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Response of Typha x glauca to Phosphorus, Hydrology, and Land Use in Lake Ontario Coastal Wetlands

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Response of *Typha* x *glauca* to Phosphorus, Hydrology, and Land Use in Lake Ontario Coastal Wetlands

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Biographical Sketch

Aaron W. Heminway was born and raised in western New York in a rural area bordering Iroquois National Wildlife Refuge. The refuge provided Aaron with a living laboratory and a place of reflection and intuitive learning until graduating from Medina High School in 1995. Aaron received an associate's degree from Genesee Community College in 2008 and was subsequently hired by the college to tutor students in math, biology, and English. Aaron then transferred to State University of New York College at Brockport where he graduated in two years with a bachelor's degree in Environmental Science (terrestrial ecology). In his senior year at the College at Brockport, Aaron became the first student to enter the newly created combined BS/MS degree program in Environmental Science and Biology. Under the supervision of Douglas Wilcox, Ph.D., Aaron pursued his master's degree in wetland ecology while working on the Great Lakes Restoration Initiative, gathering data on close to 50 Lake Ontario coastal wetlands over two summers.

Dedication:

I dedicate this in memory of my grandfather, Everett "Satch" Heminway, a man whose courage and unquenchable spirit I will never forget.

ABSTRACT

A combination of field sampling, a greenhouse growth experiment, and GIS was used to quantify the effects of phosphorus, hydroperiod, watershed land use, and wetland hydrogeomorphic classification on the invasive cattail *Typha* x *glauca* Godron across 18 Lake Ontario coastal wetlands. To determine *T.* x *glauca* density and frequency in coastal wetlands, vegetation was sampled in 1-m^2 quadrats along stratified random transects, each of which crossed three wetland vegetation zones when present (submergent, emergent, and wet meadow). In each wetland, water samples were collected and shipped for laboratory analysis to determine total phosphorus concentrations in wetland waters. For each wetland, ESRI ArcGIS was used to determine its watershed area, watershed land use as croplands, and length of lotic surface waters. A greenhouse growth experiment using a full factorial random block design was used to investigate the effects of variable hydroperiod and phosphorus concentrations on *T.* x *glauca* biomass allocation.

Multiple linear regressions revealed that frequency of occurrence of *T.* x *glauca* cannot be predicted by the individual and combined effects of wetland water mean total phosphorus (mg/L) or croplands in wetland watersheds (p = 0.345), However, these variables were predictors of increases in cattail density (p = 0.021). Increases in mean water total phosphorus concentrations can be predicted by the combined effect of wetland watershed croplands and total

length of watershed lotic waters ($p = 0.002$), but individually, croplands were the only significant predictor ($p = 0.001$; lotic waters, $p = 0.414$). Wetland hydrogeomorphic classification did not predict cattail density (ANOVA, $p = 0.389$) or frequency ($p = 0.665$). Wetland mean total phosphorus concentrations increased from lacustrine to riverine wetland systems ($p = 0.040$) but there were no differences between riverine and barrier wetlands ($p = 0.598$) or between lacustrine and barrier wetlands ($p = 0.169$)

A full factorial *T.* x *glauca* growth experiment with variable hydroperiods and phosphorus concentrations was performed over the course of eight weeks. As assessed by MANOVA, there was an increase in above-and below-ground biomass allocation for the simple main effects of hydroperiod ($p < 0.000$), phosphorus concentrations ($p < 0.000$), and their interaction ($p < 0.000$). Multiple pairwise interaction comparisons within block hydrology between nutrient treatments results revealed that as hydroperiod and phosphorus concentrations increased, the more pronounced the differences in their interaction became.

Overall, results of this study demonstrated that increasing concentrations of phosphorus positively influenced cattail growth in a controlled setting as well as in Lake Ontario coastal wetlands. Although phosphorus positively influenced growth, hydrologic regime had the greatest influence on cattail growth and biomass allocation, with increased biomass as hydroperiod

increased. Results could be used by Lake Ontario stakeholders or other land managers to craft policies that reduce phosphorus inputs into wetlands and manage hydrologic regimes in a manner that limits or reverses the spread of this invasive species.

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This research project and resulting thesis would not have been possible without the support of many people. My deepest gratitude and highest accolades go to my supervisor, Dr. Douglas Wilcox. Without Dr. Wilcox's tireless pursuit of funding, moral and intellectual support, and supreme patience, I would not have had the opportunity to engage in this research. I also thank the members of my thesis committee, Dr. Chris Norment and Dr. James Haynes, for their insight and advice throughout this process. A special thank you to Robert Cornish, Matthew Piche, David Sanderson-Kilchenstien, and Kathryn Des Jardin, the fellow graduate students who participated in the Great Lakes Restoration Initiative field work. I cannot forget to thank Mr. Bradley Mudzrynski, a fellow plant enthusiast and my GLRI supervisor. None of this would have been possible without my parents, James and Diane Heminway, my loving wife, Maura Misiti Heminway, and my son John J. Heminway. Thank you all.

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INTRODUCTION

Great Lakes Coastal Wetlands

Some of North America's most productive ecosystems are Great Lakes coastal wetlands (Environment Canada 2006). Great Lakes wetland systems provide a number of ecological functions and services and support a large diversity of flora and fauna, including some species listed as threatened or endangered by the U.S. Fish and Wildlife Service (2012). Mammals, fish, birds, amphibians, reptiles, and invertebrates use Great Lakes wetlands for breeding and rearing young (Mitsch and Gosselink 2007).

Coastal wetlands with naturally fluctuating water-levels mitigate floods by intercepting storm runoff and absorbing wave energy (Mitsch and Gosselink 2007). Wetlands may also act as filters by processing some nutrient loads and other pollution from runoff and groundwater. This filtering function is important in Great Lakes coastal wetlands, particularly those in Lake Ontario, given their proximity to urban and agricultural areas (Carpenter *et al.* 1998).

Since European settlement of the Great Lakes region in the early 1800s, 50 to 90 percent of Great Lakes coastal wetlands have been lost due to anthropogenic land-use changes, hydrological alterations, climate change, nutrient inputs, and invasive species (Moser *et al.* 1996, SOLEC 2005). Loss of wetlands has continued to occur, despite regulations, and their value in aquatic processes such as sediment and nutrient filtration, and providing habitat for plants, mammals, fish, invertebrates, and birds has decreased (Maynard and Wilcox 1997). The historical and current loss and alteration

wetlands only serves to reinforce the importance of the need to study, preserve, and restore these systems.

Threats to Coastal Wetlands

Water Quality: Land Use

Point and non-point sources of nitrogen and phosphorous are the leading causes of degradation of freshwater systems (Carpenter *et al.* 1998). Point-source pollution can be relatively easy to detect, monitor, and regulate. Non-point sources are not as easily detected or controlled and have been identified as the largest source of freshwater pollution in the United States (U.S. Environmental Protection Agency 1996). Sources of non-point pollution include, but are not limited to, atmospheric deposition of nitrogen, agriculture, and urban runoff. In particular, agricultural and urban land use in wetland catchments of the lower Great Lakes affects nutrient enrichment, water clarity, and sediment quality (Crosbie and Chow-Fraser 1999). In a basin-wide study, Lougheed *et al.* (2001) concluded that the proportion of agricultural and urban land in wetland watersheds was a statistically significant predictor of water quality. In coastal wetlands, the flow of water between wetland and the lake can be reversed depending on watershed inputs, seiches, and water levels (Botts 1999). Wetland water mixing with lake water in riverine systems may mitigate effects of upstream pollution. In addition, wind and wave action in exposed or otherwise unprotected coastal marshes may lead to export of organic matter from the wetland to the lake (Day *et al.* 1988).

Water Quality: Phosphorus

Phosphorus is one of the six macronutrients that all plants need for healthy growth and reproduction; next to nitrogen it is the second most limiting nutrient in wetlands and virtually all temperate freshwater systems (Hinsinger 2001). There are two common forms of phosphorus in soils: organic and inorganic. Organic forms of phosphorus are commonly found in humus and other organic materials. Inorganic forms of phosphorus occur in combination with metals such as iron, aluminum, and calcium, most of which are insoluble in water (Schulte and Kelling 1996). Organic and inorganic forms of phosphorus are important sources of phosphorus for plant growth, but their availabilities are controlled by soil characteristics and environmental conditions (Schulte and Kelling 1996). Phosphate ions ($H_2PO_4^-$ in acidic soils or HPO_4^{2-} in alkaline soils) become strongly attached to the surfaces of metals to form insoluble phosphate precipitates (Schulte and Kelling 1996). Sources of phosphorus containing the ions $H_2PO_4^-$ or HPO_4^{2-} are named orthophosphates. Since orthophosphates are water-insoluble, they mainly enter surface water attached to fine soil particles. The role of phosphorus in the eutrophication of surface waters has been thoroughly documented (Vollenweider 1970, Correll 1998, Daniel *et al.* 1998). Eutrophication distorts community balance in aquatic ecosystems, often in the form of algal blooms (Schindler 1974).

From the 1960s to present, water quality of Lake Ontario has been monitored by government and non-government organizations. Nutrient surveys of Lake Ontario began in the 1960s. Results of those surveys indicated that cultural eutrophication was partially

to blame for the declining health of the lake and attached ecosystems (ILOWPB 1969). Long-term trends in Lake Ontario open water indicate a general decline in concentrations of total phosphorus, although there have been slight increases in springtime measurements since 2000 (Dove 2009).

Invasive Flora

The introduction of invasive flora may alter wetland functions by shifting species composition or completely replacing native flora (Galatowitsch *et al.* 1999, Werner and Zedler 2002). Second only to habitat loss and fragmentation, invasive species are a major threat to wetland biodiversity (Wilcove *et al.* 1998, Allendorf and Lundquist 2003). The transitional nature of wetland systems and their role as landscape sinks may facilitate invasion (Zedler and Kercher 2004). The spatiotemporal expansion of invasive species over the last two centuries has been linked to anthropogenic infrastructure and commerce (Wilcox 1989, Mack *et al.* 2000). Introductions of some non-native species are intentional (e.g., *Salmo trutta* L. (brown trout)), but most are the result of unintentional actions, (e.g., *Dreissena polymorpha* Pallas (zebra mussel)). Some invasive plant species were contaminants in crop seeds, while most were intentionally introduced (e.g., *Eichornia* spp. (water hyacinth)) (Mack *et al.* 2000). Many previous studies have focused on understanding the patterns of plant invasions (Mills *et al.* 1993, Galatowitsch *et al.* 1999, Mack *et al.* 2000, Hager 2004, MacDougall and Turkington 2005, Crowl *et al.* 2008, Tuchman *et al.* 2009), and several life history trait(s) hypotheses have been developed to explain how some invasive species are more successful than others or the natives they displace (Levine *et al.* 2003). In addition to alteration of native plant

diversity and range, invasive species can alter hydrology (Kercher *et al.* 2007), food-web dynamics (Zedler and Kercher 2004), and sedimentation and decomposition rates (Werner and Zedler 2002, Freyman 2008).

Typha x *glauca* Godron [*angustifolia* × *latifolia*]

One of the most common invasive plant species found in emergent zones of Lake Ontario coastal wetlands is the hybrid cattail *Typha* x *glauca* Godr. In Lake Ontario wetlands, this plant represents a combination of hybrids of *Typha latifolia* L. (broadleaf cattail) and *Typha angustifolia* L. (narrowleaf cattail) (Green and Galatowitsch 2001, Kercher *et al.* 2007). The native status of *T. angustifolia* is unclear in the Great Lakes region; *T. latifolia* is native. Until recently, *T. angustifolia* has been considered non-native to North America, but paleo-ecological pollen studies of pre-European settlement sediments suggest that *T. angustifolia* may be native to the northeastern United States in estuarine marshes (Pederson *et al.* 2005, Shih and Finkelstein 2008).

There are several traits that allow *T.* x *glauca* to proliferate in Lake Ontario wetlands. Clonal expansion of *T.* x *glauca* through rhizomes allows it to spread rapidly; in a 412-ha wetland that was hydrologically stabilized, the cattail expanded 0.0081 ha/year (Boers and Zedler 2008). Like many hybrids, *T.* x *glauca* shares traits of both parent species. Aerenchyma tissue, which is spongy tissue with large air spaces located between cells, enables *T.* x *glauca* to tolerate high water conditions, much like its parent species. *Typha* x *glauca* also has a high capacity for biomass production, much like its parent *T. latifolia* (Grace and Wetzel 1981). The large amount of above-ground biomass

of *T.* x *glauca* allows it to shade out competitors, while rapid rates of nutrient uptake enable it to out-compete native species. In addition, *T.* x *glauca* can stimulate rates of soil nitrogen-fixation greater than either parent species (Eckardt and Biesboer 1988).

Typha x *glauca*: Nutrients and Hydrology

Due to its relatively fast growth rates and ability to take up nutrients rapidly, *T.* x *glauca* thrives in areas of high nutrient input (i.e., nitrogen and phosphorous) (Newman *et al.* 1996, Miao and Sklar 1997, Mack *et al.* 2000). Woo and Zedler (2002) conducted nitrogen and phosphorous addition experiments with *T.* x *glauca* and native sedge-meadow species to determine if these additions accelerated the expansion of *T.* x *glauca* into wet meadow zones. They determined that *T.* x *glauca* increased above-ground biomass, stem density, and height with nutrient additions, while native sedge species showed no significant response.

Like many species of invasive wetland plants, the physiology of *T.* x *glauca* is well-adapted to large fluctuations in water levels (Harris and Marshall 1963, Wilcox *et al.* 1985, Miller and Zedler 2003, Wilcox *et al.* 2008). Aerenchyma tissue enables the cattail to survive high water periods through oxygen transport to its roots (Mitsch and Gosselink 2007). Wilcox *et al.* (2008) showed that regulated Lake Ontario water levels of lake-level Plan 1958-DD may have enabled invasive *Typha* dominance, as native sedge and grass species lost their competitive advantage over *Typha* during low lake-level periods, which no longer occurred. If high water conditions also carry nutrients, the competitive advantage of high nutrient uptake rates enables *T.* x *glauca* to maintain and

expand its dominance (Wilcox *et al.* 1985, Miao and Sklar 1997). In addition, phosphorus binds to oxidized Fe^{+3} in dewatered soil during low water conditions but is released during flooded conditions when redox reactions convert the iron to Fe^{+2} (Boers and Zedler 2008). Boers and Zedler (2008) determined that this reaction caused "internal eutrophication," which increased cattail growth.

Experiments with nutrient additions involving *T.* x *glauca* have involved either a mesocosm approach (Woo and Zedler 2002) or cattail species other than *T.* x *glauca* (Macek and Rejmánková 2007). Lishawa *et al.* (2014) combined field and mesocosm approaches to assess effects of *T.* x *glauca* populations on wetland functions along Lake Michigan. There has been relatively little or no research performed with *T.* x *glauca* from Lake Ontario coastal wetlands involving phosphorus and hydroperiods, leaving much to be learned from further studies.

Lake Ontario Hydrology and Wetland Floral Communities

Construction of the Moses-Saunders hydroelectric dam on the St. Lawrence River between the United States and Canada was completed in 1958. This project initially served as a means to generate electricity for both countries but also regulated Lake Ontario water levels for the benefit of the shipping industry and other stakeholders. Around this time, operation of the St. Lawrence Seaway began. Subsequent lake-level regulation muted the historical highs and lows of Lake Ontario water levels (Wilcox and Xie 2007).

Lake Ontario water levels are currently regulated under the International Joint Commission Plan 1958DD (Carpentier 2003). Plan 1958DD was designed for the benefit of a few stakeholders, namely hydroelectric power generators, the shipping industry, and lake-front property owners. This plan did not consider environmental ramifications of altered hydrologic regimes, as it was developed and implemented before the development of the modern environmental movement and resultant environmental laws and increased research on Great Lakes wetland ecosystems. Plan 1958DD has reduced annual lake-level fluctuations from 1.5 m to 0.7 m, approximately half of the pre-regulation amplitude (Wilcox and Whillans 1999).

The upper Laurentian Great Lakes are subject to climate-driven ~33 year lake-level cycles (Baedke and Thompson 2000). These cycles are one of the main drivers that shape associated wetland plant community dynamics (Wilcox 2004, Wilcox *et al.* 2008). During high lake levels, emergent macrophytes that have invaded lower elevations bordering the submergent zone are eliminated, as well as woody species such as shrubs and trees that have invaded the emergent zone from the upland edge. Conversely, periodic lows provide an opportunity for production from the seed bank of less competitive species (Keddy and Reznicek 1986, Maynard and Wilcox 1997, Wilcox and Nichols 2008). Repetition of this cycle of highs and lows drives wetland floral communities, distribution, and diversity (Wilcox *et al.* 2008).

Anthropogenic manipulation of water levels alters wetland floral community dynamics, productivity, and function (Keddy 2002, Nilsson and Svedmark 2002). Shay *et*

al. (1999) demonstrated that administration of water-level regulations coincided with expansion of *Typha* toward upland edges and into shallow water. Wetland floral communities invaded by *Typha* in water-level-regulated wetlands undergo significant decreases in diversity (Grubb 1977, Wilcox *et al.* 2008, Lishua *et al.* 2010).

Recently, a new Lake Ontario water-level regulation plan was proposed that may go into effect within the next few years, pending review and a public comment period. Plan 2014, which incorporates plan Bv7, the Balanced Environmental Plan, and "discretionary decisions," "strives to return the Lake Ontario-St. Lawrence River system to a more natural hydrologic regime, while limiting impacts to other interests" (IJC 2014). If implemented, this plan will aid wetland restoration projects by producing hydrologic conditions that more closely mimic past water-level fluctuations.

Wetland Classifications

The combined effects of hydrology, local bedrock geology, and wetland geomorphology, referred to jointly as hydrogeomorphic (HGM) factors, tend to be the primary regional determinants of plant community structure in wetlands and littoral systems (Lougheed *et al.* 2001). HGM classifications of Great Lakes coastal wetlands, as established by Albert *et al.* (2005), fall broadly into three categories: lacustrine, riverine, and barrier-protected. Coastal wetlands can be further defined and classified under this system, but for the purposes of this project, Lake Ontario wetlands will be categorized into these three HGM categories.

HYPOTHESES

In this study, I hypothesized that as the proportion of agriculture (croplands) increases in a wetland's watershed, the concentration of total phosphorus (TP) within wetland waters will also increase. Concentrations of TP could also be predicted by the total length of lotic surface waters combined with the percent of croplands in the wetland's watershed. I expected that in watersheds with greater total lengths of lotic surface waters, wetland waters would have decreased concentrations of TP and vice versa. This assumption is based upon the adage, "dilution is the solution to pollution." I also expected that when the proportion of a watershed utilized as cropland increased, total phosphorus concentrations in wetland water would increase. Similar research found spatio-temporal correlations between a watershed's agricultural land use and TP-loading in streams and their outputs (Makarewicz and Lewis 2002, Makarewicz 2009, Makarewicz and Lewis 2009). Previous studies also demonstrated a positive relationship between the biomass of aquatic micro- and macrophytes and TP at stream mouths in littoral systems (Makarewicz and Lampman 1994, Makarewicz 2009). Ultimately, I predicted that increases in TP would increase the frequency of occurrence (frequency) and density (as percent cover) of the cattail within Lake Ontario wetlands. I also expected that a wetland's HGM classification would have direct effects on TP concentrations, as well as frequency and density of the cattail. Specifically, wetlands that have greater connectivity to Lake Ontario would have lower TP concentrations than those that are less connected, so that barrier systems would have the highest TP concentrations, lacustrine systems would have the lowest, and riverine systems would have intermediate

concentrations. In addition, I expected that wetland HGM classification would affect the frequency and densities of the cattail, also as a function of connectivity to Lake Ontario as posited for TP concentrations, so that frequency and density of the cattail could be predicted by HGM classification.

To assess relationships between land use, wetland HGM classification, surface waters, mean wetland water phosphorus concentration, and frequency and densities of the cattail, data were collected from Lake Ontario wetlands over a 2-yr. span during the growing seasons of 2011 and 2012. To augment field observations, I conducted a greenhouse growth experiment on cattail using several combinations of hydroperiods and phosphorus concentrations. One of my hypotheses was that the cattail would allocate greater amounts of above- and below-ground biomass as the duration of hydroperiods increased. I also hypothesized that the cattail would respond to the interaction of hydroperiod and increasing phosphorus concentrations by increasing total biomass. This interaction would be increasingly pronounced with the simultaneous increases in hydroperiod and phosphorus additions.

METHODS

Lake Ontario Coastal Wetland Sites

Over two years, from May to August 2011 and 2012, I sampled vegetation in 18 coastal Lake Ontario wetlands through a grant from the United States Environmental Protection Agency's (EPA) Great Lakes Restoration Initiative (GLRI) (Table 1 and Figure 1). Sampled wetlands varied in connectivity to Lake Ontario and were classified

into three HGM types as defined by Albert *et al.* (2005): lacustrine, riverine, and barrier-protected. Locations and boundaries of the wetlands randomly sampled over the 2-yr. period were determined by Uzarski *et al.* (2011).

At all sites, the submergent and emergent vegetation zones were present. Due to anthropogenic influences, including lake-level regulation and land use, many wetlands sampled did not contain a wet meadow zone. If a sampled wetland did contain a wet meadow zone, it was often restricted to a narrow fringe (< 12 m) between the emergent zone and upland edge. Emergent zones were dominated by the invasive cattails, *T.* x *glauca* and *T. angustifolia,* and associated standing dead material. Substrate in all emergent zones often was composed of floating mats of organic material, in many cases >250 cm thick. Water quality in sampled sites ranged from hypereutrophic and turbid to mesotrophic with low turbidity.

All sampled wetlands met the following criteria as set forth in the Quality Assurance Project Plan, GLIC: Implementing Great Lakes Coastal Wetland Monitoring (QAPP): 1) 4 ha or larger, 2) a direct, obvious surface-water connection to Lake Ontario or connecting channel, 3) close enough to that lake or connecting channel to be influenced by it, and 4) herbaceous or standing-water wetland zones present (Uzarski *et al.* 2011).

Transect Sampling

Vegetation sampling followed the protocols set forth in the QAPP prepared for the EPA (Uzarski *et al.* 2011). Primary data collection at each site focused on the identification and quantification of all wetland plant species occurring in a specified number of sampling quadrats. Within wetlands, sampling occurred along three transects that ran perpendicular to depth contours and therefore crossed wetland vegetation zones if present (wet meadow, emergent, submergent). The starting point of each transect was randomly located along the upland or swamp forest edge or the outer wetland edge. Once the width of a vegetation zone was established using a 100-m measuring tape, that width was divided by six to establish where the first of five equidistant quadrats would be placed. I surveyed vegetation in 1-m^2 quadrats at regular intervals along three transects, for a total of 30 to 60 quadrats per wetland (15 quadrats/zone). Within each quadrat, all macrophyte species were identified to lowest possible taxonomic unit, generally to species level (www.Efloras.org). In each quadrat, I visually estimated percent cover of each plant species, total vegetation cover, standing dead cover, and detritus cover to the nearest one percent up to ten percent, then by five percent increments. Water depth, substrate type and depth were also measured in each quadrat. GPS starting and ending locations for each transect and associated quadrats were recorded using a Garmin Rino model 530HCx global positioning system.

Water Quality: Macronutrient Quantification

Water quality sample collection and analyses also followed protocols set forth in the GLRI QAPP. In summary, *in situ* samples were collected in sterile containers at mid-depth at each fyke net (used in fish sampling portion of GLRI project), with special care that substrates were not disturbed before or during sample collection. Water samples were immediately placed in coolers and then frozen before being shipped for analysis by the Natural Resource Research Institute at University of Minnesota Duluth. Laboratory and field measurement parameter objectives, precision, accuracy, and method detection limits are found in Uzarski *et al.* (2011). After lab results were received, I averaged water concentrations of total phosphorus (mg/L) at each fyke net site in each wetland for ease of analysis in my thesis (Table 2).

Wetland Watershed Land Use and Surface Waters

Within each of the 18 wetland watersheds, I used ESRI ArcGIS v10.1 to determine size of sampled wetland (ha), size of wetland watershed (ha), length of lotic surface waters (km), and size (ha) and extent (percent) of croplands (Table 2). I accessed the National Hydrography Dataset (NHD), which provided an ArcGIS base layer for lotic surface waters that aided in determining the area of each wetland's watershed to the eighth hydrologic unit code (HUC). HUC are nested and define geographic watershed areas based on the four levels: regions, sub-regions, accounting units, and cataloging units. The greater the number of digits in a HUC, the smaller the geographic area. An eight digit HUC represents the smallest geographic area (USGS 2013). As I examined the

publically available GIS layer datasets of agricultural land use, I noticed that these layers were out-of-date for the years of 2011 and 2012. To assess the current size and extent of croplands within watersheds accurately, I manually digitized each cropland and created maps (Appendix A) using ArcGIS orthoimagery basemaps, which are updated on a more frequent basis than land-use GIS layers. After digitization, cropland areas were converted to a percentage of the wetland's total watershed area to represent the proportion of influence agriculture may have on other site variables. Due to their hydrogeomorphic nature, I assigned lacustrine wetlands zero values for the variables total watershed area, percentage of agriculture in wetland watershed, and total length of lotic surface waters in the wetland watershed.

Growth Experiment

To assess the potential interaction and discrete effects of variable hydrology and phosphorus concentrations on the cattail growth and biomass allocation, I used an eight-week hydroponic greenhouse growth experiment that I initiated on 1 June 2012. Eighty individual *T.* x *glauca* plants were collected from Brush Creek, a Lake Ontario coastal wetland, on 31 May 2012. Leaves were trimmed to a standard length of 20 ± 1 cm from the base of the plant where the leaf sheaths meet the rhizomes. Rhizomes were trimmed to 10 ± 1 cm in length measured from the start of the rhizome below the leaf sheaths. Roots on all rhizomes were trimmed to 1 ± 0.2 cm. Trimmed samples were then cleaned of residual soil with deionized water and placed in deionized water for 12 h to clean remaining wetland soil from the samples and to help flush nutrients from the rhizomes.

I chose a two-factor balanced and complete random block design for the growth experiment (Figure 2). The experiment was blocked by hydroperiod (hydro-block) to limit variation among units within blocks rather than between blocks. The experiment was designed with the intent of using MANOVA, as it assesses two (or more) related dependent variables while controlling for the correlation between the dependent variables.

I assigned 20 of the trimmed cattails randomly to each of the four hydro-blocks: static, pulsed one time then drained, pulsed once every two weeks then drained, and pulsed once every four weeks then drained. Nutrient treatments varied only by phosphorus concentrations: a control group with no phosphorus (C), low concentrations as treatment one (T1), moderate concentrations as treatment two (T2), and high concentrations as treatment three (T3) (Table 3). Each of the nutrient treatments was assigned to cattail samples using the random selection procedure in IBM's SPSS v20.0.0 (SPSS), with five replicates each in the four hydro-blocks for a total N=80.

Nutrient additions were performed with modified Hoagland's nutrient solutions mixed with deionized water (Hoagland and Arnon 1950, Epstein 1972). Two different solutions were given originally by Hoagland; in the first solution, all of the nitrogen came in the form of nitrate. The second, however, used some ammonium as a means of keeping the pH lower. Higher plants are able to assimilate nitrogen as NH_4^+ and NO_3^-. In aerated soils with a pH above 4, NO_3^- is the prevailing nitrogen compound, and NH_4^+ is found in

low concentrations, but in waterlogged soils, this ratio is reversed as a consequence of depressed bacterial nitrification activity and denitrification of NO_3^- (Brix *et al.* 2002).

In this experimental setup, I included NH_4^+ in the micronutrient solution in the form $(NH_4)_6Mo_7O_{24} * 4\ H_2O$ and NO_3^- in the macronutrient solution in the forms of $Ca(NO_3)^2 * 4\ H_2O$ and KNO_3 (Table 4). Phosphorus was added in the form of KH_2PO_4, a form commonly used in cattail growth experiments (Shipley and Keddy 1988, Woo and Zedler 2002, Macek and Rejmánková 2007, Escutia-Lara *et al.* 2009). I prepared all stock solutions with deionized water and stored them in a refrigerator at 3°C for the duration of the experiment. Stock solutions were not combined into macro- and micro- mixes until the day of application to avoid chemical reactions that would alter availability. Once solutions were mixed, pH was adjusted to 6 with 1M HCl or 1M NaOH and set aside until ambient air temperature was reached before application.

The cultivation medium was a 50:50 mix of silica sand and granulated absorbent rockwool in 5 mm 4.7L hydroponic polyethylene film containers, which were then placed in 5L HDPE containers for stability. There was no artificial aeration of hydroponic solutions in any block. Before application of new nutrient solutions in pulsed and constant block treatments, I drained the growth media and flushed it with deionized water to avoid toxic salt accumulation. For pulsed treatments, nutrient solutions were applied for 15 min to allow for complete media saturation and then gravity-drained.

I recorded daily records for ambient air temperature and relative humidity inside the greenhouse with General Tools© HT50 RH/Temp Data Loggers (Table 5). Weekly measurements of volumetric water content (percent) were recorded using a Vegetronix™ VG-METER-200 soil moisture meter before solution renewals.

I recorded measurements of above-ground growth weekly during the test by measuring any leaf growth above the original 20 ± 1 cm cut and of any new genets that emerged. During the course of the experiment, a leaf or genet was considered dead if more than two-thirds of its length was brown and dry; its mortality then was noted, and final lengths recorded. Any cattail not surviving past week three was not included in analyses as it was most likely using stored starches for growth until mortality and was not responding to treatment. At test termination on 28 July 2012, all plants were rinsed in deionized water before being fractionated into shoots/leaves, rhizomes, and roots and placed in labeled paper bags. Bagged samples were then placed in a drying oven at 60°C to dry for biomass allocation determination. After 24 h, each bag was weighed hourly until weight changes were less than 0.01 g, which was achieved at 29 h.

Since I hypothesized that increases in phosphorus concentrations and hydroperiods would result in increased production of above- and below-ground biomass, with discrete positive correlations for the independent variables and their interactions, this design also allowed determination of whether the effects of each of the factors were consistent across levels of the others.

STATISTICAL ANALYSES

Lake Ontario Coastal Wetland Sites

Multiple Linear Regressions

In an attempt to model the potential individual and combined effects of watershed land use, length of surface lotic waters, and wetland water concentrations of phosphorus on the cattail, I used multiple linear regressions (MLR) for analysis. All assumptions of multiple linear regressions and analysis were checked using the Linear Regression procedure in SPSS (Field 2009). All test outputs were run with the same initial linear regression statistics setting options: estimates of regression coefficients, confidence intervals (95%), model fit, descriptives, part and partial correlations, collinearity diagnostics, residuals (Durbin Watson, and casewise diagnostics),with outliers set to three standard deviations outside the mean.

For examination of assumptions, histogram and normal probability plots, as well as all partial plots, were produced. Unstandardized predicted values, studentized and studentized deleted residuals, Cook's and leverage values were saved and examined for influential and leveraging points. Q-Q plots of studentized residuals were also produced to aid in assessment of normality.

Cattail Frequency, Phosphorus, and Croplands

I used multiple linear regressions of total phosphorus and watershed cropland percentages as predictors of the number of quadrats in which the cattail occurred (frequency) to evaluate the hypothesis that the two predictors could significantly predict

the frequency of the invasive cattail in this population of wetlands. The assumption homoscedasticity was violated as assessed by the scatterplot of unstandardized predicted values versus studentized residuals. The dependent variable, number of quadrats with the cattail, was square-root transformed. I removed the East Creek riverine wetland from the data set due to a high leverage value and high Cook's distance value (influential point), and the analysis was re-run. All assumptions were met after transformation and removal of East Creek.

Cattail Density, Croplands, and Phosphorus

I used total phosphorus concentrations and watershed cropland percentages to evaluate my hypothesis that the two predictors could significantly predict the density of the invasive cattail in this population of wetlands. All assumptions were met, with the exceptions of a high leverage value and an influential point (Cook's distance value) for the riverine wetland, East Creek. East Creek data were removed and the analysis re-run.

Phosphorus, Croplands, and Lotic Surface Waters

I ran multiple linear regressions of watershed croplands and length of lotic surface waters as predictors of site mean total phosphorus to evaluate my hypothesis that the two predictors could significantly predict site mean phosphorus in this population of wetlands. Several of the assumptions of this test were not met, including linearity (the partial plots revealed no linearity for length of lotic surface waters), homoscedasticity, multicollinearity (percent of total watershed area that is cropland), and the leveraging

data sets of the outliers East Creek and South Colwell. The independent variables were square-root transformed and the analysis re-run.

As a follow-up, I used a simple linear regression with percent croplands as a predictor of site mean total phosphorus concentrations. All assumptions of normality, homogeneity, and independence were met.

East Creek, a riverine wetland on the southcentral shore of Lake Ontario, had the highest ratio of watershed land use as croplands of all the sampled wetlands (Figure 1, Table 2, and Appendix A). South Colwell, a lacustrine wetland on the eastern shore, had the largest watershed area and the greatest total length of lotic surface waters of all the sampled wetlands (Figure 1 and Table 2). Compared to the other five lacustrine systems, South Colwell also had the lowest ratio of watershed area land use as croplands (Table 2).

One-Way ANOVAs

I selected one-way ANOVA tests to explore wetland HGM classification vs. number of quadrats of the cattail occurrence (frequency), wetland HGM vs. site mean percent cover the cattail (density), and wetland HGM vs. site mean total phosphorus. Due to having more than two groupings in the independent variable, HGM classification, I used the dedicated one-way ANOVA procedure in SPSS to determine whether there were differences between the means of the independent vs. dependent variables. A balanced design with a sample size of six of each of the three HGM classified wetlands allowed me to determine if there were differences between the groups' means in the population. Assumptions were examined with boxplots (for outliers), normality plots

(Shapiro-Wilk's test due to sample size <50), and Levene's Test for Homogeneity of Variances. I used Welch's ANOVA, which provides a robust ANOVA in the event that the assumption of homogeneity of variances is violated. To determine which HGM classifications differed in the event that the results of the test were statistically significant, I selected Tukey's and Games-Howell post-hoc tests. When an outlier was identified, I used "sensitivity tests" of ANOVA with and without the outlier to determine if it had an appreciable effect on significance values. If the outlier had no appreciable impact on significance values, it was left in the analysis.

Long Pond and Long Carry wetlands were identified as outliers during analyses. Long Pond, a barrier wetland, had the highest frequency of cattail occurrence of all barrier wetland systems. Long Carry, a lacustrine wetland, had the greatest mean total phosphorus concentrations of all lacustrine systems and the greatest density of cattail of all wetlands.

Growth Experiment

I used two separate Discriminant Analyses (DA) in SPSS, with hydroperiod and nutrient treatments as grouping variables and dried leaf and rhizome weights as independent variables, to determine if the grouping variable functions were discriminated from one or both of the independent variables. I examined SPSS outputs to determine if DA met the assumptions of normal distribution, homogeneity of variances/covariances, outliers, correlations between means and variances, matrix not ill-conditioned, and acceptable tolerance values. I used the canonical structure matrix to assign meaningful

labels to functions, and standardized discriminant function coefficients were used to assess the importance of dried leaf and rhizome weights unique contributions to the discriminant function(s).

I used two-way MANOVA with the General Linear Models multivariate procedure in SPSS, with the independent variables (IV) hydro-block and nutrient treatments alone, as well as with interactions, to determine possible effects on the dependent variables (DV), dried leaf weight (g), dried root weight (g), and dried rhizome weight (g). Data were tested for normality using the Descriptive Statistics function of SPSS. For testing normality with a two-way MANOVA, I split the file to organize the output based on groups—in this case, the hydro-block and nutrient treatment. Skewness, normality plots, histograms, and Shapiro-Wilks outputs were examined for the assumption of normality. Assessments of Q-Q plots were used to check the assumption of linearity, and boxplots were checked for outliers. Homogeneity was assessed by Levene's Test of Equality of Error Variances. Box's Test of Equality of Covariance Matrices was produced and assessed for violation of the assumption of equal covariance matrices. Since sample sizes were equal, if data failed Box's test of equality of covariance matrices, this result can be ignored as MANOVA test statistics are robust to violations of this assumption (Field 2009). I used Pearson's Correlation analysis to determine if the dependent variables were statistically significantly correlated to determine if multicollinearity was present. If data did not meet the assumptions, I transformed them

and assumptions were re-investigated. Pearson's Correlation was also run for dried rhizome and dried root weights, as I suspected that these two variables were correlated.

A full factorial two-way multivariate linear model with main effects of the independent variables, as well as interactions using Type III sum of squares, was then performed with Tukey's Post Hoc test to identify if significant interactions occurred once the data met required assumptions. The six combinations produced for each pairwise comparison among hydro-blocks, nutrient treatments, and their interactions allowed me to determine if there were any significant differences on their effects on leaf and rhizome biomass.

Mortality after Week 3 occurred in three of the four hydro-blocks. To maintain a balanced design and account for this systematic loss, a randomly chosen replicate of each treatment in each block was selected to be removed from the dataset. The removal of a replicate using the random function in SPSS resulted in four replicates per treatment remaining, for a total population of N= 64.

RESULTS

Cattail in Lake Ontario Coastal Wetlands

Cattail Frequency vs. Watershed Land Use and Phosphorus Concentration

I expected that simultaneous increases in mean total phosphorus concentrations and watershed croplands would cause significant, predictable increases in cattail frequency, but this was not the case. The combined effects of total phosphorus

concentrations and watershed croplands were not significant in predicting mean cattail frequency in the sampled wetlands (MLR: $F = 1.150$, $df = 2$, $p = 0.345$) (Table 6).

Cattail Density vs. Watershed Land Use and Phosphorus Concentration

Regardless of HGM classification, increases in cattail density were significantly predicted by increases in a wetland's water total phosphorus concentrations (mg/L) while watershed percent croplands decreased. This result was inconsistent with my hypothesis: as total phosphorus concentrations in wetland waters increased with a simultaneous decrease in cropland area, density of cattail (mean percent cover/quadrat) increased significantly (MLR: $F = 5.154$, $df = 2$, $p = 0.021$) (Table 7).

By using the coefficients formula below, I found that an increase of 0.712 mg/L of total phosphorus and a decrease of 0.867 percent of croplands resulted in a one percent increase in density of cattail (Table 8):

Predicted density of cattail = 15.826 - (1.248*percent croplands) +
(182.742*total phosphorus concentrations)

Wetland Water Phosphorus vs. Watershed Land Use and Inflowing Stream Length

In a wetland's watershed, the combined effect of an increased proportion of croplands, coupled with decreases in total length of lotic waters, correlated with increases in a wetland's water total phosphorus concentration (MLR: $F = 9.645$, $df = 2$, $p = 0.002$) (Table 9). However, the individual effect of increases in croplands was the true driver of mean total phosphorus concentrations in a wetland's waters, as a wetland's contributing

surface waters alone had no effect. The individual effect of croplands was significant (p = 0.001) but was not significant for total length of lotic surface waters (p = 0.414) (Table 10). The total variation in site mean phosphorus concentrations (mg/L), as assessed by the coefficient of determination, had an adjusted R^2 = 0.504 (Table 11).

Mean value total phosphorus concentration in wetland waters can be predicted by the linear equation (Table 10):

Predicted total phosphorus concentration (mg/L) = 0.043 + (0.022* percent croplands) - (0.002*total length of lotic surface waters (km))

An increase of 0.814 percent of croplands with a simultaneous decrease of 0.163 km total length of lotic surface waters resulted in a 1.0 mg/L increase of total phosphorus concentration.

A simple linear regression using only croplands significantly predicted increases in wetland water total phosphorus concentrations (MLR: F=20.493, df=1, $p < 0.000$) (Table 12). Using the unstandardized coefficients (Table 13), the increase in mean total phosphorus can be predicted by the equation:

Predicted mean total phosphorus concentration (mg/L) = 0.050 + (0.003x (percent cropland area (ha))

So, for every 1 % increase in the ratio of croplands to watershed area, total phosphorus concentrations should increase by 0.053 mg/L. The total variation in site mean phosphorus concentrations (mg/L) had an adjusted R^2 = 0.534 value (Table 14).

Cattail Frequency vs. Wetland Hydrogeomorphic Classification

Contrary to what I had expected, there was no significant difference in cattail frequency among barrier, lacustrine, and riverine wetland systems in this population of sampled wetlands. Significance was not affected, when as a sensitivity test, the outlier Long Pond was included in analysis (ANOVA: $F = 0.418$, $df = 2$, $p = 0.665$) (Table 15), then removed (ANOVA: $F = 1.493$, $df = 2$, $p = 0.258$) (Table 16).

Cattail Density vs. Wetland Hydrogeomorphic Classification

There were no significant differences (ANOVA: $F = 1.006$, $df = 2$, $p = 0.389$) between the means of cattail densities among HGM classifications (Table 17). Consequently, HGM classification could not be used to predict cattail density in this population of wetlands.

Phosphorus Concentrations vs. Wetland Hydrogeomorphic Classification

HGM classification can only be used to distinguish total phosphorus concentrations between riverine and lacustrine systems.

Long Carry wetland was an outlier, but when I removed it from the analysis, the differences were still significant (ANOVA: $F = 4.414$, $df = 2$, $p = 0.031$) (Table 18). When I examined the Games-Howell post-hoc multiple comparisons table, the only significant difference ($p = 0.040$) was an increase of 0.096 mg/L mean phosphorus concentrations from the lacustrine to riverine systems (Table 19 and Figure 3).

Growth Experiment

Discriminant Analysis

Cattail biomass could be used to predict and distinguish among the four hydro-blocks in which it was grown (Table 20 and Figure 4), but not among the three phosphorus treatments and the control (Table 21 and Figure 5).

Using both rhizome and leaf weights, I discovered that analysis for hydroperiod yielded two significant discriminant functions (Table 22).

Hydroperiod as function 1 = -1.153*dried leaf weight (g) + 1.942*dried rhizome weight (g)

Dried leaf weight as function 2 = -1.560*dried rhizome weight (g) + 2.209*dried leaf weight (g)

Hydroperiod was a better grouping function than the dried leaf weight function because it explained greater variance (89.3 percent) and had a higher correlation value (r = 0.96) (Table 23).

Cattail Biomass, Phosphorus Treatments, and Hydroperiod

As expected, rhizome weights and root weights were significantly correlated (r = 0.933, $p \leq 0.01$), so root weights were removed before I began MANOVA (Table 24).

The main effects of hydroperiod, phosphorus treatments, and their interaction all had significant effects on cattail, generally increasing all biomass measurements as duration of hydroperiod and phosphorus concentrations increased. Although all the main

effects were significant, rhizome weights were a better fit of the corrected model ($F = 153.657$, $df = 15$, $r^2 = 0.980$, $p \leq 0.000$) than leaf weights ($F = 75.710$, $df = 15$, $r^2 = 0.959$, $p \leq 0.000$). This trend continued, as the individual models of hydroperiod ($F = 703.657$, $df = 3$, $r^2 = 0.978$, $p \leq 0.000$), nutrient treatments ($F = 37.742$, $df = 3$, $r^2 = 0.702$, $p \leq 0.000$), and their interaction ($F = 8.962$, $df = 9$, $r^2 = 0.627$, $p \leq 0.000$) were a slightly better fit for rhizome weights than for leaf weights: hydroperiod ($F=328.823$, $df = 3$, $r^2 = 0.954$, $p \leq 0.000$), nutrient treatments ($F = 24.850$, $df = 3$, $r^2 = 0.608$, $p \leq 0.000$), and their interaction ($F = 8.292$, $df = 9$, $r^2 = 0.609$, $p \leq 0.000$) (Table 25).

Because the model was significant for all main effects, and that each had a greater effect on below-ground biomass than above-ground biomass, Tukey's Post-Hoc revealed more detail through multiple pairwise comparisons, as follows.

Cattail Biomass and Hydroperiod

Tukey's Post-Hoc pairwise comparisons of hydroperiods revealed that accumulation of above-ground biomass was greater than below-ground biomass in cattail pulsed every two weeks when compared to those pulsed every four weeks Below-ground biomass was not affected by the increased duration of hydroperiod from pulsing once to every four weeks, but this increased duration of hydroperiod did result in increases of above-ground biomass. Cattail grown in a static hydroperiod accumulated a greater amount of below-ground than above-ground biomass than the other three hydro-blocks.

I first compared mean dried leaf weights among the four hydro-blocks (Table 26). From those cattail grown in a static hydroperiod, there was an overall increase of 6.03 g from those pulsed once ($p \leq 0.000$), an increase of 4.07 g in those pulsed every two weeks ($p \leq 0.000$), and an increase of 5.28 g in those pulsed every four weeks ($p \leq 0.000$). Mean leaf weights of cattail pulsed once were 1.96 g less than those pulsed every two weeks ($p \leq 0.000$), and 0.75 g less than those pulsed every four weeks ($p = 0.004$). Mean leaf weights of cattail pulsed every two weeks were 1.21 g ($p \leq 0.000$) more than those pulsed every four weeks.

Next, I compared mean dried rhizome weights (Table 27). Those cattail grown in a static hydroperiod (hydro-block) weighed 9.04 g more than those pulsed once ($p \leq 0.000$), 8.25 g more than those pulsed every two weeks ($p \leq 0.000$), and 8.92 g more than those pulsed every four weeks ($p \leq 0.000$). Mean rhizome weights of cattail pulsed once weighed 0.80 g less than those pulsed every two weeks ($p = 0.007$). There was no significant difference between cattail pulsed once and those pulsed every four weeks ($p = 0.958$). Mean rhizome weights of cattail pulsed every two weeks were 0.68 g ($p = 0.028$) more than those pulsed every four weeks.

Generally, cattail accumulated more above- and below- ground biomass as the hydroperiod duration increased.

Cattail Biomass and Phosphorus

On average, all cattail responded to increasing phosphorus concentrations by increasing both above- and below-ground biomass. The Tukey's Post-Hoc pairwise

comparisons revealed that there was no difference in biomass accumulation between cattail grown in the control and those exposed to a low concentration of phosphorus. When phosphorus treatments increased from the moderate to high concentrations, cattail did not allocate more biomass to above-ground portions but did respond with greater allocations to below-ground biomass. The largest difference in cattail biomass response was between the control and the highest phosphorus concentration treatment.

I first compared mean dried leaf weights among the three phosphorus treatments and the control (Table 28). From those cattail grown in the control group, there was no difference to those grown in the low concentration treatment ($p = 0.661$). There was an increase of 1.07 g from the control to the moderate treatment ($p \leq 0.000$) and an increase of 1.60 g to the high concentration treatment ($p \leq 0.000$). From the low to the moderate concentration treatments, there was an increase of 0.83 g ($p = 0.001$), as well as an increase of 1.36 g to the high concentration treatment ($p \leq 0.000$). There was no difference between the moderate and the high concentration treatments ($p = 0.069$).

Next, I compared mean dried rhizome weights (Table 29). There was no difference between the control and the low concentration treatment ($p = 0.988$). There was an increase of 1.21 g from the control to the moderate treatment ($p \leq 0.000$) and an increase of 2.13 g to the high concentration treatment ($p \leq 0.000$). From the low concentration to the moderate concentration treatment, there was an increase of 1.13 g ($p = 0.001$) and an increase of 2.06 g to the high concentration treatment ($p \leq 0.000$). There

was increase of 0.92 g from the moderate concentration treatment to the high concentration treatment ($p = 0.001$).

Cattail Biomass Response to Hydroperiod and Phosphorus Interactions

Within this experiment, as hydroperiod duration increased, the more pronounced the differences among phosphorus treatments became in their effect on cattail biomass allocation, with the greatest number of differences within the static hydro-block. Generally, the longer the duration of hydroperiod and the greater the concentration of phosphorus, cattail responded by increasing leaf and rhizome weights.

Based on the previous results that the independent variables of phosphorus concentrations and duration of hydroperiod generally increased cattail leaf and rhizome weights, I expected that interaction of these two variables would produce similar results.

As assessed by Tukey's Post-Hoc, there were five significant differences in the interactions by those cattail grown in the static hydro-regime, one in the hydro-block pulsed every four weeks, three in the hydro-block pulsed every two weeks, and none in the hydro-block pulsed only once.

Within the static hydro-block, leaf biomass increased from the phosphorus treatment control group to the low treatment by 1.881 g ($p \leq 0.000$), 3.193 g to the moderate treatment ($p \leq 0.000$), and 4.062 g to the high concentration treatment ($p \leq 0.000$). From the low concentration treatment, there was an increase of 1.312 g to the

moderate treatment ($p = 0.018$) and a 2.181 g increase to the high concentration treatment ($p \leq 0.000$). There was no significant difference of effect on leaf biomass within this hydro-block between the moderate and high phosphorus treatments ($p = 0.261$).Within the hydro-block pulsed once, the only significant effect on leaf biomass was a decrease of 1.193 g from the low phosphorus treatment to the control (Table 30).

In the hydro-block pulsed every two weeks, there were no differences in leaf biomasses between the control and the low phosphorus treatment ($p = 0.963$), the low to the moderate treatments ($p = 0.437$), or from the moderate to the high concentration treatments ($p = 0.340$). From the control to the moderate phosphorus treatment, there was an increase of 1.367 g ($p = 0.012$), as well as an increase of 2.185 g of leaf biomass to the high phosphorus treatment ($p \leq 0.000$) (Table 31).

Tukey's post-hoc revealed there were four significant differences between treatments in the static hydro-block, three within the hydro-block pulsed every two weeks, one within the hydro-block pulsed once, and none in hydro-block pulsed every four weeks (Table 32).

In the static hydro-block, rhizome biomass increased from the control to the moderate phosphorus treatment by 3.016 g ($p \leq 0.000$) and by 5.009 g to the high phosphorus treatment ($p \leq 0.000$). Rhizome biomass within this hydro-block also increased by 3.018 g from the low to moderate treatments ($p \leq 0.000$) and by 4.285 g from the low to the high phosphorus treatments ($p \leq 0.000$). There were no differences in

rhizome weights between the control and low treatment ($p = 0.766$) or between the moderate and high treatments ($p = 0.056$).

The single significant difference between nutrient treatments in the hydro-block pulsed once was a rhizome weight increase of 1.331 g from the low to the high dose treatments ($p = 0.039$).

Within the hydro-block pulsed every two weeks, rhizome weights increased by 1.821 g from the control to the high dose treatment ($p = 0.002$), increased by 1.888 g from the low to high dose treatment ($p = 0.001$), and 1.327 g from the moderate to high level treatments ($p = 0.040$).

DISCUSSION

Typha x *glauca* in Lake Ontario Coastal Wetlands

In this study, the only significant difference in mean phosphorus concentrations was between riverine and lacustrine systems; riverine systems had higher concentrations than lacustrine systems. Many of the riverine and barrier wetlands have inflowing streams and are subject to nutrient loading from watersheds with agriculture. Barrier wetlands generally have a relatively reduced hydrologic connection to Lake Ontario, which may explain the lack of significant differences of mean phosphorus concentrations between riverine and barrier systems.

Cattail frequency could not be significantly predicted by phosphorus concentrations and croplands within a wetland's watershed. Outside of the few small

fringe wet meadows, cattail was found within every sampled quadrat. I suspect that because all Lake Ontario coastal wetlands are subjected to the same anthropogenic hydrologic regime, on average, all would contain some cattail regardless of the length of the transect sampled, and occurrence would not be influenced by these two variables.

Conversely, cattail density could be significantly predicted using these same two variables. However, the increase in cattail density was associated with a decrease in croplands. In the MLR analysis, as I assigned no watershed or croplands to lacustrine systems. MLR may have been influenced by this design, as the cattail was still present in these wetland systems. It is also possible that phosphorus inputs from non-agricultural sources, such as residential lawn fertilizers, may have influenced total phosphorus concentrations.

Much like my growth experiment, cattail in the wetlands may be responding to increased concentrations of phosphorus and limited variation in inundation by increasing biomass, especially below-ground biomass, which is the main method by which this cattail propagates. The emergent zones in Lake Ontario coastal wetlands have expanded over the years, in large part influenced by unnatural hydrologic regimes (Wilcox *et al.* 2008). This alteration of natural hydrologic variation creates conditions under which there has been increased suitable habitat for this invasive species (Frieswyk and Zedler 2007, Wilcox *et al.* 2008). If I were to examine this relationship in more detail, I would sample coastal wetlands of one of the Great Lakes that was not, or minimally, subjected to unnatural hydrologic variability and compare those results to those of this study.

My analysis also revealed that increases in the ratio of croplands to a wetland's total area, coupled with a decrease in the watershed's total length of lotic surface waters, resulted in a significant increase in mean wetland water total phosphorus concentrations. This result seems fairly obvious, because as the amount of available water to dilute phosphorus inputs decreases, concentrations would increase. However, the individual effect of croplands, but not water inputs, was a significant influence on total phosphorus concentrations. To me, this seemed like another obvious result. If there are more croplands in a watershed relative to that watershed's area, then there would be a greater number of sources for inputs into the wetlands. This conclusion is similar to those of other studies of land use and nutrient inputs into waterbodies (Johnes and Heathwaite 1997, Johnson and Rejmánková 2005).The lack of significance for the individual effect of length of watershed surface waters on phosphorus is likely because the amount of water flowing into a wetland alone would not affect phosphorus inputs. Riparian buffers and concentrations and frequency of nutrient applications could influence the amount of phosphorus transported to the terrestrial source water inputs to wetlands. Future analyses could include measurement of the extent of riparian buffers associated with croplands within a wetland's watershed by remote sensing. Quantifying nutrient inputs and frequency of application may not be feasible, unless I had unlimited time and resources, but would be of great interest.

I noticed a pattern when examining the maps I had created to determine the extent of croplands within a wetland's watershed (Appendix A). With the exception of the

wetland Mud Bay, the riverine systems were all located on the southern shore, which has a greater intensity of agricultural land use and hardened infrastructure, relative to the eastern and northeastern portions of Lake Ontario, where all the sampled lacustrine systems are located. Barrier systems were scattered between the south-central and eastern-central portions of Lake Ontario. I suggest that the open nature of the lacustrine systems allows dilution of phosphorus, as partially evidenced by the low standard deviation of mean phosphorus concentrations among sampled lacustrine systems (Table 19).

There were no significant differences in cattail frequency or density among any of the three wetland classifications, which was unexpected given the protections provided by barrier and riverine systems. On Lake Ontario, lacustrine systems are generally subjected to greater erosive forces and hydrologic variability in relation to barrier and riverine systems (Minc 1997, Lishawa *et al.* 2010). The lacustrine systems sampled in this study were all located in the northeast portion of Lake Ontario and mostly in bays that were oriented away from the prevailing easterly winds. One lacustrine wetland (Parrot Bay) was located behind a road bridge that narrowed the hydrologic connection point to Lake Ontario. The bridge crossing at Parrot Bay served as a buffer from the waves of the open water, as observed during the site visit. It is possible that the geographic orientation of Parrot Bay, coupled with the reduced level of the hydrologic stressor of wave action, decreased the erosion rates of sediments in the emergent vegetation zone, effectively increasing the available habitat for cattail. These factors may

explain the relatively greater frequency of cattail in Parrot Bay wetland relative to the other lacustrine systems.

Each Lake Ontario wetland is unique, and variability of these systems within each of the three HGM classifications would likely reduce or eliminate any possibility of producing a generalized linear model with any significant statistical power that could be applied to Lake Ontario coastal wetlands. However, the results of my analysis are consistent with previous research using similar variables and their influence on cattail invasion (Crosbie and Fraser 1999, Davis *et al.* 2000, Robertson and Saad 2011).

Growth Experiment

The cattail response of increased growth in above- and below-ground biomass to the interaction of increasing durations of hydroperiod and increasing phosphorus concentrations is consistent with other growth experiments with cattails involving nutrient additions and variable water regimes (Farmer e*t al.* 2005, Boers and Zedler 2007). This pattern of growth was especially pronounced in the constantly flooded conditions of hydro-block 1 (Figure 6). Interestingly, cattail grown within this hydro-block was greater in below-ground than above-ground biomass allocation. This result may be due to the season in which cattail for this experiment were collected. Commencing in late spring, the cattails had begun metabolizing starch reserves that were stored during the winter months to grow leaves (Sojda and Solberg 1993). By the time the cattail were collected in late May, the cattail may have used most of their starch reserves for above-ground biomass allocation. The combined effect of ideal hydrological

conditions, increased availability of a limiting nutrient, and seasonal timing of the experiment most likely led to the cattail allocating more biomass to rhizomes to store starches for the winter. In future experiments, the cattail could be collected for a similar experiment in late fall, a time when starch reserves in the rhizomes are greatest to test if they would respond similarly.

I suspect that decreasing water availability in hydro-blocks impacted the growth of the cattail, resulting in earlier weekly mean mortality as the duration between pulses of water increased (Figure 7). Constant flooding may result in anaerobic conditions, and cattails are adapted to saturated, anaerobic conditions. A growth experiment involving the parent species, *T. latifolia*, reported similar results in biomass allocation with increasing water depths (Grace 1989). With extended anoxic conditions of another experiment, the same parent species responded with increased shoot elongation (Braendle and Crawford 1987). Cronk and Fennessey (2001) hypothesized that rapid leaf and rhizome growth enables such a plant to have greater access to light, oxygen, and CO_2.

The constantly flooded conditions in the block with a static hydroperiod over the eight weeks may have created conditions under which the phosphorus bound to Fe^{+3}, the form of iron most prevalent in dewatered conditions, and then was released as the iron was reduced to Fe^{+2} which would be consistent results from similar research (Farmer *et al.* 2005, Boers and Zedler 2008). If this redox reaction in static hydrological conditions was a factor in growth and survival, a similar experiment using increasing concentrations

of iron, in addition to the independent variables used in this experiment, would aid in understanding this interaction.

Future growth studies of cattail growth could extend the duration of the experiment and vary other nutrients vital to all plant growth and function. Collection of cattail for this growth experiment was from a single Lake Ontario coastal wetland where local phenotypes possibly could have affected the results of the experiment, as Grace (1980) hypothesized in experiments with the parent species, *T. latifolia*. In the future, cattail could be collected from wetlands of varying HGM classifications within Lake Ontario across latitudinal gradients, so that several HGMs are represented. There may also be local phenotypes that respond differently in biomass allocation in such an experiment. If this experiment was to be repeated, weekly measurements of volumetric water content of the growing media and weekly measurements of leaf length could be incorporated as repeated measures in a three-way full factorial mixed-model MANOVA.

CONCLUSIONS

Lake Ontario coastal wetlands continue to be degraded through unnaturally managed hydrologic regimes, nutrient inputs, and other cultural factors that negatively influence natural processes. Anthropogenically induced stressors increase susceptibility of wetland systems to invasion by *T.* x *glauca*, which often outcompetes and displaces native species in emergent and wet meadow zones.

Within my experiment, as hydroperiod and phosphorus concentrations increased, so did cattail biomass. In addition, as hydroperiod decreased, cattail biomass also decreased and rates of mortality increased. There were similar trends in *T.* x *glauca* response to phosphorus in the sampled wetlands. In coastal wetlands of Lake Ontario, there was an increase in total phosphorus concentrations in wetland waters as land use as croplands increased in the wetland's watershed. Interestingly, cattail densities also increased as total phosphorus concentrations increased in wetland water. These responses of *T.* x *glauca* to variable hydrology and nutrient inputs may provide insight into effective methods of cattail control and wetland restoration techniques. In managed wetlands or waterbodies, control methods could include mimicking natural hydrologic regimes that favor wet meadow species and decreasing habitat availability for the cattail. While it is impossible to eliminate nutrient inputs into wetlands and waterbodies, increasing the width of vegetative buffers around in riparian and abutting upland areas could reduce transport of nutrients into these systems through reduced erosion and nutrient uptake by the vegetation in the buffers. Specific to Lake Ontario, it may be beneficial for coastal wetland watershed stewards and all stakeholders to create and implement water-level regimes that mimic natural variations that may reverse or slow the expansion of this invasive species.

Landowners, soil and water conservation districts, scientists, and the agricultural industry could use the results of this study to aid in making informed decisions regarding nutrient applications and their effects on the spread of the cattail. The negative effects on

functions, services, and floral diversity in Lake Ontario coastal wetlands invaded by *T.* x *glauca* may not be completely reversible, but the effects of invasion may be curtailed if stakeholders can agree on sustainable lake-level management plans and agricultural fertilizer regulations that include controls on the timing, concentrations, and rates of application.

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TABLES

Table 1. Sampled Lake Ontario coastal wetland name, hydrogeomorphic classification, decimal degree location, and year sampled.

Wetland Name	HGM Classification	Location	Year Sampled
Long Carry Marsh	Lacustrine	44.0513, -76.2730	2011
Isthmus Marsh South	Lacustrine	44.0179, -76.2853	2011
Chaumont River Mouth	Lacustrine	44.0667, -76.1508	2012
Sand Bay	Lacustrine	44.1501, -76.5027	2011
Parrot Bay	Lacustrine	44.2206, -76.6910	2011
Adolphus Reach	Lacustrine	44.1030, -76.9287	2012
East Creek	Riverine	43.3381, -77.7961	2011
Mud Bay	Riverine	44.0788, -76.3159	2012
Golden Hill	Riverine	43.3708, -78.4755	2012
Little Pond	Riverine	43.2645, -77.6357	2012
Red Creek	Riverine	43.3028, -76.7853	2011
Eight Mile Creek	Riverine	43.4116, -76.6209	2011
Maxwell Bay	Barrier	43.2686, -77.0258	2011
Payne Beach	Barrier	43.3265, -77.7325	2011
South Pond	Barrier	43.5797, -76.1923	2011
South Colwell	Barrier	43.7001, -76.1932	2012
Long Pond	Barrier	43.2891, -77.6952	2011
North Pond	Barrier	43.6556, -76.1882	2012

Table 2. Wetland and area (ha), wetland watershed characteristics, mean site total phosphorus (mg/L), number of quadrats in which *Typha* x *glauca* occurred (frequency), and mean quadrat percent cover of *Typha* x *glauca* (density).

Wetland Name	Wetland Area (ha)	Total Watershed Area (ha)	Cropland Area in Watershed (ha)	Watershed Percent Cropland	Length Surface Waters in Watershed (km)	Mean Total Phosphorus (mg/L)	Number of Quadrats with *Typha* x *glauca*	Mean Percent Cover *Typha* x *glauca*/Quad
Long Carry Marsh	7.69	0.00	0.00	0.00	0.00	0.0940	15	43.13
Isthmus Marsh South	6.45	0.00	0.00	0.00	0.00	0.0335	19	23.89
Chaumont River Mouth	11.32	0.00	0.00	0.00	0.00	0.0376	12	30.17
Sand Bay	9.80	0.00	0.00	0.00	0.00	0.0160	1	6.00
Parrot Bay	31.43	0.00	0.00	0.00	0.00	0.0420	25	30.20
Adolphus Reach	20.32	0.00	0.00	0.00	0.00	0.0148	0	0.00
East Creek	14.19	863.05	476.81	55.25	14.48	0.2140	23	28.87
Mud Bay	113.57	5897.91	927.80	15.73	99.60	0.2008	9	35.00
Golden Hill	2.98	5505.87	2029.37	36.86	90.99	0.1731	0	0.00
Little Pond	16.30	1422.69	0.00	0.00	12.21	0.0847	5	48.00
Red Creek	154.34	6842.57	1300.75	19.01	85.02	0.0540	21	23.67
Eight Mile Creek	6.31	2637.55	207.62	7.87	22.87	0.0860	1	8.00
Maxwell Bay	19.24	11829.32	2038.90	17.24	136.84	0.2010	8	18.50
Payne Beach	76.95	442.69	110.37	24.93	5.76	0.1150	0	0.00
South Pond	143.61	7209.06	840.55	11.66	99.03	0.0530	0	0.00
South Colwell	85.36	26177.46	1951.39	7.45	435.61	0.0724	7	10.71
Long Pond	233.90	6400.33	1123.19	17.55	78.58	0.1220	25	29.60
North Pond	1020.78	21720.19	1678.31	7.73	311.82	0.0230	1	15.00

Table 3. Macronutrients and concentrations of modified Hoagland's solution used in eight week *Typha* x *glauca* greenhouse growth experiment.

Macronutrients			Control		T1 (low)		T2 (moderate)		T3 (high)	
Form	$g.L^{-1}$	Stock	ml $stock.L^{-1}$	µM	ml $stock.L^{-1}$	µM	ml $stock.L^{-1}$	µM	ml $stock.L^{-1}$	µM
KH_2PO_4	136.09	1M	0	0	0.50	500	2.00	2000	6.00	6000
KNO_3	101.11	1M	5.10	5100	5.10	5100	5.10	5100	5.10	5100
$Ca(NO_3)_2$ * 4H2O	236.15	1M	2.02	2020	2.02	2020	2.02	2020	2.02	2020
$MgSO_4$ * $7H_2O$	246.48	1M	1.00	1000	1.00	1000	1.00	1000	1.00	1000

Table 4. Micronutrients and concentrations of modified Hoagland's solutions used in eight week *Typha* x *glauca greenhouse* growth experiment.

Micronutrients				Final Concentration
Form	$g.L^{-1}$	Stock solution	ml $stock.L^{-1}$ of DI water	(µM)
$MnCl_2$•$4H_2O$	1.979	0.010M	0.406	4.06
$ZnSO_4$ * $7H_2O$	0.288	0.001M	0.618	6.18
$CuSO_4$ * $5H_2O$	0.250	0.001M	0.420	4.20
$(NH_4)_6Mo_7O_{24}$ *$4H_2O$	1.236	0.001M	0.278	2.78
H_3BO_3	0.618	0.010M	1.936	19.36
NaFe-DTPA (10% Fe)	33.240	0.071M	1.000	71.00

Table 5. Monthly mean maximum and minimum temperatures (°C) and relative percent humidity inside greenhouse during eight week *Typha* x *glauca* growth experiment.

Month	Mean maximum temperature (°C)	Mean minimum temperature (°C)	Mean maximum relative humidity (%)	Mean minimum relative humidity (%)
June	32.02	16.70	98.20	78.93
July	35.04	19.50	99.03	76.32

Table 6. Multiple linear regression ANOVA model for predicting the number of quadrats in which *Typha* x *glauca* occurred (frequency) from site mean total phosphorus (mg/L) and percentage of the wetland watershed that is cropland.

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	7.753	2	3.876	1.150	0.345
Residual	47.182	14	3.370		
Total	54.935	16			

Table 7. Multiple linear regression ANOVA model predicting the quadrat mean percent cover (density) of *Typha* x *glauca* from site mean total phosphorus (mg/L) and ratio of total wetland watershed area to cropland area (ha).

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	1656.627	2	828.314	5.154	0.021
Residual	2249.819	14	160.701		
Total	3906.446	16			

Table 8. Summary of multiple regression analysis predicting the quadrat mean percent cover (density) of *Typha* x *glauca* from site mean total phosphorus (mg/L) and percentage of the wetland watershed that is cropland.

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	SE_B	β		
(Constant)	15.826	5.332		2.968	0.010
Watershed percent croplands	-1.248	0.396	-0.867	-3.150	0.007
Total Phosphorus (mg/L)	182.742	70.607	0.712	2.588	0.021

Table 9. Multiple linear regression ANOVA model predicting site average total phosphorus (mg/L) from the percent of watershed that is cropland and total length of lotic surface waters in a wetland's watershed (km).

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	0.042	2	0.021	9.645	0.002
Residual	0.033	15	0.002		
Total	0.075	17			

Table 10. Summary of multiple linear regression predicting site mean total phosphorus (mg/L) from the percent of watershed that is cropland and total length of lotic surface waters in a wetland's watershed (km).

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	SE_B	β		
(Constant)	0.043	0.018		2.451	0.027
Watershed percent croplands	0.022	0.005	0.814	4.192	0.001
Watershed total length lotic waters	-0.002	0.002	-0.163	-0.841	0.414

Table 11. Multiple linear regression model summary for predicting site mean total phosphorus (mg/L) from the percent of watershed that is cropland and total length of lotic surface waters in a wetland's watershed (km).

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	0.750[a]	0.563	0.504	0.0468952	2.037

Table 12. Simple linear ANOVA predicting site mean total phosphorus (mg/L) from watershed percent croplands.

Model	Sum of Squares	df	Mean Square	F	Sig.
Regression	0.042	1	0.042	20.493	0.000
Residual	0.033	16	0.002		
Total	0.075	17			

Table 13. Simple linear regression coefficients predicting site mean total phosphorus (mg/L) from the percent of watershed that is cropland.

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	SE_B	β		
(Constant)	0.050	0.014		3.578	0.003
Watershed percent croplands	0.003	0.001	0.749	4.527	0.000

Table 14. Model summary of simple linear regression predicting site mean total phosphorus (mg/L) from watershed percent croplands.

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.749	0.562	0.534	0.0455

Table 15. Descriptive statistics of one-way ANOVA of wetland HGM classification versus the frequency of *Typha* x *glauca* occurrence in sampled Lake Ontario coastal wetlands with the outlier dataset of Long Pond wetland included in analysis.

HGM Classification	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	80.778	2	40.389	0.418	0.665
Within Groups	1447.667	15	96.511		
Total	1528.444	17			

Table 16. Descriptive statistics of one-way ANOVA of wetland HGM classification versus the density of *Typha* x *glauca* occurrence in sampled Lake Ontario coastal wetlands with the outlier Long Pond wetland removed from analysis.

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	224.249	2	112.125	1.493	0.258
Within Groups	1051.633	14	75.117		
Total	1275.882	16			

Table 17. One-way ANOVA of wetland HGM classification versus the density of *Typha* x *glauca* occurrence in sampled Lake Ontario coastal wetlands.

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	473.060	2	236.530	1.006	0.389
Within Groups	3526.635	15	235.109		
Total	3999.694	17			

Table 18. ANOVA of mean wetland waters total phosphorus concentrations (mg/L) as a predictor of wetland HGM classification Lake Ontario wetlands.

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	0.028	2	0.014	4.414	0.031
Within Groups	0.047	15	0.003		
Total	0.075	17			

Table 19. ANOVA Games-Howell post-hoc of mean wetland waters total phosphorus concentrations (mg/L) as a predictor of HGM classification of sampled Lake Ontario coastal wetlands.

(I) HGM Classification	(J) HGM Classification	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Lacustrine	Riverine	-0.0957833*	0.0303818	0.040	-0.186165	-0.005402
	Barrier	-0.0580833	0.0282591	0.169	-0.141244	0.025077
Riverine	Lacustrine	0.0957833*	0.0303818	0.040	0.005402	0.186165
	Barrier	0.0377000	0.0379878	0.598	-0.066563	0.141963

Table 20. Discriminant Analysis Wilks' Lambda using hydroperiod as the grouping function for effects on the combined dependent variables, dried rhizome weight (g) and dried leaf weight (g), after eight week greenhouse growth experiment on *Typha* x *glauca*.

Test of Function(s)	Wilks' Lambda	Chi-square	df	Sig.
1 (hydroperiod) through 2	0.04	197.649	6	0.000
2 (dried leaf weight)	0.44	49.803	2	0.000

Table 21. Discriminant Analysis Wilks' Lambda using nutrient treatment as the grouping function for effects on the combined dependent variables, dried rhizome weight (g) and dried leaf weight (g), after eight week greenhouse growth experiment on *Typha* x *glauca*.

Test of Function(s)	Wilks' Lambda	Chi-square	df	Sig.
1 (hydroperiod) through 2	0.919	5.071	6	0.535
2 (dried leaf weight)	0.990	0.581	2	0.748

Table 22. Discriminant Analysis standardized canonical discriminant function coefficients using hydroperiod as the grouping function for effects on the combined dependent variables, dried rhizome weight (g) and dried leaf weight (g), after eight week greenhouse growth experiment on *Typha* x *glauca*.

	Function	
	1	2
Dried Rhizomes (g)	1.942	-1.560
Dried Leaf (g)	-1.153	2.209

Table 23. Discriminant Analysis eigenvalues using hydroperiod as the grouping function for effects on the combined dependent variables, dried rhizome weight (g) and dried leaf weight (g), after eight week greenhouse growth experiment on *Typha* x *glauca*.

Function	Eigenvalue	% of Variance	Cumulative %	Canonical Correlation
1 (hydroperiod)	10.753[a]	89.3	89.3	0.96
2 (dried leaf weight)	1.293[a]	10.7	100.0	0.75

a. First 2 canonical discriminant functions were used in the analysis.

Table 24. Pearson's correlations between dried rhizome (g) and dried root (g) weights of *Typha* x *glauca* after eight week greenhouse experiment.

		Dried rhizome weights (g)	Dried root weights (g)
Dried rhizome weights (g)	Pearson Correlation	1	0.933**
	Sig. (2-tailed)		0.000
	N	64	64
Dried root weights (g)	Pearson Correlation	0.933**	1
	Sig. (2-tailed)	0.000	
	N	64	64

** Correlation is significant at the 0.01 level (2-tailed).

Table 25. MANOVA of between-subjects simple main effects of hydroperiod, nutrient treatments, and their interaction on dried leaf weights (g) and dried rhizome weights (g) for eight week greenhouse experiment on *Typha* x *glauca*

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	Dried Leaf Weight (g)	399.255[a]	15	26.617	75.710	0.000	0.959
	Dried Rhizome Weight (g)	1006.522[b]	15	67.101	153.657	0.000	0.980
Intercept	Dried Leaf Weight (g)	1811.660	1	1811.660	5153.124	0.000	0.991
	Dried Rhizome Weight (g)	3654.626	1	3654.626	8368.777	0.000	0.994
Hydroperiod	Dried Leaf Weight (g)	346.808	3	115.603	328.823	0.000	0.954
	Dried Rhizome Weight (g)	921.856	3	307.285	703.657	0.000	0.978
Nutrient Treatment	Dried Leaf Weight (g)	26.209	3	8.736	24.850	0.000	0.608
	Dried Rhizome Weight (g)	49.445	3	16.482	37.742	0.000	0.702
Hydroperiod * Nutrient Treatment	Dried Leaf Weight (g)	26.238	9	2.915	8.292	0.000	0.609
	Dried Rhizome Weight (g)	35.221	9	3.913	8.962	0.000	0.627
Error	Dried Leaf Weight (g)	16.875	48	0.352			
	Dried Rhizome Weight (g)	20.961	48	0.437			
Total	Dried Leaf Weight (g)	2227.790	64				
	Dried Rhizome Weight (g)	4682.110	64				
Corrected Total	Dried Leaf Weight (g)	416.130	63				
	Dried Rhizome Weight (g)	1027.484	63				

a. $R^2 = 0.959$ (Adjusted $R^2 = 0.947$)
b. $R^2 = 0.980$ (Adjusted $R^2 = 0.973$)

Table 26. MANOVA Tukey's HSD post-hoc multiple comparisons between hydro-blocks for mean dried leaf weights (g) after eight week *Typha* x *glauca* growth experiment. The mean dried leaf weights (g) associated with each of the four hydro-blocks are located in the first two columns. Columns (I) and (J) represent the mean dried leaf weights (g) between the two hydro-blocks that are being compared. Column (I-J) represents the mean difference in dried leaf weights (g) between hydro-blocks.

Hydro-block and Associated Mean Dried Leaf Weights (g)		Comparing Mean Dried Leaf Weights (g) Between Hydro-blocks		(I-J) Mean difference between dried leaf weights (g) of hydro-blocks	Std. Error	Sig.	95% Confidence Interval	
Hydro-block	Mean Dried Leaf Weights (g)	(I)	(J)				Lower Bound	Upper Bound
Hydro-block 1 - Static	9.166	Hydro-block 1	Hydro-block 2	6.032*	0.209	0.000	-6.590	-5.474
Hydro-block 2 - Pulsed Once	3.134		Hydro-block 3	4.071*	0.209	0.000	-4.629	-3.513
Hydro-block 3 - Pulsed Every Two Weeks	5.095		Hydro-block 4	5.279*	0.209	0.000	-5.837	-4.721
Hydro-block 4 - Pulsed Every Four Weeks	3.887	Hydro-block 2	Hydro-block 3	-1.961*	0.209	0.000	1.403	2.519
			Hydro-block 4	-0.753*	0.209	0.004	0.195	1.311
		Hydro-block 3	Hydro-block 4	1.208*	0.209	0.000	-1.766	-0.650

* The mean difference is significant at the 0.05 level.

Table 27. MANOVA Tukey's HSD post-hoc of multiple comparisons between hydro-blocks for mean dried rhizome weights (g) after eight week *Typha* x *glauca* growth experiment. The mean dried rhizome weights (g) associated with each of the four hydro-blocks are located in the first two columns. Columns (I) and (J) represent the mean dried rhizome weights (g) between the two hydro-blocks that are being compared. Column (I-J) represents the mean difference in dried rhizome weights (g) between hydro-blocks.

Hydro-block and Associated Dried Rhizome Weights (g)		Comparing Mean Dried Rhizome Weights (g) Between Hydro-blocks		(I-J) Mean Difference Between Dried Rhizome Weights of Hydro-Blocks (g)	Std. Error	Sig.	95% Confidence Interval	
Hydro-block	Mean Dried Rhizome Weight (g)	(I)	(J)				Lower Bound	Upper Bound
Hydro-block 1 - Static	14.109	Hydro-block 1	Hydro-block 2	9.041*	0.234	0.000	-9.663	-8.419
Hydro-block 2 - Pulsed Once	5.068		Hydro-block 3	8.245*	0.234	0.000	-8.867	-7.623
Hydro-block 3 - Pulsed Every Two Weeks	5.864		Hydro-block 4	8.924*	0.234	0.000	-9.545	-8.302
Hydro-block 4 - Pulsed Every Four Weeks	5.186	Hydro-block 2	Hydro-block 3	-0.796*	0.234	0.007	0.174	1.418
			Hydro-block 4	-0.118	0.234	0.958	-0.739	0.504
		Hydro-block 3	Hydro-block 4	0.678*	0.234	0.028	-1.300	-0.057

* The mean difference is significant at the 0.05 level.

Table 28. MANOVA Tukey's HSD post-hoc of multiple comparisons between the control (C), low (T1), moderate (T2), and high (T3) phosphorus treatments for effects on mean dried leaf weights (g) after eight week *Typha* x *glauca* growth experiment. The mean dried leaf weights (g) associated with each of the three phosphorus treatments and the control are located in the first two columns. Columns (I) and (J) represent the mean dried leaf weights between the two treatments that are being compared. Column (I-J) represents the mean difference in dried leaf weights (g) between treatments.

Phosphorus Treatment and Associated Mean Dried Leaf Weights (g)		Comparing Mean Dried Leaf Weights (g) Between Phosphorus Treatments		(I-J) Mean Difference Between Dried Leaf Weights of Phosphorus Treatments (g)	Std. Error	Sig.	95% Confidence Interval	
Phosphorus Treatment	Mean Dried Leaf Weight (g)	(I)	(J)				Lower Bound	Upper Bound
C - Control	4.594	C	T1	-0.241	0.210	0.661	-0.317	0.799
T1 - Low	4.835		T2	-1.068*	0.210	0.000	0.510	1.626
T2 - Moderate	5.662		T3	-1.597*	0.210	0.000	1.039	2.155
T3 - High	6.191	T1	T2	-0.827*	0.210	0.001	0.269	1.385
			T3	-1.356*	0.210	0.000	0.798	1.914
		T2	T3	-0.530	0.210	0.069	-0.028	1.087

* The mean difference is significant at the 0.05 level.

Table 29. MANOVA Tukey's HSD post-hoc of multiple comparisons between the control (C), low (T1), moderate (T2), and high phosphorus treatments (T3) for effects on mean dried rhizome weights (g) after eight week *Typha* x *glauca* growth experiment. The mean dried rhizome weights (g) associated with each of the three phosphorus treatments and the control are located in the first two columns. Columns (I) and (J) represent the mean dried rhizome weights of the two treatments that are being compared. Column (I-J) represents the mean difference in dried rhizome weights (g) between treatments.

Phosphorus Treatment and Associated Mean Dried Rhizome Weights (g)		Comparing Mean Dried Rhizome Weights (g) Between Phosphorus Treatments		(I-J) Mean Difference Between Dried Rhizome Weights of Phosphorus Treatments (g)	Std. Error	Sig.	95% Confidence Interval	
Phosphorus Treatment	Mean Dried Rhizome Weight (g)	(I)	(J)				Lower Bound	Upper Bound
C - Control	6.703	C	T1	-0.076	0.234	0.988	-0.546	0.698
T1 - Low	6.779		T2	-1.207*	0.234	0.000	0.586	1.829
T2 - Moderate	7.910		T3	-2.131*	0.234	0.000	1.509	2.753
T3 - High	8.834	T1	T2	-1.131*	0.234	0.000	0.509	1.753
			T3	-2.055*	0.234	0.000	1.433	2.677
		T2	T3	-0.9237*	0.234	0.001	0.302	1.546

* The mean difference is significant at the 0.05 level.

Table 30. MANOVA Tukey's HSD post-hoc multiple comparisons of the interaction effects within hydro-blocks among the control (C), low (T1), moderate (T2), and high (T3) phosphorus concentration treatments on dried leaf weights (g), after eight week *Typha* x *glauca* growth experiment. The mean dried leaf weights (g) associated with each of the three phosphorus treatments and the control within each of the four hydro-blocks are located in the first two columns. Columns (I) and (J) represent the mean dried leaf weights of the treatments that are being compared within each hydro-block. Column (I-J) represents the mean difference of dried leaf weights (g) between the treatments.

Within Hydro-block, Between Phosphorus Treatments, and Associated Mean Dried Leaf Weight (g)		Comparing Mean Dried Leaf Weight (g) Within Hydro-block, Between Treatments		(I-J) Mean Difference Between Dried Leaf Weights (g)	Std. Error	Sig.	95% Confidence Interval	
Hydro-block	Phosphorus Treatments and Mean Dried Leaf Weight (g)	(I)	(J)				Lower	Upper
Hydro-block 1 – Static	C (6.882 g) T1 (8.763 g) T2 (10.075 g) T3 (10.944 g)	C	T1	-1.881*	0.419	0.000	0.727	3.035
			T2	-3.193*	0.419	0.000	2.039	4.347
			T3	-4.062*	0.419	0.000	2.909	5.216
		T1	T2	-1.312*	0.419	0.018	0.158	2.466
			T3	-2.181*	0.419	0.000	1.028	3.335
		T2	T3	-0.869	0.419	0.261	-0.285	2.023
Hydro-block 2 - Pulsed Once	C (3.578 g) T1 (2.385 g) T2 (3.197 g) T3 (3.374 g)	C	T1	1.193*	0.419	0.039	-2.347	-0.039
			T2	0.381	0.419	1.000	-0.773	1.535
			T3	0.204	0.419	1.000	-0.950	1.358
		T1	T2	-0.812	0.419	0.351	-0.341	1.966
			T3	-0.989	0.419	0.134	-0.164	2.143
		T2	T3	-0.177	0.419	1.000	-0.977	1.331
Hydro-block 3 - Pulsed Every Two Weeks	C (4.048 g) T1 (4.655 g) T2 (5.424 g) T3 (6.243 g)	C	T1	0.598	0.419	0.963	-0.556	1.751
			T2	-1.367*	0.419	0.012	0.213	2.521
			T3	-2.185*	0.419	0.000	1.032	3.339
		T1	T2	-0.769	0.419	0.437	-0.385	1.923
			T3	-1.588*	0.419	0.003	0.434	2.742
		T2	T3	0.819	0.419	0.340	-0.335	1.973

Within Hydro-block, Between Phosphorus Treatments, and Associated Mean Dried Leaf Weight (g)		Comparing Mean Dried Leaf Weight (g) Within Hydro-block, Between Treatments		(I-J) Mean Difference Between Dried Leaf Weights (g)	Std. Error	Sig.	95% Confidence Interval	
Hydro-block	Phosphorus Treatments and Mean Dried Leaf Weight (g)	(I)	(J)				Lower	Upper
Hydro-block 4 - Pulsed Every Four Weeks	C (3.858 g) T1 (3.537 g) T2 (3.950 g) T3 (4.203 g)	C	T1	0.321	0.419	1.000	-0.833	1.475
			T2	-0.092	0.419	1.000	-1.062	1.246
			T3	-0.345	0.419	1.000	-0.809	1.499
		T1	T2	-0.413	0.419	1.000	-0.741	1.567
			T3	-0.666	0.419	0.713	-0.488	1.820
		T2	T3	-0.253	0.419	1.000	-0.901	1.407

* The mean difference is significant at the 0.05 level. Based on estimated marginal means.

Table 32. MANOVA Tukey's HSD post-hoc multiple comparisons of the interaction effects within hydro-blocks between the control (C), low (T1), moderate (T2), and high (T3) phosphorus concentration treatments on dried rhizome weights (g), after eight week *Typha* x *glauca* growth experiment. The mean dried rhizome weights (g) associated with each of the three phosphorus treatments and the control within each of the four hydro-blocks are located in the first two columns. Columns (I) and (J) represent the mean dried rhizome weights of the treatments that are being compared within each hydro-block. Column (I-J) represents the mean difference of dried rhizome weights (g) between the treatments.

Within Hydro-block, Between Phosphorus Treatments, and Associated Mean Dried Rhizome Weight (g)		Comparing Mean Dried Rhizome Weight (g) Within Hydro-block, Between Treatments		(I-J) Mean Difference Between Dried Rhizome Weights (g)	Std. Error	Sig.	95% Confidence Interval	
Hydro-block	Phosphorus Treatment and Rhizome Weight (g)	(I)	(J)				Lower	Upper
Hydro-block 1 - Static	C (11.740 g) T1 (12.464 g) T2 (15.483 g) T3 (16.749 g)	C	T1	-0.724	0.467	0.766	-0.562	2.010
			T2	-3.018*	0.467	0.000	1.732	4.304
			T3	-5.009*	0.467	0.000	3.723	6.295
		T1	T2	-3.018*	0.467	0.000	1.732	4.304
			T3	-4.285*	0.467	0.000	2.999	5.571
		T2	T3	-1.267	0.467	0.056	-0.019	2.553
Hydro-block 2 - Pulsed Once	C (4.966 g) T1 (4.281 g) T2 (5.412 g) T3 (5.613 g)	C	T1	0.685	0.467	0.895	-0.601	1.971
			T2	-0.446	0.467	1.000	-0.840	1.731
			T3	-0.646	0.467	1.000	-0.640	1.932
		T1	T2	-1.130	0.467	0.116	-0.155	2.416
			T3	-1.331*	0.467	0.039	0.045	2.617
		T2	T3	0.201	0.467	1.000	-1.085	1.487
Hydro-block 3 - Pulsed Every Two Weeks	C (5.302 g) T1 (5.235 g) T2 (5.796 g) T3 (7.123 g)	C	T1	-0.066	0.467	1.000	-1.219	1.352
			T2	-0.495	0.467	1.000	-0.791	1.780
			T3	-1.821*	0.467	0.002	0.535	3.107
		T1	T2	-0.561	0.467	1.000	-0.725	1.847
			T3	-1.888*	0.467	0.001	0.602	3.174
		T2	T3	-1.327*	0.467	0.040	0.041	2.613

Within Hydro-block, Between Phosphorus Treatments, and Associated Mean Dried Rhizome Weight (g)		Comparing Mean Dried Rhizome Weight (g) Within Hydro-block, Between Treatments		(I-J) Mean Difference Between Dried Rhizome Weights (g)	Std. Error	Sig.	95% Confidence Interval	
Hydro-block	Phosphorus Treatment and Rhizome Weight (g)	(I)	(J)				Lower	Upper
Hydro-block 4 - Pulsed Every Four Weeks	C (4.804 g) T1 (5.136 g) T2 (4.951 g) T3 (5.852 g)	C	T1	-0.331	0.467	1.000	-0.955	1.617
			T2	-0.147	0.467	1.000	-1.139	1.433
			T3	-1.048	0.467	0.178	-0.238	2.334
		T1	T2	0.185	0.467	1.000	-1.101	1.471
			T3	0.716	0.467	0.791	-0.570	2.002
		T2	T3	-0.901	0.467	0.359	-0.385	2.187

* The mean difference is significant at the 0.05 level. Based on estimated marginal mean.

FIGURES

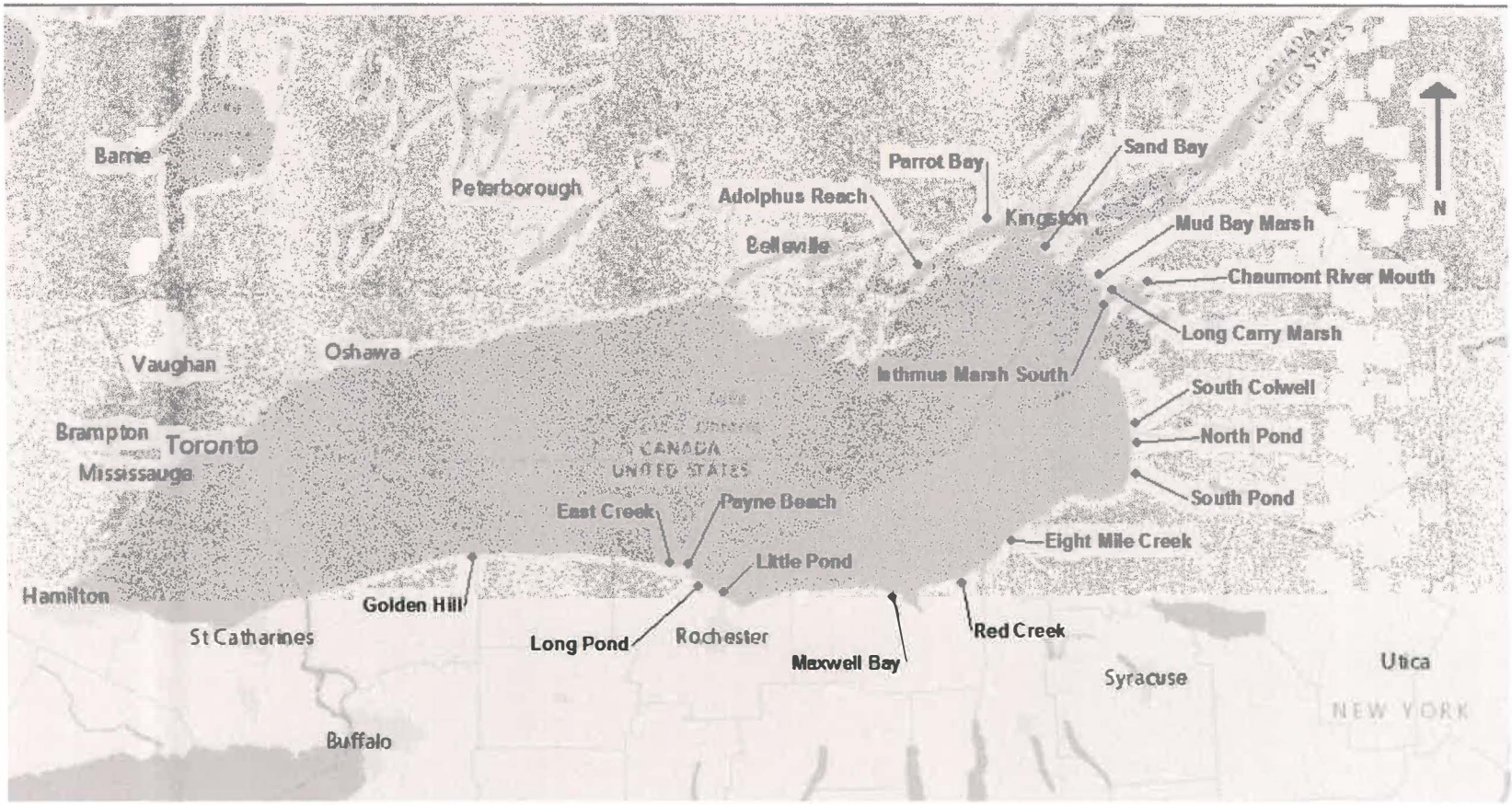


Figure 1. Name and general location of Lake Ontario coastal wetlands sampled in 2011 and 2012 and used in my analyses.

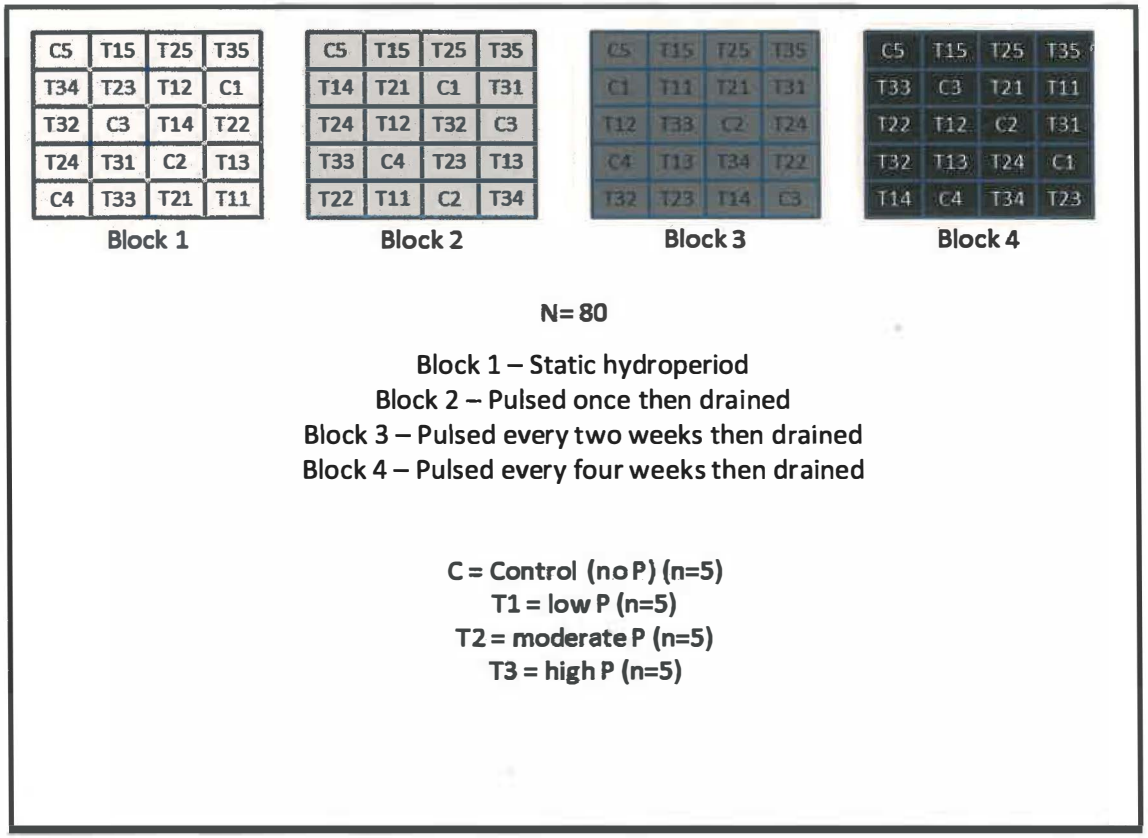


Figure 2. Random block design of eight week greenhouse experiment on *Typha* x *glauca* with varying phosphorus and hydroperiods.

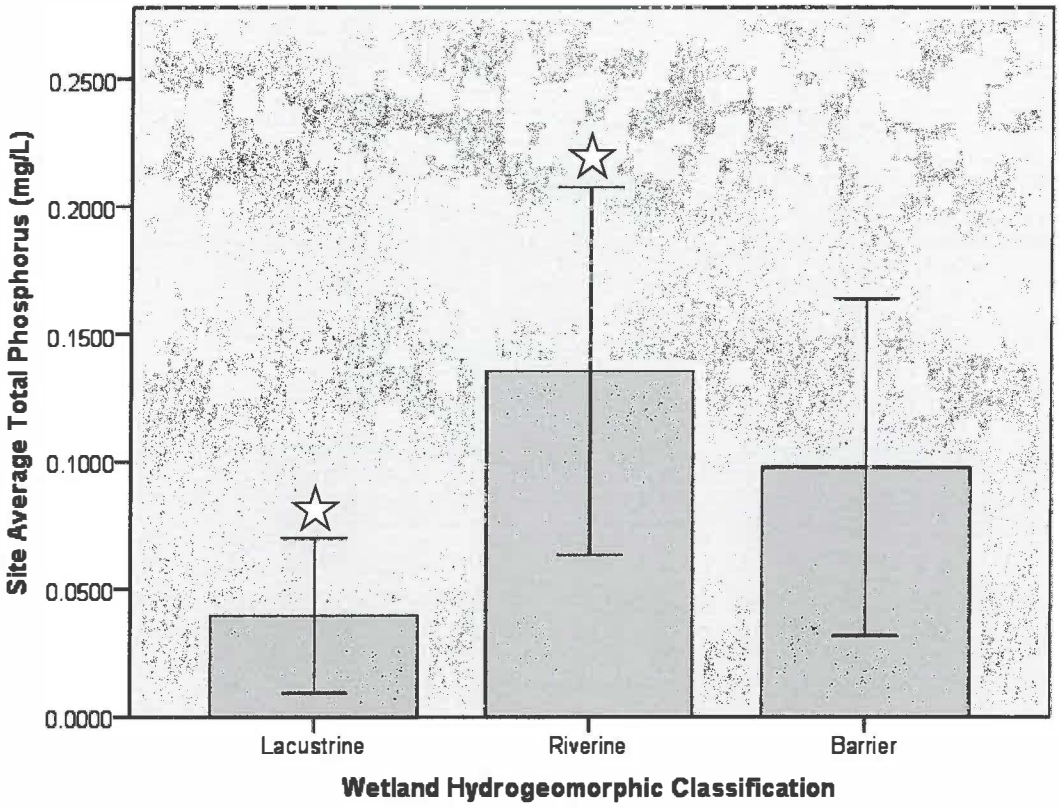


Figure 3. Boxplots of the one-way ANOVA of wetland HGM classification versus the wetland site mean total phosphorus concentration (mg/L). Stars represent the significant increase of total phosphorus concentrations (mg/L) from lacustrine to riverine wetlands ($p = 0.040$). Error bars represent 1 standard error.

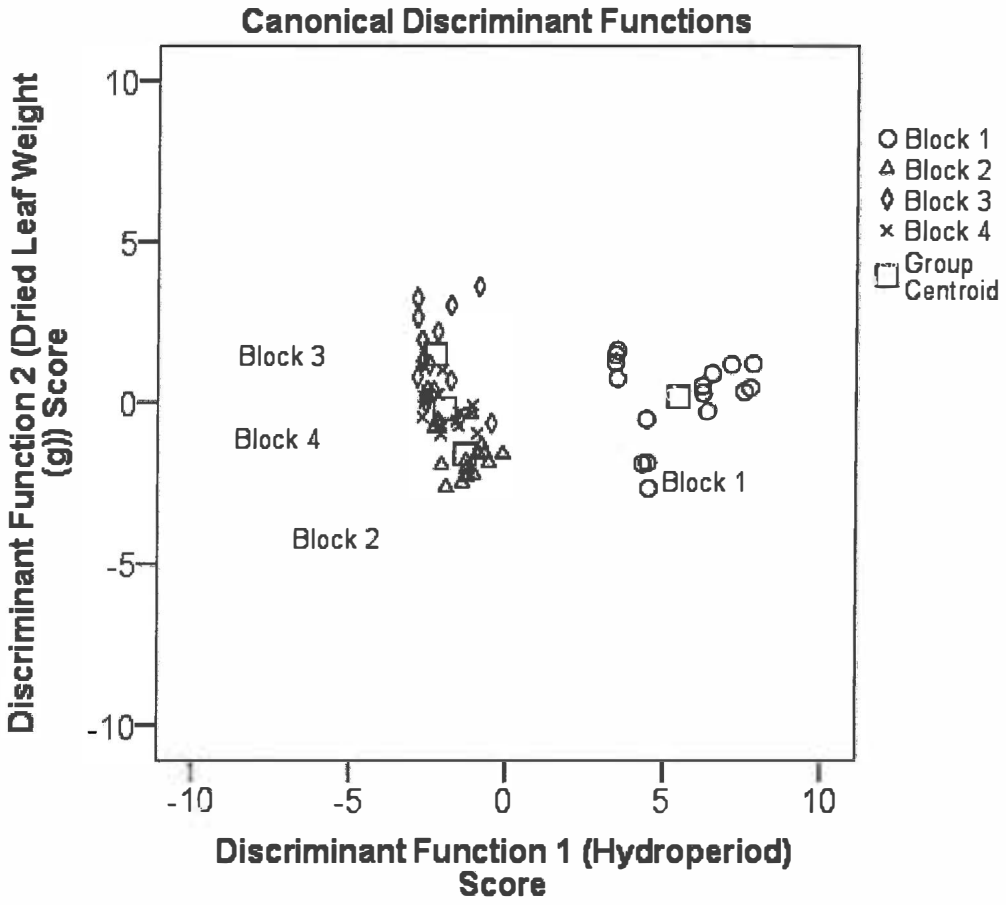


Figure 4. Discriminant functional analysis canonical discriminant function combined group plot of dried leaf weights (g) and dried rhizome weights (g) of *Typha* x *glauca* as functions of hydroperiod in *Typha* x *glauca* eight week greenhouse growth experiment. Hydroperiods consisted of hydro-block one (static), hydro-block two (pulsed once), hydro-block three (pulsed every two weeks), and hydro-block four (pulsed every four weeks).

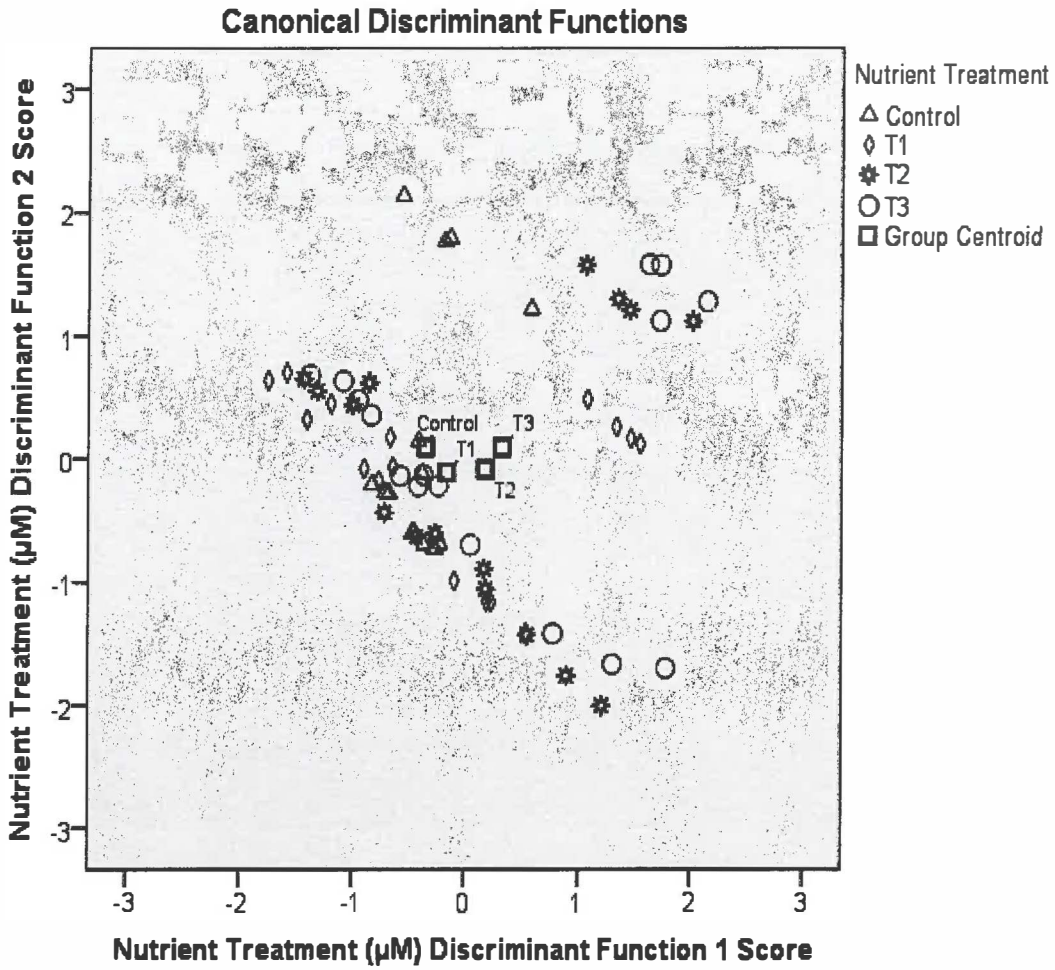


Figure 5. Discriminant analysis canonical discriminant function combined group plot of dried leaf weights and dried rhizome weights of *Typha* x *glauca* as functions of nutrient treatments in eight week greenhouse growth experiment. Treatments consisted of a control with no phosphorus additions, treatment one (T1) with low phosphorus concentrations (500 µM), treatment two (T2) with moderate phosphorus concentrations (2000 µM), and treatment three (T3) with high phosphorus concentrations (6000 µM).

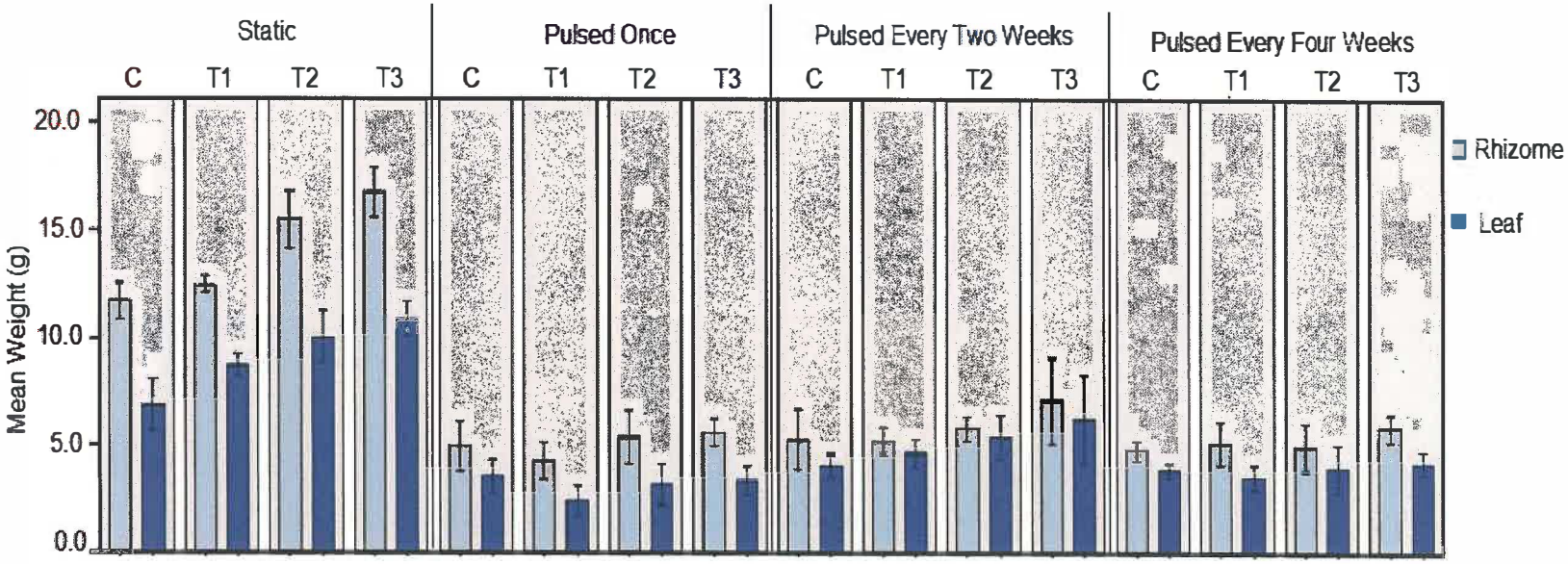


Figure 6. Means and 95% confidence intervals (error bars) of, dried rhizome weights (g) and dried leaf weights (g) withi hydro-blocks, between nutrient treatments in *Typha* x *glauca* eight week greenhouse growth experiment. The hydroperiod of block one was static, block two was pulsed once, block three pulsed every two weeks, and block four pulsed every four weeks. Treatments consisted of a control with no phosphorus additions, treatment one (T1) with low phosphorus concentrations (500 µM), treatment two (T2) with moderate phosphorus concentrations (2000 µM), and treatment three (T3) with high phosphorus concentrations (6000 µM).

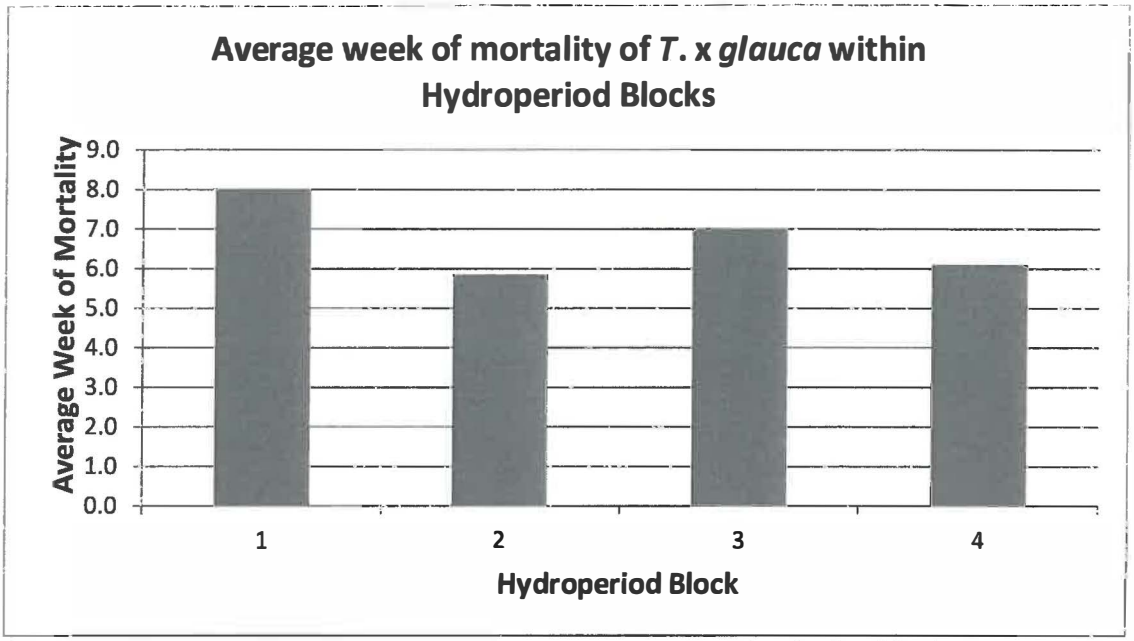


Figure 7. Average week of *Typha* x *glauca* mortality of within hydro-blocks in eight week greenhouse growth experiment. Hydroperiods consisted of hydro-block one (static), hydro-block two (pulsed once), hydro-block three (pulsed every two weeks), and hydro-block four (pulsed every four weeks).

APPENDIX A

Wetlands, watersheds, and associated cropland maps

Adolphus Reach

HGM Classification - Lacustrine

0 0.25 0.5 0.75 1 Kilometers

1 centimeter=0.16 kilometers

Wetland Centroid: 44.102991° N, -76.928672° W

Coordinate System: GCS WGS 1984

Legend

Sampled Wetland Area

Author: Aaron W Heminway

Chaumont River Mouth

HGM Classification - Lacustrine

0 0.25 0.5 0.75 1 Kilometers

1 centimeter = 0.178 kilometers

Wetland Centroind: 44.066762° N, -76.150780° W

Coordinate System: WGS 1984 Web Mercator Auxiliary Sphere

Legend

Sampled Wetland Area

Author: Aaron W. Heminway

East Creek

HGM Classification - Riverine

0 0.75 1.5 2.25 3 Kilometers

1 centimeter = 1 kilometers

Wetland Centroid: 43.338660°, -77.799685°

Coordinate System: WGS 1984 Web Mercator Auxiliary Sphere

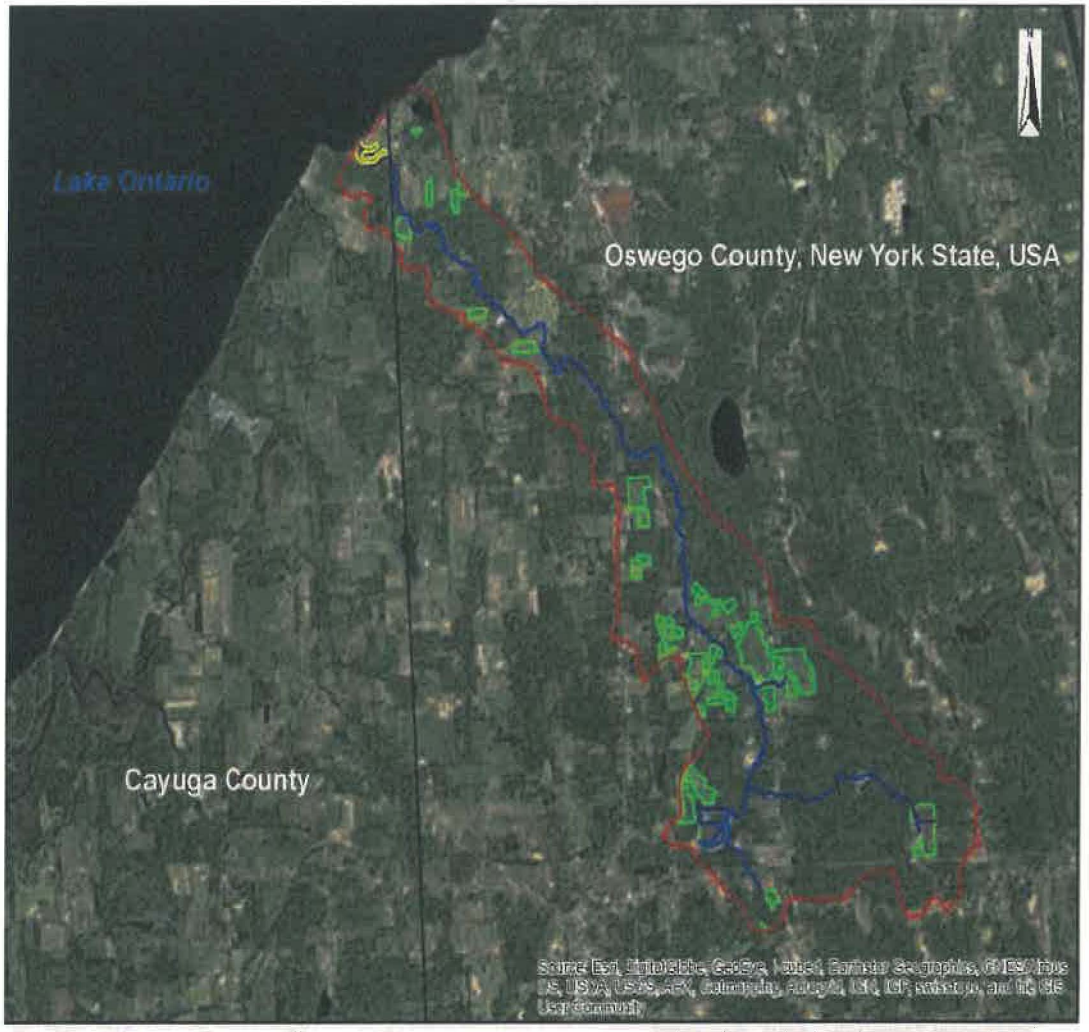
Legend

- Watershed Boundary
- Sampled Wetland Area
- NHD Waters
- Cropland

Author: Aaron W. Hemmway

Eight Mile Creek

HGM Classification - Riverine



0 1 2 4 6 8 Kilometers

1 centimeter = 1 kilometers

Wetland Centroid: 43.412182°, -76.621885°

Coordinate System: WGS 1984 Web Mercator Auxiliary Sphere

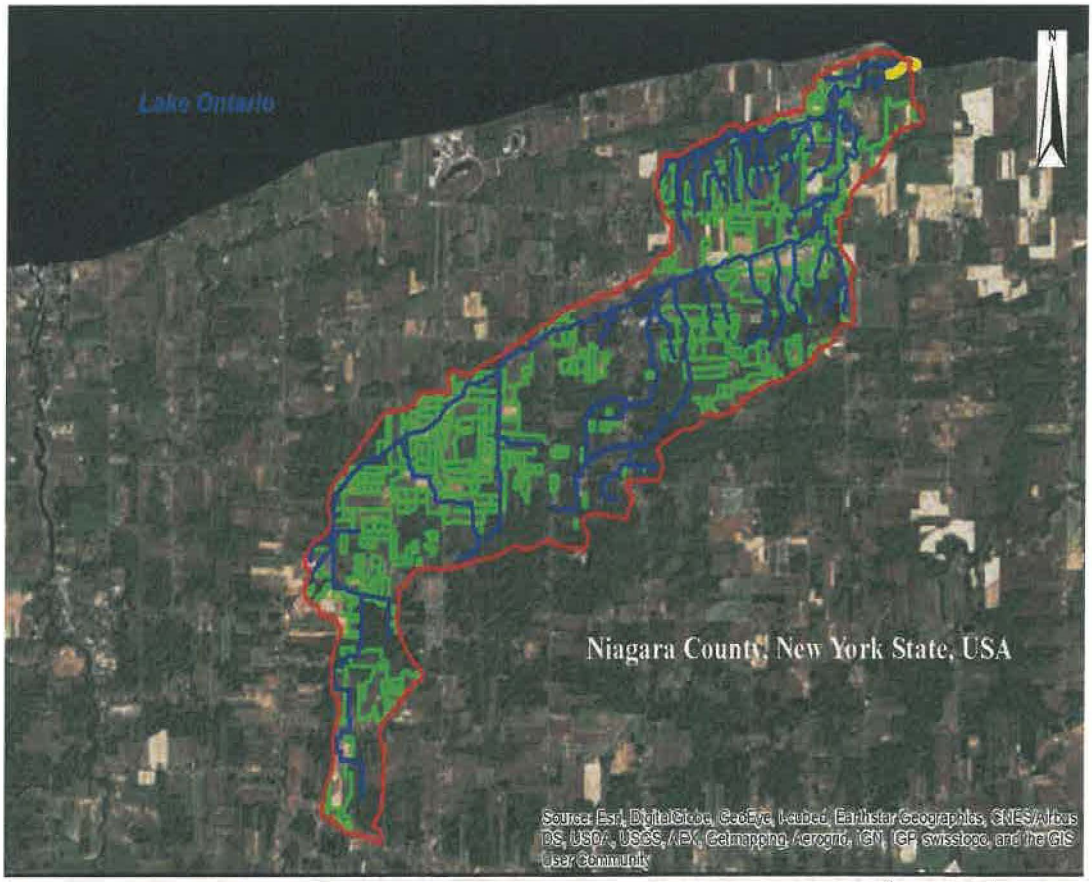
Legend

- Watershed Boundary
- Sampled Wetland Area
- NHD Waters
- Cropland

Author: Aaron W Heminway

Golden Hill

HGM Classification - Riverine



0 1 2 4 6 8 Kilometers

1 centimeter = 1.59 kilometers

Wetland Centroid: 43.371078° -78.477432°

Coordinate System: WGS 1984 Web Mercator Auxiliary Sphere

Legend

- Watershed Boundary
- Sampled Wetland Area
- NHD Waters
- Cropland

Author: Aaron W. Heminway

Isthmus Marsh South

HGM Classification - Lacustrine

0 0.250.5 1 1.5 2 Kilometers

1 centimeter = 0.36 kilometers

Wetland Centroid: 44.018217°, -76.284912°

Coordinate System: WGS 1984 Web Mercator Auxiliary Sphere

Legend

Sampled Wetland Area

Author: Aaron W. Heminway

Little Pond

HGM Classification - Riverine

0 1.5 3 4.5 6 Kilometers

1 centimeter = 1 kilometers

Wetland Centroid: 43.264519°, -77.635710°

Coordinate System: WGS 1984 Web Mercator Auxiliary Sphere

Legend

- Watershed Boundary
- Sampled Wetland Area
- NHD Waters

Author: Aaron W. Heminway

Long Carry Marsh

HGM Classification - Lacustrine

0 0.25 0.5 0.75 1 Kilometers

1 centimeter = 125 meters

Wetland Centroid: 44.051979°, -76.273974°

Coordinate System: WGS 1984 Web Mercator Auxiliary Sphere

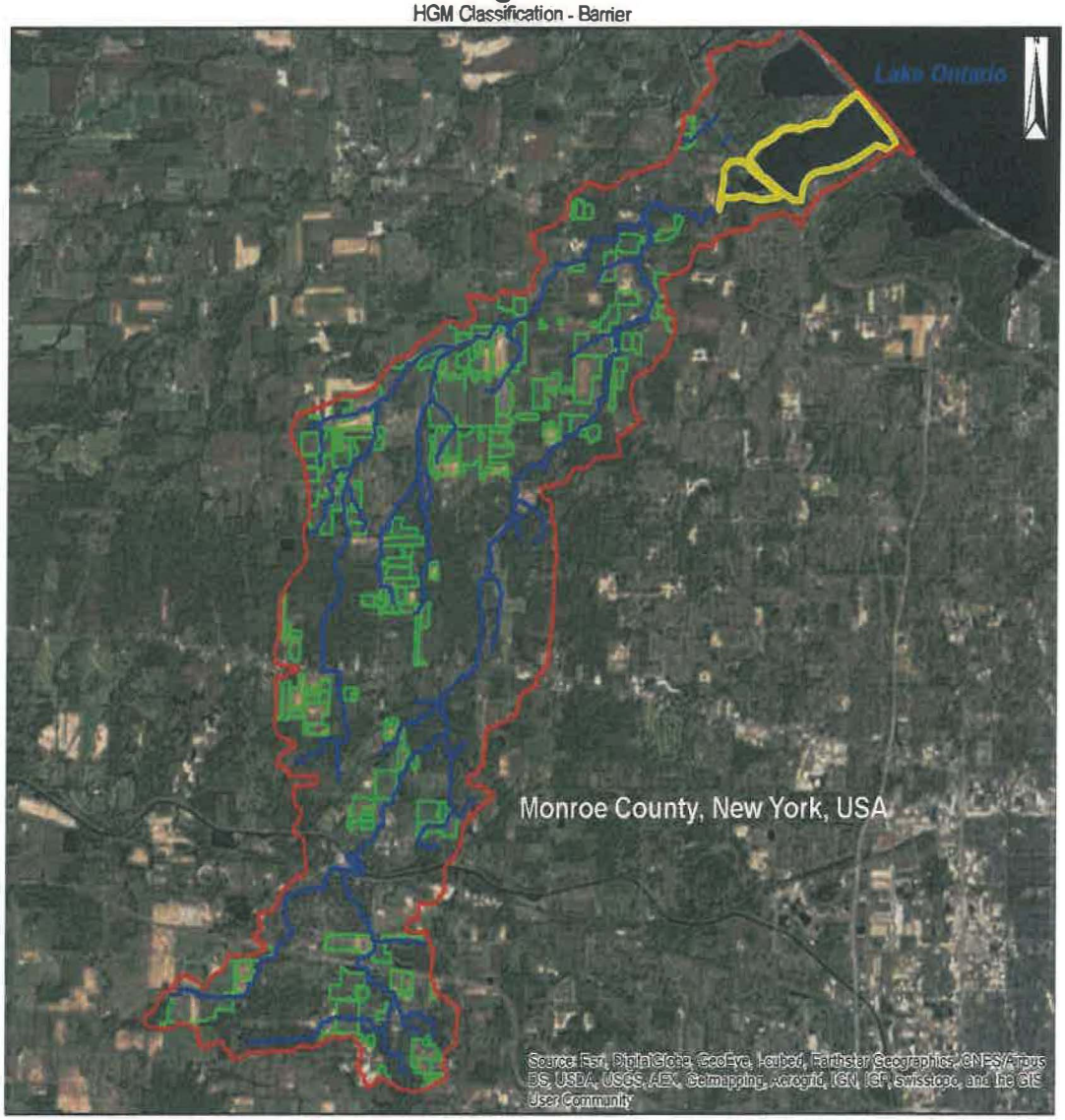
Legend

Sampled Wetland Area

Author: Aaron W. Heminway

Long Pond

HGM Classification - Barrier



0 1.5 3 4.5 6 Kilometers

1 centimeter = 1 kilometers

Wetland Centroid: 43.289850°, -77.694840°

Coordinate System: WGS 1984 Web Mercator Auxiliary Sphere

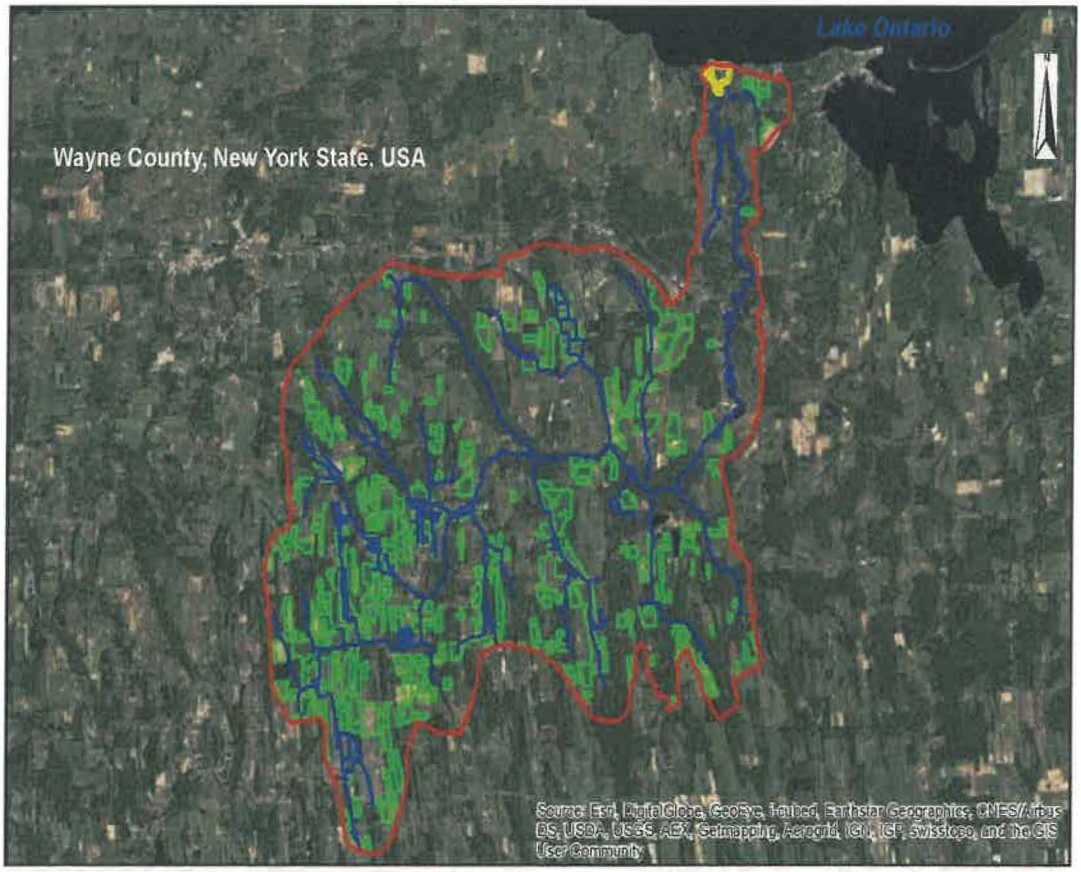
Legend

- Watershed Boundary
- Sampled Wetland Area
- NHD Waters
- Cropland

Author: Aaron W. Hemingway

Maxwell Bay

HGM Classification - Barrier



0 2 4 6 8 Kilometers

1 centimeter = 2 kilometers

Wetland Centroid: 43.288519°, -77.025334°

Coordinate System: WGS 1984 Web Mercator Auxiliary Sphere

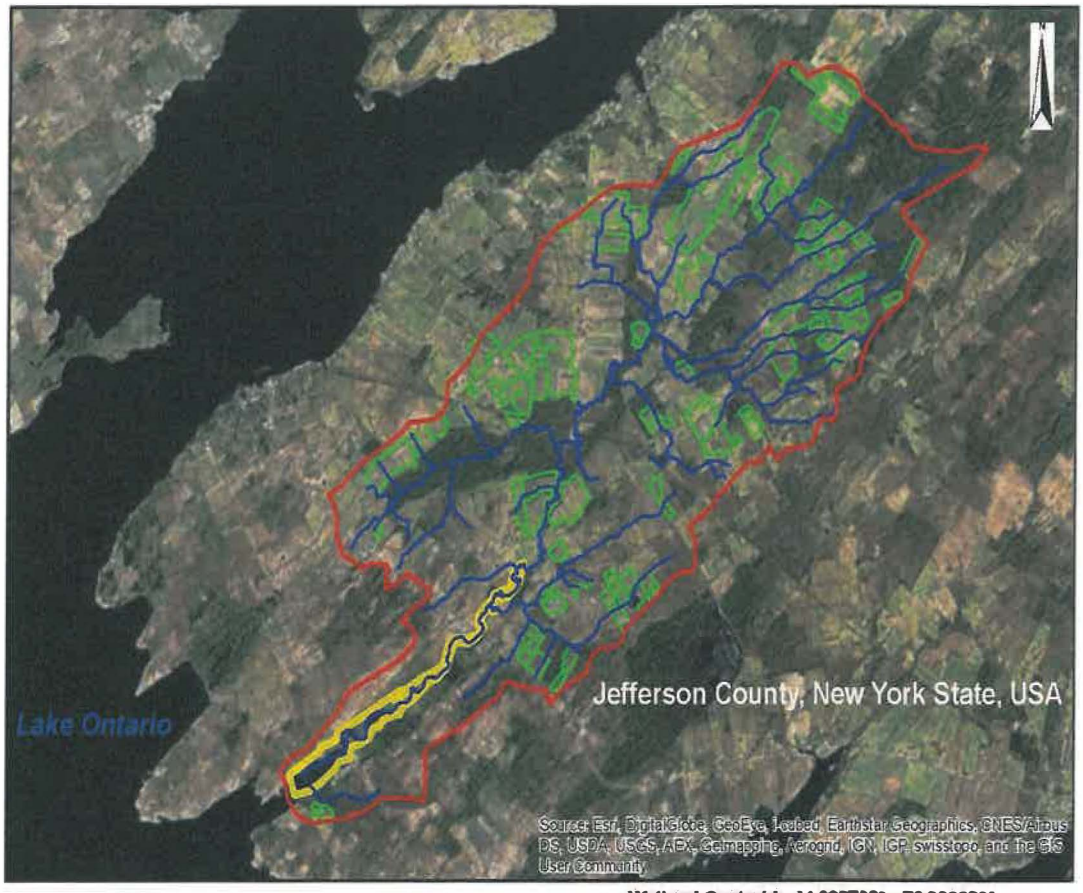
Legend

- Watershed Boundary
- Sampled Wetland Area
- NHD Waters
- Cropland

Author: Aaron W. Heminway

Mud Bay Marsh

HGM Classification - Riverine



0 1.5 3 4.5 6 Kilometers

1 centimeter = 1 kilometers

Wetland Centroid: 44.082703°, -76.308323°

Coordinate System: WGS 1984 Web Mercator Auxiliary Sphere

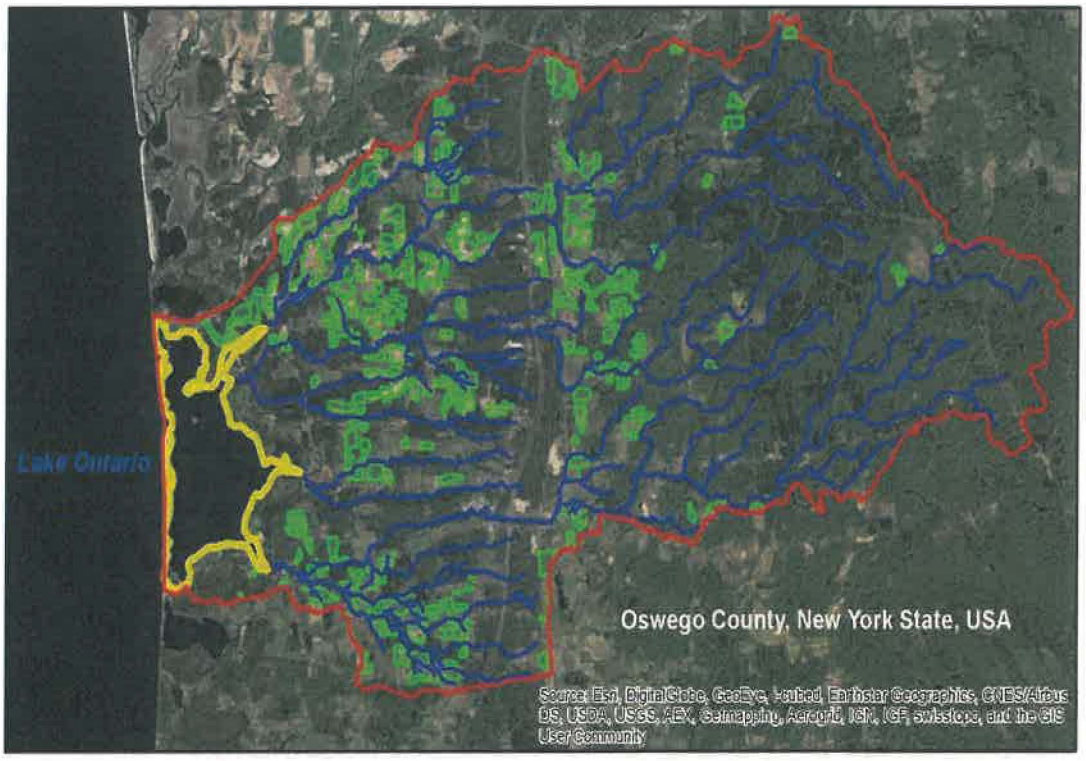
Legend

- Watershed Boundary
- Surface Hydrology
- Sampled Wetland Area
- Cropland

Author: Aaron W. Heminway

North Pond

HGM Classification - Barrier



0 2.5 5 7.5 10 Kilometers

1 centimeter = 2 kilometers

Wetland Centroid: 43.656115°, -78.181767°

Coordinate System: WGS 1984 Web Mercator Auxiliary Sphere

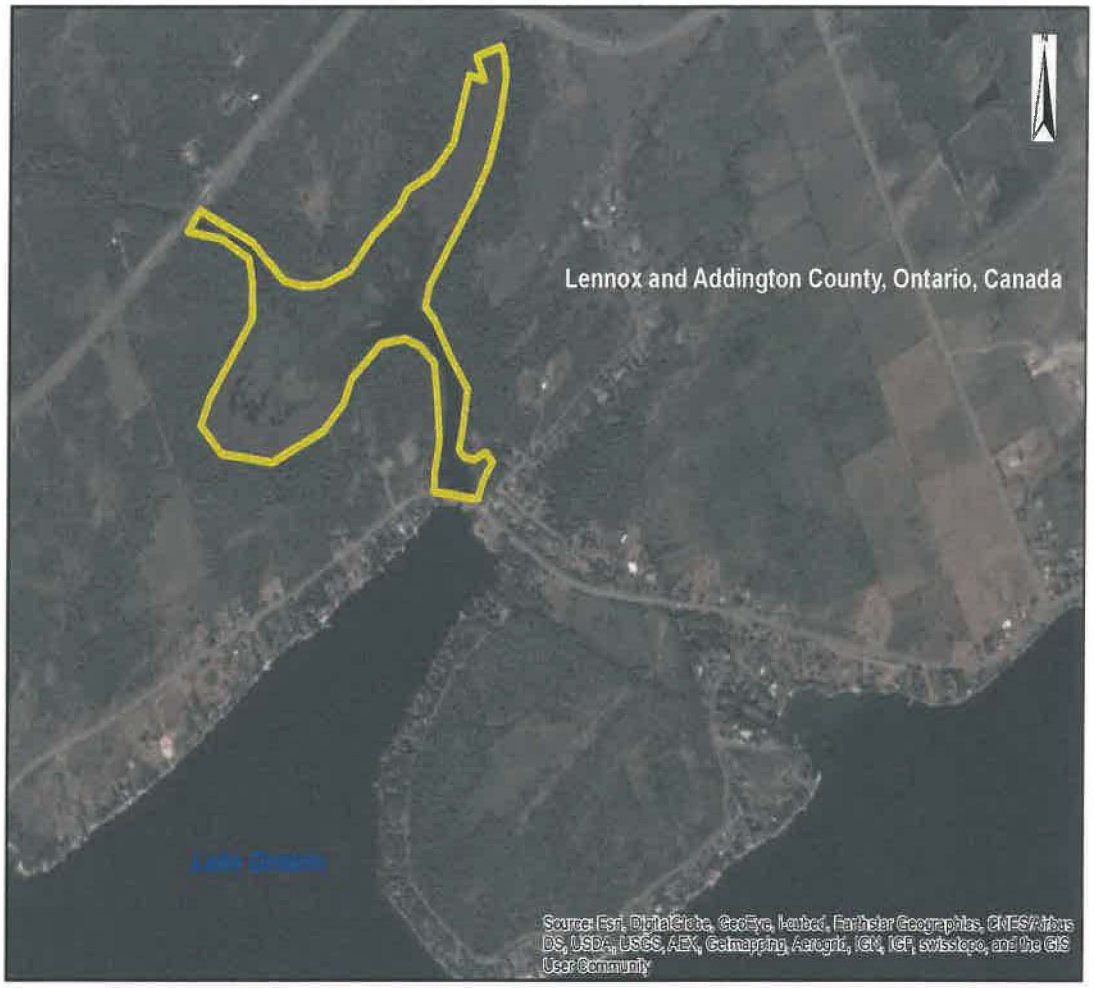
Legend

- Watershed Boundary
- Sampled Wetland Area
- NHD Waters
- Cropland

Author: Aaron W. Heminway

Parrot Bay

HGM Classification - Lacustrine



0 0.25 0.5 0.75 1 Kilometers

1 centimeter = 0.21 kilometers

Wetland Centroid: 44.220575°, -76.691255°

Coordinate System: WGS 1984 Web Mercator Auxiliary Sphere

Legend

Sampled Wetland Area

Author: Aaron W. Heminway

Payne Beach

HGM Classification - Barrier

1 0 1 Kilometers

1 centimeter = 415 meters

Wetland Centroid: 43.326459°, -77.729307°

Coordinate System: WGS 1984 Web Mercator Auxiliary Sphere

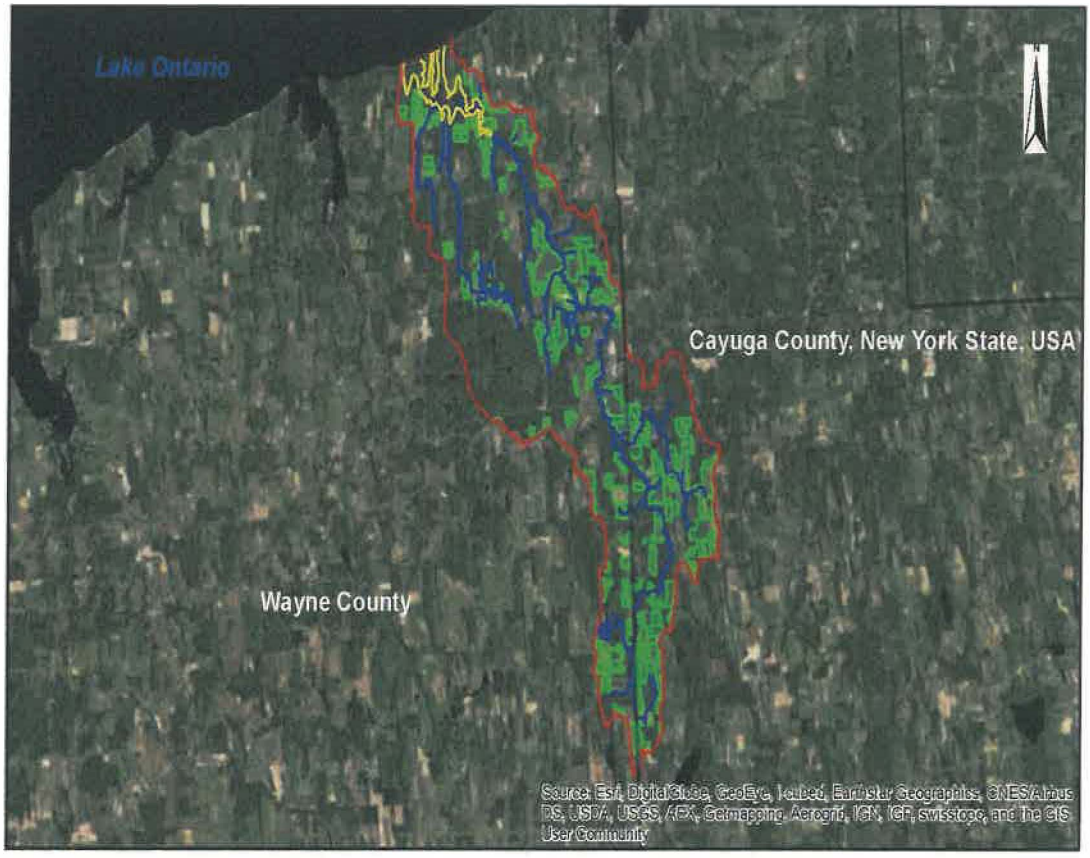
Legend

- Watershed Boundary
- Sampled Wetland Area
- NHD Waters
- Cropland

Author: Aaron W. Heminway

Red Creek

HGM Classification - Riverine



0 3 6 9 12 Kilometers

1 centimeter = 2 kilometers

Wetland Centroid: 43.301058°, -76.784904°

Coordinate System: WGS 1984 Web Mercator Auxiliary Sphere

Legend

- Watershed Boundary
- Sampled Wetland Area
- NHD Waters
- Cropland

Author: Aaron W. Heminway

Sand Bay

HGM Classification - Lacustrine

0 0.25 0.5 0.75 1 Kilometers

1 centimeter = 133 meters

Wetland Centroid: 44.150194°, -76.502219°

Coordinate System: WGS 1984 Web Mercator Auxiliary Sphere

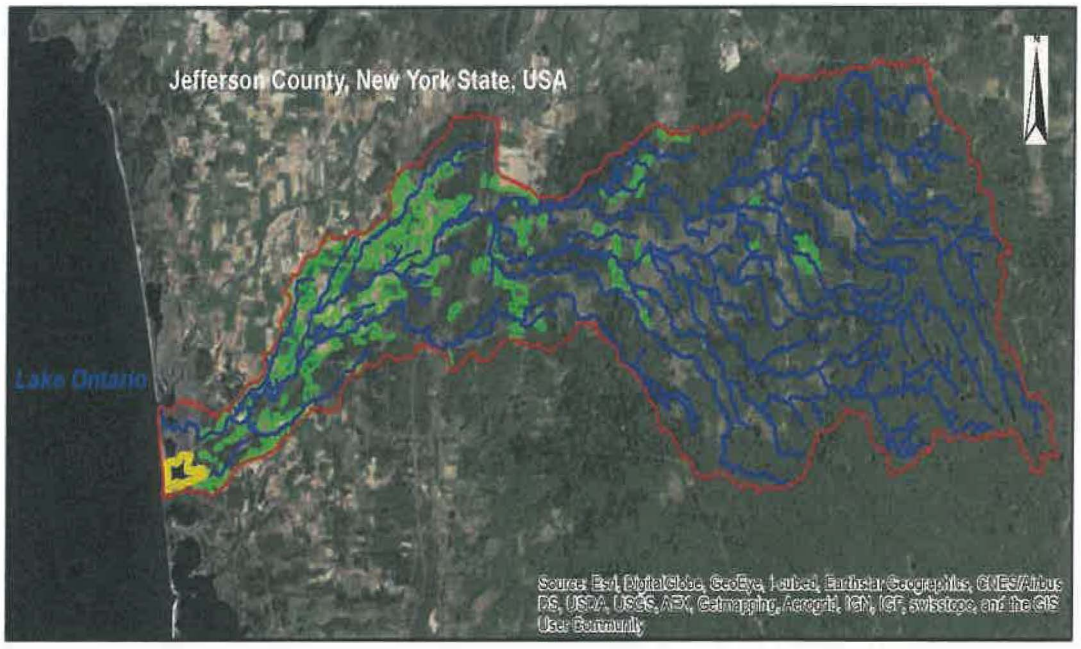
Legend

Sampled Wetland Area

Author: Aaron W. Heminway

South Colwell

HGM Classification - Barrier



0 2.5 5 7.5 10 Kilometers

1 centimeter = 2.85 kilometers

Wetland Centroid: 43.700026°, -76.193164°

Coordinate System: WGS 1984 Web Mercator Auxiliary Sphere

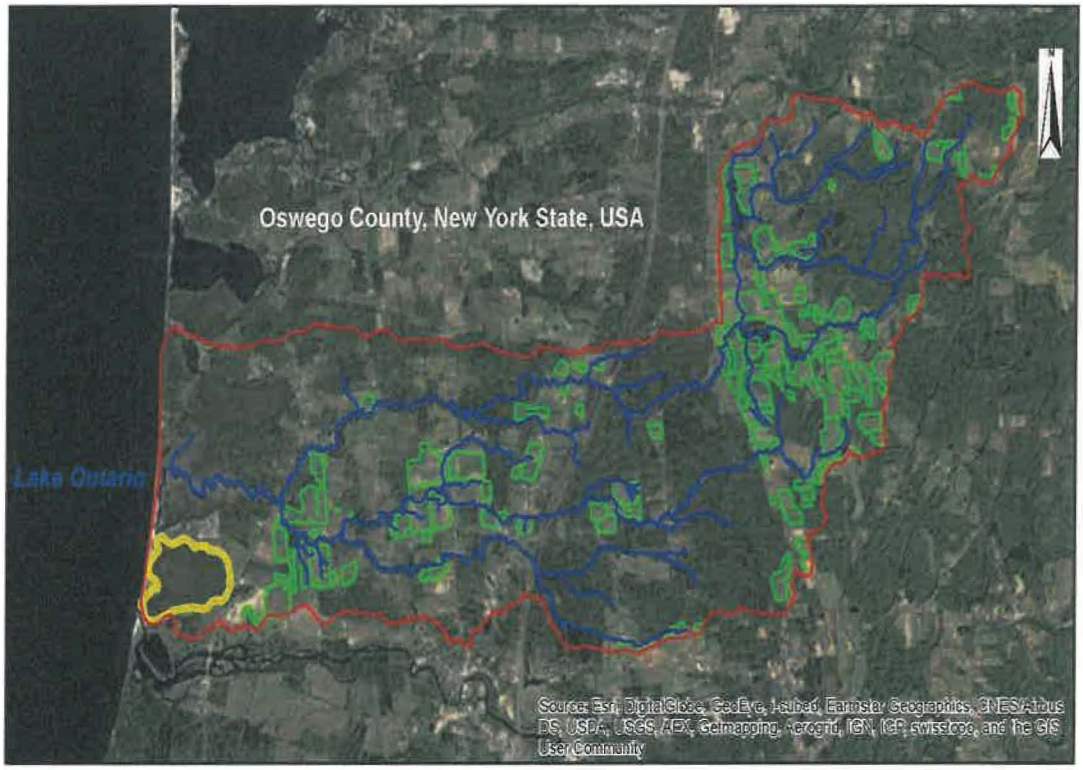
Legend

- Watershed Boundary
- Sampled Wetland Area
- NHD Waters
- Cropland

Author: Aaron W. Hemingway

South Pond

HGM Classification - Barrier



0 1 2 3 4 Kilometers

1 centimeter = 1 kilometers

Wetland Centroid : 43.579637°, -76.192461°
Coordinate System: WGS 1984 Web Mercator Auxiliary Sphere

Legend

- Watershed Boundary
- Sampled Wetland Area
- NHD Waters
- Cropland

Author: Aaron W. Heminway