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TECHNICAL ARTICLE

Plant community recovery after herbicide management to remove *Phragmites australis* in Great Lakes coastal wetlands

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Invasive plants, such as *Phragmites australis*, are a global threat to plant diversity and are commonly controlled using herbicide management. The purpose of this study was to evaluate the plant community response 6–10 years after large-scale herbicide management to remove *Phragmites* from Great Lakes coastal wetlands along the shores of western Lake Erie. Vegetation surveys were conducted in nine wetlands undergoing herbicide management and four unmanaged *Phragmites*-dominated wetlands. The relative percent cover of *Phragmites* was dramatically lower in the managed (1.3%) compared to unmanaged wetlands (93.0%; $p < 0.001$), although relative percent cover of other non-natives following herbicide management averaged 39.2% (ranging from 6.4 to 67.6%). The cover-weighted floristic quality index was significantly higher in managed wetlands ($p < 0.01$), with the highest indices (12.4–17.0) at sites that received prescribed fire after herbicide treatment ($p < 0.05$). Species richness and diversity were significantly higher in managed wetlands ($p < 0.001$); however, there was no significant difference between wetlands treated only with herbicide and those treated with herbicide and prescribed fire. Our results indicate that herbicide management is effective in reducing *Phragmites* and improving floristic quality over timescales of 6–10 years. However, continued spot-treatment and management of new invasive species may be required, and the return of high-quality plant communities may be unrealistic in the study region.

Key words: floristic quality assessment, floristic quality index, Great Lakes coastal wetlands, herbicide management, invasive species, *Phragmites australis*, post-restoration monitoring

Implications for Practice

- Herbicide management has the potential to improve floristic quality in *Phragmites*-invaded Great Lakes coastal wetlands over timescales of 6–10 years when multiple follow-up treatments are conducted. Ongoing efforts are likely required to maintain these gains.
- Floristic quality was highest at sites that received prescribed fire following herbicide treatment.
- New invasives colonizing or emerging from the seedbank in the absence of competition from the targeted invasive may limit the gains in floristic quality achievable through herbicide management in disturbed wetlands.
- Continued research and monitoring are needed to optimize adaptive management and to understand long-term outcomes of herbicide management and its costs and benefits.

Introduction

Invasive species are major drivers of global change causing ecosystem degradation and loss of biodiversity (Mack et al. 2000) and are therefore common targets of restoration projects (Pysek & Richardson 2010). Extensive effort and resources are devoted to attempting to control invasive species (D'Antonio et al. 2004; Quirion et al. 2018), yet our understanding of the factors that affect restoration outcomes remains limited due to a lack of long-term follow-up studies (Miller & Hobbs 2007; Suding 2011; Wortley et al. 2013). Wetland degradation worldwide is of major concern because wetlands provide a number of critical ecosystem services, including biodiversity support (MEA 2005). Widespread loss of wetlands over the past century due to agricultural expansion and development (Johnston 1994) has made restoring wetlands a high priority (MEA 2005). Wetlands are particularly susceptible to invasive species (Zedler & Kercher 2004), and invasive species control is a central focus of wetland management (Martin & Blossey 2013).

High-impact invasive species dramatically alter ecosystem structure and function and are difficult to eradicate due to traits such as high rates of growth and biomass production that result in dense monotypic stands often with extensive networks of

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rhizomes (Hejda et al. 2009). One particularly high-impact invasive wetland plant is *Phragmites australis* (hereafter referred to as *Phragmites*), the common reed. *Phragmites* has a cosmopolitan distribution (Haslam 1972), but the introduction of European lineages to the United States in the 1800s led to its rapid spread (Saltonstall 2002). *Phragmites* produces large amounts of biomass, outcompeting native flora and dramatically reducing plant and animal biodiversity (Chambers et al. 1999; Weinstein & Balletto 1999). *Phragmites* is considered a significant ecological and economic threat (GLRI 2015) and possess traits that may enhance its advantage under global change scenarios (Caplan et al. 2014; Eller et al. 2017). Because up to two-thirds of the plant's biomass occurs in below-surface rhizomes (Haslam 1972), it is extremely difficult to eradicate (Warren et al. 2001; Hazelton et al. 2014).

The most common approach for restoring *Phragmites*-invaded wetlands involves repeated spraying with a broad-spectrum herbicide, typically glyphosate products, in combination with mechanical removal by burning or harvesting (Kettenring & Adams 2011; Hazelton et al. 2014). A number of studies have documented short-term (i.e. 1–3 years) effectiveness of this management approach (e.g. Mozdzer et al. 2008; Zimmerman et al. 2018), but the efficacy of herbicide management seems to be reduced as patch size increases. For example, one study found that eradication occurred in 83% of very small plots (0.36 m^2), but dropped to 25% of small patches (45 m^2) and only 2% of large patches (3,000 m^2) following 7 years of herbicide treatment (Quirion et al. 2018). Land managers' ability to more effectively control invasive plants is limited by a severe lack of post-restoration monitoring data, particularly with respect to plant community composition responses (Kettenring & Adams 2011; Hazelton et al. 2014; Quirion et al. 2018). Between 2010 and 2014, the Great Lakes Restoration Initiative (GLRI) spent over $25 million toward the eradication of *Phragmites* in the Great Lakes Basin with the goal of improving habitat quality and biodiversity (GLRI 2015). In southeast Michigan, since 2011, the Detroit River-Western Lake Erie Cooperative Weed Management Area (DR-WLE CWMA) received just over $1 million to manage *Phragmites* (DR-WLE CWMA unpublished data). However, to date, little has been done to evaluate the longer-term response of plant communities following this large-scale effort.

The purpose of this study was to assess the outcome of 6 or more years of herbicide management to remove *Phragmites* on plant communities in wetlands along the Michigan shoreline of Lake Erie. We hypothesized that if herbicide management releases native plant species from competition, we would see an increase in species richness, diversity, and floristic quality at managed sites. Additionally, because fire removes much of the standing dead biomass that remains after herbicide treatment, increasing light and promoting regeneration from the seedbank, we expected higher richness, diversity, and floristic quality in sites that were burned following herbicide treatment. Alternatively, herbicide management might fail to eradicate *Phragmites* or promote other invasive species. To test these hypotheses, plant communities were surveyed in four unmanaged *Phragmites*-dominated and nine herbicide-treated coastal wetlands in the summer of 2018, at least 6 years after the initiation of herbicide management. We measured plant species richness and calculated diversity and a floristic quality index (FQI; Freyman et al. 2016) to compare different plant community metrics.

Methods

Study Site

The study was conducted at 13 Great Lakes coastal wetlands within the Detroit River International Wildlife Refuge (DRIWR). Nine managed sites received herbicide treatment coordinated by the DR-WLE CWMA (Table 1; Fig. 1), most beginning in 2011, although one site, Humbug Marsh, was first treated in 2007 with pre-GLRI funding. Because we did not have survey data prior to herbicide treatment, we also surveyed four unmanaged *Phragmites*-dominate sites to compare to the managed sites. All sites are classified as freshwater emergent wetlands (https://www.fws.gov/wetlands/data/mapper.html) and were heavily invaded by *Phragmites australis*, haplotype M, prior to 2011 (DR-WLE CWMA unpublished data). Historically, emergent plant communities in these wetlands included broadleaf cattail (*Typha latifolia*; coefficient of conservatism [C] = 1), soft stem bulrush (*Schoenoplectus tabernaemontani*; C = 4), common arrowhead (*Sagittaria latifolia*; C = 4), bur reed (*Sparganium eurycarpum*; C = 5), pickerel weed (*Pontederia cordata*; C = 8), and wild rice (*Zizania aquatica*; C = 9) (Herdendorf 1987). In 2011, 637 ha of *Phragmites* along the Michigan shoreline of Lake Erie were aerially sprayed with a broad-spectrum herbicide [2% solution of Aquaneat or Aquapro (53.8% solution of glyphosate) and Habitat (28.7% solution of isopropylamine salt of imazapyr) with Cygnet Plus as a surfactant] (DR-WLE CWMA 2013). The next year, another 823 ha were treated. Following initial treatment, follow-up spot treatments were conducted at all sites, usually with a MarshMaster, an amphibious tracked vehicle, but sometimes by helicopter or backpack spraying, although the frequency, method, and extent of follow-up treatments differed among sites (Table 1). Three sites received prescribed fire after the initial herbicide treatment to remove the dead thatch. Because prescribed burns were not feasible at all sites, mowing was sometimes used as an alternative, but few CWMA partners kept records on when mowing occurred.

Vegetation Surveys

We characterized the plant community composition in late summer 2018, when most species were flowering, by running transects along a gradient of shallow to deep water. If a depth gradient was not present, the transect was randomly oriented. Surveys consisted of three 100 m transects at each site in areas that were formerly monocultures of *Phragmites*, determined by the analysis of aerial imagery from 2009 (DR-WLE CWMA unpublished data). We surveyed eleven 1-m^2 plots located every 10 m along each transect at each site (33 plots per site). In each plot, we identified all plant species and estimated percent cover of each. Water depth measurements were taken at the center of each quarter of each plot.

Table 1. Table of herbicide treatment history at each study site from 2011 (′11) through 2017 (′17). "H" indicates herbicide treatment and "F" indicates prescribed fire. *Humbug Marsh was first treated with herbicide in 2007. MDNR, michigan department of natural resources; USFWS, US fish and wildlife service; HCMA, huron-clinton metropolitan authority.

Site and Abbreviation		*Latitude, Longitude*	*Owner*	*′11*	*′12*	*′13*	*′14*	*′15*	*′16*	*′17*
Vermet unit	Ver	42.011, −83.189	MDNR		H,F	H	H		H	H
Strong	Str	41.992, −83.240	USFWS	H	H,F	H	H	H	H	H
Fix	Fix	41.975, −83.260	USFWS	H	H	H,F	H	H	H	H
Walpatch unit	Wal	42.023, −83.216	MDNR		H	H	H	H	H	H
Gibraltar Bay	Gib	42.089, −83.209	USFWS	H		H	H	H	H	H
Plum Creek Bay	PC	41.893, −83.387	USFWS	H	H	H	H	H	H	H
Tishkof	Tis	41.984, −83.248	USFWS	H				H		
Lake Erie Metro Park	LE	42.076, −83.201	HCMA		H	H	H		H	
Humbug Marsh*	HM	42.112, −83.190	USFWS	H	H	H	H	H	H	H
Pointe Mouillee North	PMN	42.043, −83.202	MDNR							
Humbug South	HS	42.101, −83.191	USFWS							
Pointe Aux Peaux	PAP	41.944, −83.271	MDNR							
Gibraltar Wetland	GW	42.084, −83.217	USFWS							

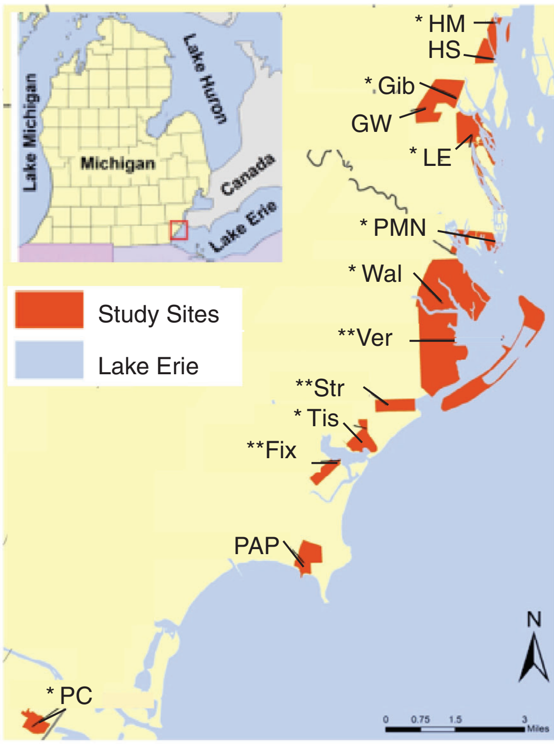

Figure 1. Map of study sites within the Detroit River-Western Lake Erie Cooperative Weed Management Area (see Table 1 for site name abbreviations). *, sites treated with herbicide; **, sites treated with herbicide + prescribed fire.

Data Analysis

Plant community response to herbicide treatment was characterized using several metrics, including species richness (S), the most commonly collected vegetation metric (Stirling & Wilsey 2001), the Shannon-Wiener diversity index (H′; $H' = \sum([p_i] \times \ln[p_i])$, where p_i is the relative abundance of the i^{th} species), and the FQI. The floristic quality assessment (FQA) calculator (https://universalfqa.org/) was used to calculate the FQI using Michigan as the geographic region (Freyman et al. 2016). The FQA provides a cover-weighted FQI (*w*FQI) based on S, the relative abundance of each species (based on percent cover), and C, a measure of the "quality" of each species, when percent cover data are available (Bourdaghs et al. 2006). FQI calculated without relative abundance data using only S and C is referred to as total FQI. A site with an FQI greater than 19 is considered a "high-quality aquatic resource" (USFWS FQA 2019). All three indices (S, H′, and FQI) were calculated at the site level (rather than the mean of individual quadrats). We also looked at the relative importance of plant functional groups identified by the FQA (non-native grass, native forbs, non-native forbs) using relative percent cover, the percent of the total cover for each species.

To determine whether % *Phragmites*, S, H′, *w*FQI, and % cover of each plant functional group differed between managed and unmanaged sites, we used a two-sample *t* test (nine herbicide-treated sites and four untreated sites). To assess whether fire affected recovery after herbicide treatment, we split the herbicide-treated sites into two categories, based on whether they had also received prescribed fire, and used a one-way analysis of variance to determine if there were differences in S, H′, and *w*FQI across three different treatments (untreated [$n = 4$], herbicide only [$n = 6$], herbicide + fire [$n = 3$]), using a Tukey HSD test for pairwise comparisons across the three treatments. We examined the role of water depth and frequency of herbicide treatment on *w*FQI by running regression analyses using (1) all sites (managed and unmanaged) and (2) only managed sites. The latter approach allowed us to evaluate whether water depth or treatment history affected plant community recovery at the managed sites. All tests were run using VassarStats (www.vassarstats.net) with $\alpha = 0.05$.

Results

A total of 60 species were found at the 13 sites (11 non-native and 49 native), with C values ranging from 0

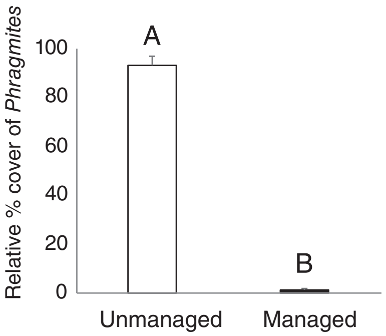

Figure 2. Relative percent cover of *Phragmites* in unmanaged ($n = 4$) and managed ($n = 9$) sites. Letters indicate significant differences; error bars indicate ± SE.

to 8 (Tables S1–S13; Note that the FQA classifies *Phalaris arundinacea* [C = 0] as a native grass, although many genotypes of this species are non-native [Nelson et al. 2014]). There was a dramatic difference in the average percent cover of *Phragmites* between managed (1.2%) and unmanaged sites (93%) ($p < 0.001$; Fig. 2), although the relative percent cover of other non-natives in the managed sites averaged 39.2% (range of 6.4–67.6%; Table 2). The average S, H′, and *w*FQI were all significantly higher in managed wetlands than in unmanaged sites. When compared to unmanaged sites, S was two times greater ($p = 0.017$; Fig. 3; Tables S2–S14), H′ was over four times higher ($p < 0.001$; Fig. 4), and *w*FQI was three and a half times higher ($p < 0.001$; Fig. 5) in managed sites. Variation in *w*FQI within the managed sites ranged from 6.2 to 17.0, with no site achieving the FQI threshold of 19, indicative of high-quality habitat (Table 2). Within managed sites, *w*FQI was 60% higher in sites that received prescribed fire than those that were treated only with herbicide (Fig. 5B; $p < 0.05$), but there was no significant difference in S or H′ between sites that were burned and those that were not (Figs. 3B & 4B).

No significant relationship was detected between water depths and *w*FQI for all sites or for only the managed sites

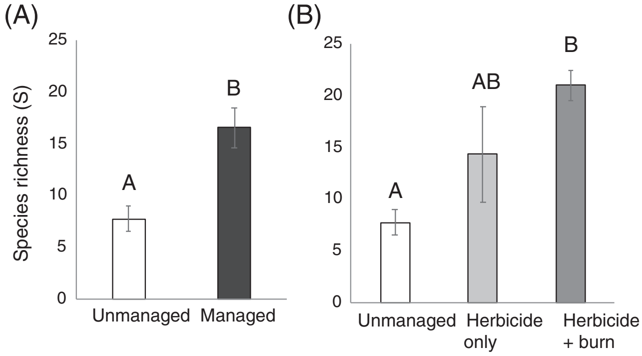

Figure 3. Species richness in (A) unmanaged ($n = 4$) and managed ($n = 9$) sites, and (B) unmanaged ($n = 4$), herbicide-treated only ($n = 6$), and herbicide-treated and burned ($n = 3$) sites. Letters indicate significant differences; error bars indicate ± SE.

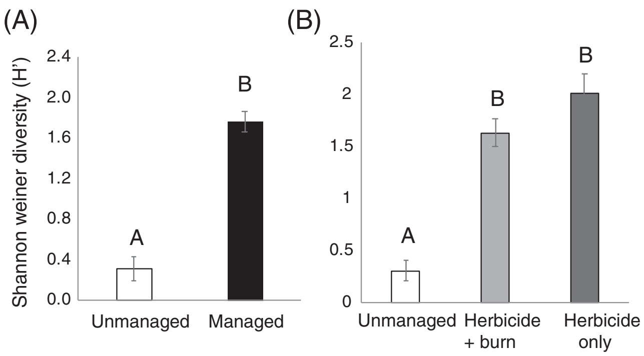

Figure 4. Shannon-Wiener diversity index in (A) unmanaged ($n = 4$) and managed ($n = 9$) sites and (B) unmanaged ($n = 4$), herbicide-treated only ($n = 6$), and herbicide-treated and burned ($n = 3$) sites. Letters indicate significant differences; error bars indicate ± SE.

($p > 0.05$). There was a positive relationship between the number of years a site was treated with herbicide and *w*FQI ($r^2 = 0.322$; $y = 0.858x + 4.630$; $p < 0.05$); however, this was

Table 2. Plant species richness (S), the number of non-native species (N), Shannon-Wiener diversity (H′), cover-weighted floristic quality index (*w*FQI), total FQI (FQI_T), relative percent cover of non-native species (R%C NN), and mean coefficient of conservatism (C) for each site. H + F (herbicide-treated and prescribed fire), H (herbicide-treated), and U (unmanaged).

Site and Treatment		*S*	*NN*	*H′*	*Mean C*	w*FQI*	FQI_T	*R%C NN (%)*
Ver	H + F	21	5	3.3	2.3	17.0	15.1	25
Str	H + F	13	3	3.2	2.1	13.7	11.5	27
Fix	H + F	29	5	3.4	1.6	12.4	18.3	67
Wal	H	19	5	2.8	2.0	13.1	12.2	8
Gib	H	15	4	2.4	1.8	9.3	9.3	58
PC	H	10	3	3.1	1.1	6.3	9.8	6
Tis	H	18	4	3.6	1.9	11.0	15.3	53
LE	H	12	4	3.0	1.5	8.0	10.4	53
HM	H	12	2	3.2	1.5	6.2	11.1	68
PMN	U	11	3	3.1	0.4	6.0	10.3	95
HS	U	5	3	2.2	0.6	1.3	4.9	88
PAP	U	8	5	1.9	0.2	1.1	5.4	99
GW	U	7	2	1.4	0.1	1.1	3.7	99

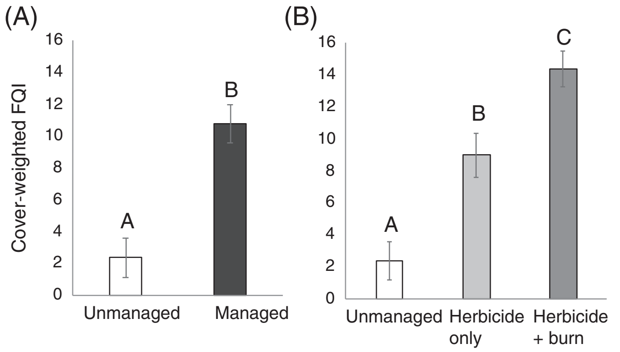

Figure 5. Cover-weighted FQI in (A) unmanaged ($n = 4$) and managed ($n = 9$) sites, and (B) unmanaged ($n = 4$), herbicide-treated only ($n = 6$), and herbicide-treated and burned ($n = 3$) sites. Letters indicate significant differences; error bars indicate ± SE.

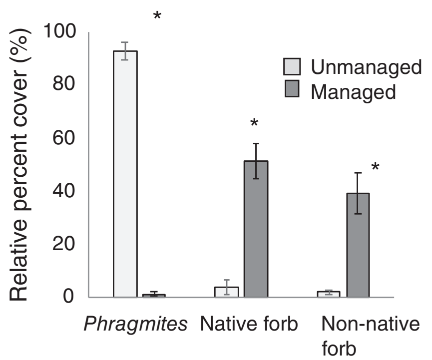

Figure 6. Relative percent cover of plant functional groups in unmanaged and managed coastal wetlands. Stars indicate significant difference between unmanaged and managed sites for each functional group; error bars indicate ± SE.

driven largely by the low *w*FQI in the unmanaged sites. When unmanaged sites were removed from the analysis, there was no significant relationship between years of treatment and *w*FQI ($p = 0.43$).

Plant community functional group composition differed between managed and unmanaged sites. Unmanaged wetlands were dominated by non-native grasses (i.e. *Phragmites*), while managed wetlands were dominated by both native and non-native forbs (Fig. 6). Relative abundance of non-native grass was 92% lower ($p < 0.001$), of non-native forbs was 37% higher ($p = 0.012$), and of native forbs was 48% higher ($p < 0.001$) in managed wetlands compared to unmanaged wetlands. Native grasses and sedges comprised only a small proportion of species at both managed and unmanaged sites.

Discussion

Our study documented the extent of wetland plant community recovery after at least 6 years of herbicide management and establishes a baseline for longer-term assessment. The findings suggest that the model of herbicide management is effective in reducing the cover of *Phragmites* and improving floristic quality and diversity over timescales of 6–10 years. We found dramatically lower coverage of *Phragmites* and significantly higher values of S, H′, and *w*FQI in managed wetlands compared to unmanaged wetlands. Our study also indicates that prescribed fire following herbicide treatment may produce additional benefits in terms of floristic quality, but more research is needed to determine if these benefits are worth the costs. There was no evidence that water levels influenced floristic quality after treatment.

Plant species richness was more than two times greater at managed sites, indicating that increased light and reduced competition following herbicide treatment promotes germination from the seedbank and/or rapid colonization of many species. H′ was more than four times higher in managed than unmanaged sites, highlighting the increase in evenness following management. *w*FQI was also much higher in managed than unmanaged wetlands (approximately three and a half times). Because FQI is sensitive to non-native species, it may be more suitable than S or H′ for assessing invasive species management. However, while *w*FQI was higher in the managed wetlands, no site was above the threshold of 19 required to be considered a high-quality aquatic resource (USFWS FQA 2019). The western Lake Erie shoreline has experienced high levels of disturbance, and warmer temperatures in the southern portion of the Great Lakes facilitate the spread of invasives. Thus pre-settlement plant communities and an FQI value of 19 may be unrealistic goals in this region. Johnston et al. (2010) found a positive relationship between total FQI and latitude in coastal wetlands throughout the Great Lakes, which they argue could be used to establish targets for restoration. Average total FQI in our managed sites was about 6 points higher than the average total FQI in Lake Erie wetlands used in that study and was similar to total FQI found in wetlands at higher latitudes, providing some measure of the success of herbicide management in our wetlands.

Sites treated with prescribed fire following herbicide management had significantly higher *w*FQI (Fig. 5B), but not S or H′ (Figs. 3B & 4B), than sites treated only with herbicide. The positive effect of burning appears to occur through promoting high-quality native species; burning did not have a significant effect on non-native species cover (although the site with the lowest non-native cover was burned; Table 2). Prescribed fire removes standing dead *Phragmites* that can persist for multiple growing seasons blocking sunlight in the same manner as living *Phragmites*. Burning may be most effective when a strong native seed bank exists. Prescribed fire has been shown to increase diversity in other habitat types such as short- and tall-grass prairies (e.g. Bowles & Jones 2013) and oak savannas (e.g. Lettow et al. 2014). Unfortunately, the difficult nature of prescribed fire limits its use; only three of our study sites used this treatment method.

Reinvasion by the same or different invasive species is a key challenge in invasive species management because disturbance, reduced competition, and increased resources following management activities favor invasives (D'Antonio & Meyerson 2002; Kettenring & Adams 2011). While *Phragmites* did not appear in the study plots at some of the managed sites, total eradication was not observed at any site (i.e. it was spotted outside the plots). Other studies have found that multiple years of intense follow-up treatments are typically needed, and total eradication is rare and may not be a realistic goal (Warren et al. 2001; Quirion et al. 2018). We found no relationship between the frequency of follow-up treatments and *w*FQI; however, our study was not well designed to test this, because most of the sites received herbicide treatment in 6 or 7 of the 7 years of the study.

While the overall coverage of *Phragmites* was low at the managed sites (1.2%; Fig. 2), other non-native species were common (Table 2; Fig. 6). A number of these non-natives are known to spread rapidly and outcompete natives and had a relative percent cover of >10% in at least one of the managed sites. At five of the nine managed sites, the plant species with the highest relative percent coverage was a non-native species (two additional sites had a non-native species as the second most abundant). European frog's bit (*Hydrocharis morsus-ranae*) was the most abundant non-native species found in managed sites, with an average relative percent coverage of 24% (maximum of 62% in the Fix Unit). This species was not common in the unmanaged sites (0.3%), likely due to increased shading (Zhu et al. 2014), suggesting that large-scale removal of *Phragmites* in the region has provided the opportunity for European frog's bit to expand. Narrow-leaved cattail (*Typha x glauca* and *Typha angustifolia*) was the next most abundant non-native species with an average relative percent cover of 10%. Other non-natives found in lower abundances in the managed wetlands included flowering rush (*Butomus umbellatus* 3.3%), spiny naiad (*Najas marina* 2.2%), *Phragmites* (1.2%), and purple loosestrife (*Lythrum salicaria* <1%). The first record of water primrose (*Ludwigia grandiflora*) in the state of Michigan was also discovered in a managed site. Other studies have found that reinvasion or the arrival of new invasives can prevent the reestablishment of native vegetation, ultimately preventing desired restoration outcomes (e.g. Aronson & Galatowitsch 2008; Prach & Hobbs 2008). While we did not find a significant relationship between the number of times a site received follow-up treatment and *w*FQI, the presence and ubiquity of non-native species in our plots suggest that ongoing management may be required to maintain or improve floristic quality or gains in floristic quality may be lost.

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LITERATURE CITED

Aronson MFJ, Galatowitsch S (2008) Long-term vegetation development of restored prairie pothole wetlands. Wetlands 28:883–895

Bourdaghs M, Johnston CA, Regal RR (2006) Properties and performance of the floristic quality index in Great Lakes coastal wetlands. Wetlands 26:718–735

Bowles ML, Jones MD (2013) Repeated burning of eastern tallgrass prairie increases richness and diversity, stabilizing late successional vegetation. Ecological Applications 23:464–478

Caplan JS, Wheaton CN, Mozdzer TJ (2014) Belowground advantages in construction cost facilitate a cryptic plant invasion. Aob Plants 6:plu020

Chambers RM, Meyerson LA, Saltonstall K (1999) Expansion of *Phragmites australis* into tidal wetlands of North America. Aquatic Botany 64:261–273

D'Antonio C, Meyerson LA (2002) Exotic plant species as problems and solutions in ecological restoration: a synthesis. Restoration Ecology 10:703–713

D'Antonio CM, Jackson NE, Horvitz CC, Hedberg R (2004) Invasive plants in wildland ecosystems: merging the study of invasion processes with management needs. Frontiers in Ecology and the Environment 2:513–521

DR-WLE CWMA (2013) Detroit River–Western Lake Erie Cooperative Weed Management Area 2012. Annual report. http://driwr.emich.edu/driwr/?q=node/15 (accessed 8 Oct 2017)

Eller F, Scalova H, Caplan JS, Bhattarai GP, Burger MK, Cronin JT, et al. (2017) Cosmopolitan species as models for ecophysiological responses to global change: the common reed *Phragmites australis*. Frontiers in Plant Science 8:1833

Freyman WA, Masters LA, Packard S (2016) The Universal Floristic Quality Assessment (FQA) calculator: an online tool for ecological assessment and monitoring. Methods in Ecology and Evolution 7:380–383

GLRI (2015) Great Lakes Restoration Initiative Report to Congress and the President: Fiscal years 2010–2014, https://www.epa.gov/sites/production/files/2015-09/documents/21050720-report_to_congress-2.pdf

Haslam SM (1972) *Phragmites communis* Trin. (*Arundo phragmites* L., *Phragmites australis* [Cav.] Trin. Ex Steudel). Journal of Ecology 60:585–610

Hazelton ELG, Mozdzer TJ, Burdick DM, Kettenring KM, Whigham DF (2014) *Phragmites australis* in North America and Europe: *Phragmites australis* management in the United States: 40 years of methods and outcomes. Aob Plants 6:plu001

Hejda M, Pysek P, Jarosik V (2009) Impact of invasive plants on the species richness, diversity and composition of invaded communities. Journal of Ecology 97:393–403

Herdendorf CE (1987) The Ecology of the Coastal Marshes of Western Lake Erie: A Community Profile. USFWS Biological Report 85(7.9) 171 pp

Johnston CA (1994) Cumulative impacts to wetlands. Wetlands 14:49–55

Johnston CA, Zedler JB, Tulbure MG (2010) Latitudinal gradient of floristic condition among Great Lakes coastal wetlands. Journal of Great Lakes Research 36:772–779

Kettenring KM, Adams CR (2011) Lessons learned from invasive plant control experiments: a systematic review and meta-analysis. Journal of Applied Ecology 48:970–979

Lettow MC, Brudvig LA, Bahlai CA, Landis DA (2014) Oak savanna management strategies and their differential effects on vegetative structure, understory light, and flowering forbs. Forest Ecology and Management 329:89–98

Mack RN, Simberloff D, Lonsdale WM, Evans H, Clout M, Bazzaz FA (2000) Biotic invasions: causes, epidemiology, global consequences, and control. Ecological Applications 10:689–710

Martin LJ, Blossey B (2013) The runaway weed: costs and failures of *Phragmites australis* management in the USA. Estuaries and Coasts 36:626–632

MEA (Millennium Ecosystem Assessment) (eds) (2005) Ecosystems and human well-being: wetlands and water synthesis: a report of the Millennium Ecosystem Assessment. World Resources Institute, Washington D.C.

Miller JR, Hobbs RJ (2007) Habitat restoration – do we know what we're doing? Restoration Ecology 15:382–390

Mozdzer TJ, Hutto CJ, Clarke PA, Field DP (2008) Efficacy of imazapyr and glyphosate in the control of non-native *Phragmites australis*. Restoration Ecology 16:221–224

Nelson MF, Anderson NO, Casler MD, Jakubowski AR (2014) Population genetic structure of N. American and European *Phalaris arundinacea* L. as inferred from inter-simple sequence repeat markers. Biological Invasions 16:353–363

Prach K, Hobbs RJ (2008) Spontaneous succession versus technical reclamation in the restoration of disturbed sites. Restoration Ecology 16:363–366

Pysek P, Richardson DM (2010) Invasive species, environmental change and management, and health. Pages 25–55. In: Gadgil A, Liverman DM (eds) Annual review of environment and resources. Vol 35. Annual Reviews, Palo Alto, California

Quirion B, Simek Z, Davalos A, Blossey B (2018) Management of invasive *Phragmites australis* in the Adirondacks: a cautionary tale about prospects of eradication. Biological Invasions 20:59–73

Saltonstall K (2002) Cryptic invasion by a non-native genotype of the common reed, *Phragmites australis*, into North America. Proceedings of the National Academy of Sciences of the United States of America 99:2445–2449

Stirling G, Wilsey B (2001) Empirical relationships between species richness, evenness, and proportional diversity. American Naturalist 158:286–299

Suding KN (2011) Toward an era of restoration in ecology: Successes, failures, and opportunities ahead. Pages 465–487. In: Futuyma DJ, Shaffer HB, Simberloff D (eds) Annual review of ecology, evolution, and systematics. Vol 42. Annual Reviews, Palo Alto, California

USFWS FQA (US Fish and Wildlife Service Floristic Quality Assessment) (2019) https://www.fws.gov/midwest/endangered/section7/s7process/plants/FQA.html (accessed Feb 2019)

Warren RS, Fell PE, Grimsby JL, Buck EL, Rilling GC, Fertik RA (2001) Rates, patterns, and impacts of *Phragmites australis* expansion and effects of experimental *Phragmites* control on vegetation, macroinvertebrates, and fish within tidelands of the lower Connecticut River. Estuaries 24: 90–107

Weinstein MP, Balletto JH (1999) Does the common reed, *Phragmites australis*, affect essential fish habitat? Estuaries 22:793–802

Wortley L, Hero J-M, Howes M (2013) Evaluating ecological restoration success: a review of the literature. Restoration Ecology 21:537–543

Zedler JB, Kercher S (2004) Causes and consequences of invasive plants in wetlands: opportunities, opportunists, and outcomes. Critical Reviews in Plant Sciences 23:431–452

Zhu B, Ellis MS, Francher KL, Rudstam LG (2014) Shading as a control method for invasive European Frogbit (*Hydrocharis morsus-ranae* L.). PLoS One 9:e98488

Zimmerman CL, Shirer RR, Corbin JD (2018) Native plant recovery following three years of common reed (*Phragmites australis*) control. Invasive Plant Science and Management 11:175–180

Supporting Information

The following information may be found in the online version of this article:

Table S1. Species information for the Vermet unit of Pointe Mouillee (Herbicide + prescribed fire).
Table S2. Species information for the Strong site (Herbicide + prescribed fire).
Table S3. Species information for the Fix site (Herbicide + prescribed fire).
Table S4. Species information for the Walpatch unit of Pointe Mouillee (Herbicide).
Table S5. Species information for the Gibraltar Bay Wetland (Herbicide).
Table S6. Species information for the Plum Creek Bay site (Herbicide)
Table S7. Species information for the Tiskoff site (Herbicide).
Table S8. Species information for the Lake Erie Metropark site (Herbicide)
Table S9. Species information for the Humbug Marsh site (Herbicide)
Table S10. Species information for the North Pointe Mouillee site (Untreated)
Table S11. Species information for the South Humbug Marsh site (Untreated)
Table S12. Species information for the Pointe Aux Peaux site (Untreated).
Table S13. Species information for the Gibraltar Wetlands site (Untreated).

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