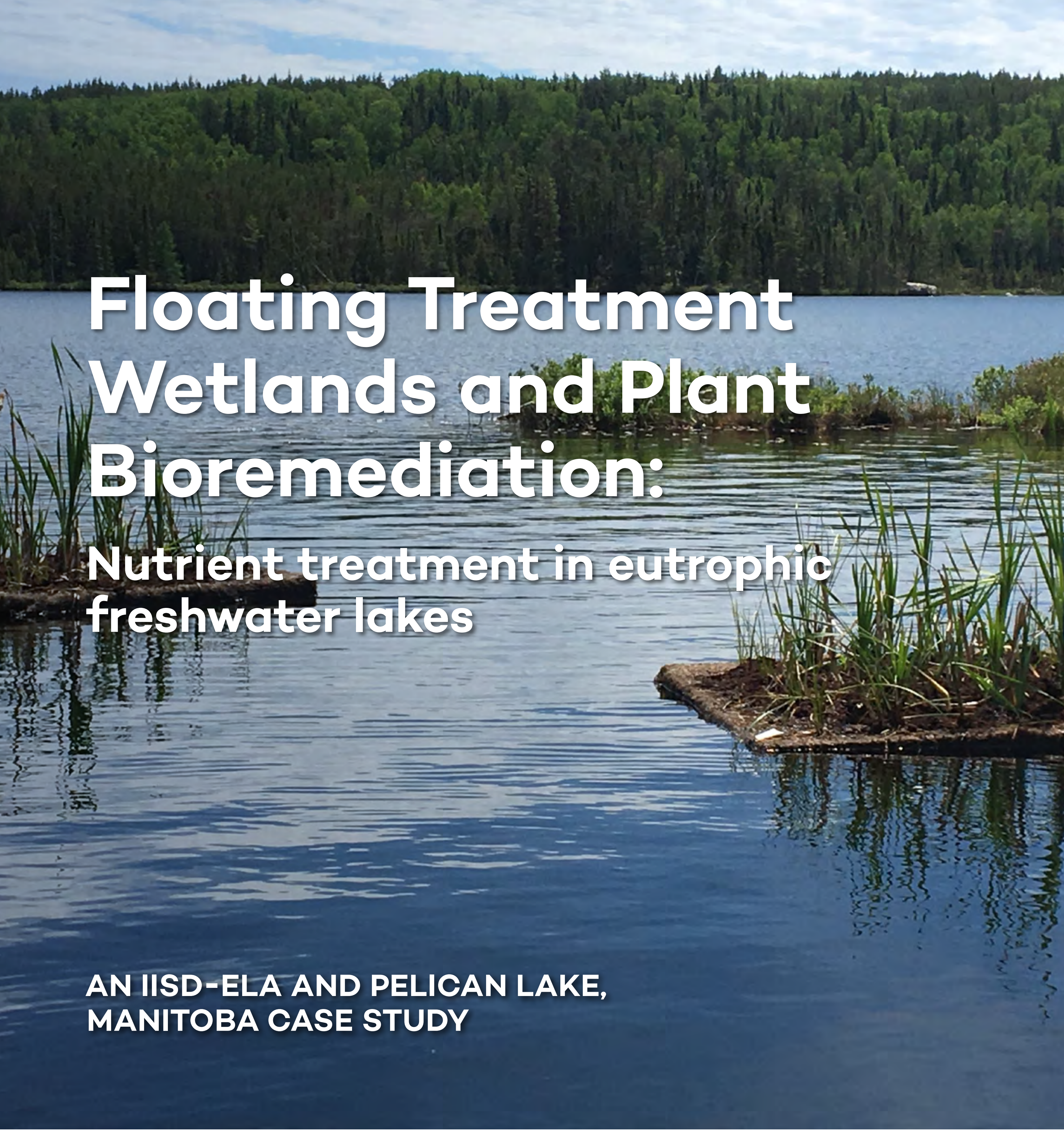

Floating Treatment Wetlands and Plant Bioremediation:

Nutrient treatment in eutrophic freshwater lakes

AN IISD-ELA AND PELICAN LAKE, MANITOBA CASE STUDY

IISD
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IISD
Experimental Lakes Area

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About IISD-ELA

IISD Experimental Lakes Area (IISD-ELA) is the world's freshwater laboratory. A series of 58 lakes and their watersheds in northwestern Ontario, Canada, IISD-ELA is a unique scientific site where researchers can experiment directly on freshwater lakes to discover the impacts of human activity and pollutants. Since 1968, IISD-ELA has helped us reveal everything from the impact of phosphorus on algal blooms, to the effects of mercury on freshwater systems, to how acid rain affects lakes. The site works with local and global researchers and with local communities, First Nations, schools and universities. It is funded by the governments of Canada, Ontario and Manitoba, and by many other generous partners and donors.

IISD-ELA

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Written by Richard Grosshans, Kimberley Lewtas, Geoff Gunn and Madeline Stanley

About this Report

This report builds upon previous work on prairie lake remediation, which included a review and assessment on in-lake remediation treatments and strategies characterizing available lake chemistry and hydrological data for Manitoba prairie lakes, and the development of a remediation decision support framework. This research is also part of a broader IISD-Experimental Lakes Area research program on Bioremediation and Floating Treatment Wetlands.

IISD acknowledges funding support for this research from the Government of Manitoba, and support from the field staff at the IISD-Experimental Lakes Area.

Executive Summary

Shallow lakes are one of the most common types of lakes globally and, because of their shallow nature, are often the most heavily impacted by natural and human pressures. Eutrophication is the over-enrichment of nutrients such as nitrogen and phosphorus in a lake or water body, often exacerbated by human-related nutrient runoff from the surrounding watershed. It is a pervasive water quality issue affecting surface waters in many jurisdictions across Canada and locally in Manitoba in lakes such as Lake Winnipeg and smaller prairie lakes like Pelican Lake. This study examines the use of floating treatment wetlands (FTWs) as an innovative bioremediation option for smaller eutrophic water bodies based on new primary research carried out at IISD-Experimental Lakes Area (IISD-ELA) in northwestern Ontario, analysis at Pelican Lake, Manitoba, and building on case studies from the literature.

Wetlands and their aquatic plant communities play an important role in improving water quality. Larger emergent plants such as cattail (*Typha* spp.), take up and remove nutrients (i.e., phosphorus and nitrogen) and break down contaminants and toxins from the sediment and water, incorporating them into their plant material or biomass. The use of wetlands, both natural or constructed, for improving water quality (bioremediation) is widely practised around the world, especially for the treatment of stormwater runoff, municipal wastewater effluent and treating contaminants from landfill leachate and mine tailings ponds.

FTWs are an innovative variant of a constructed treatment wetland that allows water treatment in water bodies that are too deep for plants to grow and under fluctuating water levels. FTWs are a proven concept globally and have been successfully deployed around the world for the treatment of surface water and stormwater runoff, municipal wastewater effluent, landfill leachate and mine site tailings ponds. They have also been well documented for their additional benefits for fish and wildlife habitat enhancement as well as shoreline protection by reducing wave erosion.

FTWs can be quickly established as "natural infrastructure" in any water body as a managed bioremediation system, such as in small eutrophic lakes or wastewater lagoons. In eutrophic water bodies, the excess nutrients create conditions for rapid plant growth, not unlike hydroponics. Plant roots spread through the floating islands and down into the water creating dense columns of roots. Not only do the plants take up nutrients and contaminants, the plant roots and floating island material provide extensive surface area for formation of biofilm—the slimy layer of algae, bacteria and other microbes that adheres to the surface area. Research suggests that it is the biofilm that coats roots and the island surface where the majority of nutrient uptake and degradation occurs in the FTW system.

Floating wetland platforms were deployed in two lakes of different phosphorus concentrations at IISD-ELA in northwestern Ontario: two in Lake 227 (L227), a lake where phosphorus has been added and studied since 1969, and two in Lake 114 (L114) as a natural reference lake. The goal of this research was to quantify the impact of phosphorus enrichment in lake ecosystems on plant productivity and to assess nutrient sequestration of cattail plants growing on floating platforms. This primary research was then applied to a typical prairie lake, Pelican Lake, to determine how FTWs would work as a bioremediation option for eutrophic water bodies.

The L227 studies showed that a relatively small increase in phosphorus loading resulted in a rapid increase in plant productivity on floating platforms in L227, with an increase in overall plant growth and biomass production. This in turn increased phosphorus uptake, particularly below water in the root zone (or rhizosphere). This confirmed that cattails are opportunistic consumers of nutrients and will reproduce and grow bigger with more available nutrients, such as phosphorus. As a remediation option, the use of cattails is therefore effective in eutrophic lakes.

Based on the results from the deployment of FTWs in lakes at IISD-ELA and case studies from the literature, the potential of FTWs in remediation of smaller eutrophic prairie lakes in Manitoba was evaluated. Pelican Lake, Manitoba, was used as a representative case study of Manitoba prairie lakes. Based on the estimated phosphorus removal by FTW systems, multiple scenarios were established for determining the surface area coverage of FTWs required to achieve a range of potential total phosphorus (TP) removal targets. It was estimated that FTW coverage of 5 per cent of the Pelican Lake surface could reduce TP levels in the lake by up to 50 per cent, depending on TP removal levels by the FTW system. Given the size of Pelican Lake, FTWs alone would not decrease lake TP concentration below the provincial guideline (0.025 mg/L). Nevertheless, in prairie lakes such as Pelican Lake, FTWs are one component of options that need to be considered in combination for lake remediation.

This study demonstrated that FTWs are an effective passive biological bioremediation option to enhance the removal of nutrients and help remediate eutrophication in surface waters in Manitoba. FTWs offer an innovative "natural infrastructure" alternative to conventional in-lake remediation strategies. Ultimately, FTWs deployed in combination with other in-lake remediation treatments and watershed nutrient reduction strategies, targeting both internal and external nutrient loading sources, would be most effective and provide additional positive contributions to the health of the aquatic environment. This maximizes the effectiveness of programs and government priorities related to phosphorus reduction in surface waters, such as in Lake Winnipeg.

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1.0 Introduction

1.1 Eutrophication of Shallow Lakes

Shallow lakes are one of the most common types of lakes globally and, because of their shallow nature, are often the most heavily impacted by natural and human pressures. Urbanization, waste treatment, landscape change, agriculture and natural resource extraction cause runoff of nutrients, contaminants, petroleum products and organics to these water bodies that can significantly impact lake water quality.

Eutrophication is the over-enrichment of nutrients such as nitrogen and phosphorus in a lake or water body, most often caused by human-related nutrient runoff from the surrounding watershed. This over-enrichment essentially adds fertilizer and causes excessive growth of plants, algae blooms and increased spread of invasive species. It can also cause fish die-offs and loss of other aquatic species from a lack of oxygen and toxins from certain blue-green algae. Eutrophication is a well-documented freshwater quality issue globally (Anderson, Glibert, & Burkholder, 2002; Ansari & Gill, 2014; Chislock, Doster, Zitomer, & Wilson, 2013) and is a pervasive water quality issue affecting surface waters in many jurisdictions across Canada and locally in Manitoba in lakes such as Lake Winnipeg (Environment Canada & Manitoba Water Stewardship, 2011).

Some freshwater bodies in Manitoba are possibly naturally eutrophic due to regional soil fertility, runoff patterns and geology, encouraging eutrophic conditions (Environment Canada & Manitoba Water Stewardship, 2011; Lewtas, Paterson, & Venema, 2015). However, eutrophication in large lakes such as Lake Winnipeg and smaller lakes like Pelican Lake have been linked to human-induced cultural eutrophication (Environment Canada & Manitoba Water Stewardship, 2011). This is caused by an increase in nutrients entering the lake from the surrounding watershed from sources such as agriculture, fertilizer, and rural and urban sewage effluent.

IISD previously carried out a comprehensive review on remediation techniques applicable to Canadian and Manitoba prairie lakes (Lewtas, Roy, & Paterson, 2016), exploring a range of biological engineering, physical engineering and chemical applications for remediation related to eutrophication. Floating treatment wetlands (FTWs) were explored as one of three biological and ecological engineering options, with an assessment of successful applications in other regions, such as Eucha Lake and Pasco County in the United States. Benefits of FTWs based on our analysis included construction efficiency, reduction of anoxic conditions, improved habitat, nutrient reduction, water quality improvement and potential for greater nutrient removal through biomass harvesting. FTWs in general were found to be most applicable for smaller ponds, lagoons, reservoirs and retention basins, with limited remediation benefits on larger lakes (Lewtas et al., 2016).

This report examines FTWs as an innovative bioremediation option for smaller eutrophic water bodies based on new primary research carried out at IISD-ELA in northwestern Ontario, at Pelican Lake, Manitoba, and case studies from the literature.

1.2 FTWs and Bioremediation

1.2.1 Wetlands and Bioremediation

Wetlands and their aquatic plant community, both emergent and submersed, play an important role in improving water quality. Larger emergent plants, such as cattail (Typha spp.), take up and remove nutrients (i.e., phosphorus and nitrogen) and break down contaminants and toxins from the sediment and water, incorporating them into their plant material or biomass. They also provide shelter and surface area for small fish, plankton and microorganisms, which are all important components for nutrient uptake and contaminant breakdown. Wetlands rely on these natural processes to biologically filter water as it passes through shallow areas of dense aquatic vegetation and permeable bottom soils. The primary mechanisms for nutrient removal is transformation and uptake by microorganisms (microbes) and plants, assimilation and absorption into organic and inorganic sediments, and conversion into gases released to the air through volatilization (Stewart et al., 2008). Enhancing or engineering biological treatment of nutrients and contaminants is possible by harnessing the natural ability of plants, microbes and biological processes, a process known as bioremediation.

The use of wetlands, both natural or constructed, for bioremediation is widely practiced around the world for treatment of stormwater runoff and municipal wastewater effluent. There has also been success in using wetlands for treating contaminants from landfill leachate and holding ponds from natural resource extraction (Kadlec & Knight, 1996; Mitsch et al., 2000). Constructed treatment wetlands can be subsurface flow or open-surface water wetlands, planted with diverse free-floating aquatic plants and sediment-rooted submersed and emergent wetland plants (Kadlec & Knight, 1996; Vymazal, 2007).

1.2.2 FTWs

FTWs, or islands, are an innovative variant of a constructed treatment wetland that allows water treatment in water bodies that are too deep for plants to grow. Floating wetlands do occur naturally, where under certain conditions a 40–60 cm deep floating organic mat can break away from the bottom sediment and float supporting plant growth (Headley & Tanner, 2006). Artificial wetland islands can be constructed from various materials to mimic this same effect and allow aquatic emergent plants to grow as a floating mat without risk of inundation regardless of changes in water level (McAndrew, Ahn, & Spooner, 2016). Rooted plants experience alternate periods of flooding and drying, whereas the water level for plants on a floating wetland is effectively constant. FTWs can adjust to fluctuations in water levels in rainfall-driven systems and are potential alternatives to traditional constructed wetlands for remediating nutrient-rich water bodies. Due to this adaptive feature, FTWs can be quickly established as “natural infrastructure” in any water body for a managed bioremediation scenario, such as in small eutrophic lakes and ponds or wastewater lagoons. FTWs are distinguishable from free-floating aquatic plant systems because of their larger emergent plants growing on a consolidated mat (Figure 1), as opposed to an unconsolidated mass of small, individual buoyant plants (Headley & Tanner 2006).

Eutrophic water bodies create conditions for plant growth, not unlike hydroponics. Plant roots spread through the floating islands and down into the water, creating dense columns of roots with considerable surface area. Not only do the plants take up nutrients and contaminants themselves, the plant roots and floating island material provide extensive surface area for formation of biofilm—the slimy layer of algae, bacteria and other microbes that adheres to all the surface area. Research suggests the plants only account for a small fraction of the overall treatment; it is the biofilm that coats roots and the island surface where the majority of nutrient uptake and degradation occurs in the FTW system (Tanner & Headley 2011; Winston et al., 2013). The greater the surface area, the greater the biofilm development and treatment potential (Figure 1). The biofilm layer facilitates adsorption and breakdown of nutrients, toxins and contaminants by the microbe community and promotes growth of invertebrates that provide food for fish and other aquatic insects. The cover and shelter provided by the floating island also allows settling of sediment and elements by reducing turbulence and mixing by wind and waves. The unique nature of wetland plants and the FTW ecosystem that develops gives the potential to capture nutrients and transform pollutants into harmless by-products. They can be strategically placed to filter water of pollutants and suspended sediments from stormwater ponds or lagoons before they enter natural rivers and lakes. FTWs also enhance a waterbody's aesthetics, provide valuable wildlife habitat, and act as wind and wave breaks to protect shorelines from erosion.

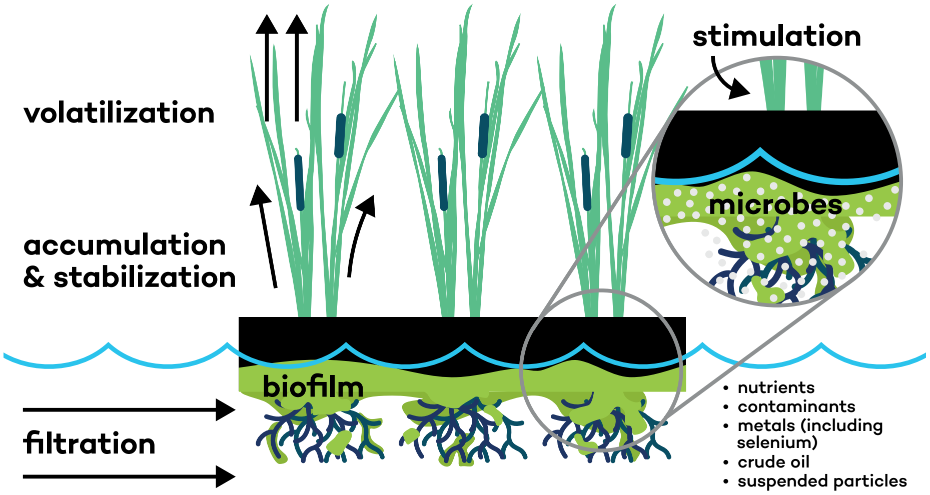

Figure 1. **Cross-sectional diagram of a typical floating treatment wetland system. Source: Authors**

2.0 FTWs: IISD-ELA research

2.1 Project Background

FTWs are used in many parts of the world and are a potential alternative biological approach to water treatment in stormwater ponds, wastewater lagoons and lake remediation (Lewtas et al., 2015). Despite these benefits, there have been few investigations into the performance and functioning of FTWs for bioremediation in Canada. Increasingly, natural infrastructure and nature-based solutions such as managed and constructed wetlands are being recognized in North America as an important component in combination with built grey infrastructure (Cohen-Shacham, Janzen, Maginnis, & Walters, 2016; Frey, Kosco, Williamns, & LaDuca, 2015; Moudrak, Feltmate, Venema, & Osman, 2018; Stanley, Puzyreva, & Roy, 2019; United Nations World Water Assessment Programme, 2018). Europe and China are currently investing billions into natural infrastructure and constructed wetlands to restore ecosystem functions (European Environmental Agency 2017; Kennedy, Zhong, & Corfee-Morlot, 2016; World Business Council for Sustainable Development, 2017). Canada and Manitoba have both identified priorities for investments in natural infrastructure and climate resilience, having just launched the new federal 10-year CAD 2 billion Disaster Mitigation and Adaptation Fund for disaster mitigation, protection and green infrastructure projects. More recently, Manitoba moved to protect wetlands and invest in greater environmental protection through the new Conservation Trust Fund and Manitoba Climate and Green Plan (Province of Manitoba, 2018).

The acquisition of the Experimental Lakes Area (IISD-ELA) in 2014 by IISD provided an opportunity to conduct an active in-lake bioremediation study relevant to other IISD research areas. This project builds upon IISD's previous bioeconomy research,[1] which has focused on wetlands, water retention and other nature-based solutions for nutrient and contaminant remediation in the Lake Winnipeg Watershed, as well as the Manitoba Prairie Lakes Project,[2] which identified remediation strategies appropriate for eutrophic prairie lakes, similar to Pelican Lake, Manitoba, which was used here as a case study.

2.2 Objectives and Hypothesis

In June 2015, four floating wetland platforms were deployed in two different lakes of different phosphorus concentrations at IISD-ELA in northwestern Ontario: two in Lake 227 (L227), the lake famous for phosphorus additions since 1969, and two in Lake 114 (L114) as a natural reference lake. The goal of this research was to quantify the impact of phosphorus enrichment in lake ecosystems on plant productivity and to assess nutrient sequestration of cattail plants growing on floating platforms as it relates to bioremediation of eutrophic water bodies. The hypothesis is that excess phosphorus in L227 would enhance cattail nutrient uptake and potentially cattail growth. This study examined specifically the component of plant uptake to overall removal capacity on FTWs.

Objectives

- To quantify plant nutrient uptake in a controlled and monitored eutrophic lake (L227).
- To quantify plant nutrient uptake and distribution in plant tissue, including aboveground plant tissue, belowground rhizomes and in-water roots.
- To characterize plant growth/productivity and phosphorus uptake as it relates to increased eutrophic lake conditions.

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[1] See: http://www.iisd.org/topic/watersheds-and-bioeconomy

[2] See: https://www.iisd.org/project/manitoba-prairie-lakes-and-eutrophication

- To characterize the potential benefit of FTWs on shallow eutrophic lakes—using Pelican Lake, Manitoba, as a case study example—based on physio-chemical parameters established for development of the lake's nutrient mass balance in 2016.

2.3 Methods

2.3.1 Site Description: Experimental Lakes Area

This research was conducted at the IISD-ELA research facility, located east of Kenora, Ontario. IISD-ELA is an exceptional natural laboratory comprised of 58 small lakes and their watersheds, set aside for scientific research.[3] Located in a sparsely populated region of northwestern Ontario, the lakes in the region are mostly unaffected by human impacts. By manipulating these small lakes, scientists can examine how all aspects of the ecosystem—from the atmosphere to fish—respond. Findings from these real-world experiments are often much more accurate than those from research conducted at smaller scales, such as in labs. ELA has been amassing a long-term data set monitoring atmospheric conditions, water quality and biological variables since 1968. Furthermore, unlike the laboratory setting, whole-ecosystem impacts, including trophic interactions, can be considered at IISD-ELA. Many of the lakes at IISD-ELA are essentially pristine and used as reference lakes, while some have undergone additions or modifications as long-term experiments to test the impacts of pollutants, such as phosphorus.

Floating platforms were installed on two lakes of different phosphorus concentrations: L114 (surface area 12.1 hectares and volume 2.07 x 10^5 m^3) was used as a natural reference lake and L227 (surface area 5.0 hectares and volume 2.21 x 10^5 m^3), which has undergone regular additions of phosphorus since 1969 to understand the impacts of eutrophication on water chemistry, flora and fauna, and plankton. Despite ELA's location in the Canadian Shield, research on L227 can serve as an analogue to prairie lakes affected with both higher natural background nutrient loads and effluent from agricultural land use. In comparison, L114 is of similar size but serves as a reference site due to its natural oligotrophic (nutrient-deficient) chemistry, much like the surrounding lakes.

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[3] For more information on IISD-ELA, see: https://www.iisd.org/ela.

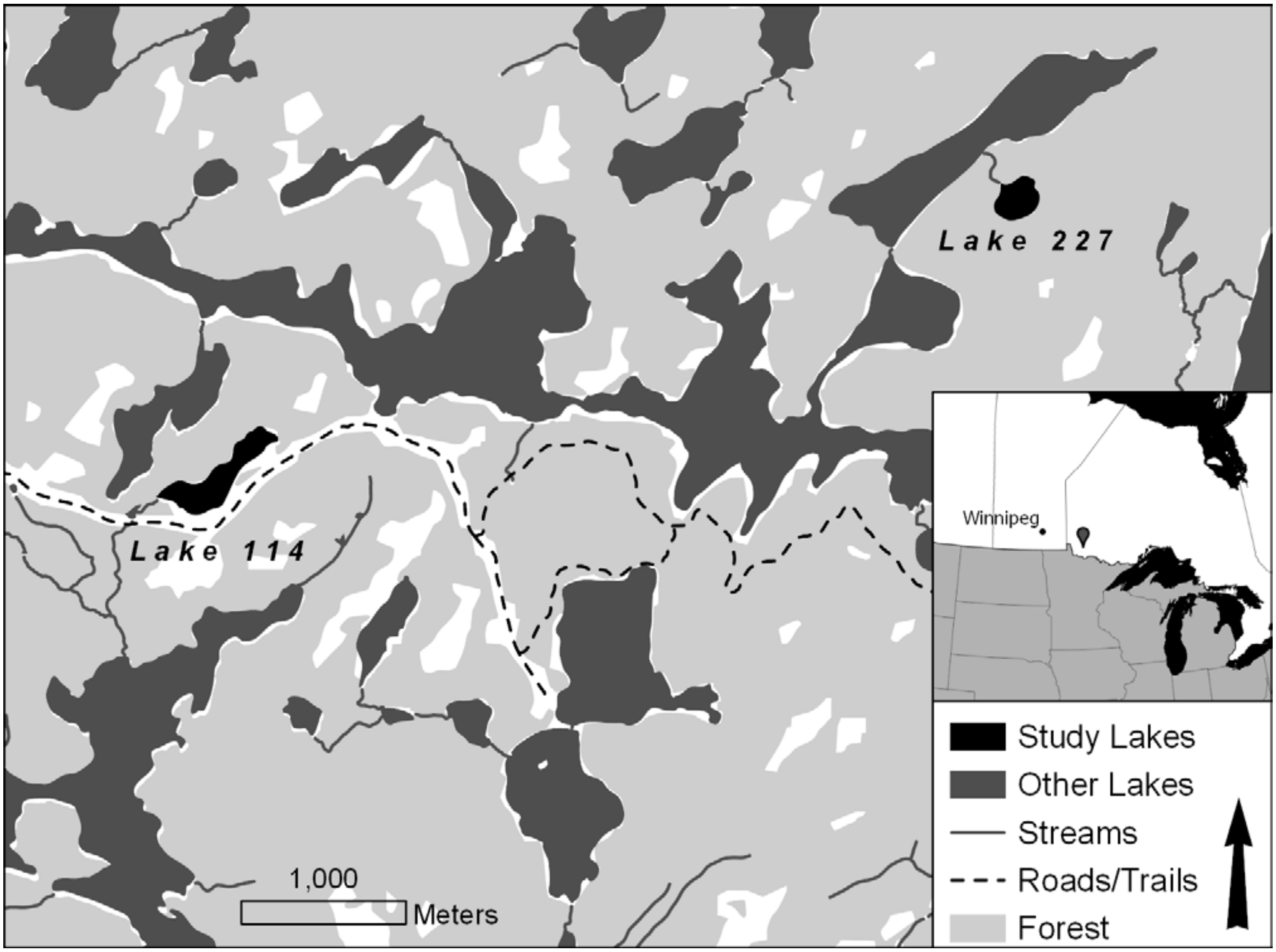

Figure 2. FTWs placement locations on L114 (nutrient-poor reference lake) and L227 (nutrient-rich P-addition lake). Image centred at 49.679N, 93.725W. Source: IISD (G. Gunn).

2.3.2 Platform Design

Four floating platforms were constructed utilizing 12-foot-diameter (3.65 m) floating foam rings originally constructed to hold floating mesocosms or limnocorrals. A hanging 2 x 4 foot frame was built inside each ring to mount four plastic bread trays that would support sediment and cattails. A layer of erosion control landscaping blanket made from coconut husk fibre was used to line each bread tray to retain the plant material and sediment while allowing roots and rhizomes to penetrate as they would through a natural litter layer (Figure 3). Cattail plants, rhizomes and soil were obtained from a nearby donor site on the IISD-ELA camp road and each bread tray filled. Plant growth and nutrient uptake were monitored during the growing season to observe differences observed between the two lakes. The use of bread trays was modelled after similar floating bioplatforms developed by Curry Industries in Winnipeg, Manitoba, for initial research at FortWhyte Alive (Stanley, 2015).

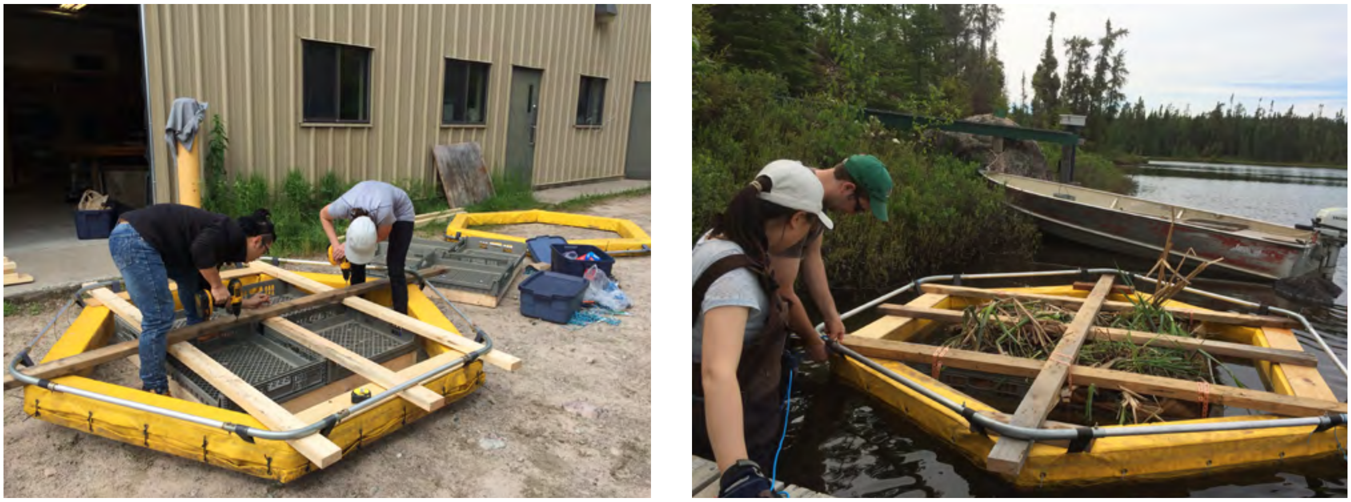

Figure 3. Construction and deployment of floating platforms. Each platform supports four bread trays for growing plants.

Photo: IISD

Two floating platforms of four trays each were deployed in each lake (eight trays per lake), approximately 10 metres apart. Two lines with cinder block anchors secured the platforms to prevent rotation and tangling in storm and wind events with enough slack to allow for water-level rise. The bottom of the plastic tray was approximately 2–5 cm below the waterline, ensuring water would reach the plant material without fully covering transplanted plants or rhizomes (Figure 3).

2.3.3 Plant Material Collection and Planting

Plant material—including a mixture of rhizomes, sprouted cattails and litter—was collected from a nearby wetland site to avoid the risk of introducing invasive species from elsewhere. Samples were collected from cattail-dominant parts of the marsh, but also included sedges, grasses and forbs in addition to dead material (detritus). This matter was augmented with manually collected cattail plants (roots, rhizomes, and shoots) and individual rhizomes. Approximately equal amounts of material and live plants were randomly placed in each tray and trays were randomly assigned to platforms.

2.3.4 Sampling Method

Plant tissue samples were taken in early June and mid-August to characterize maximum growth and again in mid-September near the end of the growth season. Sampling consisted of both observational and destructive segments. The observational segment included cattail height measurements, number of cattail shoots and estimates of ground coverage, allowing for measurement of diversity and success of cattail establishment as well as biomass volume estimation from allometric relationships.

The destructive sampling segment included removal and separation of plant components within and below the tray: cattail shoots, rhizomes and roots were collected along with a handful of litter for measurement of wet weight, dry weight and macro-/micronutrient analysis.

2.3.5 Analysis Method: FTW bioremediation calculation

In connection to the ongoing FTW research at IISD-ELA and international applications examining plant tissue nutrient retention and microbial biofilm remediation of FTWs, a standardized equation modified from Stanley (2015) is used in Section 3 to determine the percentage of surface area cover of FTWs in connection to a desired percentage of phosphorus reduction based on plant shoot uptake, root uptake and microbial biofilm removal (Equation 1), where only aboveground plant shoot uptake was considered for harvesting (Equation 2). Multiple FTW surface area coverage scenarios are presented for Pelican Lake by examining a combination of targets for the reduction of in-lake total phosphorus (TP) concentration (%) and mean TP concentration in aboveground plant tissue observed and microbial TP reduction calculated from the literature. Nutrient concentration (TP) and lake characteristics for Pelican Lake are then used in comparison to that of floating treatment wetland applications for in-lake research internationally. This project looks at the potential of in-lake remediation appropriate for eutrophic lakes in Manitoba and in other parts of the world.

Equation 1 – Percent (%) surface area coverage by FTWs

$$\left(\frac{\text{Total P in lake water (g/L)} \times \text{Lake volume(L)} \times \text{Percent of P reduction} \times 0.01}{\text{Total P aboveground plant tissue (g/m}^2\text{)} + \text{Total P FTW (g/m}^2\text{)} \times \text{Surface area of lake (m}^2\text{)}}\right) \times 100$$

Equation 2 – Percent (%) surface area coverage by FTWs (Stanley 2015)

$$\left(\frac{\text{Total P in water (g}\cdot\text{L}^{-1}\text{)} \times \text{Site volume(L)} \times \text{Percent P reduction desired} \times 0.01}{\text{Total P in aboveground tissue (g/m}^2\text{)} \times \text{Surface area of lake (m}^2\text{)}}\right) \times 100$$

2.4 Results

2.4.1 Lake Chemistry

Lake water samples were collected as part of the long-term monitoring program at ELA. Mean total nitrogen (TN) and TP samples from 2015 were collected in the epilimnion at a depth of 0.5 to 4.0 m from the surface (L114 average 3.5 m, L227 average 1.8 m): L227, the eutrophic lake from long-term nutrient additions, showed expectedly higher concentrations of dissolved and suspended nitrogen and phosphorus (Figure 4). L114, the reference lake, reported half as much phosphorus and nitrogen, although relatively more nitrogen was dissolved as opposed to suspended. The two lakes were noticeably different in terms of availability of nutrients: L114 would be considered a nutrient-poor site and L227 a nutrient-rich site.

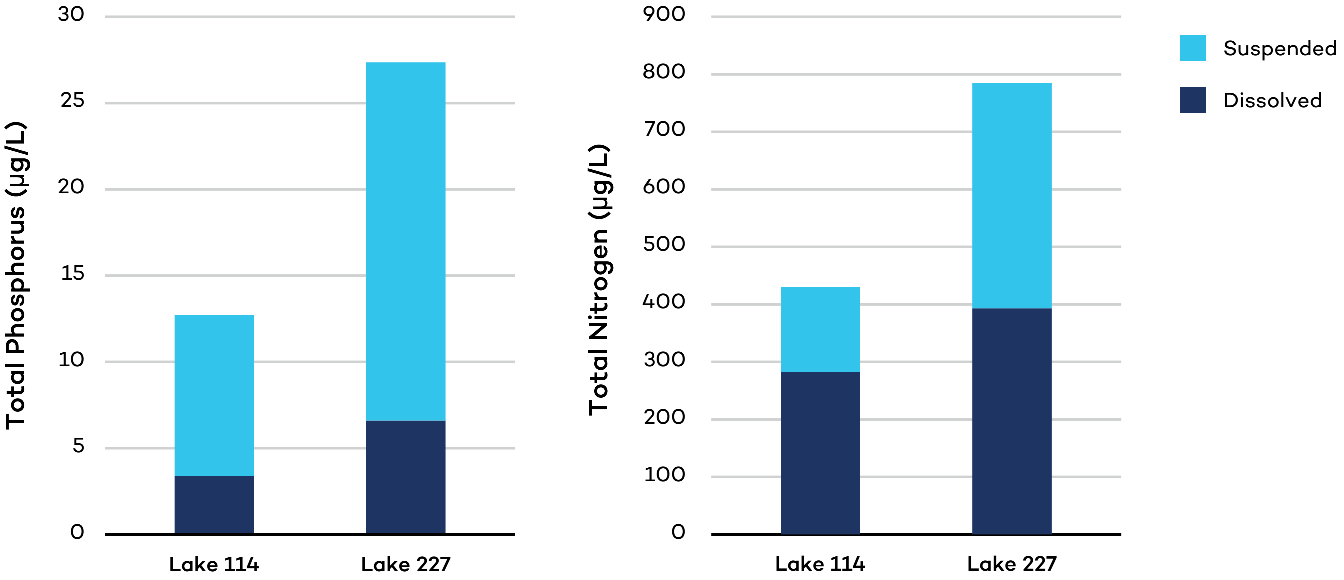

Figure 4. TP and TN concentrations (suspended and dissolved) at a depth of 1 m expressed as µg/L in L114 and L227 for 2015

TP and TN concentrations (µg/L) differed between L227 and L114, with much higher levels in L227 for most of May to October 2015 (Figure 5). Following ice-off in early May, TN concentrations in L114 were initially higher than L227 (800 µg/L compared to 500 µg/L), but quickly dropped and remained near 450 µg/L from June to October. This corresponded to low TP levels in L114 (13 to 15 µg/L) throughout most of May to October. In L227, TP concentrations increased to 35 µg/L from May to June with a corresponding increase in TN concentrations (1200 µg/L). This was followed by a rapid drop in mid-June of TN to 600 µg/L and decrease of TP to near 20 µg/L, with a gradual increase in both until October. This is typical for TP and TN patterns in L227, responding to the growth and die-off of algae blooms (Higgins et al., 2018).

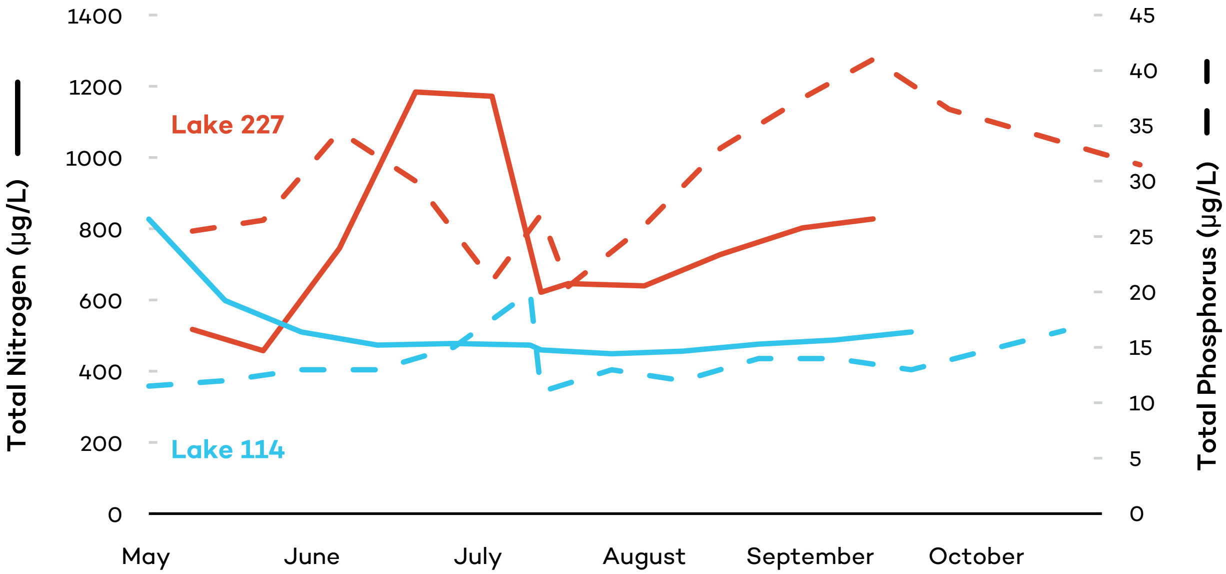

Figure 5. Lake TP and TN concentration (µg/L) in the epilimnion comparison between L114 and L227 between May and October 2015. Samples collected at a depth of 0.5 to 4.0 m from the surface (L114 average 3.5 m, L227 average 1.8 m)

2.4.2 Plant Growth and Nutrient Uptake: Shoots, roots and rhizomes

A clear difference was observed in plant development between platforms in each lake in 2015. Six bread trays in L114 showed a more stressed, less lush and much less dominant cattail regime with more coverage by grasses and sedges (Figure 6, left). Both of the platforms and all eight bread trays in L227 were vibrant and green with excellent plant growth and a dominance of cattail (Figure 6, right).

Figure 6. Floating platforms in August 2015 with sampling showing growth of plants in the bread trays in L114 (left) and L227 (right).

Photo: IISD

Observations of plant community structure also differed between lakes. L114 had considerably more litter, grasses and sedge in terms of ground cover, while L227 showed more cattails and forbs (Figure 7). While cattails were the majority of donor material, it was apparent that other plants also established. Sedges and grasses both made up lower percentages than cattail—with most of these losses to cattail and forb growth—in the nutrient-poor lake.

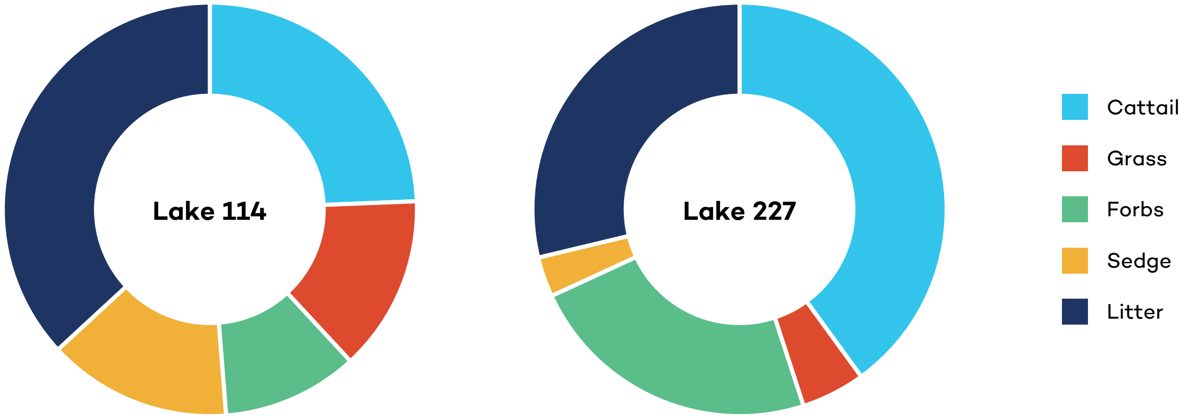

Figure 7. Observed ground cover percentage (mean of eight bread trays per lake) in August 2015

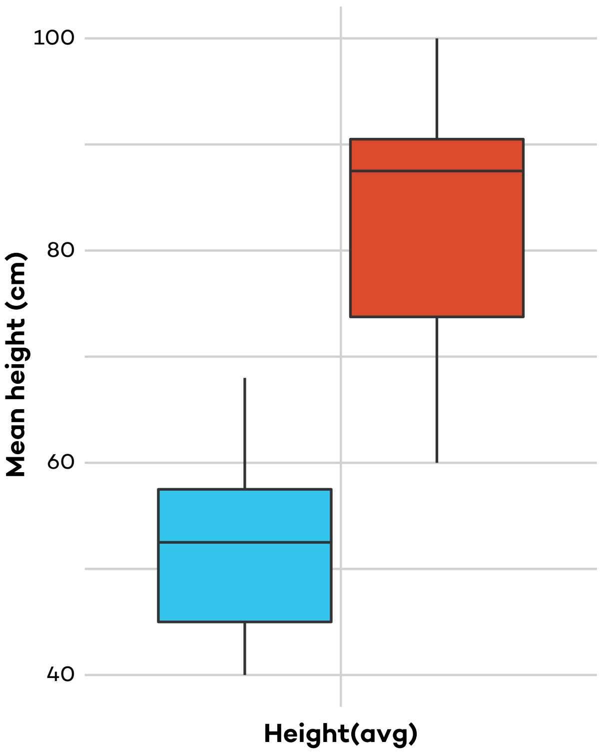

Figure 8. Cattail shoot height (2015)

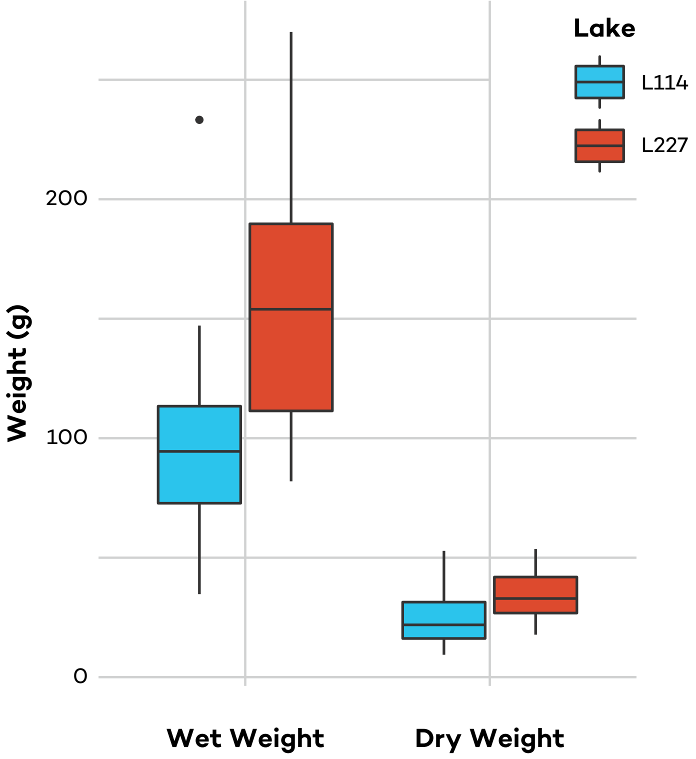

Figure 9. Cattail wet and dry weight (2015)

Data collected from destructive sampling supports these observed differences between the lakes. Based upon a sample of 36 cattail shoots per lake, a considerable difference in populations between the lakes in terms of morphology was observed (Figure 8). Cattail plants in L227 were significantly taller on average, as well as greater both in dry and wet weight. Cattail located in L114—the oligotrophic lake—had a wider variation in moisture content, which may indicate stress, while individuals sampled in L227 were consistently between 75 and 80 per cent moisture.

While emergent shoot matter is the most visible and easily harvested part of phytoremediation, the roots play a much larger role in sequestering nutrients and providing surface area for microbial biofilm uptake. Figure 10 shows different phosphorus concentrations between roots, shoots and rhizomes in plants from both lakes. The plants in L114 ranged in phosphorus concentration from 0.1 to 0.2 per cent, whereas roots in the nutrient-rich L227 had nearly twice the concentration by dry weight, from 0.25 to 0.55 per cent, of any other plant part (Figures 10 and 11).

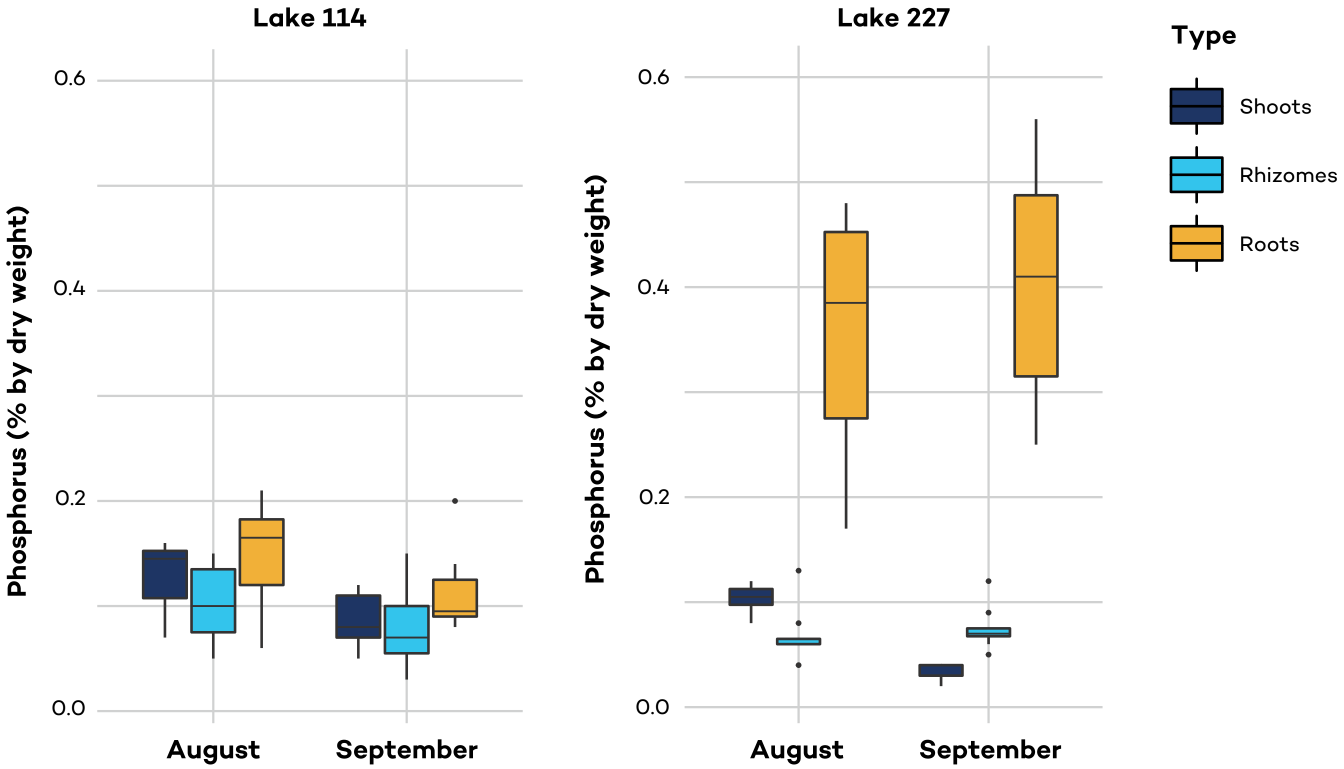

Figure 10. Phosphorus sequestration by cattail parts (% of dry weight)

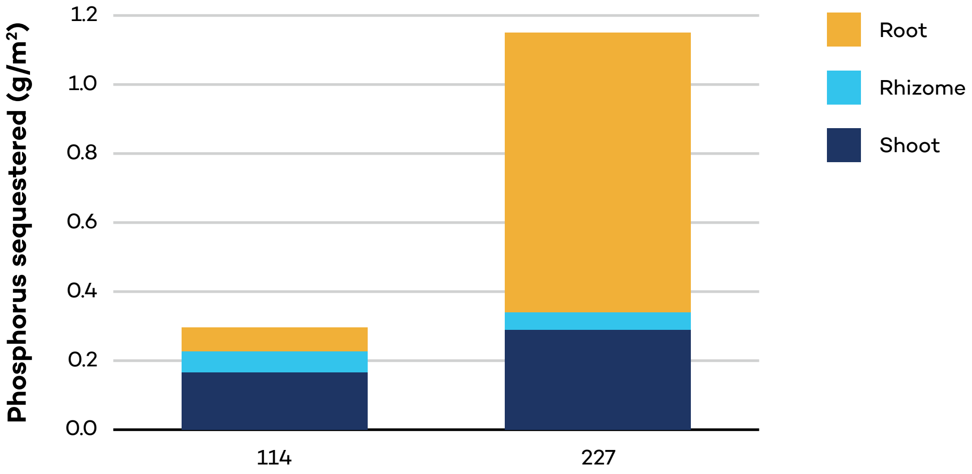

Figure 11. Phosphorus sequestration (g/m²) by cattail parts, September 2015

By aggregating the data, we estimated the amount of phosphorus sequestered in each plant segment on an annual basis. Using sample values from August (shoots and rhizomes) and September when root mass was completely removed, it was determined that cattail roots were a major site of phosphorus sequestration (Figure 11; Table 1).

Table 1. Summary of phosphorus retention in cattail tissue in FTWs at L114 and L227.

Plant tissue	Lake	DW (g) per tray	DW (g) per m^2	TP (g) per tray	TP retention (g/m^2)
Aboveground	114	47.2	128	0.06	0.166
	227	103	279	0.11	0.290
Rhizome	114	17.5	47.4	0.02	0.060
	227	29.5	79.9	0.02	0.055
Roots	114	18.0	48.6	0.03	0.068
	227	84.3	228	0.30	0.809

Note: Cattail aboveground tissue was collected in August 2015; rhizome tissue was collected August 2015; root tissue was collected in September 2015. DW = dry weight

Plant tissue was also analyzed for other elements and metals, and, similar to phosphorus, the rhizomes and roots were a major site for metal sequestration (Table 2).

Table 2. Average uptake (% and ppm) per unit of dry weight of vegetation on FTWs on lakes 114 and 227 during August and September sampling, 2015

Site	Vegetation	TN (%)	TP (%)	K (%)	S (%)	Ca (%)	Mg (%)	Na (%)	Zn (ppm)	Fe (ppm)	Cu (ppm)
114	Cattail	1.8	0.1	2.2	0.2	1.0	0.2	0.0	27	144	2.8
	Rhizome	1.6	0.1	1.8	0.2	0.4	0.2	0.1	33	3500	3.8
	Root	1.9	0.1	2.8	0.3	0.5	0.4	0.2	103	2657	7.7
227	Cattail	1.4	0.1	1.7	0.1	1.0	0.2	0.0	14	51	1.6
	Rhizome	1.2	0.1	1.3	0.2	0.5	0.2	0.1	29	3508	3.4
	Root	4.1	0.4	1.9	0.4	0.4	0.4	0.4	80	4055	6.8

3.0 FTW Potential at Pelican Lake, Manitoba

3.1 Pelican Lake and Shallow Prairie Lake Remediation

Pelican Lake in southeast Manitoba was used as a representative case study as part of a larger prairie lakes initiative to understand nutrient loading and remediation options. It was selected based on its small watershed, controlled water flow-through and physical features representative of other prairie lake watersheds. As with other shallow prairie lakes, the eutrophication of Pelican Lake has become increasingly pronounced over recent years, with beach closures and water quality warnings, raising the concern of local residents.

A water and nutrient mass balance model was developed for Pelican Lake to identify the relative importance of nutrient sources and internal lake processes, to be used as a general model for shallow prairie lakes (Lewtas, Osman, Dunn, & Roy, 2017). Additionally, a review of remediation techniques applicable to Canadian and Manitoba prairie lakes, which included biological, physical and chemical applications, found that FTWs were a potential remediation option for smaller ponds, lagoons, reservoirs and retention basins (Lewtas et al., 2016) and could be considered as a potential in-lake remediation treatment option for shallow prairie lakes in Manitoba. Case studies on FTWs from the literature are presented.

3.2 Case Studies for Nutrient Retention Analysis

3.2.1 FortWhyte Alive Lakes, Winnipeg, Manitoba

FortWhyte Alive is a wildlife habitat and recreational site located in Winnipeg, Manitoba. Water quality concerns of three waterbodies at FortWhyte Alive, which are experiencing impacts from increased nutrient loading, led to the evaluation of FTWs and the harvesting of *Typha* spp to reduce nutrient concentration in the water column. Results of this collaborative research by Ducks Unlimited Native Plant Solutions, University of Manitoba, the International Institute for Sustainable Development, Red River College, Curry Industries and the Province of Manitoba indicate that there was an overall increase of phosphorus in roots and shoots of cattail collected from July to October 2013.

Table 3. Summary of lake and nutrient parameters evaluated at three waterbodies at FortWhyte Alive

Parameter	Cargill Lake	Treatment Wetland	Stormwater Retention Pond
TP (Oct 2013, mg/L)	0.20	1.3	0.38
Mean TP (2014, mg/L)	0.16 ± 006	0.19 ± 0.02	0.37 ± 0.30
Mean depth (m)	3.0	0.88	0.54
Max depth (m)	7.5	1.1	0.80
Area (m^2)	58,675	1,314	99,531
Trophic status	Hypereutrophic	Hypereutrophic	Hypereutrophic
Mean TP aboveground biomass (g/m^2)	0.03	0.018	0.03

Source: Modified from Stanley, 2015.

It was suggested that FTWs and harvesting cattail could be used to remove phosphorus from the lake water in order to reduce eutrophic conditions (Stanley, 2015). The mean TP of all cattail aboveground tissue measurements was estimated at 0.19 ± 0.11 g/m^2. No measurements of root or microbe removal was quantified. Total FTW TP removal from roots and microbes could potentially be another 80 per cent higher based on the literature for nutrient removal rates of FTW ecosystems (Tanner & Headley 2011; Winston et al., 2013).

3.2.2 Lake Apopka, Florida

Lake Apopka is a large (125 km^2), shallow (mean depth 1.6 m) hypereutrophic lake located in central Florida, United States. The lake has been classified as hypereutrophic due to the phosphorus loading from floodplain agricultural land and high levels of phytoplankton (Chlorophyll-a was estimated at 80 µg/L; Coveney, Stites, Lowe, Battoe, & Conrow, 2002). To combat high nutrient loading from the surrounding catchment, a 2 km^2 pilot-scale flow-way wetland was implemented to examine the capacity of a wetland system to remove suspended sediments and particulate nutrients from Lake Apopka. The demonstration project was designed to evaluate the relationships between nutrient removal, flow and loading. The hydraulic behaviour of the wetland filtration was variable, where inflow varied from 0.15 to 1.5 m^3/s, equivalent to hydraulic loading rates from 6.5 to 65 m/year and a mean hydraulic resident time of approximately seven days (Coveney et al., 2002).

Table 4. Summary of Lake Apopka nutrient ambient and loading concentrations

Parameter	**Median Loading to the Wetlands** (mg/m^2 per day)	**Inflow** (mg/L)	**Outflow** (mg/L)
TN	475	3.0 – 9.0	2.0 – 4.0
TP	18	0.08 – 0.38	–

Note: Particulate organic P (POP) made up 90 per cent of the TP. Values over the 29-month operational period.

TP in the inflow from Lake Apopka ranged from approximately 0.08 to 0.39 mg/L (Table 4). POP typically made up more than 90 per cent of the TP.

Table 5. Fluxes for dry matter, nitrogen and phosphorus in the first wetland cell in Lake Apopka, Florida

Parameter	Dry Matter (g/m^2)	Nitrogen (g/m^2)	Phosphorus (g/m^2)
Particulate removed	4,750	155	5.48
Sediment accumulation	2,020 (43%)	65.3 (42%)	4.62 (84%)
Soluble release	–	24.8 (16%	3.39 (62%)
Vegetative biomass	1,540	31.0 (20%)	2.81 (51%)

Note: Vegetative biomass mass included aboveground and belowground. Values in parentheses are the percentage of particulate mass removal. Value over the 29-month operational period.

Particulate phosphorus removal from lake water in the wetland totalled approximately 5.5 g/m^2. It was estimated that 4.6 g/m^2 or 84 per cent was recovered in the accumulated sediment and 2.8 g/m^2 was recovered in the vegetative biomass (Table 5). The removal efficiency of phosphorus, based on both TP and POP, ranged from about 5 to 30 per cent (Coveney et al., 2002).

3.2.3 Baiyangdian Lake, China

Baiyangdian Lake is the largest lake in North China. It plays an important role in providing water resources and controlling floods for the basin. The area includes 143 small, shallow lakes linked by thousands of ditches, with a collective surface area of 366 km^2 and a mean depth of 2 metres (Zhao, Yang, Xia, & Wang, 2012). The monthly average TN and TP concentrations in the lake were 2.6 to 5.6 mg/L and 0.1 to 0.6 mg/L (2000–2009), respectively (Zhao, Xia, Yang, & Xia, 2011).

Aboveground nutrient storage was estimated by multiplying TN or TP concentrations in plant tissue and the aboveground biomass. Maximum nutrient retention occurred in September and was estimated at 61.4 to 74.5 g/m^2 for nitrogen and 6.3 to 6.9 g/m^2 for phosphorus. Minimum nutrient retention occurred in June and were 22.8 to 32.4 g/m^2 for nitrogen and 2.4 to 2.7 g/m^2 for phosphorus (Zhao et al., 2012).

Results of this study showed that both TN and TP removal efficiencies increased with the increasing plant (reed) coverage. It was determined that water quality improved best at a coverage of 60 per cent (72 plants/m^2). It was also determined that the highest aboveground nutrient storage occurred in September; therefore, it was recommended that the remediation strategy for Baiyangdian Lake was that plant coverage should be adjusted to 60 per cent coverage and harvested each September. Zhao et al. (2012) determined that harvesting could have the potential to remove 117.8 g/m^2 of TN and 4.0 g/m^2 of TP.

3.2.4 Shepherd Pond, Montana, United States

Floating Islands International (2011, 2014) reported on six case studies to illustrate the Biohaven FTW technology and its ability to reduce nutrient concentrations in various waterways. Two case studies of interest are Shepherd Pond and Yingri Lake, which are both lake restoration projects. The nutrients of concern highlighted in these case studies are nitrogen and phosphorus. Four of the systems presented in Table 6 are variations of wastewater lagoons at different scales (MBRCT test pond, Rehberh Ranch, Wiconisco and McLean's pit).

TN removal ranged from 40 to 87 per cent in the five case studies (Table 6). The case study of particular relevance is Shepherd Pond, a lake restoration project, with a TN removal of 80 per cent at 1.60 kg/m^3 per year.

Table 6. Floating treatment wetland TN removal from five case studies as reported by Floating Islands International

	Nitrogen (mg/L)			Percent Removal (%)		Removal Rate (kg/m^3 per year)	
Study	**Inflow**	**FTW**	**Control**	**FTW**	**Control**	**FTW**	**Control**
MBRCT Test Pond	172	22	112	87	35	14.4	6.41
Rehberg Ranch	50.2	14.1	24.5	72	51	19.2	12.8
Wiconisco	46.3	18.6	20.9	60	55	40.1	36.8
McLean's Pit	-	-	-	40	-	38.4	-
Shepherd Pond	0.5	0.1	-	80	-	1.60	-

Note: MBRCT test pond, Rehberg Ranch, Wiconsico and McLean's pit are small wastewater lagoons.

Source: Floating Islands International, 2011.

TP removal ranged from 42 to 91 per cent in the five systems presented in Table 7. Shepherd Pond's TP removal rate was 67 per cent at 0.80 kg/m^3 per year.

Table 7. Floating treatment wetland TP removal from five case studies

	Phosphorus (mg/L)			Percent Removal (%)		Removal Rate (kg/m^3 per year)	
Study	**Inflow**	**FTW**	**Control**	**FTW**	**Control**	**FTW**	**Control**
MBRCT Tank Test	15.9	1.5	-	91	-	8.33	-
MBRCT Test Pond	13.6	5.2	6.4	62	53	2.08	1.28
Wiconisco	8.1	4.7	5.1	42	37	4.81	4.17
Shepherd Pond	0.6	0.2	-	67	-	0.80	-
Yingri Lake	0.93	0.29	-	69	-	-	-

Note: MBRCT test tank and pond, and Wiconsico are small wastewater lagoons.

Source: Floating Islands International, 2011.

3.2.5 Retention Pond, Pasco County, Florida, United States

Twenty FTWs were installed in a reclaimed municipal retention pond in Pasco County, Florida, to assist in meeting total maximum daily load limits (TMDL), as well as to provide ancillary benefits of increased habitat and pond aesthetics. Each FTW measured 2.5 x 3 metres (7.5 m^2) and accommodated 154 plants (Floating Island International, 2014). The FTWs were 150 m^2 and 20 cm thick.

The water source to the wetlands was secondary effluent from wastewater treatment facilities, at a flow rate of 31 m^3 per hour. The pond was 1.2 metres deep and 1.6 hectares in size. The 20 FTWs installed covered 0.9 per cent of the retention pond. The water quality of the pond was monitored bi-weekly over a 17-month study period and changes in nutrient concentrations are summarized in Table 8.

Table 8. Summary of FTWs installation effect on pond water nutrient concentrations in Pasco County, Florida

	FTW – 8-month period			Control – 3 months following FTW removal		
Parameter	**In (mg/L)**	**Out (mg/L)**	**Removal (%)**	**In (mg/L)**	**Out (mg/L)**	**Removal (%)**
TN	6.10	2.04	67	4.47	3.44	23
TP	1.96	0.63	68	1.37	1.00	27
pH	-	9.96	-	-	11.25	-

TN removal rate was 27 kg/m^3 per year (1.7 lb/ft^3 per year) and 8.65 kg/m^3 per year (0.54 lb/ft^3 per year) for TP. It was estimated that 0.3 per cent of the nitrogen removed was contained in the aboveground plant matter during the FTW 8-month growth period and 0.8 per cent during the control period (Floating Treatment International, 2014). The remaining nitrogen removal was attributed to plant roots, microbial activity and chemical/physical processes.

3.2.6 Open Waterbody Between Raritan River and Lake, New Jersey, United States

FTWs were installed on an open waterbody connected to the Raritan River in New Jersey, United States. The FTWs installed were 83 m^2 and 20 cm thick, which covered 2 per cent of the waterway. The water source to the FTWs was the Raritan River and flowed at a rate of 160 m^3 per hour. The waterbody had a surface area of 4,050 m^2 and a mean depth of 2 metres (Floating Island International, 2011).

Over the 2011 growing season, FTWs removed an estimated 30 kg of TP, an amount of phosphorus that has the potential to generate up to 15,000 kg of wet algae biomass (Floating Islands International, 2011). The mean inlet and outlet TP concentrations were 0.105 mg/L and 0.065 mg/L, respectively, which equated to a 38 per cent reduction over the 2011 growing season. Net removal rate was estimated at 0.833 kg/m^3 per year (0.052 lb/ft^3 per year).

3.3 Pelican Lake, MB: FTW nutrient removal and bioremediation potential

3.3.1 Site Description

Pelican Lake is located in southwestern Manitoba and is one of several smaller, shallow lakes along the Pembina River. The lake is located in the northwestern portion of the Pembina River basin and is a eutrophic lake that has experienced regular algae blooms in recent years. The lake's surface area is 27.7 km^2, mean depth is 3.88 metres and mean lake volume is 108,084,000 m^3 (Province of Manitoba, 2015). Pelican Lake is fully regulated, and inflow from the Pembina River and outflow data are recorded by a provincial hydrometric station at the southern end of the lake.

Water samples were collected from Pelican Lake between June and October 2016. Specifically, nutrient concentrations were estimated for the requirements of a nutrient budget and to determine appropriate in-lake remediation treatments specific to the lake's hydrological and chemical characteristics. Mean monthly concentrations are presented in Table 9.

Table 9. Summary of Pelican Lake water quality parameter concentrations measured in 2016

Parameter	June	July	August	September	October
Ammonia (mg/L)	0.011	0.044	0.037	0.022	0.020
Chl-*a* (µg/L)	12.4	13.9	21.6	22.9	22.5
TN (mg/L)	1.71	1.66	1.71	1.77	1.64
Total Kjeldahl nitrogen (mg/L)	1.71	1.63	1.71	1.77	1.64
Oxygen dissolved (mg/L)	8.0	5.4	5.3	7.0	8.1
TP (mg/L)	0.256	0.295	0.376	0.346	0.253
Particulate phosphorus (mg/L)	0.03	0.042	0.04	0.059	0.043
Dissolved phosphorus (mg/L)	0.226	0.253	0.336	0.287	0.210
Total suspended solids (mg/L)	<MDL	6.0	9.0	8.0	10
Turbidity (Ntu)	3.72	4.9	12	9.72	7.45

3.3.2 Floating Treatment Wetland Treatment Calculation

Equation 1 is a standardized formula to estimate the percentage of water surface area covered by FTWs to reduce phosphorus concentration in eutrophic waterbodies.

Equation 1. Percent (%) surface area coverage by floating treatment wetlands

$$\left(\frac{\text{Total P in lake water (g/L)} \times \text{Lake volume(L)} \times \text{Percent of P reduction} \times 0.01}{(\text{Total P aboveground plant tissue (g/m}^2) + \text{Total P FTW (g/m}^2) \times \text{Surface area of lake (m}^2)}\right) \times 100$$

To assess the impact of FTWs on nutrient reduction in Pelican Lake, the mean TP concentration rates from reviewed case studies were used to estimate the percentage of nutrient reduction in connection to FTW surface area coverage (Table 10).

Table 10. Summary of TP concentration of aboveground plant tissue and biomass removal rates in case studies

	Waterbody Characteristics			FTW Characteristics				
Waterbody	**Mean TP (mg/L)**	**Mean depth (m)**	**Area**	**Mean TP conc (g/m^2)** aboveground plant (estimated to account for 20% removal)	**Mean TP conc (g/m^2)** root and microbial (estimated remaining 80% removal)	**Surface Water cover (%)**	**TP Removal (%)**	**TP Removal kg/m^3 per year**
Lake 227, IISD-ELA	0.016	-	50,000 m^2	0.29	1.16	-	-	-
Cargill Lake, Winnipeg, MB	0.16	3	58,675 m^2	0.19	0.95	-	-	-
Lake Apopka, Florida	0.3	1.6	125 km^2	2.81	14.05	-	-	-
Baiyangdian Lake, China	0.3	2.0	366 km^2	4.0	20	-	-	-
Shepherd Pond, Montana	0.6	1.2	42 m^2	-	-		67	0.80
Retention pond, Florida	1.96	1.2	16,000 m^2	-	-	0.9	68	8.65
Raritan River, New Jersey	0.106	2.0	4,050 m^2	-	-	2	38	0.833

Pelican Lake is approximately 27.7 km^2 in surface area and 108 million m^3 in volume. Between June and October 2016, Pelican Lake TP mean concentration was measured at 0.305 mg/L. A range in mean TP concentration of aboveground plant tissues measured from IISD research on FTW at IISD-ELA's Lake 227 (L227) was used to determine a range of surface area covered by FTWs required to reduce a chosen percentage of nutrient reduction. For example, to reduce phosphorus in the lake by 10 per cent each year, it is estimated that Pelican Lake would require approximately 8 per cent surface area coverage using L227 mean TP removal estimates by FTW (aboveground tissue value + estimated additional 80 per cent removal from root uptake and microbial community = 0.29 g/m^2 + 1.16 g/m^2; Table 2; Equation 1).

Using the Province of Manitoba Water Quality Standards for nutrients for general guidance (unless it can be demonstrated that TP is not a limiting factor, considering the morphological, physical, chemical or other characteristics of the waterbody), TP should not exceed 0.025 mg/L in any reservoir, lake, pond, or tributary at the point where it enters such bodies of water (Province of Manitoba, 2011). In comparison, Pelican Lake ambient mean TP is 0.305 mg/L (2016).

Multiple scenarios for Pelican Lake (Table 11) were estimated by examining a combination of targets for the reduction in lake TP concentration (%). The mean TP removal by an FTW system (g/m^2) ranged in values from 1.0 to 20 g/m^2 (Table 10) based on IISD-ELA values of 1.4 g/m^2 to FTW systems in the case studies of 14 g/m^2 in Lake Apopka and 20 g/m^2 in Baiyandian Lake, China (Table 10). A higher nutrient removal rate by plants, roots and biofilm microbes as components of an FTW system provides a reduced FTW surface area coverage for a desired TP lake concentration reduction or target (Table 11).

Table 11. The percentage of lake surface area coverage of FTWs in relation to lake TP reduction scenarios (%) and mean TP removal by FTW system in Pelican Lake, MB (g/m^2)

Mean TP Removal by FTW System (g/m^2)	Percent Reduction in Lake TP				
	10 %	20 %	30 %	40 %	50 %
1.0	11.9 %	23.8 %	35.7 %	47.6 %	59.5 %
2.0	6.0 %	11.9 %	17.9 %	23.8 %	29.8 %
3.0	4.0 %	7.9 %	11.9 %	15.9 %	19.8 %
4.0	3.0 %	6 %	9 %	12 %	15 %
5.0	2.4 %	4.8 %	7.2 %	9.6 %	12 %
10.0	1.2 %	2.4 %	3.6 %	4.8 %	6 %
15.0	0.8 %	1.6 %	2.4 %	3.2 %	4 %
20.0	0.6 %	1.2 %	1.8 %	2.4 %	3 %

4.0 Discussion

4.1 FTWs

FTWs provide a potential natural infrastructure alternative to the more conventional in-lake remediation strategies to solve problems associated with eutrophication in surface waters. This study examined the contribution of plant uptake to overall removal capacity of FTWs and estimated total FTW removal based on applied research and the literature. The research at IISD-ELA demonstrates that planted FTWs can, with relative ease, be constructed and deployed as a phytoremediation option for eutrophic shallow lakes. It also demonstrated that, with a relatively small increase in phosphorus loading, plant productivity responds quite dramatically. Although L227 phosphorus levels are considered nutrient-rich for lakes at IISD-ELA compared to lakes such as L114, L227 phosphorus concentrations would be considered quite low when compared to most prairie lakes in Manitoba. Comparatively, L227 mean TP concentrations were 0.02 mg/L to 0.04 mg/L, while Pelican Lake mean TP concentrations were 0.305 mg/L—over an order of magnitude higher than L227. FTWs and their plant and microbial communities receiving higher loading rates of nitrates and phosphorus from stream runoff would respond quite readily to increased nutrient conditions, and as a bioremediation treatment option, they have the potential to considerably reduce non-point source nutrient enrichment. FTWs can be considered for treatment of agricultural and waste runoff waters.

Compared to conventional pond and wetland systems, FTWs have advantages that enhance certain contaminant removal processes. Plant roots and biofilm play a major role in the treatment processes within FTWs as water passes directly through the extensive root system beneath the floating platform and the FTW matrix. The floating island matrix and the plant root zone provide significant surface area for enhanced biofilm growth, which is where the majority of nutrient uptake and degradation occurs—upwards of 80 per cent (Floating Islands International, 2011). In addition, FTWs allow plants to grow and proliferate in water that is too deep for plants to grow, compared to sediment-rooted wetland plants that are predominantly restricted to water depths of less than 0.5 metres. The cover and shelter provided by the floating mat also promotes conditions to allow settling, reducing turbulence and mixing by wind, waves and thermal mixing. They also provide greater water volume, reduce flow velocities and enhance settling of contaminants (Headley & Tanner, 2006). FTWs can be used in some cases for wetland compensation to quickly establish a viable growth medium in lakes with little-to-no establishment of marsh ecosystem.

FTWs are being applied in a variety of innovative situations worldwide for water quality treatment, but the predominant bioremediation applications have been for stormwater, municipal wastewater, urban lake water, landfill leachate and water supply reservoirs (Hu, Zhou, Hou, Zhu, Zhang, 2010; Keizer-Vlek, 2014). The use of FTWs should be considered as a viable best management practice to increase the efficiency for on-site removal of nutrients such as nitrogen and phosphorus from holding ponds before release into aquatic systems or to groundwater. Beyond nutrient sequestration and removal, FTWs provide ancillary benefits to degraded waterbodies, including habitat improvement, shelter for fish and wildlife, shoreline erosion protection and aesthetic enhancement. Apart from solving issues related to water quality and excessive algae growth, FTWs could potentially play a role in the recovery of phosphorus (Shilton, Powell, & Guieysse, 2012) if the aboveground plant biomass is harvested and removed (Grosshans et al., 2014). Harvested plant material is a valuable source of nutrients, carbon and organic matter that can be applied directly back onto agricultural fields. This form of green compost recycles valuable nutrients (nitrogen and phosphorus), enhances soil fertility and improves soil moisture capacity (Keizer-Vlek, 2014), which represents a valuable component of the circular economy. However, when FTWs are applied to remediate waters with elevated heavy metals, hydrocarbons or other hazardous contaminants, plant uptake could lead to elevated metal concentrations and, in this case, would not be suitable for use.

4.2 Cattail Growth and Nutrient Uptake

The effect of lake nutrient concentrations on plant productivity was estimated based on differences between floating platforms in L114 (reference lake) and L227 (treatment lake). Biomass growth patterns and distribution were estimated according to the weight changes of the plants and tissue. Results of this research observed greater shoot growth and height in L227, with noticeable differences between the two lakes by mid-August. The enhanced productivity in L227 could be explained by the increased nutrient loading, facilitating greater biomass accumulation. The lower accumulated biomass by cattail in L114 could be a result of limited nutrient supply. The hypothesis was that excess phosphorus in L227 would enhance cattail nutrient uptake and cattail growth. Platforms in both lakes successfully sequestered nutrients in the plant material; however, the excess phosphorus of L227 greatly enhanced cattail productivity and nutrient uptake. Cattail aboveground shoots in L227 had eight times greater productivity or growth, five times that of roots than those in L114, and four and 11 times more phosphorus in aboveground shoots and in the roots, respectively. Results also showed the majority of the phosphorus is in the roots, with seven times more phosphorus in the roots than in the aboveground shoots.

Cattails in general are opportunistic consumers of nutrients and did appear to have minimum thresholds for biomass production. Lake chemistry appeared to impact cattail productivity/biomass production and overall nutrient sequestration, with a clear difference in community structure, cattail morphology and cattail lushness between L114 and L227. This may suggest that cattail may not be appropriate for phytoremediation of certain contaminants on lakes that are nutrient-poor, with low phosphorus and nitrogen loads. Low levels of nutrients in L114 did appear to cause stress and negatively impacted cattail growth, which allowed other marsh plants such as sedges to outcompete cattail on the platforms. At L114's phosphorus concentrations, cattails appeared stressed and suffered in biomass production. In these cases, it may be desirable to examine other water-tolerant species such as sedges and hyper-accumulators of targeted contaminants to maximize remediation potential.

In terms of phosphorus sequestration, the results from L227—gathered in a whole-ecosystem study at IISD-ELA—are consistent with smaller-scale laboratory results on other species of cattail. Santos et al. (2015) reported a similar relationship to cattail morphology under a variety of phosphorus concentrations; however, the response rate of biomass production from that laboratory study on *Typha domegensis* was much higher than this study. Differences in laboratory and field settings may explain this difference, as well as the natural-environment exposure of this study.

4.3 Nutrient Removal by Aboveground Tissue Harvesting

To maximize nutrient removal by harvesting the aboveground shoots, it is important to understand the temporal variation of phosphorus and nitrogen uptake in the cattail plants. The results of this research support previous research on cattail nutrient uptake (Grosshans 2014; Grosshans et al., 2014) and suggests that FTWs could be harvested in August or September to enhance nutrient removal, while ensuring plant survival over the winter. The plant dry weight data indicates that the maximum amount of harvestable plant biomass (dry weight) was not equated with the highest removal of phosphorus, suggesting that harvesting during late summer could remove the maximum amount of phosphorus, but less biomass (higher phosphorus content). Alternatively, harvesting at the end of the growing season (September) could also reduce leaching of stored nutrients that occurs from senescence (Wang, Samples, & Bell, 2014) and winter freeze-thaw cycles (Grosshans, 2014).

Depending on the phytoremediation objectives, managers could also consider the necessity of removing below-surface roots to maximize pollutant sequestration. This study showed that roots and rhizomes sequestered nutrients in relatively large quantities, much greater than uptake by aboveground shoot portions. The literature also shows that certain plant species contain much greater proportions of nutrients in roots (Pavlineri et al., 2017). Root growth below the platforms stretched up to 1 metre vertically and created a dense mat of roots under the platforms, potentially making roots relatively easy to remove. Additionally, this study observed considerable growth of biofilm on roots and island surfaces, shown in the case studies to provide up to 80 per cent of the nutrient removal in FTW systems (Floating Islands International, 2011). The treatment capacity of biofilm far outweighs any need to harvest aboveground shoots or below-surface root material. Even though shoot harvesting can be important for preventing senescence and avoiding nutrient reintroduction into the water column (Grosshans et al., 2014), plant harvesting may not be a viable management scenario for survival of the FTW ecosystem.

4.4 FTWs and Lake Management

FTWs are suitable for a wide range of lake remediation and water quality conditions. FTW effectiveness is dependent on a combination of platform characteristics (design, sizing approach, macrophyte species), specific lake characteristics (temperature, pH, nutrient concentrations, hydrology), and proportion of surface coverage and management requirements as determined for nutrient reduction or contaminant treatment. Successful application of FTWs has been well documented in a variety of situations and water body sizes, and there is a remediation benefit in any water body (Lewtas et at., 2015). Nevertheless, depending on the remediation objectives, such as nutrient reduction, FTWs could be most efficient in smaller lakes and bodies of water, such as reservoirs, retention ponds and wastewater lagoons.

The goal of the research at IISD-ELA was to focus on phosphorus uptake by plant components and the impacts of eutrophication on plant productivity and phosphorus uptake. In order to more accurately estimate phosphorus removal rates by an FTW, research needs to consider the entire FTW ecosystem as a whole in a contained or flow-through system. Research shows that the removal efficiency by plants only accounts for 20 per cent or less of total removal efficiency of the FTW, and biofilm activity provides up to 80 per cent of the nutrient removal performed by FTWs. Just considering plant uptake misses the most important treatment components. The literature also shows greater phosphorus concentrations in the aboveground plants than those measured at IISD-ELA. In comparison, phosphorus levels in L227 could be considered quite low compared to phosphorus levels in most lake systems, such as Pelican Lake. This suggests removal rates by FTWs in the Pelican Lake example are most likely greater than calculated, with a lower lake surface area requirement, as indicated in Table 11

When assessing the results of the IISD-ELA research in combination with the potential application at Pelican Lake, Manitoba, it is important to consider the scale of this experiment in relation to the use of an FTW system in a larger lake that is influenced by stream-driven nutrient loading and also internal recycling through lake sediment. It is also important to consider the FTW ecosystem as a whole and not just consider plant uptake. The primary mechanisms for nutrient removal from FTWs are microbial transformation and uptake (biofilm), plant assimilation, absorption into organic and inorganic substrate materials, and volatilization (Stewart et al., 2008). Surface area is necessary for microbial growth within a wetland, as the greater surface area allows for a larger microbe community and therefore greater growth and uptake of nutrients from the water. FTW systems provide extensive surface area for growth of microbe communities, therefore the greater the FTW coverage the greater the remediation potential.

Multiple scenarios for the Pelican Lake example were estimated by examining a combination of targets in reduction of lake TP concentration (%) and a range of potential TP removal by FTWs. Given the size of Pelican Lake, no combination of FTW surface coverage percentage would decrease lake TP concentration below the provincial guideline (0.025 mg/L) by using FTWs alone. Nevertheless, in prairie lakes such as Pelican Lake, FTWs are simply one component of several options that need to be considered for lake remediation. FTWs are most successful when deployed in combination with other remediation strategies and management practices, targeting both internal and external nutrient loading sources. Management practices are necessary in the watershed to address the sources of nutrients and reduce nutrient loading long before it reaches the lake. A combination of in-lake and watershed options would have significant benefits for decreasing nutrient loading and improving overall lake water quality. Research also shows that additional management additions in combination with simply deploying FTWs may also enhance biofilm development and treatment potential, such as creating flow-through systems, installing membrane barriers and using aeration (White & Cousins, 2013).

Constructed wetlands, including FTWs, have been recognized as a viable and economical option for controlling watershed nonpoint source pollution (Fink & Mitsch, 2004). Based on wetland studies in the United States and Sweden, Verhoeven, Arheimer, Yin and Hefting (2006) determined that wetlands should cover at least 2–7 per cent of the catchment area in order to achieve significant water quality benefits. The ideal location of these wetlands for nonpoint source nutrient loading is the riparian zone between the lake and surrounding catchment land use. In the case of Pelican Lake, which has a catchment area land use of predominately agriculture (58 per cent), targeting regions in the watershed where there is high nutrient loading as a result of high agricultural land use and low wetland area would increase the efficacy of wetlands and FTWs as a remediation strategy. Targeted placement of wetlands or FTWs in retention ponds out in the watershed may be able to improve the quality of water flowing from these sub-catchment areas before they enter downstream into Pelican Lake.

5.0 Conclusions and Recommendations

Floating Treatment Wetlands: Natural Infrastructure in Lake Remediation

Key Findings:

1. Floating treatment wetlands are an innovative natural infrastructure and biological treatment alternative to conventional in-lake remediation strategies to help improve the quality of water in smaller eutrophic water bodies.
2. FTWs have been successfully used around the world for treatment of surface water runoff, wastewater, landfill leachate, mine site tailings and other contaminants.
3. Research at IISD-ELA demonstrated that, with a relatively small increase in phosphorus loading, plant productivity responded with an increase in overall plant growth and biomass production.
4. Multiple scenarios for the Pelican Lake example looked at surface area coverage of FTWs required to achieve a range of potential TP removal targets: based on estimated TP removal by FTW systems, FTW coverage of 5 per cent of lake surface could reduce TP levels in the lake from 10 to 50 per cent, depending on TP removal levels by the FTW system.
5. Ultimately, for any lake remediation effort, a combination of in-lake and watershed options would most significantly decrease nutrient loading and improve overall lake health.

FTWs have been successfully deployed around the world for treatment of surface water and stormwater runoff, municipal waste water effluent, landfill leachate and mine site tailings ponds. They have also been well documented for their additional benefits for fish and wildlife habitat enhancement, as well as shoreline protection by reducing wave erosion.

This study demonstrated that FTWs are an effective passive biological option to enhance the removal of nutrients and help remediate eutrophication in surface waters in urban and agricultural settings in Manitoba, while also providing additional co-benefits such as wildlife enhancement. The L227 studies showed that a relatively small increase in phosphorus loading resulted in a rapid increase in plant productivity on floating platforms in L227, with an increase in overall plant growth and biomass production. This confirmed that cattails are opportunistic consumers of nutrients and will reproduce and grow bigger with more available nutrients, such as phosphorus. The floating cattail platforms and hydroponic-like conditions allowed for greater growth and greater nutrient sequestration in a lake with higher available nutrient (phosphorus) concentrations (L227) compared to a lake with lower nutrient levels (L114).

Based on the results from the deployment of FTWs in lakes at IISD-ELA and case studies from the literature, the potential of FTWs in remediation of smaller eutrophic prairie lakes in Manitoba was evaluated. Pelican Lake, Manitoba, was used as a representative case study of Manitoba prairie lakes. Multiple scenarios were established for determining the surface area coverage of FTWs required to achieve TP removal targets. It was estimated that FTW coverage of 5 per cent of the Pelican Lake surface could reduce TP levels in the lake up to 50 per cent, depending on TP removal levels by the FTW system. FTWs alone in larger water bodies would not considerably reduce high nutrient concentrations to required water quality standards, but they would be most effective in combination with other in-lake remediation treatments and watershed nutrient reduction strategies.

Ultimately, FTWs deployed in combination with other in-lake remediation treatments and watershed nutrient reduction strategies that target both internal and external nutrient loading sources would be most effective and provide additional positive contributions to the health of the aquatic environment (Lewtas et al., 2015). This combination maximizes the effectiveness of programs and government priorities related to phosphorus reduction in surface waters, such as Lake Winnipeg, enhancement of wildlife habitat and angling, and remediation of prairie lakes. Building partnerships with local communities and municipalities is key to successful implementation, particularly to ensure ongoing monitoring and management of FTW systems.

In current discussions of green infrastructure and nature-based solutions, FTWs were shown to offer an innovative "natural infrastructure" alternative to the more conventional in-lake remediation strategies, to help improve water quality in smaller eutrophic water bodies.

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