Information Management

An analysis of aquatic invasive species management in the Niagara region of Ontario, Canada: establishment of a database to improve knowledge sharing

Lyn Brown[1] and Liette Vasseur[1,2,*]

[1]Environmental Sustainability Research Centre, Brock University, 1812 Sir Isaac Brock Way, St Catharines, On L2S3A1, Canada
[2]UNESCO Chair on Community Sustainability: From Local to Global, Dept. of Biological Sciences, Brock University, 1812 Sir Isaac Brock Way, St Catharines, On L2S3A1, Canada

Author e-mails: lvasseur@brocku.ca (LV), lbrow43@uwo.ca (LB)

*Corresponding author

Abstract

The UN Convention on Biological Diversity has declared invasive species a global threat and requested increased data sharing to prevent further impact. Existing worldwide and local databases mainly focus on distribution, abundance, identification, and impacts of invasive species, but very few record management activities. In the Niagara region of Ontario, Canada, no database focuses specifically on invasive species management. The goal of this study was to document current aquatic and riparian invasive species management activities in the Niagara region and develop a database that would become a tool to facilitate collaboration at the regional level. The objectives were to (1) inventory current invasive species detection and control activities in the Niagara region; (2) examine perceived efficacy of control techniques; and (3) develop a database integrated with a GIS mapping component. Seventy-one organizations involved in riparian/aquatic invasive species management in the Niagara region were contacted and 16 in-depth interviews were conducted. In 2017–2018, 35 separate control efforts were reported, involving 10 riparian invasive species and two aquatic invasive species, mostly concentrated along the Niagara River. Collaboration efforts were minimal, occurring for only six specific projects. Recommendations include develop a regional invasive species plan; increase control efforts along the Welland Canal and Lake Erie shoreline; adopt a wider variety of control techniques; and increase collaboration, information-sharing and resource-sharing among organizations. Overall, the newly developed database provides a baseline for the current state of aquatic and riparian invasive species management activities in the region. It can also help bridge the gap between invasive species science and decision-making by forming a tool to identify resource-sharing opportunities, management efficacy, priority areas, areas of improvement, and future resource needs. The database will enrich the global invasive species information network by providing Niagara-specific information. The database could also act as a model for tracking management activities of other invasive species and in other regions of North America.

Key words: ArcGIS, community collaboration, data management, invasive species database, riparian species, species control

Introduction

As of 2019, 187 nonindigenous aquatic species have established themselves in the Great Lakes region (Sturtevant et al. 2019). Many of these species are

considered invasive species because they are harmful in some way (Russell and Blackburn 2017). They could potentially be in the Niagara region of Ontario, Canada, an ecologically and economically valuable area that lies within the Great Lakes region. Lack of information sharing, and collaboration may limit invasive species managers' capacity to respond to the threats of invasive species and undermine attempts to manage and control them in Ontario and specifically in the Niagara region (Sherman 2015). Databases can provide support for invasive species management activities, by implementing knowledge sharing (Ricciardi et al. 2000; Graham et al. 2008).

Researchers and international organizations have called for the creation of invasive species databases (Ricciardi et al. 2000; Ramsar Convention Secretariat 2002; United Nations Environment Programme [UNEP] and Convention on Biological Diversity [CBD] 2002; Graham et al. 2008; Holcombe and Stohlgren 2010). The aggregation of many local databases can be combined to form a comprehensive global database of invasive species. Some international and regional databases for North America, Europe, and the United States include: the Global Invasive Species Database (GISD), Global Register of Introduced and Invasive Species (GRIIS), Global Invasive Species Information Network (GISIN), North American Invasive Species Information Network (NAISN), National Institute of Invasive Species Science (NIIS), and Nonindigenous Aquatic Species (NAS). Within the vicinity of the Niagara region, local databases include the Great Lakes Aquatic Nonindigenous Species Information System (GLANSIS) and the Ontario Invasive Plant Council (OIPC) compendium, which cover the Great Lakes region and Ontario, respectively. However, GLANSIS focuses on mapping invasive species' distribution rather than control sites (National Oceanic and Atmospheric Administration [NOAA] 2018), and the OIPC compendium does not contain any organizations specific to the Niagara region (OIPC 2012). No databases are currently available specifically for the Niagara region of Ontario, Canada.

This study aimed to develop a local aquatic invasive species management database for the Niagara region of Ontario. The database can contribute to the global invasive species information network by documenting aquatic invasive species locations and management strategies in the region, and facilitating collaboration. It can also help bridge the gap between invasive species science and decision-making by forming a tool to identify resource-sharing opportunities, management efficacy, priority areas, areas of improvement, and future resource needs. The objectives were to (1) inventory current invasive species detection and control activities in the Niagara region; (2) examine perceived efficacy of control techniques; and (3) develop a database integrated with a GIS mapping component.

A major factor in the decision to make aquatic and riparian invasive species the focus of this study was the economic and ecological importance of water to the region. The Niagara region contains two of the Great Lakes

Table 1. Components of the invasive species management process and their associated tools *.

Component	Definition of Component	Tools
Predict	-Determine which species are entering a habitat, including invasive species	-Models and watch lists
Identify	-Identify among those species, which are invasive	-Watch lists, decision-making trees, and databases
Assess Risk	-Assess risk of invasion, implications, costs, management options	-Risk assessments and economic models
Detect	-Detect invasive species in the field	-Field surveys, eDNA barcoding, remote sensing, and invasive detection dogs
Monitor	-Track invasive species distribution and abundance	-Field data and visualize them with GIS maps
Contain	-Restrict an invasive species' range	-Quarantine facilities
Eradicate	-Remove all individuals of an invasive species	-Same techniques as control
Control	-Reduce the impact of an invasive species	-Physical, chemical, biological, genetic, and gastronomic control methods
Evaluate	-Assess the efficacy of management actions	-Research studies and experience

* This table was prepared based on information from the following sources: Smith and Tibbles 1980; Mansell et al. 1998; GLFC 2000; Mooney and Hobbs 2000; Djuricich and Janssen 2001; Clout and Williams 2010; Ling 2010; Piola et al. 2010; Nunez et al. 2012; Crowder and Hardwood 2014; Carboneras et al. 2017; DFO 2018.

and their connecting channel the Niagara River, along with a manageable number of other waterways and ponds. In addition, the Niagara River has been designated as a Ramsar Site (a wetland of international importance) (Ramsar Convention on Wetlands 1971) on the United States side as of October 2019, and is in the process of being designated on the Canadian side. In this study, aquatic invasive species are invasive species that live exclusively in water, while riparian invasive species are invasive species that live along watercourses or waterbodies (U.S. Department of Agriculture [USDA] 1996). Aquatic and riparian invasive species were classified as such according to the databases listed in Supplementary material Table S1. Of note is that in Sturtevant et al.'s (2019) study, some of the aquatic species included wetland plants (facultative and obligate facultative), which would be considered riparian in this study.

Materials and methods

The study area was the Ontario portion of the Niagara watershed. The Niagara Region's boundaries were used to define the limits of the study area because the Region (capitalized only when referring to the regional government) closely approximates the watershed boundaries. It includes the Lake Erie and Lake Ontario shorelines, and the Canadian side of the Niagara River. The Ecosystem Approach Principles (CBD 2000) provided a broad context for decision-making in designing this study's research questions, as well as the structure and content of the database. The principles served as a reminder to consider how invasive species management in the Niagara region relate to larger issues, including the sustainability of its social-ecological system.

For the inventory, a questionnaire (Appendix 1) was developed based on invasive species management activities (Table 1) described in several sources: OIPC best management practices (Ontario Ministry of Natural Resources and Forestry [ONMNRF] 2011, 2016); Ontario's Invading Species Awareness

Program website (Ontario Federation of Anglers and Hunters [OFAH] 2018); Department of Fisheries and Oceans Canada [DFO] reports, like those used in Asian carp control (Colm et al. 2018); activities described by ONMNRF in their shared projects with OIPC, OFAH and DFO; invasive species management efforts described in GISD (Invasive Species Survival Group [ISSG] 2018) and the Centre for Agriculture and Bioscience International [CABI] databases (CABI 2018); and invasive species management efforts described in the literature by Smith and Tibbles (1980), Great Lakes Fishery Commission [GLFC] (2000), Joshi et al. (2004), Grice (2010), Ling (2010), and Crowder and Hardwood (2014).

Seventy-one potential organizations were identified for possible inclusion in this study based on their environmental focus and interest in the Niagara region, including governmental organizations (federal, provincial, and municipal), the public educational sector (four school boards, one college and one university), and environmental groups. Environmental groups were included because preliminary research indicated they were involved in invasive species work in the Niagara region. Private individuals, businesses, and other organizations were excluded because it was not feasible to accurately identify and contact the several thousand potential subjects, given time and financial constraints. To identify specific members of the survey population, internet searches, networking, and snowball sampling were conducted. Ultimately, 16 organizations identified as part of the survey population were interviewed in person or by phone, each for up to 45 minutes. The mobile data collection application Collector for ArcGIS was used during interviews for precise location of invasive management activities.

Survey questions (Appendix 1) included the following:

1. Who is working on aquatic and riparian invasive species in the Niagara region?
2. What species do they prioritize and why?
3. What techniques are being used to detect and control these invasive species?
4. Where are control efforts occurring?
5. Are control efforts effective?
6. What are the costs associated with controlling these invasive species?
7. Are organizations collaborating with one another to address these invasive species?
8. Is invasive species activity increasing?

Data analysis

Data identifying controlled invasive species and techniques for their detection and control were collected and tabulated for analysis. Responses about invasive species priorities were pooled, and the number of organizations

controlling aquatic and riparian invasive species was tabulated. Data on costs and man-hours were summed to form a baseline for the Niagara region. Control efficacy ratings were a self-reported measure to estimate how effective a control method was at eradicating an invasive species. Respondents were asked to choose whether a control got rid of 0–25%, 25–50%, 50–75%, 75–100%, or an unknown amount of the invasive species in the area where they applied the control. Average ratings were calculated for each organization and then for the Niagara region. Because the number of respondents managing invasive species was small (n = 16), no meaningful statistical analyses could be carried out on the data collected about control technique efficacy. Content analysis identified common themes in the responses to the open-ended question about barriers. The software Cytoscape 3.7.1 was used to combine coordination and information sharing activities to develop a network that showed which organizations collaborated with which other organizations on specific invasive species.

Development of the database and ArcGIS Online map

From the data acquired in the first phase a database was constructed using Microsoft Access (https://www.dropbox.com/sh/y1bswwdxbgygd9i/AADh V35eD7ZSQ5X8tN2PodNRa?dl=0&preview=Brock_Brown_Lyn_2019_Ac cess_Database.accdb) [note: to view the database, press the download button] that included invasive species, detection and control techniques, control location, control efficacy, organization involved, and organizational contact information. This interactive system was designed to be publicly accessible and user-friendly. Therefore, a version of the database was also made available in Microsoft Excel (https://www.dropbox.com/s/buobz2hupmzl6jf/ Brock_Brown_Lyn_2019_Excel_Database.xlsx?dl=0) [note: to fully query the database, download the file].

ArcGIS software was used (ArcMap 10.6.1, ArcGIS Online, and Collector for ArcGIS) to create the map (http://www.arcgis.com/apps/web appviewer/index.html?id=beb4ee0f84f04b4ea1f3dcc4842f966a&extent=-8906 143.4734%2C5282073.6101%2C-8771614.3036%2C5355300.2832%2C102100). To display the invasive species control sites as points on the map, a geodatabase feature class defining those points was made using ArcMap. That feature class was shared as a service on ArcGIS Online, which was downloadable into Collector. Collector was used to generate the control site point data during interviews, and these data were synched with a corresponding feature class in ArcGIS Online, which was then used to develop the final web app map available online. This web application allows users to find where invasive species are being controlled and provides a pop-up box with information on controls, control efficacy and organizational contacts. Users can filter the map to specify which control locations they want to view, based on any combination of invasive species, control type, control efficacy or organization. The open-access database

and map are hosted by the Brock University United Nations Educational, Scientific and Cultural Organization (UNESCO) Chair website: https://brocku. ca/unesco-chair/research/invasive-species/.

Results

Of the 71 groups that were contacted, 55 did not meet the inclusion criteria of detecting or controlling aquatic or riparian invasive species in the Niagara region in 2017–2018. Of the 16 organizations interviewed, eight only detected invasive species, and eight detected and controlled invasive species. The majority of the species being detected or controlled were riparian plants (n = 24), followed by fish (n = 6), aquatic invertebrates and riparian insects (n = 3) (Table S2). When asked about top priority invasive species, the typical response was that the priority invasive species were the same ones as those being controlled. The exception to this was that the DFO prioritized sea lamprey (*Petromyzon marinus* L., 1758) and Asian carp, even though no control was occurring in the region.

Twelve organizations used visual surveys to detect riparian and aquatic invasive species. Organizations reported using visual surveys because they already knew where the invasive species were from fieldwork or others reporting to them. Notable exceptions were that OFAH used public citizen science reports from EDDMapS and these reports come from citizen scientists who may use multiple detection methods, and DFO-AC used various techniques for detecting Asian carp, including nets, electrofishing, and light traps. CFIA was beginning to test cutting-edge unmanned aerial vehicles. Other detection methods included chemicals, structured sampling, and observation by anglers.

The DFO was the only group with a proactive program to detect invasive species in that the aim of the program was to prevent the introduction of new aquatic invaders through regular systematic surveys of waterways. However, the DFO only had funding to focus on Asian carp and sea lamprey, neither of which were currently present in the Niagara region. The DFO program contrasts to other organizations' detection methods which were more reactive (non-systematic visual sightings of invasive species and their programs focused more on controlling the spread of existing invasive species).

In terms of riparian invasive species, the groups controlling the most riparian invasive species were the Niagara Parks Commission (NPC) (n = 10) and Friends of Malcolmson Eco-Park (FOMEP) (n = 3). Only one riparian invasive species was controlled by Hamilton Naturalists' Club (HNC), Canadian Food Inspection Agency (CFIA), Niagara College, Town of Niagara-On-The-Lake Irrigation Committee (NOTL Irrigation Committee), and Niagara Peninsula Conservation Authority (NPCA). Ontario Power Generation (OPG) was the only organization controlling any aquatic invasive species in the Niagara region in 2017–2018. The OPG was controlling two

Table 2. Types of control used in the Niagara region for aquatic/riparian invasive species in 2017–2018.

| Invasive Species	Chemical Control	Physical Control
Quagga Mussel (*Dreissena rostriformis bugensis*)	X	X
Zebra Mussel (*Dreissena polymorpha*)	X	X
Common Buckthorn (*Rhamnus cathartica*)	X	
Dog-strangling Vine (*Cynanchum rossicum*)	X	
Emerald Ash Borer (*Agrilus planipennis*)	X	
Garlic Mustard (*Alliaria petiolata*)		X
Hemlock Woolly Adelgid (*Adelges tsugae*)		X
Oriental Bittersweet (*Celastrus orbiculatus*)	X	
Phragmites (*Phragmites australis* subsp. *australis*)	X	X
Purple Loosestrife (*Lythrum salicaria*)		X
Tartarian Honeysuckle (*Lonicera tatarica*)	X	
Tree of Heaven (*Ailanthus altissima*)	X	

species: quagga mussel (*Dreissena rostriformis bugensis* Andrusov, 1897) and zebra mussel (*Dreissena polymorpha* Pallas, 1771).

NOTL was the only municipality undertaking some sort of invasive species management efforts (e.g., limited mowing of some scattered patches of phragmites (*Phragmites australis* ssp. *australis* Trin. Ex Steud). Niagara College did limited-intermittent control of phragmites in a couple of patches for teaching purposes. None of the Niagara school boards were participating in invasive species management efforts, and neither was Brock University (2018, *personal communication*).

Thirty-five separate control efforts were reported and included in the database. Of the 42 riparian/aquatic invasive species detected in the Niagara region in 2017–2018, only 12 were controlled by at least one organization at one site. This meant less than 30% of the detected invasive species in 2017–2018 were subject to some control activity. The species most often controlled included common buckthorn (*Rhamnus cathartica* L.) and phragmites. Three organizations attempted to control phragmites. Tartarian honeysuckle (*Lonicera tatarica* L.) was controlled by two organizations, as was purple loosestrife and hemlock woolly adelgid (*Adelges tsugae* Annand, 1928).

Across the organizations, the only types of controls employed were chemical and/or physical. Six organizations were using physical control, while four organizations were using chemical control in the Niagara region. Phragmites, quagga mussel, and zebra mussel were the only invasive species that had more than one type of control applied (chemical and physical) (Table 2).

Spatially, invasive species were being controlled along the Niagara Parkway (n = 7), at the Niagara Glen (n = 5), Malcolmson Eco-Park (n = 3), generating stations (n = 2), Grimsby Wetlands (n = 1), around Niagara College (n = 1), Queenston docks (n = 1), and Saint Johns Conservation Area (n = 1) (Figure 1). Within the Niagara region, the 16 organizations did not control any invasive species along the Welland Canal, Lake Erie or Lake Ontario shoreline, or in creeks.
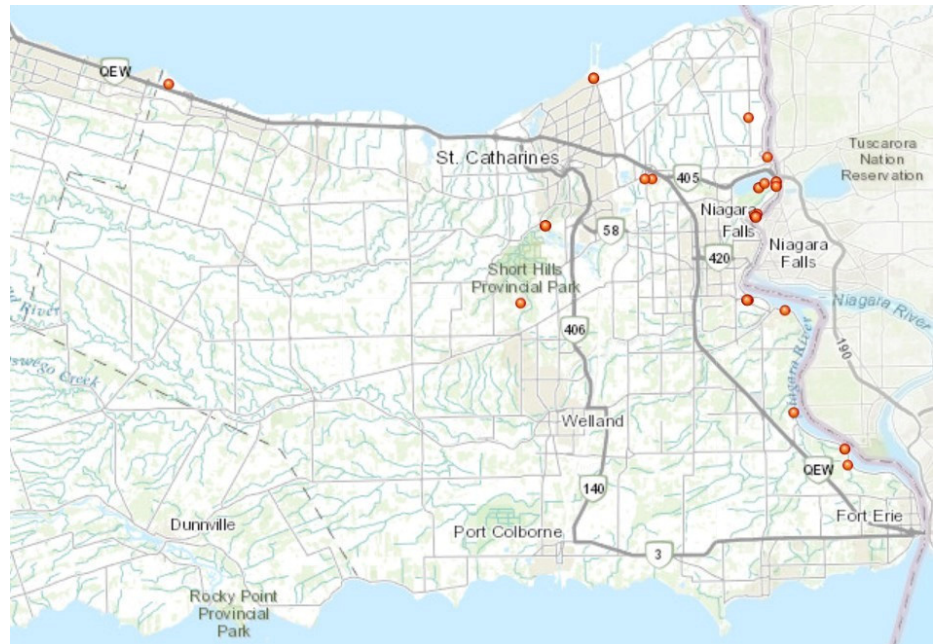
Figure 1. Screenshot of ArcGIS Online web map app. This shows 2017–2018 aquatic and riparian invasive species control sites in the Niagara region of Ontario, Canada.
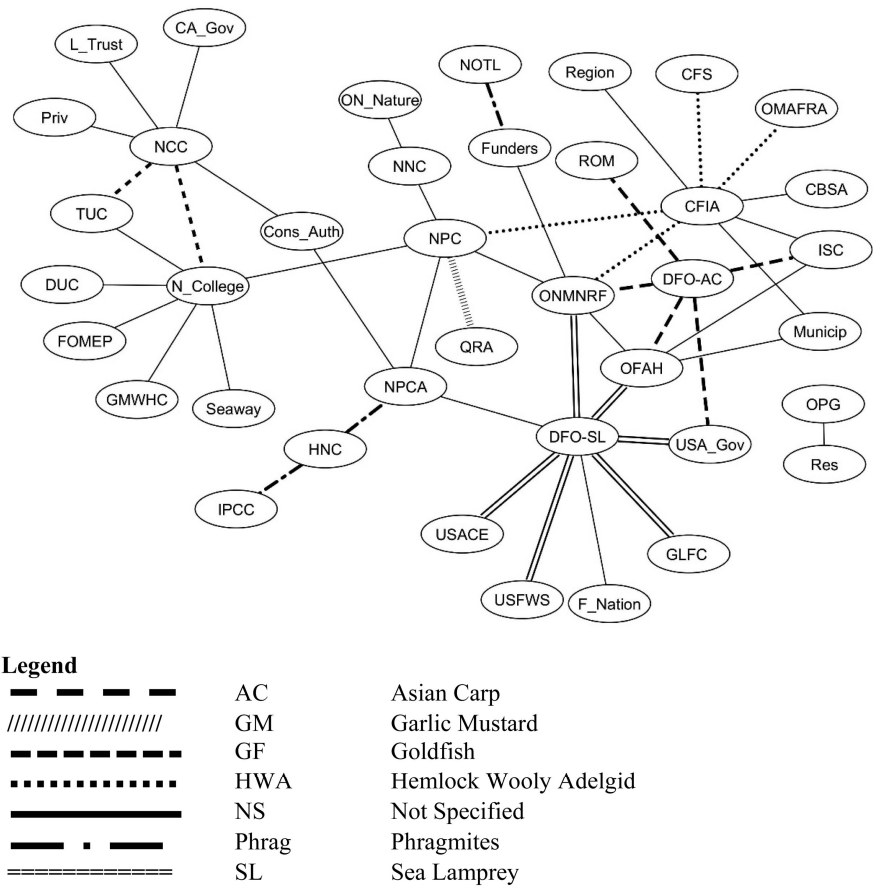
Seven organizations reported cost information. Total man-hours spent controlling aquatic and riparian invasive species in the Niagara region in 2017/18 was estimated at 4,570. The total direct expenses were CAD 1,216,718/year. Direct costs were primarily for chemicals, mowing, installation of control treatment infrastructure, and labour.

With respect to barriers, five organizations mentioned that lack of funding prevented them from managing invasive species. Four organizations mentioned lack of man-power and two mentioned herbicide laws and logistics. Lack of interest and "science not being able to fix the problem" were mentioned by one organization. However, five organizations said there were no barriers preventing invasive species management.

Organizations provided mixed responses to the question of invasive species activity, in terms of distribution and abundance. Overall, more participants reported that invasive species populations were increasing (n = 8 organizations) than decreasing (n = 3 organizations). Five stated that invasive species distribution and abundance remained the same. Note that answers from this question were not truly comparable because some respondents answered for overall invasive species populations versus specific invasive species populations (e.g., NPC answered that overall invasive species populations were increasing, while HNC answered that phragmites populations were increasing).

The network analysis from this study revealed that 39 organizations were linked by invasive species-related collaborative activities in the region (Figure 2). Note that these results reflect this study's analysis rather than an official network in the region. Additionally, the network only contains collaborative efforts by interviewed organizations. Figure 2 may not depict

Legend

▬ ▬ ▬ ▬	AC	Asian Carp
/////////////////////	GM	Garlic Mustard
▬ ▬ ▬ ▬ ▬ ▬	GF	Goldfish
▪▪▪▪▪▪▪▪▪▪▪▪▪▪	HWA	Hemlock Wooly Adelgid
———————	NS	Not Specified
▬ ▪ ▬ ▪ ▬	Phrag	Phragmites
=============	SL	Sea Lamprey

Figure 2. Network of invasive species collaboration efforts in the Niagara region, Ontario, Canada. Nodes represent organizations and edges represent specific invasive species-related collaboration efforts. Abbreviations for organizations are as follows: CA_Gov (Canadian Government); CBSA (Canadian Border Services Agency); CFIA (Canadian Food Inspection Agency); CFS (Canadian Forest Service); Cons_Auth (Conservation Authorities); DFO-AC (Department of Fisheries and Oceans Canada, Fisheries and Aquatic Sciences); DFO-SL (Department of Fisheries and Oceans Canada, Sea Lamprey Control Centre); DUC (Ducks Unlimited Canada); F_Nation (First Nations); FOMEP (Friends of Malcolmson Eco-Park); Funders (Funders); GLFC (Great Lakes Fishery Commission); GMWHC (General Motor Wildlife Habitat Council); HNC (Hamilton Naturalists' Club); IPCC (Invasive Phragmites Control Centre); ISC (Invasive Species Centre); L_Trust (Land Trusts); Municip (Municipalities); N_College (Niagara College Canada); NCC (Nature Conservancy of Canada); NNC (Niagara Nature Clubs (Bert Miller Nature Club, Niagara Falls Nature Club, and the Peninsula Field Naturalists)); NOTL (Niagara-On-The-Lake Irrigation Committee); NPC (Niagara Parks Commission); NPCA (Niagara Peninsula Conservation Authority); OFAH (Ontario Federation of Anglers and Hunters); OMAFRA (Ontario Ministry of Agriculture, Food and Rural Affairs); ON_Nature (Ontario Nature); ONMNRF (Ontario Ministry of Natural Resources and Forestry); OPG (Ontario Power Generation); Priv (Private Land Owners); QRA (Queenston Residents Association); Region (The Niagara Region); Res (Researchers); ROM (Royal Ontario Museum); Seaway (Seaway); TUC (Trout Unlimited Canada); USA_Gov (USA Government); USACE (U.S. Army Corps of Engineers); and USFWS (U.S. Fish and Wildlife Service).

all collaborative efforts by non-interviewed organizations. Collaboration efforts were limited to six invasive species management projects occurring in the Niagara region: hemlock woolly adelgid control at Niagara Glen (NPC and CFIA); Asian carp management projects (DFO-AC and OFAH); phragmites control in Grimsby (HNC and NPCA); garlic mustard (*Alliaria petiolata* Bieb.) control at the Queenston docks (NPC and Queenston Residents' Association (QRA)); sea lamprey control (DFO-SL, U.S. Army Corps of Engineers (USACE), U.S. state agencies and ONMNRF; and

invasive species monitoring (NPC, CFIA, and Niagara Nature Clubs (Bert Miller Nature Club [BMNC], Niagara Falls Nature Club [NFNC], and the Peninsula Field Naturalists [PFN]). Ten organizations reported some coordination activities in 2017–2018 (Table S3).

All organizations reported that they shared information, although the amount and types of information shared varied among organizations. Twelve organizations shared information with 32 cited partners. The information was about scientific findings, monitoring, funding, projects, advice, certifications, and scheduling. No information sharing was mentioned that dealt with planning or decision-making specifically, although there was probably information sharing on joint projects. Seven organizations shared information with the public through the Invading Species Awareness Program website, reports/publications, or workshops. There was an apparent lack of information sharing by the organizations studied with the education sector: only one organization shared information at a research conference. Lastly, two organizations made their information available upon request.

For all control efforts occurring in the Niagara region in 2017–2018, the average control efficacy rating was 61.2–86.2%. There were not enough control efficacy ratings to run any statistical analyses due to the limited number of control efforts undertaken by only a few organizations. No relationship could be found between average organizational control efficacy rating and the number of groups they coordinated with. NPC coordinated with the most groups (n = 9), and its average organizational control efficacy rating fell in the middle (62.5–87.5%). In comparison, OPG coordinated with the fewest number of groups (n = 1), but had one of the highest organizational control efficacy ratings at 75–100%.

The data were successfully integrated into a database using Microsoft Access (https://www.dropbox.com/s/4k2ra7jot4gcg8o/Brock_Brown_Lyn_2019_Access_Database.accdb?dl=0) [note: to view the database, press the download button] and Excel (https://www.dropbox.com/s/buobz2hupmzl6jf/Brock_Brown_Lyn_2019_Excel_Database.xlsx?dl=0) [note: to fully query the database, download the file] as described. The map (http://www.arcgis.com/apps/webappviewer/index.html?id=beb4ee0f84f04b4ea1f3dcc4842f966a&extent=-8906143.4734%2C5282073.6101%2C-8771614.3036%2C5355300.2832%2C102100) was successfully produced into a web app as described in Methods. It displays where aquatic and riparian invasive species were being controlled in the Niagara region in 2017–2018. For each control site, there is a pop-up box of information on the invasive species, the control, control efficacy, organization, and contact information (Figure 3).

Discussion

How does this study contribute to invasive species management?

This study is the first attempt to develop an aquatic/riparian invasive species database specifically for the Niagara region of Ontario, Canada.

Figure 3. Screenshots of map and pop-up box. The map shows where aquatic and riparian invasive species are being controlled in the Niagara region. When users click on a point, a pop-up box appears displaying information on the invasive species being controlled, the type of control, control effectiveness, and contact information.

Practically, this forms a foundation and baseline for the current state of aquatic and riparian invasive species management initiatives in the Niagara region. This database already has an international presence since the official websites of several major organizations in Canada and the U.S. have added links to this study's database, including the Environmental Protection Agency (EPA) (https://www.epa.gov/greatlakes/invasive-species-great-lakes), USDA (https://www.invasivespeciesinfo.gov/resources-indexed?f%5B0%5D=field_location%3A163&page=9), NOAA (https://www.glerl.noaa.gov/glansis/additionalResourcesPartners.html), Invasive Species Centre (https://www.invasivespeciescentre.ca/), and the Canadian Council of Invasive Species (https://canadainvasives.ca/programs/resources/). Databases can operate at different spatial scales with the role of local databases being to a create richer and more accurate global database network (Simpson et al. 2009). The Niagara Aquatic and Riparian Invasive Species Control Database is now a part of the global information network on invasive species made up of over 150 databases (Ricciardi et al. 2000; Sellers 2004; Deriu et al. 2017).

Locally, this study's database can help bridge the gap between invasive species management science and decision-making to determine which control methods are effective and appropriate given the situation and location. For example, an environmental club in the Niagara Region that wants to address common buckthorn but does not know where to start, could view the database, and see that another group like the NPC is controlling common buckthorn with triclopyr, and that this strategy is 75–100 percent effective. The club could contact the NPC to gain insights into the invasive species control technique, specifics on timing and application, and costs.

What are the major findings?

The most striking findings were the limited invasive species work occurring in the Niagara region and the unorganized nature of the

management response to aquatic and riparian invasive species. These findings have serious implications for the future of invasive species management in this part of Ontario and beyond.

What detection and control methods should be used in the Niagara region?

Even though 42 invasive species were detected in the Niagara region in 2017–2018, techniques like eDNA, remote sensing, and invasive species detection dogs can increase detection abilities, speed, efficacy, and ensure more invasive species are found that may bypass human eyes (Joshi et al. 2004; Alvarez-Taboada et al. 2017; Klymus et al. 2017; Shields and Austin 2018; Working Dogs for Conservation 2018). Early detection is an essential part of tackling an invasive species problem proactively, because preventing invasive species from becoming established is much cheaper than trying to eradicate an established population (Leung et al. 2002). An example of effective proactive management is the Canadian Federal Government's Asian Carp Program. In 2009–2010, when a lone silver carp (*Hypophthalmichthys molitrix* Valenciennes, 1844) was detected with eDNA above the Chicago Sanitary and Shipping Canal, this led to surveys, containment and eradication (Jerde et al. 2011). The Asian carp early detection and rapid response program should be a catalyst to inspire more proactive management of aquatic and riparian invasive species.

Many organizations that detected invasive species took no control steps. Of the 42 detected invasive species, only 12 were controlled in any way. Organizations were not asked why they did not engage in control efforts, but this question should be included in future studies. This study speculates possible reasons for the low number of controlled species relative to the number of detected species. 1) Time lags in detection reporting versus control implementation. Crooks (2005) notes that time lags within the invasion process may lead managers to perceive a lower risk of invasion, and stall decision-making and action surrounding control efforts. 2) Some detections may not trigger control because of different invasive species, priorities, impacts, or lack of required resources to control invasive species. 3) Trebitz et al. (2017) discusses the tradeoff between allocating resources for detection or control, and brings up that the resources for both usually come from the same pot. Therefore, organizations in this study may have been allocating more resources for detection rather than control.

Of the 12 controlled invasive species only two were aquatic. This study considers the limited number of aquatic invasive species control efforts a major gap, given there are potentially 187 nonindigenous aquatic species in the Great Lakes region (Sturtevant et al. 2019). This problem is being further exacerbated because new aquatic invaders enter the Great Lakes at a rate of 0.25 species/year (Sturtevant et al. 2019).

In 2017–2018, the 16 organizations in the region relied exclusively on physical control, chemical control or both. Even though it was not specifically

asked why organizations in the region use physical and chemical control techniques and not biological (Crowder and Hardwood 2014), genetic (Thresher et al. 2019), or gastronomic control techniques (Nunez et al. 2012), three possible reasons can be speculated. 1) Physical and chemical control techniques are favoured because they are effective, so there is no incentive to change. 2) Physical and chemical control techniques are the most common (Kettenring and Adams 2011; OIPC 2012), so the region may use them because of their popularity. 3) Physical and chemical control are proven methods as opposed to other methods that can be risky. This study therefore recommends that local organizations in the region should branch out to control methods like gastronomic, biological, and genetic controls because best practices of invasive species management set out by ONMNRF (2011), Sherman (2015), and ONMNRF (2016) advocate using multiple control methods rather than solely relying on one.

Where are the current invasive species control efforts taking place?

There appears to be no baseline inventory of invasive species and their locations in the Niagara region. Such an inventory could be used to track invasive species' expansion and/or control. The results suggest that many aquatic and riparian invasive species could potentially be going unnoticed and unchecked in the region. Spatially, the most invasive species control efforts were concentrated along the edge of the Niagara River. These efforts were driven by the NPC who owns and manages much of the land along the Niagara River. Based on the 16 interviewed organizations, no invasive species were detected or controlled along the Welland Canal and no invasive species work was occurring along the Lake Erie or Lake Ontario shoreline, except for the DFO-AC work.

This study concludes that the Welland Canal is considered a major gap, especially since it has been identified as a top dispersal pathway for aquatic invasive species between Lake Erie and Lake Ontario (Kim and Mandrak 2016). In 1989, it was the Welland Canal that allowed zebra mussels to move from Lake Erie to the Lake Ontario drainage basin (Griffiths et al. 1991).

This study recommends that the Lake Erie shoreline should be among the priorities for invasive species work within the Niagara region because it is one of the largest waterbodies shared by the U.S. and Canada, and it can act as a major vector for aquatic invasive species. This is demonstrated with 67 confirmed established aquatic invasive species, and a potential 54 aquatic invasive species that have been collected or have an unknown status in the Lake Erie drainage basin, according to the GLANSIS database (NOAA 2018).

How much is being spent on invasive species management in the Niagara region?

This study found that the 16 organizations in the Niagara region spent CAD 1,216,718 in direct expenses and 4,570 man-hours controlling aquatic

and riparian invasive species in the region. This forms a baseline of how much is spent in terms of dollars and man-hours per year to control aquatic and riparian invasive species in the Niagara Region. To provide context, the 2017–2018 Canadian federal budget allocated CAD 43.8 million over the next five years to combat aquatic invasive species (McGuire 2018). In comparison, in 2017, the U.S. spent CAD 4.19 billion (USD 2.996 billion) on invasive species activities (National Invasive Species Council Secretariat 2018), and Australia spent CAD 3.42 billion (AUD 3.77 billion) from 2011 to 2012 (Hoffmann and Broadhurst 2016). Despite the amount being spent, lack of funding and man-power were the two most common barriers named that prevented organizations from managing invasive species. Martin and Blossey (2013) confirm the same barriers existed for phragmites management in 285 land properties in the U.S.

How do local invasive species priorities compare with those at the provincial and national level?

The Compendium of Invasive Plant Management in Ontario (OIPC 2012) reports garlic mustard, buckthorn species, dog-strangling vine (*Cynanchum rossicum* Kleo, 1929), and giant hogweed (*Heracleum mantegazzianum* Sommier and Levier, 1895) as the top invasive species priority for control provincially. Of the four priorities named in the Compendium, three were controlled in some fashion in the Niagara region, with the exception being giant hogweed because it was not detected in 2017/2018.

The Canadian legislation/leading authorities list serves as a comparison for the Niagara region, and may introduce some new priority invasive species that the region could pursue (Table S4). Prioritized invasive species in the Niagara region were not completely aligned with legislation and recommendations by leading authorities like those listed in the DFO's 2015 Fisheries Act, or the OIPC's best management practices (ONMNRF 2011, 2016). Participants stated that priority species were based on the invasive species being controlled. This study speculates that this may demonstrate one of the following: (1) Confirmation bias whereby organizations are sure they are managing the right species, (2) Organizations have not considered re-prioritizing species, or (3) Participants were unsure of how priorities were originally made. In contrast, the literature's method of prioritizing invasive species is based on invasion potential, impacts, and risk assessments (Ricciardi and Rasmussen 1998; Kolar and Lodge 2002; McGeoch et al. 2016; Carboneras et al. 2017). For example, the DFO runs ecological-social risk assessments to prioritize aquatic invasive species like Asian carp (Cudmore et al. 2017).

Who should assume responsibility for each aspect of invasive management in the Niagara region?

Sherman (2015) recommends that a combination of governmental agencies at local, provincial, and federal levels, conservation authorities, local

community groups, private consultants and landowners should collaborate to manage invasive species. Overall in the Niagara region, local environmental groups like NPC, FOMEP and HNC were undertaking significant invasive species management efforts, which contrasted with efforts taken by governmental bodies. Only one out of a possible 12 municipalities was doing anything; however, even this is ending. As of November 2018, the Niagara-On-The-Lake Town Superintendent of Environmental Services, Brett Ruck said, "There is no money budgeted for 2019 [towards phragmites control]" (Coles 2018, p. 9). Provincially, it appears that the ONMNRF had a responsibility to deal with invasive species under the Ontario Invasive Species Act (2015), the Fisheries Act (2015) and Annex 6 of the Canada-Ontario Agreement on Great Lakes Water Quality and Ecosystem Health (Environment Canada and the Ontario Ministry of the Environment and Climate Change 2014). However, ONMNRF did not do any invasive species control work in 2017–2018 in the Niagara region. At the federal level, according to the Senior Science Advisor on aquatic invasive species and the Manager for DFO's Centre of Expertise for Aquatic Risk Assessment (CEARA), "For addressing aquatic invasive species in the Great Lakes, the DFO is currently funded to address Asian carps… and most invertebrate arrivals are mitigated through Transport Canada's Ballast Water Regulations" (B. Cudmore, December 10, 2018, *personal communication*).

How should invasive species management in the Niagara region move forward?

Discussions have started with a non-governmental organization working in the Niagara region to maintain the database and add some new components. It is also envisioned that future Brock University graduate students could help maintain and update the database through yearly interviews with participating organizations in the region. Future Brock University graduate students could also expand the geographic scope to the U.S. side, and explore the bi-national coordination of aquatic and riparian invasive species work along the Niagara River and the Great Lakes. Another possible study could increase the population of interest to include private groups like landowners, agriculture and businesses. This may shed light on cooperative policies that should be drafted among private, government, and volunteer organizations to improve invasive species management and coordination.

Recommendations

1. More local, provincial, and federal governmental bodies especially municipalities, the Niagara Region, the ONMNRF, and the federal government should participate in helping to control these invasive species. One organization should be appointed to facilitate this collaboration so that all can be held accountable.

2. Provincial organizations should place more emphasis on the management of aquatic invasive species.

3. Local, provincial, and federal organizations should expand areas where invasive species are managed, especially to the Welland Canal and Lake Erie shoreline.

4. The Niagara Region should do a region-wide ecological-social risk assessment similar to that done for Asian carp by Cudmore et al. (2017) to prioritize which invasive species to control, while taking into account national level priorities.

5. Local, provincial, and federal organizations should achieve earlier detection of invasive species through the use of innovative techniques such as invasive species detection dogs, eDNA, and remote sensing.

6. Local organizations should diversify control methods because it has been shown that multiple control types have more effective results.

7. Organizations should improve collaboration in invasive species management by sharing more information regarding planning and decision-making among organizations, and making use of databases such as the OIPC compendium and DFO Asian carp genetic database.

8. The Niagara Region should create an invasive species plan modelled after St. Thomas' Phrag Free City. In 2013, St. Thomas created a goal to be "phrag free" by 2020. The city budgeted CAD 13,000 annually towards this, mapped the phragmites infestation and identified priority areas of concern. Using glyphosate, the city eradicated 90% of the phragmites at the initial lake of concern (Collins 2017).

9. The database should be maintained and updated. This could be accomplished through collaborative efforts between the authors of this study and another organization such as OFAH or OIPC. Alternatively, future Brock University graduate students could maintain the database.

Acknowledgements

Funding Declaration

References

Alvarez-Taboada F, Paredes C, Julián-Pelaz J (2017) Mapping of the invasive species *Hakea sericea* using unmanned aerial vehicle (UAV) and WorldView-2 imagery and an object-oriented approach. *Remote Sensing* 9: 913, https://doi.org/10.3390/rs9090913

CABI (2018) Centre for Agriculture and Bioscience International. Invasive Species Compendium. https://www.cabi.org/isc (accessed 15 May 2019)

Carboneras C, Genovesi P, Vilà M, Blackburn TM, Carrete M, Clavero M, D'hondt B, Orueta JF, Gallardo B, Geraldes P, González-Moreno P, Gregory RD, Nentwig W, Paquet J, Pyšek P, Rabitsch W, Ramírez I, Scalera R, Tella JL, Walton P, Wynde R (2017) A prioritised list

of invasive alien species to assist the effective implementation of EU legislation. *Journal of Applied Ecology* 55: 539–547, https://doi.org/10.1111/1365-2664.12997

CBD (2000) Convention on Biological Diversity. COP 5 Decision V/6 - Ecosystem Approach. https://www.cbd.int/decision/cop/?id=7148 (accessed 15 May 2019)

Clout MN, Williams PA (2010) Introduction. In: Clout MN, Williams PA (eds), Invasive Species Management: A Handbook of Principles and Techniques. Oxford University Press, New York, pp v-ix, https://doi.org/10.1086/656850

Coles P (2018) Phragmites could end sustainability of specialty crops. https://img1.wsimg.com/blobby/go/80918cb8-76d5-4cb4-902d-b164080ed0bc/downloads/1csm9o82k_852233.pdf?ver=1580570558436 (accessed 2 February 2020)

Colm J, Marson D, Cudmore B (2018) Results of Fisheries and Oceans Canada's 2016 Asian Carp Early Detection Field Surveillance Program. Canadian Manuscript Report of Fisheries and Aquatic Sciences No 3147, 76 pp

Collins D (2017) St. Thomas plan of action: Phrag free city 2020. https://www.ontarioinvasiveplants.ca/wp-content/uploads/2016/06/St.-Thomas-Phragmites-Action-Plan.pdf (accessed 15 May 2019)

Crooks JA (2005) Lag times and exotic species: The ecology and management of biological invasions in slow-motion. *Écoscience* 12: 316–329, https://doi.org/10.2980/i1195-6860-12-3-316.1

Crowder DW, Hardwood JD (2014) Promoting biological control in a rapidly changing world. *Biological Control* 75: 1–7, https://doi.org/10.1016/j.biocontrol.2014.04.009

Cudmore B, Jones LA, Mandrak NE, Dettmers JM, Chapman DC, Kolar CS, Conover G (2017) Ecological Risk Assessment of Grass Carp (*Ctenopharyngodon idella*) for the Great Lakes Basin. Department of Fisheries and Oceans Canada Canadian Science Advisory Secretariat. Res. Doc. 2016/118, 121 pp

Deriu I, D'Amico F, Tsiamis K, Gervasini E, Cardoso AC (2017) Handling big data of alien species in Europe: The European Alien Species Information Network Geodatabase. *Frontiers in ICT* 4: 1–8, https://doi.org/10.3389/fict.2017.00020

DFO (2018) Department of Fisheries and Oceans Canada. Centre of Expertise for Aquatic Risk Assessment (CEARA). http://www.dfo-mpo.gc.ca/science/coe-cde/ceara/index-eng.html (accessed 2 February 2020)

Djuricich P, Janssen J (2001) Impact of round goby predation on zebra mussel size distribution at Calumet Harbor, Lake Michigan. *Journal of Great Lakes Research* 27: 312–318, https://doi.org/10.1016/S0380-1330(01)70646-6

Environment Canada and the Ontario Ministry of the Environment and Climate Change (2014) Canada-Ontario agreement on great lakes water quality and ecosystem health. Annex 6: Aquatic invasive species. Queen's Printer for Ontario, pp 48–52

Fisheries Act (2015) Aquatic invasive species regulations. http://canadagazette.gc.ca/rp-pr/p2/2015/2015-06-17/html/sor-dors121-eng.html (accessed 15 May 2019)

Graham J, Simpson A, Crall A, Jarnevich C, Newman G, Stohlgren TJ (2008) Vision of a cyberinfrastructure for non-native, invasive species management. *BioScience* 58: 263–268, https://doi.org/10.1641/B580312

GLFC (2000) Great Lakes Fishery Commission. TFM and sea lamprey control: A success story. http://www.glfc.org/pubs/FACT_4.pdf (accessed 15 May 2019)

Grice T (2010) Chapter 5: Principles of containment and control of invasive species. In: Clout MN, Williams PA (eds), Invasive Species Management: A Handbook of Principles and Techniques. Oxford University Press, New York, pp 61–76, https://doi.org/10.1086/656850

Griffiths RW, Schloesser DW, Leach JH, Kovalak WP (1991) Distribution and Dispersal of the Zebra Mussel (*Dreissena polymorpha*) in the Great Lakes Region. *Canadian Journal of Fisheries and Aquatic Sciences* 48: 1381–1388, https://doi.org/10.1139/f91-165

Hoffmann BD, Broadhurst LM (2016) The economic cost of managing invasive species in Australia. *NeoBiota* 31: 1–18, https://doi.org/10.3897/neobiota.31.6960

Holcombe T, Stohlgren TJ (2010) Chapter 3: Detection and early warning of invasive species. In: Clout MN, Williams PA (eds), Invasive species management: A handbook of principles and techniques. Oxford University Press, New York, pp 36–45, https://doi.org/10.1086/656850

Invasive Species Act (2015) Government of Ontario. S.O. 2015, c. 22. - Bill 37, https://www.ontario.ca/laws/regulation/r16354 (accessed 19 June 2020)

ISSG (2018) Invasive Species Specialist Group. Global Invasive Species Database. http://www.iucngisd.org/gisd/ (accessed 15 May 2019)

Jerde CL, Mahon AR, Chadderton L, Lodge DM (2011) "Sight-unseen" detection of rare aquatic species using environmental DNA. *Conservation Letters* 4: 150–157, https://doi.org/10.1111/j.1755-263X.2010.00158.x

Joshi CM, de Leeuw J, van Duren IC (2004) Remote sensing and GIS applications for mapping and spatial modelling of invasive species. In: Altan O (ed) (2004) Proceedings of the XXth ISPRS congress: Geo-imagery bridging continents: Commission VII Papers. Istanbul, Turkey, July 12-23, 2004. International Society for Photogrammetry and Remote Sensing (ISPRS), Istanbul, Turkey, pp 669–677

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, https://doi.org/10.1111/j.1365-2664.2011.01979.x

Kim J, Mandrak NE (2016) Assessing the potential movement of fishes through the Welland Canal. *Journal of Great Lakes Research* 42: 1102–1108, https://doi.org/10.1016/j.jglr.2016.07.009

Klymus KE, Marshall NT, Stepien CA (2017) Environmental DNA (eDNA) metabarcoding assays to detect invasive invertebrate species in the Great Lakes. *PLoS ONE* 12: e0177643, https://doi.org/10.1371/journal.pone.0177643

Kolar CS, Lodge DM (2002) Ecological predictions and risk assessment for alien fishes in North America. *Science* 298: 1233–1236, https://doi.org/10.1126/science.1075753

Leung B, Lodge DM, Finnof D, Shogren JF, Lewis MA, Lamberti G (2002) An ounce of prevention or a pound of cure: Bioeconomic risk analysis of invasive species. *Proceedings of the Royal Society of London B* 269: 2407–2413, https://doi.org/10.1098/rspb.2002.2179

Ling N (2010) Chapter 13: Management of invasive fish. In: Clout MN, Williams PA (eds), Invasive Species Management: A Handbook of Principles and Techniques. Oxford University Press, New York, pp 185–203, https://doi.org/10.1086/656850

Mansell D, Christl L, Maher R, Norman A, Patterson N, Whillans T (1998) Temperate wetlands restoration guidelines. Ontario Ministry of Natural Resources, Toronto, Canada, 159 pp

Martin LJ, Blossey B (2013) The runaway weed: Costs and failures of *Phragmites australis* management in the USA. *Estuaries and Coasts* 36: 626–632, https://doi.org/10.1007/s12237-013-9593-4

McGeoch MA, Genovesi P, Bellingham PJ, Costello MJ, McGrannachan C, Sheppard A (2016) Prioritizing species, pathways, and sites to achieve conservation targets for biological invasion. *Biological Invasions* 18: 299–314, https://doi.org/10.1007/s10530-015-1013-1

McGuire R (2018) Feds respond to questions about their actions on invasive mussels; admit most of funds announced last year won't address mussels. https://www.osoyoostimes.com/feds-respond-questions-actions-invasive-mussels-admit-funds-announced-last-year-wont-address-mussels/ (accessed 3 February 2020)

Mooney HA, Hobbs RJ (2000) Introduction. In: Mooney HA, Hobbs RJ (eds), Invasive species in a changing world. Island Press, Washington, DC, pp xiii-xv, https://doi.org/10.1086/656850

National Invasive Species Council Secretariat (2018) National Invasive Species Council crosscut budget. U.S. Department of the Interior Office of the Secretary, 5 pp. https://www.doi.gov/sites/doi.gov/files/uploads/crosscut_25january2018.pdf

NOAA (2018) National Oceanic and Atmospheric Administration. Great Lakes Aquatic Nonindigenous Species Information System (GLANSIS). https://www.glerl.noaa.gov/glansis/index.html (accessed 15 May 2019)

Nunez MA, Kuebbing S, Dimarco RD, Simberloff D (2012) Invasive species: To eat or not to eat, that is the question. *Conservation Letters* 5: 334–341, https://doi.org/10.1111/j.1755-263X.2012.00250.x

OFAH (2018) Ontario Federation of Anglers and Hunters. http://www.invadingspecies.com/ (accessed 15 May 2019)

OIPC (2012) Ontario Invasive Plant Council. Compendium of Invasive Plant Management in Ontario. https://www.ontarioinvasiveplants.ca/wp-content/uploads/2016/07/ManagementCompendium_FINAL.pdf (accessed 15 May 2019)

ONMNRF (2011) Ontario Ministry of Natural Resources and Forestry. Invasive *Phragmites* - Best management practices. https://www.ontarioinvasiveplants.ca/wp-content/uploads/2016/07/Phragmites_BMP_FINAL.pdf (accessed 15 May 2019)

ONMNRF (2016) Ontario Ministry of Natural Resources and Forestry. Purple Loosestrife - Best management practices. https://www.ontarioinvasiveplants.ca/wp-content/uploads/2016/07/Purple-Loosestrife-BMP-April-2016-final.pdf (accessed 15 May 2019)

Piola RF, Denny CM, Forrest BM, Taylor MD (2010) Chapter 14: Marine biosecurity: Management options and response tools. In: Clout MN, Williams PA (eds), Invasive Species Management: A Handbook of Principles and Techniques. Oxford University Press, New York, pp 185–203, https://doi.org/10.1086/656850

Ramsar Convention on Wetlands (1971) The criteria for identifying wetlands of international performance. Ramsar Information Paper No 5, 2 pp

Ramsar Convention Secretariat (2002) Resolution VIII.18: Invasive species and wetlands. In: Peck (ed) (2002) 8th Meeting of the Conference of the Contracting Parties to the Ramsar Convention on Wetlands. Prince Phillip Science Museum, Valencia, Spain, November 18-26, 2002, 4 pp

Ricciardi A, Rasmussen JB (1998) Predicting the identity and impact of future biological invaders: A priority for aquatic resource management. *Canadian Journal of Fisheries and Aquatic Sciences* 55: 1759–1765, https://doi.org/10.1139/f98-066

Ricciardi A, Steiner WWM, Mack RN, Simberloff D (2000) Toward a global information system for invasive species. *BioScience* 50: 239–244, https://doi.org/10.1641/0006-3568(2000)050[0239:TAGISF]2.3.CO;2

Russell JC, Blackburn TM (2017) Invasive alien species: Denialism, disagreement, definitions, and dialogue. *Trends in Ecology and Evolution* 32: 312–314, https://doi.org/10.1016/j.tree.2017.02.005

Sellers E (2004) Databasing invasions: A review in the context of the Global Invasive Species Information Network (GISIN). Experts meeting towards the implementation of a Global

Invasive Species Information Network (GISIN). Information International Associates Inc., Baltimore, April 22, 2004, 34 pp

Sherman K (2015) Creating an invasive plant management strategy: A framework for Ontario municipalities. https://www.ontarioinvasiveplants.ca/wp-content/uploads/2016/07/PlantManagement Strategy_2015_March172015_D3_PRINTFINAL.pdf (accessed 15 May 2019)

Shields J, Austin LM (2018) Monitoring invasive and threatened aquatic amphibians, mammals, and birds. In: Richards NL (ed), Using detection dogs to monitor aquatic ecosystem health and protect aquatic resources. Palgrave Macmillan, Cham, Switzerland, pp 71–118, https://doi.org/10.1007/978-3-319-77356-8

Simpson A, Jarnevich C, Madsen J, Westbrooks R, Fournier C, Mehrhoff L, Browne M, Graham J, Sellers E (2009) Invasive species information networks: Collaboration at multiple scales for prevention, early detection, and rapid response to invasive alien species. *Biodiversity* 10: 5–13, https://doi.org/10.1080/14888386.2009.9712839

Smith BR, Tibbles JJ (1980) Sea lamprey (*Petromyzon marinus*) in Lakes Huron, Michigan, and Superior: History of invasion and control, 1936-78. *Canadian Journal of Fisheries and Aquatic Sciences* 37: 1780–1801, https://doi.org/10.1139/f80-222

Sturtevant RA, Mason DM, Rutherford ES, Elgin A, Lower E, Martinez F (2019) Recent history of nonindigenous species in the Laurentian Great Lakes, An update to Mills et al., 1993 (25 years later). *Journal of Great Lakes Research* 45: 1011–1035, https://doi.org/10.1016/j.jglr.2019.09.002

Trebitz AS, Hoffman JC, Darling JA, Pilgrim EM, Kelly JR, Brown EA, Chadderton WL, Egan SP, Grey EK, Hashsham SA, Klymus KE, Mahon AR, Ram JL, Schultz MT, Stepien CA, Schardt JC (2017) Early detection monitoring for aquatic non-indigenous species: Optimizing surveillance, incorporating advanced technologies, and identifying research needs. *Journal of Environmental Management* 202: 299–310, https://doi.org/10.1016/j.jenvman.2017.07.045

Thresher RE, Jones M, Drake DAR (2019) Evaluating active genetic options for the control of sea lamprey (*Petromyzon marinus*) in the Laurentian Great Lakes. *Canadian Journal of Fisheries and Aquatic Sciences* 76: 1186–1202, https://doi.org/10.1139/cjfas-2018-0153

United Nations Environment Programme [UNEP] and Convention on Biological Diversity [CBD] (2002) Alien species that threaten ecosystems, habitats or species, UNEP/CBD/COP/6/20. Report of the Sixth Ordinary Meeting of the Conference of the Parties to the Convention on Biological Diversity. The Hague, Netherlands, April 7-19, 2002, 346 pp

USDA (1996) United States Department of Agriculture. Riparian areas environmental uniqueness functions and values. RCA Issue Brief #11

Working Dogs for Conservation (2018) Projects. https://wd4c.org/projects.html (accessed 1 October 2018)

Supplementary material

The following supplementary material is available for this article:

Appendix 1. Questionnaire.
Table S1. Resources used in this study to classify invasive species as aquatic or riparian.
Table S2. 2017–2018 Detected and controlled aquatic/riparian invasive species in the Niagara region.
Table S3. Current collaboration efforts in the Niagara region.
Table S4. Invasive species priorities in the Niagara region versus those in Canadian legislation and leading authorities.

This material is available as part of online article from:
http://www.reabic.net/journals/mbi/2020/Supplements/MBI_2020_Brown_Vasseur_etal_SupplementaryTables.xlsx
http://www.reabic.net/journals/mbi/2020/Supplements/MBI_2020_Brown_Vasseur_Appendix.pdf