SETTING PHOSPHORUS AND NITROGEN TARGETS TO IMPROVE WATER QUALITY

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Water Science and Watershed Management Branch

December 2020

Manitoba
Agriculture and Resource Development

Manitoba Agriculture and Resource Development Report

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INTRODUCTION

Manitoba and many other jurisdictions globally are experiencing an increase in the frequency and severity of harmful and nuisance algal blooms. Algal blooms occur in aquatic ecosystems as a result of excess nutrients in conjunction with favourable environmental conditions (e.g., warm water temperatures, calm weather conditions) (Foulon *et al.*, 2020). Algal blooms can spoil drinking water, adversely impact recreational use of beaches, reduce property values, and damage fish and other aquatic life. In addition, algal blooms may produce and release algal toxins that are potentially harmful to humans and other mammals. In Manitoba, the most well known example is Lake Winnipeg, which has experienced increasing frequency and intensity of cyanobacterial blooms (Bunting *et al.*, 2011; McCullough *et al.*, 2012; Environment Canada & Manitoba Water Stewardship, 2011; Environment and Climate Change Canada & Manitoba Agriculture and Resource Development, 2020), at times covering more than 10,000 square kilometers of the lake surface area. However, other lakes across the province including Pelican, Killarney, Sandy, Stephenfield, Minnewasta, and lakes in Whiteshell Provincial Park also experience algal blooms. Manitoba also occasionally posts first and/or second level advisories in an effort to protect public health when densities of cyanobacteria or concentrations of algal toxin exceed water quality objectives. While less commonly reported, algal blooms also occur in rivers and streams in Manitoba, particularly during warm weather when flows are low. Nuisance algal blooms are often composed of various types of cyanobacteria (or blue green algae), but may also include (or be dominated by) other algal species such as green algae or attached algae such as diatoms that can grow on fisher's nets and other submersed objects.

Historically, there has been acceptance that primary productivity and algal biomass is limited by: phosphorus in freshwaters (Schindler, 1974, 1977); nitrogen in marine waters (Vitousek & Howarth, 1991; Howarth & Marino 2006); and, transitions between phosphorus and nitrogen in estuaries (Hecky & Kilham, 1988). Case studies and whole lake experiments, many of which have been conducted at the Experimental Lakes Area (ELA) over multi-decade timescales, have provided evidence that the supply of phosphorus is one of the key factors controlling eutrophication in freshwaters (Schindler, 2012; Schindler *et al.*, 2016; Higgins *et al.*, 2018) and that elimination of these inputs favours better water quality (Jeppesen *et al*., 2005; McCrackin *et al*., 2017). Phosphorus abatement strategies have led to water quality improvements in many freshwaters globally within varying landscapes and of varying physiological and biogeochemical characteristics (Schindler *et al.*, 2016). However, control of phosphorus inputs has not resolved eutrophication issues in some freshwaters, which has prompted further investigation into other potentially important drivers of eutrophication, particularly nitrogen pollution and internal nutrient cycling (Sterner, 2008; Paerl *et al.*, 2016a,b).

For decades, experts have debated the relative importance of reducing nitrogen to prevent symptoms of eutrophication and to protect water quality. More recently, data are available documenting water quality improvements and reduced phytoplankton biomass through load reduction of both phosphorus and nitrogen over the long-term (Köhler *et al.*, 2005; Paerl *et al.*, 2016b; Søndergaard *et al.*, 2017). As a result, the strategy of reducing phosphorus alone to prevent symptoms of eutrophication has been challenged over the past two decades (Paerl *et al.*, 2016b; Dodds & Smith, 2016; Poikane *et al.*, 2019). The dual nitrogen and phosphorus reduction strategy is based on evidence that nitrogen can also play in important role in controlling primary productivity in a diverse array of freshwater lakes (Elser *et al.*, 1990; Dolman *et al.*, 2016; Paerl *et al.*, 2018) and rivers (Dodds & Smith, 2016; Jarvie *et al.*, 2018) and may be equally as important as phosphorus in some ecosystems (Davis *et al.*, 2015). In addition, failure to control nitrogen inputs upstream can lead to problems in aquatic environments downstream (e.g., estuarine or coastal marine environments) where nitrogen-limiting conditions contribute to marine eutrophication (Paerl *et al.*, 2018). As a result, there has been increasing support in the scientific community that both nitrogen and phosphorus need to be controlled to reduce algal blooms and the production of toxins in freshwater, estuarine, and coastal marine ecosystems (Conley *et al.*, 2009; Paerl *et al.*, 2011a, Lewis *et al.*, 2011; Dolman *et al.*, 2012; Smith *et al.*, 2016; Paerl & Otten, 2016; Paerl *et al.*, 2019; Scott *et al.*, 2019), particularly in systems that are rich in phosphorus (Bunting *et al.*, 2005; Leavitt *et al.*, 2006; Swarbrick *et al*., 2019, 2020).

Adoption of water quality criteria (or targets, benchmarks, objectives or guidelines) for both phosphorus and nitrogen to protect water quality is occurring more widely in jurisdictions around the world (Wurtsbaugh *et al.*, 2019). For example, in 2015 the United States Environmental Protection Agency (US EPA) described the need to control both nitrogen and phosphorus to prevent eutrophication (US EPA, 2015). In addition, approximately half of the member states of the European Union (EU) incorporate both nitrogen and phosphorus criteria into management strategies to protect the ecological status, including combating nutrient enrichment, of freshwater lakes and rivers (European Water Directive, 2000; Poikane *et al.*, 2019).

Other jurisdictions in the Lake Winnipeg watershed include both nitrogen and phosphorus in their nutrient reduction strategies (for example, North Dakota and Minnesota). The Prairie Provinces Water

Board (which has responsibility for transboundary water quality between Alberta, Saskatchewan, and Manitoba) has set water quality objectives for phosphorus and nitrogen in transboundary rivers including those that flow directly into Lake Winnipeg. The International Joint Commission recently recommended both phosphorus and nitrogen targets and objectives for the Red River at the US/Canada border. Of note, Manitoba is a participant in both the Prairie Provinces Water Board and the International Joint Commission's Red River work. Further, many of the larger wastewater treatment facilities across the Canadian prairies include both phosphorus and nitrogen removal (for example, Calgary and Regina). Manitoba adopted a dual nutrient management approach in the early 2000s and has continued to include both nitrogen and phosphorus in the development of nutrient reduction strategies.

The Government of Manitoba is proposing a new regulation under The Water Protection Act to establish nutrient targets for Lake Winnipeg and the major tributaries flowing into the lake. As part of this process, information and science regarding nutrients and algal blooms was reviewed and a rationale for establishing nutrient targets for both nitrogen and phosphorus to improve water quality in Manitoba is summarized below.

NUTRIENT TARGETS FOR NITROGEN AND PHOSPHORUS

The rationale for developing nutrient targets for nitrogen and phosphorus for Lake Winnipeg and its tributaries can be summarized in nine key points:

1) Nitrogen is a pollutant and concentrations are increasing in Manitoba's rivers and lakes.

Nitrogen and phosphorus are both considered pollutants when they occur in excess and concentrations of both have generally increased in Manitoba over the past several decades. Since the early 2000s, several water quality assessments have documented changes in nutrient concentrations in surface waters across the prairie region over various timescales (Jones & Armstrong, 2001; Vecchia, 2005; Paquette, 2011; Environment Canada, 2011; PPWB, 2016; Nustad & Vecchia, 2020, among others). In 2011, a national water quality assessment found that slow moving prairie rivers upstream of Lake Winnipeg had among the highest nutrient concentrations in the country (Environment Canada, 2011). In general, analyses of historical monitoring data from the 1970s to 2015 indicate that nutrient concentrations (i.e., nitrate + nitrite, total nitrogen, total dissolved phosphorus, total phosphorus) have increased in many prairie rivers (Environment Canada, 2011; PPWB, 2016; Nustad & Vecchia, 2020). In some cases, nutrient concentrations have increased by as much as 200 percent (Jones & Armstrong, 2001). In some rivers and streams, increases in nitrogen concentrations have been larger than those observed for phosphorus (Jones & Armstrong, 2001).

Effects of nitrogen pollution may also be more pronounced in waterbodies that already have high concentrations of phosphorus, such as many in southern Manitoba. Stable isotope analyses and paleolimnological studies have shown algae growth is more closely linked to nitrogen influx compared to phosphorus, particularly in phosphorus-rich systems (Bunting *et al.*, 2005; Leavitt et al., 2006, Xu *et al.*, 2010; Bogard *et al.*, 2020). Nitrogen pollution in phosphorus-rich lakes has been shown to increase cyanobacterial production and toxicity by up to 500 per cent (Donald *et al.,* 2011). It is evident that increased nitrogen and phosphorus export to surface waters owing to agricultural and urban activities has led to degraded water quality over the past century (Hall *et al.,* 1999; Maheaux *et al.,* 2016; Bunting *et al.,* 2016; Cormier *et al*., in press).

2) Some forms of nitrogen are toxic.

Studies have shown that elevated concentrations of nitrogenous species (e.g., nitrate, nitrite, ammonia) in aquatic ecosystems can have direct toxic effects to aquatic life (Canadian Council of Resource and Environment Ministers [CCREM], 1987; Canadian Council of Ministers of the Environment [CCME], 2010, 2012) and can harm humans and animals (Health Canada, 2019). Implementation of nitrogen targets assists in the management of nitrogenous species.

3) Limitations on primary production extend beyond phosphorus because concentrations of nitrogen and phosphorus vary over space and time.

Phosphorus often controls algal growth in lakes, as its rate of supply is low relative to the demands of algae (Redfield, 1958; Schindler, 1977). However, in instances where phosphorus supply is abundant through natural or human sources, control shifts to the next factor in short supply, typically nitrogen (Paerl *et al*., 2016b). Further, control of a single nutrient is an overly simplistic approach because the limitation of lake production varies in both time and space in a wide variety of waterbodies (US EPA, 2015). Studies demonstrate that nitrogen limitation, phosphorus limitation, and nitrogen and phosphorus co-limitation can occur in freshwater, estuarine, and marine systems (Paerl *et al.*, 2014; Bratt *et al.*, 2019). In some instances where both nutrients are abundant, control of algal blooms can shift to other factors such as light availability, trace elements, and changes in food web composition (Paerl & Otten, 2013). In particular, the importance of phosphorus and nitrogen as controls of phytoplankton abundance and community composition has been documented to vary seasonally

(Bullerjahn *et al*., 2016; Janssen *et al*., 2017), which highlights the importance controlling both elements (Paerl *et al*., 2011b; Swarbrick *et al.,* 2020).

As a result, a moderate reduction in nitrogen, in addition to significant phosphorus reduction, could provide benefits for improving water quality without forcing an ecosystem into severe nitrogen limitation that might favour the growth of nitrogen-fixing algal species (Glibert, 2017). Since nutrient limitation is highly variable, developing water quality targets for both nitrogen and phosphorus provides the greatest likelihood of reducing algal blooms.

4) Nutritional needs of different algae are different.

The US EPA's 2015 fact sheet regarding the need for dual control of nitrogen and phosphorus noted that aquatic flora and fauna have a diverse set of nutritional needs. The optimal nitrogen to phosphorus ratio for growth of algae has been shown to vary among species and, on occasion, within species. Therefore, organisms have distinct ecophysiological characteristics with respect to nutrient requirements and different taxonomic groups will respond differently at different nutrient levels (Glibert, 2017). The concept of single nutrient limitation relies on the assumption that the growth of all species of algae will be limited by the nutrient in shortest supply. However, some species may show phosphorus limitation while others in the same water body show nitrogen limitation or both (US EPA 2015). Unique competitive advantages of some species of algae may also influence nutrient limitation with the most obvious example being the ability of some species to fix nitrogen. On review, the EPA concludes that because of the diversity of nutritional needs, nutrient targets and objectives for both nitrogen and phosphorus are likely to be more effective in protecting aquatic ecosystems.

5) Not all species of algae fix nitrogen because it is too expensive.

Some species of algae (called nitrogen fixing cyanobacteria) are capable of using atmospheric sources of nitrogen when the aquatic nitrogen pool is in short supply, thus providing an additional source of nitrogen to waterbodies. However, nitrogen fixation is an energy-expensive process that allows less growth than if aquatic nitrogen sources were present (Finlay, *et al.*, 2010; Scott & McCarthy, 2010) and this may be the reason why nitrogen-fixing cyanobacteria preferentially use external sources of nitrogen when possible (Paerl *et al.*, 2016a; Paerl *et al.*, 2019). In addition, most species of algae, including other cyanobacteria, cannot fix nitrogen and therefore rely solely on external sources of nitrogen to support growth. Finally, several studies have shown that nitrogen fixation does not fully account for phytoplankton or ecosystem nitrogen demands in fresh or coastal marine waters (Paerl & Otten, 2013;

Scott & McCarthy, 2010, 2011; Paerl & Scott, 2010; Lewis *et al.*, 2011; Beaulieu *et al.*, 2013; Scott *et al.*, 2019), including Canadian prairie lakes (Patoine *et al.*, 2006; Hayes *et al.*, 2019).

6) Nitrogen plays a role in the production of algal toxins

Failure to reduce nitrogen concentrations could favour the growth of non-nitrogen fixing cyanobacteria that produce toxins. One of the most common and harmful non-nitrogen-fixing cyanobacterial genera in freshwater lakes is *Microcystis*. Like many other non-nitrogen-fixing cyanobacteria, *Microcystis* can produce aesthetically unpleasing surface scums, odors, and tastes; however, it also is a major source of the harmful hepatotoxin, microcystin (Paerl & Otten, 2016). *Microcystis* typically thrives in warm, well-mixed, nutrient rich, low light environments and is able to rapidly recycle nutrients because of its ability to regulate buoyancy and optimize nutrient uptake (Paerl *et al.*, 2011a). In addition, *Microcystis* also has a unique advantage over other non-nitrogen-fixers because it has the ability to sequester both dissolved inorganic and organic forms of nitrogen (Davis *et al.*, 2010). As a result, the increasing prevalence of *Microcystis* in freshwater lakes across the globe has been directly attributed to increasing nitrogen loads (Glibert, 2017). Not surprisingly, *Microcystis* is a common cyanobacteria in the shallow, well-mixed, and nutrient rich south basin of Lake Winnipeg. Work by Bunting *et al.* (2011) on Lake Winnipeg concluded with the concern that failure to reduce phosphorus and to continue nitrogen pollution could lead to further intensification of blooms of potentially toxic algae such as *Planktothrix*, *Microcystis*, and *Cylindrospermopsis* such as has occurred in the Canadian Prairies (Patoine *et al.,* 2006; Leavitt *et al.,* 2006), Europe (Scheffer *et al.,* 1990; Bunting *et al.,* 2007), China (Paerl & Scott, 2010; Xu *et al.*, 2010), and elsewhere.

Cyanobacterial toxicity appears linked to how fast they grow in the water. Thus, there is evidence that both phosphorus (Kotak & Zurawell, 2007; Poste *et al.*, 2013) and nitrogen supply (Finlay *et al*., 2010; Bogard *et al*., 2020) both promote the development of cyanobacteria blooms and their degree of toxicity; particularly in eutrophic and hypereutrophic systems (Dolman *et al.*, 2012; Paerl & Otten, 2013; Yuan *et al.,* 2014; Chaffin *et al.*, 2018). Recent evidence also suggests that nitrogen concentration and speciation may play a more critical role than originally thought (Donald *et al.,* 2011; Bogard *et al.*, 2020). For example, Orihel *et al.* (2012) investigated microcystin concentrations in phosphorus-rich Canadian lakes and determined the highest concentrations were associated with the highest nitrogen content, as well as low total nitrogen:total phosphorus ratios. In addition, total nitrogen was highly correlated to microcystin in these Canadian lakes, consistent with the importance of nitrogen supply in regulating toxin production in phosphorus-rich lakes (Donald *et al*., 2011; Bogard *et al*., 2020; Swarbrick *et al*., 2020). Indeed, nitrogen speciation and concentrations have been shown to have profound effects on cyanobacterial blooms by altering community structures, sustaining toxic blooms, and increasing toxin production and release (Beversdorf *et al.*, 2013, 2015; Monchamp *et al.*, 2014; Gobler *et al.*, 2016; Harris *et al.*, 2016; Chaffin *et al.*, 2018).

7) Cyanobacteria are not the only issue. Other species of algae can be a problem too.

Failure to control nitrogen could also contribute to the excessive growth of other forms of nuisance algae such as green algae and diatoms because they rely solely on external sources of nitrogen (and phosphorus) to support growth. Nuisance growth of green algae and diatoms have been observed in Manitoba including in rivers and on commercial fishers nets in Lake Winnipeg. In addition, some forms of diatoms are known to produce the novel algal toxin β-methylamino-L-alanine (BMAA, Violi *et al.,* 2019), a compound which has recently been measured in water samples collected from Lake Winnipeg (Pip *et al.,* 2016). Without the reduction of nitrogen inputs from external sources, many of these non-nitrogen-fixing cyanobacteria and other algal species could thrive in aquatic ecosystems, especially those that are also rich in phosphorus.

8) Nutrient targets for Lake Winnipeg should consider the downstream receiving environment.

While Lake Winnipeg is an important waterbody affected by a large region, the impact of nutrients and nutrient reduction strategies for the lake will also extend further downstream to the Nelson River and Hudson Bay. While nutrients and algal dynamics have not received the same attention or study in the Nelson River and Hudson Bay, there is reason to expect that nitrogen could play a key role. Estuaries and coastal marine environments are typically limited by nitrogen rather than phosphorus (Howarth *et al.*, 1988; Vitousek & Howarth, 1991; Boesch, 2001; Howarth & Marino, 2006; Paerl, 2009). Stewart and Lockhart (2005) suggested that incomplete vertical mixing causes nutrients, primarily nitrogen, to limit primary productivity within Hudson Bay. Ultimately, the management of nutrients (nitrogen and phosphorus) in Manitoba needs to consider the protection of downstream waters (freshwaters and coastal marine ecosystems).

9) Setting targets for both nitrogen and phosphorus allows better tracking of progress over time.

Since the early 2000s, Manitoba's strategy for water quality improvements in Lake Winnipeg has included actions to reduce both nitrogen and phosphorus. Establishing targets for both nutrients improves accountability and transparency by allowing progress to be tracked through time. For example, both the Nutrient Management Regulation and the Livestock Manure and Mortalities Management Regulation require regulation of both nitrogen and phosphorus use. The Water Quality Standards, Objectives and Guidelines Regulation and specific licenses under The Environment Act require wastewater treatment facilities serving more than 10,000 people to control nitrogen and phosphorus. In part, limits for both nutrients in wastewater are intended to encourage adoption of biological nutrient removal technologies that promote nutrient recycling and reuse (for example, as fertilizers) and that are more sustainable than chemical phosphorus removal. Many beneficial management practices, such as those funded through new incentive programs such as Growing Outcomes in Watersheds, AgAction and the Conservation Trust, are also expected to reduce both nitrogen and phosphorus loads to waterways. Recent research on beneficial management practices has examined the effectiveness for reducing both nitrogen and phosphorus (such as the recent 2020 cold climate best management practices workshop report). With the multitude of efforts aimed at reducing both phosphorus and nitrogen loads to waterways, the targets will support reporting on progress and development of future actions.

Finally, it is important to specifically mention the important research on phosphorus and nitrogen that has been conducted at the Experimental Lakes Area in northwestern Ontario. The Experimental Lakes Area (ELA) is an internationally recognized centre for the study of inland waters that was originally established in 1968 by the Canadian federal government and which has been operated by the International Institute for Sustainable Development since 2014. The ELA is a natural laboratory comprised of 58 small lakes and their watersheds in a sparsely populated, forested region of the Precambrian Shield where the lakes are not affected by human impacts. Scientists manipulate these small lakes to examine how all aspects of the ecosystem respond. One of the original priorities for this research facility was to investigate the eutrophication problem that was plaguing many lakes such as Lake Erie.

Research from the ELA in northwestern Ontario has and continues to contribute significantly to our understanding of solutions for complex water challenges including related to nutrient enrichment. The Manitoba Government is a funder of the International Institute for Sustainable Development and has closely followed the research and findings from the ELA since the work began in the late 1960s. Work done at the ELA continues to influence Manitoba policies to this day. However, there are differences between the undisturbed aquatic environments studied at the Experimental Lakes Area and those within Lake Winnipeg and its enormous highly-modified watershed, including those related to nutrient concentrations, nutrient sources, size of the watershed, lake size, and aquatic species composition. All these factors impact the nutrient reduction strategy selected for water quality improvements. For example, a recent paper by Higgins *et al.* (2018) demonstrates nitrogen fixation and other internal sources of nutrients sustain algal blooms in lakes fertilized only with phosphorus at ELA. However, this lake has less than half of the amount of phosphorus observed in Lake Winnipeg, has a 0.3 km^2 watershed that is 75,000 times smaller than that of Lake Winnipeg (23,750 km^2), is devoid of fish, and lies entirely within an undisturbed boreal forest with shallow soils. Thus, while nitrogen fixation may be a dominate source of nitrogen in the small isolated lake, nitrogen contributions through fixation in Lake Winnipeg are likely outweighed by the large external sources from the watershed, such as seen on other prairie lakes (Patoine *et al*., 2007; Hayes *et al.*, 2019). Another challenge in applying the ELA research is that Manitoba is proposing to reduce both phosphorus and nitrogen, a scenario not tested in the ELA research, but one that could be considered for future studies. Reductions in both phosphorus and nitrogen loading will undoubtedly change the response of the algae in Lake Winnipeg in a way that is different from what was experienced at the ELA.

It must be emphasized again that the ELA research is important and helps to further our understanding of algae and nutrient dynamics in lakes around the world. However, the ELA work must also be considered in the context of other studies that are relevant to Lake Winnipeg, a large prairie lake with a very extensive and impacted watershed. For example, scientific reviews of global nutrient addition studies in freshwaters (Elser *et al.* 1990, 2007) and of whole-lake nutrient addition experiments in northern latitude lakes (Paerl *et al.* 2016b) show that fertilization with both nitrogen and phosphorus together exerts the greatest effect in stimulating algal blooms. Another comparable study is the work of Leavitt *et al.* (2006) who demonstrated that urban nitrogen was an important contributor to eutrophication within phosphorus-rich lakes in the Qu'Appelle watershed of Saskatchewan.

CONCLUSION

In conclusion, the Government of Manitoba remains committed to setting nutrient targets for both nitrogen and phosphorus to combat eutrophication and improve water quality, particularly in phosphorus-rich ecosystems like Lake Winnipeg. Manitoba will continue to use science and an adaptive management approach to guide nutrient management strategies. Factors such as climate change, increasing human population, and changes in land use will provide additional challenges to reducing the transport of nutrients to surface waters into the future and is likely to exacerbate the issue of eutrophication. It is expected that setting nutrient targets for nitrogen and phosphorus and reporting regularly on progress will support our efforts towards water quality improvements in Lake Winnipeg.

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