increased after 1995, and annual runoff has increased as a result (McCullough et al., 2012; Novotny and Stefan, 2007; Fig. 4). These changes in the Red River basin resulted in larger than normal spring floods in 1997, 2005, 2009 and 2011. The unusually high recent flood frequency has expedited the transfer of phosphorus from the enriched lands of the Red River Valley to the lake as runoff contributes much more P in years with floods than in years without (McCullough et al., 2012).

Despite winter snow accounting for only 30% of precipitation on average, about 80% of the runoff from the Red River basin occurs during spring snowmelt flood season (Dibike et al., 2012). Both the annual and the winter precipitation show significant recent upward trends in the Red River basin (McCullough et al., 2012; Novotny and Stefan, 2007), despite no significant long-term trend in the Canadian part of the catchment (Dibike et al., 2012). Ebanszadeh et al. (2011) demonstrate that the runoff per unit precipitation in Red River basin has increased greatly since the mid 1990s. Although precipitation has only increased by about 10% over the last century, runoff has increased much more sharply, approximately doubling over the same period. This is undoubtedly the result of increases in soil saturation (Ebsanzadeh et al., 2011). The years since the mid 1990s have exhibited an exceptional succession of high runoff years and high runoff ratios.

Other climatic changes may have a strong effect on annual runoff under the highly peaked flow regime of the Red River and its tributaries. More frequent winter melts and more intense rainstorms have increased the number and duration of high flow periods (Novotny and Stefan, 2007). Autumn rains may also be of significance by saturating soils before freeze up. On flooded land, water stands in contact with high phosphorus soils, manure both piled and spread, and hog lagoons, sometimes for several weeks. In the largest floods to date, 1997 and 2009, 200 km² of farmland was inundated. As flood water drains away after weeks of contact with nutrient-rich soils, it carries remarkably large amounts of phosphorus with it to Lake Winnipeg, with concentrations of TP reaching several hundred mg m⁻³, mostly in dissolved form. As a result, phosphorus loading to, and concentration in the lake have more than doubled since 1994, with consequent increases in phytoplankton (Figs. 2 and 3; Kling et al., 2011; McCullough et al., 2012). The combination of increased flooding and increased fertilizer application in the Red River watershed makes it the main source of nutrients to the lake. At present, it supplies about 70% of the annual phosphorus input and 35% of the nitrogen input to the lake (Armstrong and McCullough, 2011).

In contrast to the behavior of the Red River basin, runoff from the Saskatchewan River watershed has declined, despite no long term trend in annual precipitation (Dibike et al., 2012). In the first half of the 20th century, the Saskatchewan and Winnipeg rivers delivered roughly equal amounts of water annually to Lake Winnipeg. The
Red River delivered only about 1/4 the water of either of them. Today, the Winnipeg River delivers twice as much water as the Saskatchewan, which, despite its huge catchment, now delivers only slightly more water to the lake than the Red River (McCullough et al., 2012). The decline in flows from the Saskatchewan system is in part caused not only by declining winter precipitation in the western plains, but also by increasing withdrawals for irrigation and increasing evaporative losses from several reservoirs constructed during the mid-20th century. Declines in flow are particularly acute during the summer months (Schindler and Donahue, 2006). Because the Saskatchewan River at its mouth has much lower P concentrations than the Red River (LWSB, Lake Winnipeg Stewardship Board, 2006), it has a greater dilution effect than it used to have on the incoming phosphorus load of the Red, especially in the north basin of Lake Winnipeg. Waters of the north basin are also less turbid than in earlier years, due to the reduced silt load from the river. As a result, despite higher phytoplankton biomass, the lake has become clearer, with a deeper euphotic zone than in earlier years.

In addition to the increasing frequency of high spring flows and higher nutrient loading, slow but important changes have been made to the drainage patterns in the catchment of the Red River, and to a lesser degree other southern rivers in the watershed. Farmers have systematically filled or drained wetlands and channelized flows in order to drain the land quickly for planting in spring, and to maximize the amount of land available for cultivation. These alterations have increased the area of the catchment effectively contributing runoff, and have certainly contributed to the change in runoff ratio over the last century (Ehsanzadeh et al., 2011). Much of the Red River Valley has clay soils, the result of once being the lake bottom of glacial Lake Agassiz. The soils can be almost unworkable when wet, and the short growing season has made drainage an urgent matter in order to plant crops early. The changes to drainage in the basin have made spring freshets increasingly “flashy,” with much of the runoff reaching the river in a very short period. Recent trends in agronomic practice lead to more plant waste and manure available on the soil surface for ready mobilization with the spring flood (Tiessen et al., 2010). Avoidance of plowing may reduce the suspended sediment yield but lack of incorporation of added nutrients into the soil horizon may result in higher yield of dissolved P from the soil surface, which would be expected to sustain algal growth once it reaches the lake. Similar observations have been made in the Great Lakes basin (Joosse and Baker, 2011).

Modeling of future climate change indicates that precipitation is likely to increase, and snowmelt runoff is likely to become even more intense (Dibike et al., 2012; Shrestha et al., 2012). Thus, the combination of increased runoff and nutrient concentrations threatens to cause eutrophication of the lake to intensify even more.

**Nutrients to control: phosphorus and/or nitrogen?**

In recent years, there has been a controversy over whether the observed increases in phytoplankton abundance and changes in species composition in a lake can be reversed by controlling phosphorus alone, or whether both phosphorus and nitrogen must be controlled. Whole lake experiments (Paterson et al., 2011; Schindler, 1977; Schindler et al., 2008a) and many case histories (Jeppesen et al., 2005; Welch, 2009; Schindler, in review), including the Laurentian Great Lakes and large European lakes, have shown that controlling phosphorus inputs alone can successfully reverse eutrophication. However, recently, several studies have claimed that better recoveries from eutrophication will result if nitrogen input is controlled as well or instead of phosphorus (Bunting et al., 2011; Conley et al., 2009; Elser et al., 2007; Lewis and Wurtsbaugh, 2008; Lewis et al., 2011; Scott and McCarthy, 2010, 2011). These inferences are based...
on smaller scale, short term nutrient enrichment experiments, paleoecological correlations where causation is inferred, and flawed logic (Schindler, in review). In fact, no ecosystem-scale study has demonstrated that reducing nitrogen can cause decreased algal production or biomass. Only one whole lake experiment has deliberately tested reducing inputs of nitrogen without reducing phosphorus as a way to control eutrophication (Paterson et al., 2011; Schindler et al., 2008a). It showed that reducing nitrogen inputs while maintaining phosphorus inputs did not reduce the blooms of phytoplankton significantly. Instead, the result was an increase in the prevalence of nitrogen-fixing Cyanobacteria, and in the annual magnitude of nitrogen fixation. Both consequences are undesirable.

Hecky and Kilham (1988) and Vitousek et al. (2010) have previously pointed out that proximate nutrient limitation, as obtained in short-term, small scale bottle or mesocosm experiments, is not necessarily a reliable predictor of ultimate (long term) ecological response to a nutrient limitation. Short-term experiments in Moses Lake USA showed nitrogen limitation in short, small scale experiments after nutrient loading was cut, but in the long-term, algal biomass responded in proportion to declines in phosphorus (Welch, 2009). Short term incubations cannot allow for adjustments in algal community composition or the biogeochemical cycles of lakes that would eventually occur in response to a nutrient stress. Nitrogen fixation by heterocystous Cyanobacteria is a good example of such a process that can occur if a nitrogen stress is imposed on an algal community. In brief, the Lake 227 and Moses Lake histories suggest that short-term nitrogen limitation indicate that a lake is overfertilized with phosphorus, rather than that nitrogen must be controlled.

Some of the advocates for nitrogen control have argued that N fixation is generally observed to be only a small fraction of the total daily N demand and therefore, cannot be important in allowing a phytoplankton community to overcome an imposed deficiency. This ignores the fact that much of the nitrogen fixed daily from the atmosphere is retained and recycled in lakes over longer periods of time. Mugidde et al. (2003) demonstrated that even though N fixation was less than 20% of daily N demand by phytoplankton in Lake Victoria, it accounted for nearly 80% of the annual total N loading. On a daily basis, recycled nitrogen dominated N uptake; but N fixation by heterocystous N fixers enabled them to overcome any daily limitation of N and allowed them to outcompete other algal groups for other limiting nutrients. However, these daily additions of newly fixed nitrogen to the total N pool when summed over the year were four times greater than all external sources of nitrogen compounds to Lake Victoria. Over ecological time scales of seasons to years, the combination of nitrogen fixation and net retention of recycled nitrogen allows phytoplankton to grow in proportion to phosphorus concentration and supply (Schindler, 1977; Schindler et al., 1987).

Some recent papers have observed that increasing inputs of nitrogen in lakes already saturated with phosphorus have caused nitrogen fixers to decline, being replaced by Microcystis or Planktothrix (Bunting et al., 2007; Paerl et al., 2011). It has been proposed that such changes are about to occur in Lake Winnipeg (Bunting et al., 2011). However, such changes appear to occur only in very eutrophic situations and are about to occur in Lake Winnipeg (Bunting et al., 2007; Paerl et al., 2011). It has been proposed that controlling nitrogen inputs would contribute little to reversing eutrophication in Lake Winnipeg. The many successful whole-lake experiments and case histories where lakes have been recovered by decreasing inputs of phosphorus alone indicate the most likely path to successfully reducing eutrophication of the lake. A recent model of the responses of phytoplankton in Lake Winnipeg to phosphorus control is in good agreement (Zhang and Rao, 2012). As shown by Schindler et al. (2008a) and Paterson et al. (2011) discussed by Schindler (in review), attempts to control N inputs can actually aggravate a eutrophic situation by selecting for the very N fixing species that are the major cause of concern in Lake Winnipeg.

Cost must also be a consideration. The removal of nitrogen from nutrient sources such as sewage treatment plants is quite costly, when compared to the removal of phosphorus alone. For example, to retrofit the City of Winnipeg’s north end waste water treatment plant to remove both phosphorus and nitrogen using biological nutrient removal and denitrification has been estimated to cost $400 million, while to remove phosphorus alone, plus nitrifying ammonium, is estimated to cost less than $100 million, while easily meeting provincial water quality standards. The more expensive alternative would only reduce nitrogen inputs to the lake by 1.3% (N. Szoke, Stantec Engineering, pers. comm.). Similarly, for the Baltic Sea, Håkanson (2009) estimates that removing phosphorus alone would cost 400 million Euros, while removing both elements would require 3300 million Euros. The latter cost is so great that smaller Baltic countries will probably not be able to afford it. In summary, removing both nutrients is several times more costly than removing phosphorus alone. The provincial policy commitment to reduce phosphorus input to Lake Winnipeg by 50% is ambitious, but necessary to address the eutrophication problem, and it should be the main focus of costs to the public.

**Looking ahead**

For the most part, Lake Winnipeg is well mixed, as the result of its huge area and shallow depth. However, Wassenaar (2012) and Zhao et al. (2012) report occasional periods of stratification, when hypolimnetic oxygen declines to <2.6 mg/L, in both summer and winter. In large lakes, such events are predicted to increase in frequency and duration under climate warming as they already have in the St. Lawrence Great Lakes (Magnuson et al., 1997). The density of water declines rapidly with each degree of temperature increase above 4 °C so that as surface waters warm, additional work by wind is required to mix the water column. Thus, warming increases the probability of stratification occurring, unless there are compensatory increases in wind velocity. Increasing nutrients cause increased productivity, which will also intensify rates of oxygen consumption by decomposition of algal material. As a result, oxygen could be depleted to even lower values than present minima, and become depleted more quickly as algal production increases. Together, increased stratification and increased nutrient loading can promote eutrophication by intensifying internal phosphorus loading. Hypoxia also favors denitrification, with the net effect that stratification will reduce the N:P ratio of nutrient regeneration (Hecky et al., 1996).

Lake Winnipeg’s recovery from eutrophication is likely to be slow, even if the 50% target for reducing input of phosphorus is reached. In
morphometry, it is similar to Lac la Biche, Alberta where land-use change, cottage development and a growing urban population have increased inputs of phosphorus to the lake (Schindler et al., 2008b). Both lakes are polymictic, with weak stratification developing during periods of calm weather. In Lac la Biche, during periods of even weak stratification anoxia develops quickly, and phosphorus is released from sediments. When windy conditions return, the stratification is broken and phosphorus is swept into the euphotic zone. Such events can occur several times a summer, keeping phosphorus, and thus algal densities high (Schindler, unpublished data). In lakes with such high internal recycling, recovery will be delayed until internal sources of phosphorus are buried or washed out of the lake. Studies in the USA and Europe indicate that a decade or more may be required for a lake to reach a new steady state after loading is reduced (Edmondson and Lehman, 1981; Jeppesen et al., 2005; Stich and Brinker, 2010; Welch, 2009). The rate of recovery in the lower Great Lakes was similar. The rate of recovery will not improve if nitrogen inputs are controlled. In fact, the occurrence of nuisance blooms of nitrogen fixing Cyanobacteria might increase because they are selectively favored when ironic nitrogen is low relative to phosphorus (Paterson et al., 2011; Schindler et al., 2008a).

Regional climate models connected to global models predict that by the mid-21st century, temperatures in the Lake Winnipeg basin will be 2.1–2.8°C warmer than the 1980s and precipitation will increase by 5.5 to 7.7% (Dibike et al., 2012; Shrestha et al., 2012). Such changes would certainly exacerbate the spring flooding that has been observed in recent years, thus compounding the eutrophication problem. The Red River catchment is so flat that it would be impossible to use dams to control floods and flow rates. This suggests us that aggressive control of phosphorus applied to land is the most likely measure to reduce eutrophication of the lake. Restoration of wetlands and drainage patterns would also assist by slowing the rate of runoff.

Although the eutrophication problem has been brought into better focus and to greater public attention by recent studies, the solutions will be challenging and other threats to the ecosystem health and stability of Lake Winnipeg, such as invasion by new exotic species including dreissenid mussels (Sheppard et al., 2012), are on the horizon. So far, only a few invaders have reached the lake; in contrast to the hundreds of invasive alien species in the Great Lakes (Ricciardi and MacIsaac, 2000).

Common carp, Cyprinus carpio were introduced to Lake Winnipeg by European immigrants in the late 1800s. There is a thriving population in the delta of the Red River, and the species is common in the southern basin of the lake. White bass Morone chrysops were observed in the Red River in 1963, following stocking in Lake Ashtabula, a reservoir on the tributary Sheyenne River. The species is now abundant in the lake, and many of the inflowing rivers. Rainbow smelt Osmerus mordax were first caught in Lake in 1990. The species was found earlier in Lake of the Woods, and it probably entered via the Winnipeg River. It is now widespread in the lake, where it competes with other forage fish. Other invaders so far include two species of crayfish, the Asian carp tapeworm, and the cladoceran Eubosmina coregoni. The spiny water flea Bythotrephes has recently been found in Lake of the Woods, and zebra mussel Dreissena polymorpha veliger larvae were recently found in the Red River. The Souris River diversion threatens to allow species from the Mississippi–Missouri drainage to enter Lake Winnipeg as well. It appears that a major invasion of aquatic species to the lake is starting. As found in the Great Lakes (Evans et al., 2011), these may greatly change the lake’s future trophic status via changes to the pathways for recycling of nutrients even though loading of nutrients is not changed (Carpenter et al., 1985; Elser et al., 2000; Hecky et al., 2004).

Lake Winnipeg may be unique among culturally eutrophied large lakes for two aspects: its enormous watershed and low contribution of human wastes to its nutrient enrichment. Lake Winnipeg has a drainage area to lake area ratio of 42:1, much larger than any other large lake in the world; but the population density in this huge basin is low. Winnipeg contributes only 5% to the phosphorus load, and all other point sources an estimated 4% (LWSB, Lake Winnipeg Stewardship Board, 2006). Rural populations supply less than 1% of the nutrient yield to the catchment, even in its most populous catchment, the Red River basin (Yates et al., 2012). In the Laurentian Great Lakes prior to P reduction targets imposed by the international agreement under the Great Lakes Water Quality Agreement, point sources (largely waste treatment plants) accounted for much of the P loading, e.g. nearly 50% in Lake Erie. The Great Lakes recovered rapidly after these point sources met mandated P emission standards. However the non-point sources of P were not regulated (Schindler and Vallentyne, 2008) and there is now increasing concern that agriculturally impacted regions of the Great Lakes basin may be causing eutrophication to increase again (Joosse and Baker, 2011).

Easy to control point sources are few and nearly insignificant to the basin scale P loading to Lake Winnipeg. The Province of Manitoba has risen to the challenge by recently announcing a goal of reducing P loading to the lake by 50% but the complex details of how to accomplish this goal remain to be defined. Added to this challenge are the possible roles of climate change and watershed hydrological modifications in imposing higher nutrient loading on the lake, as we have described above. Climatic factors are beyond the control by the province or any single jurisdiction in the world, and their importance is likely magnified by the extreme low slope of these prairie basins which exhibit non-linear responses in runoff to even modest changes in precipitation. However, the sensitivity of the lake to nutrient loading is clear and the need for action imperative.

As politicians procrastinate, taking little meaningful action to help curb climate warming, predictions based on science indicate that it will be difficult to keep the condition of Lake Winnipeg from worsening. From the evidence that we reviewed, reducing the eutrophication of Lake Winnipeg will require reducing both nutrient application in the watershed and flooding of the overfertilized Red River watershed. The increased flooding in recent years appears to be the result of higher runoff due to increased precipitation since the 1990s aggravated by a prior history of channelization, wetland destruction, and perhaps modification of drainage patterns by roads and urbanization (Ehsanzadeh et al., 2011). Restoration of wetlands and drainage patterns must therefore be a part of the recovery plan for the lake, as well as better phosphorus management by the agricultural sector.

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