Harvesting invasive plants to reduce nutrient loads and produce bioenergy: an assessment of Great Lakes coastal wetlands

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Abstract.   In Laurentian Great Lakes coastal wetlands (GLCWs), dominant emergent invasive plants are expanding their ranges and compromising the unique habitat and ecosystem service values that these ecosystems provide. Herbiciding and burning to control invasive plants have not been effective in part because neither strategy addresses the most common root cause of invasion, nutrient enrichment. Mechanical harvesting is an alternative approach that removes tissue-bound phosphorus and nitrogen and can increase wetland plant diversity and aquatic connectivity between wetland and lacustrine systems. In this study, we used data from three years of Great Lakes-wide wetland plant surveys, published literature, and bioenergy analyses to quantify the overall areal extent of GLCWs, the extent and biomass of the three most dominant invasive plants, the pools of nitrogen and phosphorus contained within their biomass, and the potential for harvesting this biomass to remediate nutrient runoff and produce renewable energy. Of the approximately 212,000 ha of GLCWs, three invasive plants (invasive cattail, common reed, and reed canary grass) dominated 76,825 ha (36%). The coastal wetlands of Lake Ontario exhibited the highest proportion of invasive dominance (57%) of any of the Great Lakes, primarily from cattail. A single growing season's biomass of these invasive plants across all GLCWs was estimated at 659,545 metric tons: 163,228 metric tons of reed canary grass, 270,474 metric tons of common reed, and 225,843 metric tons of invasive cattail, and estimated to contain 10,805 and 1144 metric tons of nitrogen and phosphorus, respectively. A one-time harvest and utilization for energy of this biomass would provide the gross equivalent of 1.8 million barrels of oil if combusted, or 0.9 million barrels of oil if converted to biogas in an anaerobic digester. We discuss the potential for mitigating non-point source nutrient pollution with invasive wetland plant removal, and other potential uses for the harvested biomass, including compost and direct application to agricultural soils. Finally, we describe the research and adaptive management program we have built around this concept, and point to current limitations to the implementation of large-scale invasive plant harvesting.

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INTRODUCTION

Great Lakes coastal wetlands (GLCWs) occur along the shoreline of all Laurentian Great Lakes and their connecting rivers, where waters are shallow and partially protected from the open lakes' wave energy. Great Lakes coastal wetlands and their diverse plant assemblages (Minc 1997, Albert and Minc 2004) provide critical habitat for >90% of fish species occupying the GLs (Jude et al. 2005, Burton and Uzarski 2009, Uzarski et al. 2009), support rare fauna (Kost et al. 2007), provide major stopovers along migratory corridors for waterfowl and shorebirds (Prince et al. 1992, Ewert and Hamas 1995), and harbor high invertebrate diversity (Burton et al. 2004, Uzarski et al. 2004). Great Lakes coastal wetlands also play an important role in maintaining water quality, reducing nutrient runoff into the lakes by a half (Sierszen et al. 2012). Locations of GLCWs have been well documented through basin-wide aerial photograph and satellite imagery studies (Herdendorf et al. 1981, Albert and Simonson 2004, Ingram et al. 2004); over 2000 wetlands have been mapped and classified by hydrogeomorphic type (Albert and Simonson 2004, Ingram et al. 2004, Albert et al. 2006).

Invasive species and nutrient pollution are among the chief threats to the functioning of GLCWs (Mills et al. 1993, Ricciardi 2001, Dolan and Chapra 2012, Poesch et al. 2016). In recent decades, habitat values of GLCWs have been increasingly compromised by invasive plant expansion. The three most common plant invaders with significant ecological and economic impacts in GLCWs are common reed (*Phragmites australis* (Cav.) Steud.), reed canary grass (*Phalaris arundinacea* L.), and invasive cattail (*Typha* × *glauca* Godr. and *Typha angustifolia* L.; hereafter *Typha*; Lopez and Edmonds 2001). These invaders are clonal, large, and rapid-growing species, whose dominance is facilitated by nutrient enrichment (Woo and Zedler 2002, Minchinton and Bertness 2003, Kercher and Zedler 2004, Eppinga et al. 2011, Larkin et al. 2012*b*, Uddin and Robinson 2018), and whose production and accumulation of a deep litter layer prevents other plant species from growing (Vaccaro et al. 2009, Eppinga et al. 2011, Holdredge and Bertness 2011, Mitchell et al. 2011, Larkin et al. 2012*a*, White 2014). Therefore, an invasive plant management strategy with the goal of maintaining long-term function in coastal wetlands should attempt to address both litter accumulation and nutrient enrichment.

While total phosphorus (TP) loading has decreased in all lakes since the establishment of a 1976 baseline and generally remains lower than the target goals of the 1978 Great Lakes Water Quality Agreement (GLWQA 1978), nutrient pollution continues to impact lake function (Dolan and Chapra 2012). Target loads inadequately address local nutrient pollution, as demonstrated by eutrophic conditions in nearshore waters and bays adjacent to agricultural and urbanized watersheds (Qualls et al. 2009, Dolan and Chapra 2012) and dense algae blooms that alter lake food webs, cause anoxic zones and fish die-offs, make beaches less desirable to tourists, and in the case of *Microcystis* in western Lake Erie, can render drinking water unsafe for human consumption (Pothoven et al. 2009, Auer et al. 2010, Chaffin et al. 2011).

Controlling invasive plants in GLCWs has been a high priority goal of U.S. federal programs, such as the Great Lakes Restoration Initiative. Current management practices, however, have largely focused on the eradication of invasive plant species in GLCWs without adequately addressing one of the root causes of invasion, nutrient enrichment. Typical treatments employ herbicide (Apfelbaum 1985) and controlled burning (Kostecke et al. 2005). While these methods can be effective, they often have associated side effects that are not addressed. Herbicide can increase the concentration of available N and P in sediment porewater (Lawrence et al. 2016), which often leads to algal blooms and subsequent re-establishment of invasive species (D. Albert, *personal observation*). Additionally, herbicide use does not remove accumulated leaf litter, which is key to re-establishing wetland habitat value and plant diversity (Larkin et al. 2012*a*, Lishawa et al. 2015). As a stand-alone treatment, burning has been shown to be ineffective at reducing *T.* × *glauca* density (Gleason et al. 2012). It also releases sequestered carbon back into the atmosphere, and nutrients that had been sequestered in leaf tissue are re-suspended in the water column. A substantial amount of money is spent annually on burn and herbicide treatment of invasive plants throughout the United States, with much of this

cost going toward herbicide purchase (Martin and Blossey 2013).

Because nutrient pollution and invasive plant expansion are strongly linked, we propose harvest and utilization of invasive plant biomass as an alternative management approach that both accomplishes restoration objectives and addresses a root cause of invasion, high levels of nutrients in wetland sediments. Harvesting vegetation as a nutrient removal strategy is not a new idea, and hyper-abundant problematic species such as Eurasian water milfoil (*Myriophyllum spicatum*) have been suggested as targets in the past (Carpenter and Adams 1977). Harvesting invasive plant biomass from wetlands removes large quantities of

nutrients (Cicek et al. 2006), likely reducing mechanisms which maintain invasive plants (Zedler 2009), reducing eutrophication in adjacent lacustrine environments, increasing biodiversity (Hall et al. 2008, Hall and Zedler 2010, Lishawa et al. 2015, 2017), and potentially providing revenue to offset restoration costs (Fig. 1; Nackley et al. 2013, Quinn et al. 2014). Harvested plant biomass can be used as an agricultural nutrient source or can be incorporated into the developing bioenergy economy. Bioenergy produced from invasive wetland plants requires no irrigation, herbicides, or fertilizers and originates on lands not used for food production. Clonal, near-monotypic stands of invasive plants allow for targeted, efficient
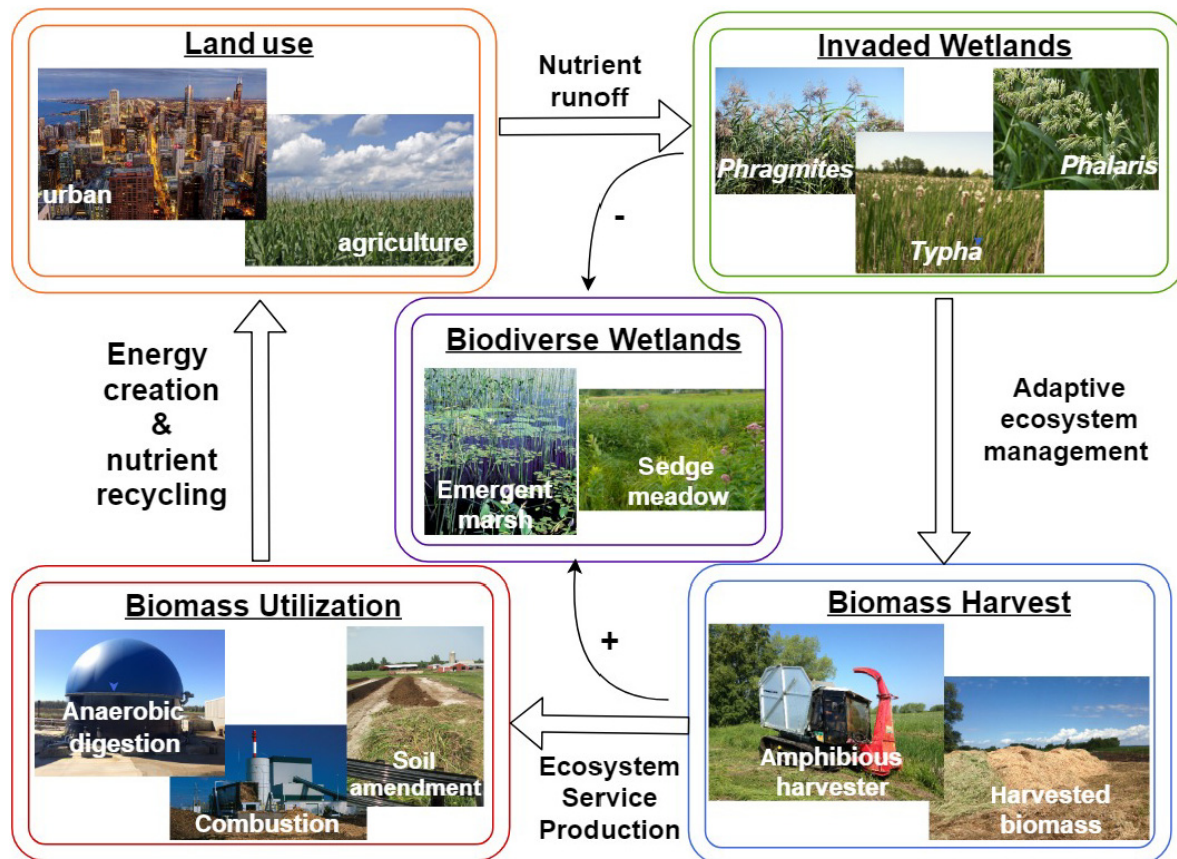

Fig. 1. Urban and agricultural land uses in the Great Lakes region increase N- and P-rich nutrient runoff, which favors dominance by three key invasive wetland plants (*Phragmites australis*, *Typha*, *Phalaris arundinacea*) that suppress (−) biodiverse wetlands and their associated services. Managing invaded wetlands via biomass harvest results in a viable biomass source that can be utilized via anaerobic digestion or combustion to create bioenergy, or can be used as a soil amendment to promote nutrient recycling and reduce reliance on synthetic fertilizers. Biomass harvest simultaneously promotes (+) the creation of biodiverse wetlands, which are critical for wildlife habitat and recreational opportunities in the region.

harvesting, with annual yields between 12 and 19 metric tons (T) dry weight per ha in unmanaged wetlands (Dubbe et al. 1988, Windham and Lathrop 1999, Meyerson et al. 2000, Angeloni et al. 2006, Vaccaro et al. 2009, Jakubowski et al. 2010). This productivity is comparable with the bioenergy crops switchgrass (*Panicum virgatum*), miscanthus (*Miscanthus × giganteus*), willow (*Salix* ssp.), and poplar (*Populus* ssp.) (Labrecque and Teodorescu 2005, Khanna et al. 2008). Furthermore, *Phr. australis* and *Pha. arundinacea* are successfully utilized as bioenergy feedstocks in their native range in Europe, yielding net positive energy balances (Hansson and Fredriksson 2004).

In this study, we sought to determine the Great Lakes-wide potential of invasive plant harvest as an ecological restoration approach for GLCWs. As part of this management model, we quantify the proportion of GLCWs that are dominated by emergent invasive plant species and evaluate the potential to harvest these species as a restoration practice coupled with the utilization of biomass for energy production and nutrient capture.

To this end, we pursued the following objectives: (1) determine the total area of coastal wetlands dominated by invasive *Phr. australis*, *Typha*, and *Pha. arundinacea* and estimate total biomass values for each of these species; (2) quantify TP and TN in the standing biomass of each of these invasive plants; (3) evaluate the biomass energy production potential for each of these invasive species; (4) calculate the total bioenergy production potential of invasive plant tissues in the GLs using the GLCW invasive plant biomass estimates (Objective 1) and the biomass energy production potential (Objective 3).

METHODS

Great Lakes coastal wetland invasive plant dominance

Intensive vegetation sampling of GLCWs was conducted in the late 1980s (Albert et al. 1987, 1989), the mid-1990s (Minc 1997, Minc and Albert 1998), and again beginning in 2011. The most recent effort involved intensive random sampling of over 500 coastal wetlands by the Great Lakes Coastal Wetland Monitoring Project (GLCWMP) using a standardized sampling protocol (Uzarski et al. 2017). For this study, we utilized the GLCWMP vegetation data from 2011 to 2013,

when 355 GLCWS sites were sampled in the USA and Canada. Each wetland vegetation survey consisted of three randomly placed transects running perpendicular to the wetlands' depth contours and separated by at least 20 m. Each transect bisected the wet meadow, emergent, and submerged aquatic vegetation zones, and included five evenly spaced 1-m^2 sampling plots per vegetation zone. We excluded data from the submerged aquatic vegetation zone in this analysis.

In a Geographic Information System (ArcGIS; ESRI, Redlands, California, USA), we linked plot locations with the complete vegetation dataset (15,975 1-m^2 sampling plots), which includes cover percentages for all plant species present, as well as environmental data such as water depth. Next, we quantified the number of plots within each wetland that was dominated by a target invasive plant (*Phalaris arundinacea*, *Phragmites australis*, or invasive *Typha*), and the proportion of total plots within each wetland dominated by each species. We chose a 25% relative cover threshold after calculating the relative cover of *Typha* from an unrelated Great Lakes wetland community dataset that contained a gradient of *Typha* dominance. If any of the three target species exhibited >25% of the total vegetative cover within a given plot, then it was considered dominant (Frieswyk et al. 2007). We joined these summary data to the Great Lakes Coastal Wetland Consortium's coastal wetland inventory spatial dataset (Central Michigan University), the comprehensive wetland mapping effort for the Great Lakes and connecting channels, within which GLCWMP sampling was conducted (Uzarski et al. 2017). The GLCWI dataset includes polygons demarcating the extent of all GLCWs. We calculated the area dominated by each invasive plant within each wetland sampled by multiplying the proportion of plots dominated by focal invasive plants by the wetland's area. Finally, we estimated the total area dominated by each invasive plant species within each Great Lake by dividing the sum area dominated by each species within each basin by the proportion of total wetland area that was sampled within each basin (i.e., the sum of total polygons sampled/sum of total wetland area within each basin; Central Michigan University).

Invasive plant biomass

We estimated biomass values for each invasive plant species by averaging productivity values

for each species from published literature (Table 1) and multiplying by the estimated area of wetland that contained >25% total cover of that species within each lake basin. Standard error estimates were calculated using the range of published values.

Bioenergy production potential

We evaluated the energy production potential of *Pha. arundinacea*, *Phr. australis*, and *Typha*. Before senescence in late summer (late August–early September) when tissue nutrient concentrations are near their peak (Grosshans et al. 2013), we composited samples of aboveground biomass from five or more arbitrarily selected plants of each species. All plants were collected from wetlands in the greater Chicago area, and all biomass samples were oven dried (65°C for ≥72 h) and ground into a fine powder with a coffee grinder prior to conducting energy production tests. We evaluated the biomass combustion-energy potential of each invasive plant species following the International Standard Test Method (ISO 2009) using a plain, static jacket, oxygen bomb calorimeter (1341 Plain Jacket Bomb Calorimeter; Parr Instrument Company, USA). The chemical composition and the biological methane potential (BMP) of the three plant species were evaluated using Automatic Methane Potential Testing Systems (AMPTS II, Bioprocess Control, Sweden AB). We used sludge inoculum from a wastewater treatment facility as the microbe source for digestion. Prior to experimentation, we stored sludge in an environmental chamber at 38°C to maintain viability and we sustained inoculum pH between 7 and 8. For each substrate, we ran a test series of three replicates in sealed glass bottles (500 mL). A reference series (three replicates) was utilized to obtain gas production from the inoculum alone without the substrate. All bottles were loaded with an inoculum to substrate ratio of 2:1 and placed in a water bath (38°C) throughout the 40-d experiment. Carbon dioxide was scrubbed from emitted biogas by running gas through NaOH-filled bottles. The CH_4 emitted over time was continuously measured by calibrated flow cells. Methane content of biogas was evaluated from samples taken before CO_2 scrubbing and determined with a Perkin Elmer Clarus 600 Gas Chromatograph on a PLOT Q column and a Thermal Conductivity Detector. Digestate characteristics were evaluated after BMP testing. We calculated the standing bioenergy production potential in GLCWs by multiplying each species' bomb calorimetry results by the biomass estimates. We made the same calculation using the BMP results to evaluate the total biogas production potential for each species.

Total nutrient removal potential

To evaluate the nutrient content of *Typha* and *Phr. australis*, we collected four field samples of each species' aboveground (i.e., harvestable) living tissue from Galien Marsh, a southern Lake Michigan coastal marsh, in September 2011 and from Shiawassee National Wildlife Refuge near Saginaw Michigan. We pulverized dried biomass with a ball grinder and determined %N with a Flash EA 1112 C-N elemental analyzer (CE Instruments, Wigan, UK) and %P with spectrophotometric procedures using a Bran-Luebbe AutoAnalyzer 3 (SPX inc.; Charlotte North Carolina, USA) following high temperature HNO_3/H_2SO_4 (2.5/0.5 v/v) acid digestion. In calculations of *Pha. arundinacea* nutrient removal potential,

Table 1. Sources for productivity values by species.

Species	Productivity data source	Tissue nutrient data source
Phragmites australis	Templer et al. (1998), Windham and Lathrop (1999), Meyerson et al. (2000), Windham (2001), Windham and Meyerson (2003)	N. Tuchman (*unpublished data*), Peverly et al. (1995), Li et al. (2014)
Typha × glauca and *T. angustifolia*	Dubbe et al. (1988), Templer et al. (1998), Angeloni et al. (2006), Vaccaro et al. (2009), S. Lishawa et al. (*unpublished data*)	Emery and Perry (1995), McJannet et al. (1995), Tuchman (*unpublished data*)
Phalaris arundinacea	Lawrence and Ashford (1969), Klopatek and Stearns (1978), Bernard and Lauve (1995), Jakubowski et al. (2010), Jelinski et al. (2011)	Jakubowski et al. (2010)

Notes: Not all of the studies cited were from Great Lakes coastal wetlands. *Typha × glauca* and *T. angustifolia* often co-occur and were jointly treated as *T. × glauca* in analyses.

we used published synthesized mean %P and %N values (Jakubowski et al. 2010). We also included published N and P values for *Phragmites* and *Typha* in our calculations of mean tissue nutrient concentration for these species (Table 1). We estimated the total N and P contained within the standing biomass of each invasive species by multiplying its mean N and P tissue values by the biomass estimates for each lake.

Statistical analyses

We evaluated the effects of species on energy density values and biological methane production using analysis of variance (ANOVA). We assessed differences between species using Tukey's honestly significant differences test. All statistical analyses were conducted using R 3.4.2 (R Core Team 2017).

RESULTS

Great Lakes coastal wetlands invasive plant dominance

A total of 211,919 ha of GLCW were identified in the GLCWC dataset. Lake Huron had the largest share of the total with 59,200 ha (28%), followed by Lake Michigan with 46,870 ha (22%), Lake Superior with 27,447 ha (13%), Lake Ontario with 22,253 ha (11%), Lake Erie with 22,071 ha (10%), and the sum of all connecting channels and rivers represented the remaining 34,079 ha (16.1%; Fig. 2). The Detroit River
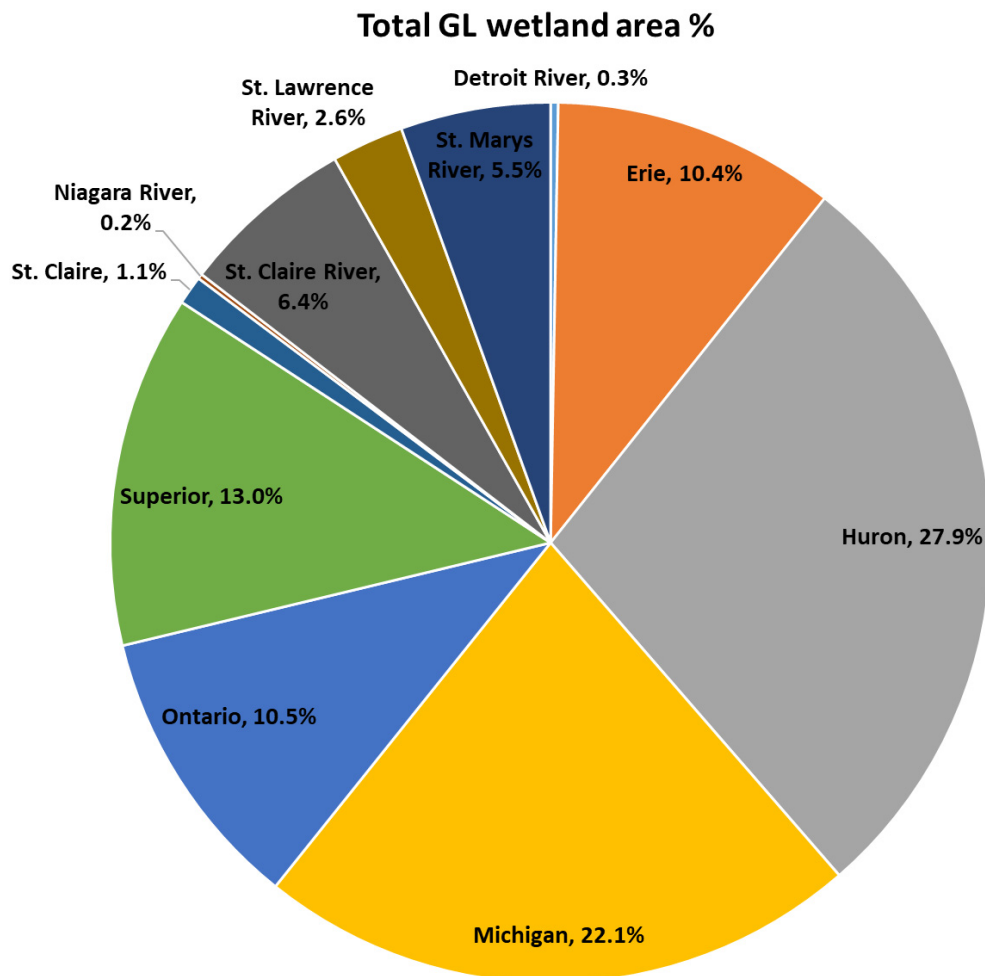
Total GL wetland area %

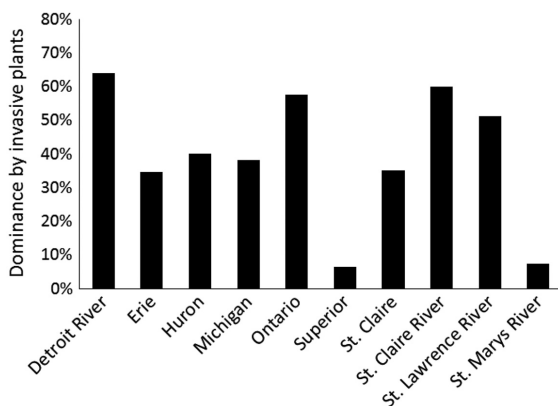Fig. 2. Percentage of the total Great Lakes coastal wetland area within each Great Lake, connecting channel, or river.

Fig. 3. Percentage of the total coastal wetlands dominated by the three most dominant invasive plants (*Phragmites australis,* invasive *Typha, Phalaris arundinacea*) within each Great Lake, connecting channel, or river.

contained the highest proportion of wetland area dominated by invasive species (64%), followed by the St. Clair River (60%) and then Lake Ontario (57%). About 40% of Lake Huron and Lake Michigan wetland areas, 35% of Lake Erie wetland area, and 5% of Lake Superior wetland area was dominated by *Typha*, *Phragmites australis*, or *Phalaris arundinacea* (Fig. 3). In lakes Huron and Michigan, *Phr. australis* was the most abundant emergent invasive, while *Typha* was the most abundant in lakes Erie and Ontario. *Phalaris arundinacea* was the most abundant in Lake Superior, though Lake Superior had the lowest proportion of invasive plant dominance (Figs. 3, 4).

Invasive plant biomass

The total standing biomass (dry weight) for these three species across all GLCWs was estimated to be 659,545 metric tons (T), with 163,228 T of *Pha. arundinacea*, 270,474 T of *Phr. australis*, and 225,843 T of invasive *Typha* spp. (Fig. 5).

Bioenergy production potential

Our bomb calorimetry testing showed that *Pha. arundinacea* had the greatest energy density, averaging 20.3 kJ/g $\pm$ 1.1 (SE), which was greater than *Typha* (16.0 kJ/g $\pm$ 0.8) and *Phr. australis* (17.2 kJ/g $\pm$ 0.9; Table 2). In the analysis of BMP, all three species produced enough methane to be viable feedstocks for anaerobic digestion (>100 mL CH_4/g; J. Aurandt, *personal communication*),

but we observed differences between species (Table 2). The two grass species tested, *Pha. arundinacea* and *Phr. australis,* had the highest overall CH_4 production, producing over 250 mL CH_4/g. The total standing energy potential of *Phr. australis* is the highest for both combustion and methane production, but each of the three species represents a substantial source of biomass energy.

Total nutrient removal potential

The mean %N and %P found in dried tissue of each species are presented in Table 3. The potential for N removal ranges from 2552.0 T $\pm$ 293.6 in *Typha* spp. to 5788.1 T $\pm$ 1406.5 in *Phr. australis*, and the potential for P removal ranges from 270.5 T $\pm$ 59.5 in *Phr. australis* to 489.7 T $\pm$ 40.8 in *Pha. arundinacea* (Table 3). The greater value of P in the latter is the result of *Pha. arundinacea* tissues having higher P/N ratio than *Phr. australis*.

DISCUSSION

Our study adds to the collective understanding of dominance patterns of three key invasive plants in GLCWs (Trebitz and Taylor 2007, Bourgeau-Chavez et al. 2015) and uniquely quantifies the potential for utilizing their biomass as a biofuel source or for nutrient load reduction. While the sampling methods of these previous studies differ from those of GLCWMP (Uzarski et al. 2017), there is agreement that these invasive plants are abundant across the GLs, and the estimate of total invasive plant dominance from the remote sensing based on Bourgeau-Chavez study (2015) is within 5% of our small plot-based estimate (34.9% and 36.2%, respectively). The accuracy of our estimates of the GLCW area dominated by each target species result from the large number (355) of wetlands and sampling plots (15,975) that were sampled in the GLCWMP, and the systematic randomization of each of the plots along each transect. Our data suggest that a substantial portion of GLCWs are currently dominated by invasive plants. The proportion dominated ranged from <10% in Lake Superior to more than 70% in Lake Ontario and more than a third of the coastal wetlands in the other GLs. Considering that more than 50% of GLCWs have been drained for agriculture and urban development over the past 170 yr (USEPA 2006),
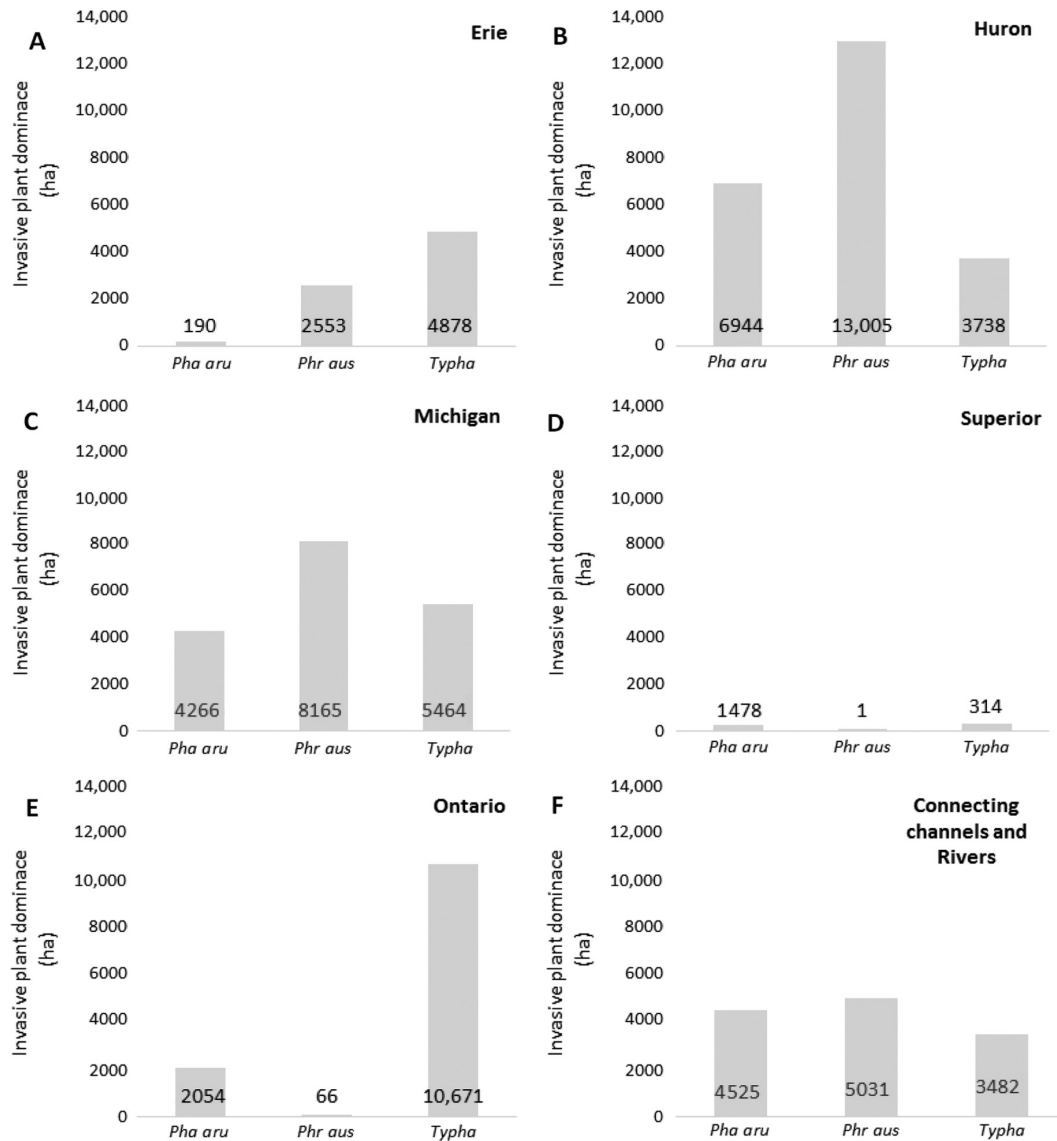
Fig. 4. Area of coastal wetlands dominated by the three most dominant invasive plants (*Phragmites australis*, invasive *Typha*, *Phalaris arundinacea*) within each Great Lake (A–E) and the connecting channel and rivers (F).

uninvaded extant wetlands are increasingly rare. Coastal wetlands play a key role in maintaining biodiversity in the GL system, and the ecosystem services they provide are in part a result of their biological and physical diversity. In the face of the rapid ecological changes occurring in this region, these systems should be managed to enhance wetland habitat, improve biodiversity, improve biogeochemical functioning, and management actions should seek to minimize cost and improve regional sustainability.

While the prevalence of invasive wetland plants is of great ecological consequence, management of these species could provide opportunities to address several interrelated environmental problems. Current management practices for most invasive species involve herbicide application, leaving the plants in situ to decompose. While this often results in mortality, it does not address two key mechanisms leading to invasive dominance in wetlands: nutrient enrichment (Woo and Zedler 2002, Kercher and Zedler 2004,
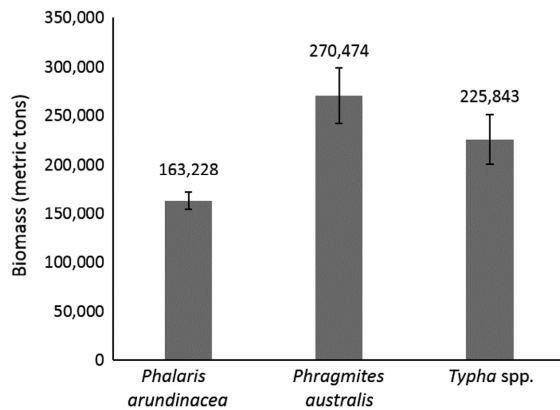
Fig. 5. The total estimated standing biomass (dry weight ±1 SE) of *Phalaris arundinacea*, *Phragmites australis*, and invasive *Typha* in Great Lakes coastal wetlands.

Lawrence et al. 2016, Uddin and Robinson 2018) and dense litter deposition (Vaccaro et al. 2009, Holdredge and Bertness 2011, Larkin et al. 2012*a*). Herbicide treatment also undermines the potential to use invasive plant biomass as an energy source or agricultural amendment. Since 2011, our research group has been focused on evaluating the efficacy of using mechanical removal as an invasive species management tool in GLCW. Mechanical removal can be seen either as an alternative to current management practices or as an additional tool wetland managers will have at their disposal (Fig. 1).

While monospecific stands present ideal targets for nutrient removal and bioenergy production, harvesting can also be an effective tool for increasing the relative abundance of co-occurring native wetland plants and increasing habitat quality. Lishawa et al. (2015) documented a significant increase in plant diversity after manually removing the aboveground biomass of *Typha* spp. in a GLCW. Four years after this treatment, *Carex* spp. were still increasing in abundance, despite the reinvasion by *Typha* spp. (S. Keyport et al., *unpublished manuscript*). Similarly, Lishawa et al. (2017) found that harvesting *Typha* spp. from a newly invaded GLCW increased the relative cover of co-occurring *Carex* spp. Additionally, preliminary results from an ongoing study documenting wetland bird and fish responses to *Typha* spp. harvesting indicate increased larval fish and bird use following harvest (A. Shrank and E. Clark, *personal communication*). While these responses are likely caused by increases in structural heterogeneity and aquatic connectivity following litter removal, these mechanisms have not yet been elucidated. To the best of our knowledge, there have not been experimental management studies conducted on the effects of harvesting *Phragmites australis* or *Phalaris arundinacea*, but the similarity of these species' growth habit and litter accumulation to *Typha* spp. suggests that plant community and habitat value responses will likely be similar. These potential ecological benefits must be weighed against the potential harm caused to wetland animal species during harvesting, and where possible, mitigating strategies should be adopted. For example, to avoid injuring breeding birds we conduct harvesting after July 15th, by which time the majority of wetland birds have left their nests. We also avoid harvesting entire stands of vegetation in a single year and instead manage the habitat as a mosaic in order to leave a standing matrix of vegetation for animals to take refuge in during a restoration event.

Table 2. Average (±SE) energy density, cumulative methane production through 40 d, and total energy production potential of *Typha* × *glauca*, *Phragmites australis*, and *Phalaris arundinacea*.

Species	Energy density kJ/g	Cumulative methane production mL CH_4/g	Total GLW energy potential		Barrels of oil equivalent	
			Combustion (PJ)	Methane (PJ)	Combustion	Methane
T. × glauca	15.99 ± 0.76[b]	173.51 ± 15.62[a]	3.61 ± 0.17	1.52 ± 0.14	590,076	248,453
Phr. australis	17.23 ± 0.91[b]	232.78 ± 26.65[b]	4.66 ± 0.17	2.44 ± 0.28	761,605	398,833
Pha. arundinacea	20.32 ± 1.05[a]	241.51 ± 27.57[b]	3.32 ± 0.17	1.53 ± 0.17	542,674	250,088
Total	NA	NA	11.59	5.49	1,894,355	897,374

Notes: Non-overlapping letters indicate significant differences ($P < 0.05$) between species, determined by ANOVA with Tukey's honestly significant difference tests. Total energy production potential in Petajoules (10^{15} joules) of values calculated by multiplying the results of our combustion and methane production experiments with the total biomass estimates.

Table 3. The mean concentration of nitrogen (N) and phosphorus (P) found in dried plant tissue and the total nitrogen and phosphorus removal potential in metric tons from *Typha × glauca*, *Phragmites australis*, and *Phalaris arundinacea*.

Species	Percent N (dried tissue)	Percent P (dried tissue)	Total N removal potential (T)	Total P removal potential (T)
T. × glauca	1.13 ± 0.13	0.17 ± 0.02	2552.0 ± 293.6	383.9 ± 54.2
Phr. australis	2.14 ± 0.52	0.10 ± 0.02	5788.1 ± 1406.5	270.5 ± 59.5
Pha. arundinacea	1.51 ± 0.07	0.30 ± 0.03	2464.7 ± 108.7	489.7 ± 40.8
Total	NA	NA	10804.9	1144.1

Note: Estimates of nutrient removal potential are for plants growing in Great Lakes Coastal Wetlands.

Energy production

Though weedy plants have long been considered as bioenergy feedstocks due to their nuisance properties and high productivity (Dubbe et al. 1988, Gunaseelan 1997), there is renewed interest in utilizing invasive plants for bioenergy in an ecosystem restoration context (Cicek et al. 2006, Grosshans et al. 2013, Nackley et al. 2013, Quinn et al. 2014, Lishawa et al. 2015). We found that the most prevalent, dominant, and ecologically disruptive invasive plants in GL coastal wetlands appear to be suitable feedstocks for combustion and biogas production via anaerobic digestion. Their energy density is comparable to commercially grown bioenergy crops such as miscanthus (*Miscanthus giganteus*) and switchgrass (*Panicum virgatum*) (Labrecque and Teodorescu 2005, Khanna et al. 2008), and they have the added advantages of not taking up arable land or requiring agricultural inputs that include irrigation, fertilizers, herbicides, and pesticides.

The potential energy yield of invasive plant species for bioenergy production via combustion is immense. Condensed plant material can be used in home-heating furnaces, coal-fired power plants can burn up to 10% non-coal biomass without significant retrofitting (Basu et al. 2011), and some power plants in the GLs basin have been retrofitted to burn biomass as their primary fuel source. Using GLCWMP data, we estimated that the standing biomass (dry) of the three most abundant emergent invasive species totals to 659,545 T. Together, the one-time harvest and combustion of these three species would provide enough energy to heat and power 156,375 average American households (USEIA online) for a year.

Anaerobic digestion is an attractive option for invasive plant biomass utilization because it does not require the added costs/energy of biomass drying or condensing, or specialized combustion equipment capable of handling high ash content fuels. Furthermore, research has demonstrated positive net energy returns from nuisance plant harvesting and utilization for biogas production (Hansson and Fredriksson 2004). A principle impediment to the widespread production of biogas is the availability of anaerobic digestion infrastructure in the GL region. Presently, there are approximately 142 operational biodigesters associated with animal agricultural operations in GL states (USEPA online), which primarily use liquid manure feedstock. Additionally, there are a few digester facilities designed to use mixed biomass sources such as food, yard, and crop waste. Test trials that we have conducted in collaboration with the University of Wisconsin-Oshkosh biodigester laboratory indicate that these mixed source digesters can easily accommodate solid biomass sources from invasive plants (B. Langolf, *personal communication*).

Nutrient removal potential

Despite reductions in P and N pollution in the GLs since the 1978 GLWQA, non-point source pollution is still a serious threat to GL biogeochemical processes and trophic systems, and the legacy of past nutrient pollution is evident in many coastal wetland sediments. Fast-growing invasive plant species like *Phr. australis*, *Typha*, and *Pha. arundinacea* use legacy nutrients to their advantage, outcompeting native species that are better adapted to low-nutrient conditions (Woo and Zedler 2002, Kercher and Zedler 2004, Uddin and Robinson 2018). The ability of these invasive species to quickly uptake phosphate (PO_4^{3+}) and mineralized N makes them well suited for nutrient-targeting phytoremediation. We estimated that there is >10,000 T of N and >1000 T of P

stored in the annual standing biomass of these three species in GLCW. The potential to remove P is particularly noteworthy, because P is the limiting nutrient in most freshwater systems (Schindler 1974). Phosphorus in invasive plant biomass represents a significant portion of the total non-point source P entering the GLs each year; TP from Michigan tributaries was ~973 T in 2005 (MI DEQ 2013). Because they occur in riparian and nearshore environments that are in close proximity to the photic zone, wetlands play an important role in regulating lacustrine P availability (Wetzel 1992). Wetland plants take up phosphate as they grow, reducing the amount of biologically available phosphate. Thus, removing plant material from the lacustrine system during the growing season reduces net P loads. Furthermore, as wetland emergent vegetation regrows following a harvesting event, it will take up more biologically available P and store it in living tissue. In an ongoing large-scale experimental harvest study in a mesotrophic *Typha*-dominated Lake Huron wetland, an extrapolation of sediment P concentrations suggests that as few as 10 harvests could remove that wetland's legacy P (Berke 2017). Because N fixation and denitrification are atmospherically mitigated, understanding the net impact of biomass harvesting on N enrichment is more difficult. However, we know that harvesting removes a substantial amount of tissue-bound N. Theoretically, wetlands that have been saturated with legacy P and N for decades could be rehabilitated through repeated harvesting of invasive plants, improving their capacity to buffer the nearshore environment from nutrient pollution. Furthermore, if legacy P can be removed from these wetlands via invasive biomass harvest, we posit that native species should become more competitive with invasives, eventually reintegrating into coastal wetlands that were once monocultures of invasive emergent species. More research is needed to examine how nutrient removal via invasive plant biomass harvest will affect nutrient uptake and cycling within coastal wetlands and connected open-water systems.

The utilization of invasive plant biomass as a soil amendment could allow agricultural land managers to improve the fertility and organic content of agricultural soils. While the large-scale agricultural use of recycled wetland biomass is currently not economically feasible, policies that incentivize reductions in P runoff from agricultural fields could create nutrient-trading markets that would further incentivize nutrient recycling. The nutrient density of biomass-derived fertilizers could be improved through composting prior to transportation and field application, and experimentation that is being conducted in partnership with a dairy farmer in northern MI has demonstrated the viability of this biomass outlet (N. Tuchman, *unpublished data*).

Invasive plant harvesting to promote multiple ecosystem services: Next Steps

While biomass harvesting is commonly used to manage wetland habitats in Europe (Hansson and Fredriksson 2004), the practice has only recently been introduced to managers in North America. In northern Lake Huron, harvesting experiments conducted in *Typha*-dominated wetlands have shown a strong response from native plant species after a one-time harvest, with the regeneration of species that had been absent for years (Lishawa et al. 2015, 2017). Ongoing longer-term (i.e., repeated annual harvests) and larger-scale experiments are currently investigating the effect invasive plant harvesting has on fish, macroinvertebrate, amphibian, and bird biodiversity, as well as its impact on wetland nutrient dynamics and carbon cycling.

In addition to the ecological costs and benefits of this management strategy, it is important to consider the technological feasibility and energetic and economic sustainability of large-scale harvesting of wetland invasives. Up to this point, most harvesting in GLCWs has been done with a Softrak amphibious tractor (Loglogic, Devon, UK), a machine adequate for conducting experimental-scale projects, but limited to harvesting in <0.6 m water depth and at a rate of ~1 ha/d in inundated GLCWs. Despite these limitations, the energy return of harvested biomass is greater than the energy invested to conduct the harvest (B. Carson, *unpublished data*). A larger version of this machine (Loglogic 120) can harvest faster (>2 ha/d) and more efficiently. In diked wetlands with managed water levels, this technology can adequately harvest monocultures of *Typha* spp., *Pha. arundinacea*, and *Phr. australis*. Other technologies such as floating harvesting machines (e.g., Swamp Devil) are capable of cutting plant material that grows beyond the depth limit of the Softrak.

The transportation of cut biomass is the most significant barrier to invasive species utilization. Due to the low density of harvested materials, trucking biomass is inefficient. However, many landscapes have closely integrated complexes of agricultural land and wetlands, and these present an opportunity to use harvested biomass as a soil amendment, potentially recycling a substantial amount of nutrients that would otherwise enter the watershed. Furthermore, compressing biomass at its site of origin has the potential to substantially reduce shipping costs. A technology currently under development involves the use of a hydraulic screw compactor that would reduce biomass to 1/20th the harvested volume (P. Wever, *personal communication*), thereby greatly increasing the efficiency of transport.

We do not expect that a for-profit market and infrastructure will develop around the use of invasive plant biomass. Instead, we argue that biomass from invasive plant species could contribute to the growing forestry and agricultural residue-based biomass economy. The primary reason for invasive plant biomass harvest and removal from GLCW sites remains habitat improvement. If biomass or nutrient markets provide an opportunity for managers to re-coup a part of the cost of invasive plant treatment, then the cost/benefit analyses of different management techniques may tip toward restoration harvesting rather than burn management or herbicide treatment.

The implementation of invasive plant nutrient recycling and bioenergy projects is currently underway in the GL region. In 2015 and 2016, pilot-scale projects were initiated in Michigan, Ohio, and Wisconsin, resulting in the utilization of approximately 15 T of *Typha* and *Phr. australis* in two industrial biogas digesters, and the conversion of *Typha* and *Pha. arundinacea* biomass into biofuel pellets. There has been some resistance fueled by fears that harvesting could result in the economic exploitation of coastal wetlands. However, the cost of harvesting is relatively high (e.g., Spinelli et al. 2017), so any gain from the valuation of biomass may help offset costs, but will not realistically produce a profit that could drive management decisions. Nevertheless, it is critical that as this new source of biomass is developed, policies are created to ensure that invasive biomass harvesting is carefully designed, monitored, and regulated and the primary goal remains improving the biological diversity and integrity of natural ecosystems.

Our research and ecological projections document that three of the most ecologically detrimental invasive plants in the GL region have the potential to be biomass energy feedstocks. The data presented here quantify the potential energy and nutrient removal benefits that would result from harvesting the standing invasive plant biomass in GLCWs. Detailed economic modeling, which incorporates the costs (e.g., harvesting, transportation, drying and condensing), sustained yield over multiple years, as well as the ecosystem service benefits (e.g., biodiversity recovery, nutrient pollution abatement, greenhouse gas reductions) will be necessary to holistically assess the economic, ecological, and societal value of using invasive species biomass as bioenergy feedstocks or soil amendments.

Acknowledgments

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