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Literature review of aquatic invasive species management in the Great Lakes region

Patterson, Sara

LITATURE REVIEW OF AQUATIC INVASIVE SPECIES MANAGEMENT IN THE GREAT LAKES REGION

Sara Patterson

An undergraduate essay submitted in partial fulfillment of the requirements for the degree of (Honours) Bachelor of Environmental Studies (Forest Conservation)

NRMT 4010- Thesis 1

Dr. Ashley Thomson

Dr. Don Henne

Dr. Leni Meyer

Faculty of Natural Resource Management

Lakehead University

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TABLE OF CONTENTS

ABSTRACT

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Invasive species are foreign organisms which out-compete and take over new landscapes and are ranked as one of the most destructive forms of habitat degradation (McCormick et al. 2009). Aquatic invasive species specifically have the potential to disrupt not only ecosystem services, but the commercial industries, and recreational activities as well. The great lakes, located between Canada and the United States, are one of the largest sources of fresh water which supports the majority of North American populations. These lakes have been subject to numerous invasive species, with new species constantly threatening to invade. The purpose of this study is to assess the current level of management of invasive species from the bordering provinces and states. A literature review was conducted focusing on three species as case studies; the round goby (*Neogobius melanostomus*) and Asian clam (*Corbicula fluminea*), species which are currently established in the great lakes, and Asian carp (*Ctenopharyngodon idella, Hypophthalmichthys molitrix, Hypophthalmichthys nobilis, Mylopharyngodon piceus)* a newly threating species coming from the United States. The established species were found to have the greatest number of publications focused on their physical (round goby) and chemical (Asian clam) control, with little publications found on their prevention or eradication. Asian carp management was centered around their prevention, with little to no studies found on control or eradication methods. The final assessment on the level of invasive species management within the great lakes, based on further research of the practicality of each method, was relatively satisfactory given current states. The suggested improvement includes the focus on creating cohesive international policies, as well as the improving public outreach programs.

TABLE OF TABLES

TABLE OF FIGURES

INTRODUCTION

Invasive species are defined as non-native species that are transported through human activities which establish within and quickly take over new ecosystems. These pests have earned a top spot amongst the top lists of global threats, ranking second only to habitat destruction (McCormick et al. 2009). With connections between and within countries becoming more advanced each year with rising demand for trade and travel, the passage of invasive species easily occurs without our knowing (Allendorf & Lundquist 2003; Sousa et al. 2010; Wittmann et al. 2014). Specifically, aquatic invasive species brought to new bodies of water through vectors such as ballast water, canals, boating, live bait or fish food markets, and unauthorized intentional introductions or pet releases (Ontario Federation of Anglers and Hunters 2018), have the potential to degrade the system they find themselves in. Causing ecological damage through the degradation of ecosystem functions and services, changing water quality, and altering food webs through reduced populations (McCormick et al. 2009). Creating economic losses through the disruption of recreational uses such as fishing, boating, and swimming, or affecting industries like commercial fishing. Leading to billions of dollars in repair methods and continued maintenance (Malcolmson & Goucher 2013). Significant cause for alarm arises over the degradation of fresh water systems, such as those of the Great Lakes within North America. Suppling key services including clean drinking water and supporting a productive fisheries industry (Malcolmson & Goucher 2013), the continued health of these major water ways is vital.

Positioned between Canada and the United States of America the Great Lakes, comprising of Lake Erie, Huron, Michigan, Ontario, and Superior, hold 20% of the worlds and 95% of North Americas available fresh water (Hayer 1973). Housing a diverse community of birds, animals, and fish, the rich biodiversity supports many species that are not found anywhere else (Malcolmson & Goucher 2013). Though the importance of these lakes is well understood by many, they are no exception to the threat of invasive species, with numerous currently broadening their range with the lakes. Species such as *Neogobius melanostomus* (round goby) or the *Corbicula fluminea* (Asian clam) which have been established for decades, or the most recent and pressing threat of Asian carp who have yet to given their invade.

Neogobius melanostomus is a notorious fresh water invader. This prolific benthic fish has expanded from its native range of the Black and Caspian Seas through most of European water bodies and into North America (N'Guyen et al. 2017). Thought to be first introduced into the Great Lakes through the St. Clair River in 1990, this habitat generalist rapidly spread through all five lakes and its adjoining water ways. Outcompeting native species for food sources such as mollusks, crustaceans, and fish eggs (Never et al. 2018), this species quickly takes over its vegetated environments. Initially inhabiting the lakes without the population control from their natural predator, native predators have now begun shifting their diet to include *N. melanstomus*, creating repercussions in the food web (N'Guyen et al. 2017).

Corbicula fluminea is considered to be one of the most ecologically and economic degrading invaders globally. Native to regions in Asia and Africa this mollusk has magnified its range to throughout Europe, South America, and North America (Colwell et al. 2017). With life history traits of rapid growth with high fecundity at a young age paired with various methods of dispersal aided by human transportation, *C. fluminea* can establish and over run almost any aquatic ecosystem that meets its temperature requirements (Colwell et al. 2017). Introduced in 1938 this species can be found throughout all Great Lakes and water ways and is still finding new environments through unknowing human activities (Colwell et al. 2017; Sousa et al. 2012). Their ability to cling to various surfaces in high densities creates damage to industrial equipment like water intake pipes or sewage treatment plants causing significant economic declines. Being a filter feeder, *C. fluminea* changes both the water quality and amount of microscopic food for other native species (Sousa et al. 2012).

The Asian carp group is comprised of four species; *Hypophthalmichthys nobilis* (Bighead carp), *Hypophthalmichthys molitrix* (Silver carp), *Mylopharyngodon piceus* (Black carp), and *Ctenopharyngodon Idella* (Grass carp). Initially imported from Asia into the southern United States to reduce algae in aquaculture ponds, this species found its way into the Mississippi river after escaping via floods (Malcolmson & Goucher 2013). Since their release in the 1970s these aggressive species have expanded into over 18 states and are on the verge of entering Lake Michigan (Varble & Secchi 2013). Consuming massive amounts of algae and other microscopic organisms paired with their ability to quickly reproduce they are easily able to out compete numerous native species (Malcolmson & Goucher 2013). Not only does this effect the biodiversity and health of infected waterways, they also pose a physical threat to recreational water users. *H. molitrix* becomes startled at the noise and vibrations of motor boats, and in reflex shoot themselves out of the water. With a body weight of up to 40 kilograms and incredibly high school densities H. molitrix can cause serious harm to persons and their equipment (Canada 2018).

These three aquatic invasive species give a clear representation of the types and severity of invaders the Great Lakes and its managers are dealing with. Two of which who are established with numerous studies conducted on different management methods, and one group yet to have moved into the Great Lakes which poses one of the greatest threats to Canadian water systems to date. Through a literature assessment of these species the level of management, knowledge, and preparedness in terms of the prevention, control, and eradication methods is determined. The objective of this study is to analyze and determine the level of competence the boarding regions of the Great Lakes have for dealing with invading alien species.

LITERATURE REVIEW

INTRODUCTION

Invasive species pose significant threats to ecosystems health and integrity. Lacking their natural predators, these exotic organisms compete for resources with native species and alter habitats and ecosystem processes, structures and functions, usually in a negative manner (Allen, 2006; Pyke et al. 2008). Specifically, aquatic invasive animals have the potential to hinder key aquatic activities such as commercial fishing and recreational hobbies. Current stressors on aquatic systems including pollution, habitat degradation, and overexploitation could be magnified by the impacts of these invasive species (Messing & Wright 2006).

This literature review is intended to exam methods used for prevention, control, and eradication of invasive species within the Great Lakes region, using three case studies as an example of the overall status of management. Northeastern American literature sources published between 2000 and 2018 was collected from multiple databases. Information was collected on two invasive species that invaded before 2000; the round goby, and Asian clam, and one more recent threat (Asian carp) that is beginning its invasion.

1. PREVENTION

1.1 SPECIES BIOLOGY

The first step in all prevention approaches is to determine the biology and requirements of each potential threat (Malcolmson & Goucher 2013; Messing & Wright 2006; Sousa et al. 2013; Phelps 2017). Life history traits such as reproductive rates, life span, diet, and preferred habitat can allow managers to better predict areas of high suitability or native species vulnerability, in turn ranking the level of prevention needed for different areas. For example, Asian clams are known to have fast growth rates and become sexually mature at a young age with a high fecundity rate, warning managers that once this species has entered new territory they can spread at alarming rates (Cowell et al. 2017). Ideal habitat, such bottom substrate preferred by the round goby, can allow mangers to narrow the search area when beginning to monitor for the pest (N'Guyen et al. 2017). Acquiring other relevant attributes can also help govern the practices which may allow potential invasive species to be accidently introduced. For example, Asian carp species can survive out of water for up to 48 hours, resulting in accidental releases of these assumed-dead fish when they are imported to sell in food markets (Malcolmson & Goucher 2013). Many of these characteristics are found through the completion of a risk assessment.

1.2 RISK ASSESSMENTS

Risk assessments have traditionally been used to quantify the impact of anthropocentric chemical stressors on wildlife populations (Allen et al. 2006). In the context of invasive species risk assessments provides dispersal patterns as well as identification of areas or species susceptible to such species. This knowledge gives managers context allowing them to allocate resources and amount of effort needed (McCormick et al. 2009).

Many studies (e.g. Allen et al., 2006; Allendorf & Lundquist, 2003; Zabin et al., 2018) have used variations of risk assessment to quantify the potential a species has to become invasive and areas at high risk of being invaded or native species that would be affected. Allen, et al. (2006), analyzed the framework for spatial risk assessments using three phases; problem formulation, risk analysis, and risk characterization. Problem formulation assessed the probability of spatial overlap between the invasive species and native species. Risk analysis aimed to determine the levels of decline in populations, regions occupied, and the alterations of the connectivity native species use within their range. The third stage, risk characterization, was formulated into a hazard index given to each invasive species. The index determines whether the likelihood of interactions between said invasive and native species will occur. Each invasive is compared with multiple native species, with a likely interaction assigned a one (1), and unlikely interactions assigned a zero (0).

Structured expert judgement (SEJ) is a form of forecasting potential invasions based on individual experts' opinions. Though forecasts remain with a high degree of uncertainty, SEJ has benefited the science community through a deeper understanding of the dynamics of a species and potential to change new environments (Wittmann et al. 2014). SEJ of the susceptibility of ecosystems to invasive species is a narrowed variation of integrated pest management (Phelps et al. 2017) or more generally, an integrated management strategy. Integrated management strategy (IMS) is a multi-tiered approach at dealing with invasive species (Colwell et al. 2018; Phelps et al. 2017: Sousa et al. 2013). Following the general format of risk assessments, individual integrated management strategies outlines four stages; determining the means of spread, identification of vulnerable water bodies, analysis of economic and environmental impacts, and creation of emergency response plan in preparation of a potential invasion. Coupled in the integrated management is the push for public engagement. The map produced through IMS aims to educate the populations in higher risk areas (Colwell et al., 2018). Integrating scientific information gathered from various disciplinary boundaries is imperative for IMS as it utilizes a multi-tired approach to the problem, allowing mangers to expand their view to all levels of action (Phelps et al. 2017)

1.3 POLICY

Policy plays a major role in the prevention of an invasive species, with laws that prohibit the import, possession, and release of such species (Pyke et al., 2008; Zabin et al., 2018). Namely, cohesive polices could effectively create a legal barrier against accidental introductions and aid in the reaction time when control and eradication measures are needed. Such uniform laws are few and far between due to their slow evolving nature and the influence states or provinces receive from national political and economic concerns (Rasmussen 2006; Wittmann et al. 2014). The national agenda paired with scientific uncertainty of management practices and effects on non-target species (Kokotovich & Andow 2017). This absence of social agreements results in neighbouring regions adopting various levels of protection against these species, creating gaps or loop holes in the system.   Studies have also suggested implementing polices towards climate change to manage invasive species. Pyke et al. (2008) showed links between the time it takes for an exotic species to establish in a new area and the fluctuating climate. Likewise, polices that aid in the removal or strict management of invasive species can increase an ecosystems resistance and resilience to climate change effects. Joining these two issues would administer long-term considerations in a typically day-to-day, resource limited management views (Pyke et al. 2008).

2. CONTROL
2.1 MONITORING

To determine the level of severity of infestation, an assessment and continued monitoring must be conducted. Factors such as time limitations, funding, or anticipated level of accuracy create variations in approaches to population estimates (Nevers et al., 2018). Methods of monitoring are not uniform across all species. Habitat type as well as physical traits alters the assessment practices. For example, electrofishing would only be efficient in sampling free swimming organisms, whereas benthic sampling may be good for assessing mollusk or bottom-dwelling species but inefficient at sampling species found in open water (Wilson et al. 2014).

2.1.1 Round Goby

One study (Juza et al., 2018) compared three passive methods of sampling, using small fyke (25 x 25 x 45 cm) and benthic gill nets (1.5m x 30 m). Fyke net mesh size was set at 4 mm whereas a variety of gill net sizes (12) were used ranging between 5 mm and 55 mm, with both methods deployed overnight for approximately 15 hours. Results were compared using a paired t-test, with both nets found to be suited for a variety of benthic habitats at different depths. Fyke nets however produced a higher catch rate at the shallowest and deepest strata, whereas the benthic gill nets decreased as depth increased. Juza et al. (2018) found that neither sampling method created and absolute catch per bottom area but produced enough data for relative density estimates.

Other physical methods, such as mark-recapture, seining, and trapping, have resulted in similar findings, though Nevers et al. (2018) argued integrating eDNA (environmental DNA) tools would improve the approximations for round goby biomass. DNA, such as fish scales or feces is shed by aquatic organisms and is left in the water until it decays. eDNA is the collection of such material to determine the presence of abundance of species (Nevers et al. 2018). Population monitoring is one aspect of determining the level of infestation. Assessing the reproductive condition of the population can help accurately project future densities, a worthwhile tool when dealing strictly with population control. Gonadosomatic indices (GSI), calculated by (GSI = gonad mass / body mass × 100%, or GSI = gonad mass / somatic mass × 100%) determines reproductive condition in fish species. Zeyl et al. (2014) found this index was able to accurately assign spawning conditions to both males and females.

2.1.2 Asian Carp

Population estimates and location of Asian carp within water systems sets the baseline for prevention and control efforts. To first determine if these invasive species are present, a combination of electrofishing and environmental DNA (eDNA) surveillance can be used. Electrofishing, a labour intensive physical assessment of the water bodies' species assemblage, is most successful when populations of small densities have been established (Wilson et al., 2014). Though this a classic sampling method, limitations exist within the depth of its use. Backpack electrofishing is limited to the chest height of the operator, whereas larger scale boat electrofishing can extend into deeper waters such as those of the Great Lakes but due to the manual netting needed to gather the fish, it is limited to the upper layer and the reach of the netter

(Wilson et al. 2014). However, in order to successfully pursue an attempt at eradication, earlier detection (i.e., before a colony is established) is needed (Malcolmson & Coucher, 2013; Wilson et al., 2014). Wilson et al. (2014) used the eDNA technique for detection at low-abundance. Water samples were collected and tested for shed DNA such as feces, urine, epidermal cells, or gametes, removing the need for direct contact with the species. Environmental DNA gives the potential to map occurrences during times of early colonization (Wilson et al., 2014; Malcolmson & Coucher, 2013).

One method of assessment once a population is confirmed is the use of hydroacoustics, which quantify the depth and habitat use of specific species (MacNameral et al., 2018). A study (MacNameral et al., 2018) took place over 4 years and tracked the movements of use with changing water temperatures and river discharge. It was found that carp densities were highest at mid-level river depths, but densities decreased in times of high discharge and depth level rose during increased temperatures.

2.1.3 Asian Clam

Conventional assessment methods have been used to survey Asian clam populations. One study (Smith et al., 2018) used a petite PONAR grab to sample benthic sediments from the Fox River, a main tributary to Green Bay of Lake Michigan in Wisconsin.

2.2 CONTROL METHODS

2.2.1 Round Goby

A diverse collection of control methods was found during the literature search. These ranged from physical, such as an increased effort of assessment techniques mentioned above (for example intensified fyke and gill net use), to chemical, olfactory, and biological control. Chemical treatments, such as the use of pesticides, have demonstrated varying levels of efficacy. Schreier et al. (2008) tested the use of four pesticides: antimycin, rotenone, 3-trifluoromethyl-4-nitrophenol (TFM), and Bayluscide, on round gobies and three native Great Lakes species (large-mouth bass, bluegill, and channel catfish). Round gobies were found to be sensitive to all four chemicals, but all three native species had a similar sensitivity, limiting the effectiveness of these pesticides. However, Bayluscide and antimycin were found to be relatively successful in targeting bottom-dwelling gobies, suggesting these chemicals could have potential in their selective removal (Schreier, 2008).

An alternative to adding chemicals is elevating the carbon dioxide (CO_2) in the water. Cupp et al. (2018) studied the effects of voluntary, free-swimming avoidance, and involuntary, equilibrium to the changes in CO_2 at varying temperatures. Effects were recorded at all levels, correspondingly the same effects were found to take place at lower temperatures and at 50% lower CO_2 levels. The application for such methods could be used at pinch points in rivers to help deter these and other invasive species from entering new passages, halting expansion and isolating the population (Cupp et al., 2018).

Methods that target the species auditory senses either attract or negatively impact their sensory structures. (Isabelle-Valenzi & Higgs, 2016; Wanger et al., 2015). Significant results were found by trapping gobies with mating and other signal calls. Traps successfully target the invasive species, making this low-impact method appealing to vulnerable areas, or to measure formation of spawning populations in new areas (Isabelle-Valenzi & Higgs, 2016). Another olfactory method is the use of seismic water guns to damage the otolith, an inner ear bone that aids in a fish's hearing and balance (Isabelle-Valenzi & Higgs 2016; Wanger et al. 2015). This approach however requires greater research, as Wanger et al. (2015) concluded that no significant damage was produced at the pressure that was tested,

2.2.2 Asian Carp

Asian carp control is a strategy many states have been forced to take on. One study proposed human consumption of Asian carp as a viable method of control (Varble & Secchi 2013). The sheer densities of the organisms once established and thriving would provide an additional source of income for parties involved in the harvesting and expand the current demand within the food market. Though Varble and Secchi (2013) warned this method should be coupled with polices that ensure this tactic is used in control with hopes of eradication, not be cultivated in the future to maintain profit.

2.2.3 Asian Clam

Control of invasive Asian clams can be achieved by both biological and chemical treatments. Control strategies can be classified as reactive (targeting the adult population), or proactive (targeting the larval stages) (Sousa et al., 2013). Physical reactive controls such as thermal shock, desiccation, oxygen deprivation, and mechanical cleaning have been suggested as possible methods for control. Along with proactive methods, infiltration galleries and sand filters, mechanical filtration, ultraviolet light, electric current, acoustics, antifouling and foul release coatings, high-speed agitators, increased speed of flow, or magnetic fields can be included (Sousa et al., 2013). Sousa et al. (2013) highlights the possibilities of invasive bivalve control but fails to give details on the efficiency or environmental side effects. Pereira et al. (2016) tested clam consumptions (direct effect) and predator-avoidance behaviour (indirect effect) of predators *Procambarus clarkia*, *Lepomis gibbosus*, and *Luciobarbus bocagei* on Asian clams. *Procambarus clarkia* was found to have great effect on Asian clam populations within the smallest size class (<1cm) and could be an integral predator. It was concluded that biological control on these invasive bivalves could have the potential to be an effective and low-cost approach to management (Pereira et al., 2016).

Chemical controls vary from altering the species's surroundings to directly inhibiting the species to control the population. Sousa et al. (2013) summarized frequently-used proactive chemical controls such as chlorine, chlorine dioxide, chloramines, ozone, bromine, hydrogen peroxide, potassium permanganate, and ferrate. Proactive controls tend to use oxidizing chemicals whereas non-oxidizing chemicals are used in proactive and reactive combination treatments. The majority of controls use biocides, chemical cleanings, or temperature enhanced chemical treatments, classifying them as reactive methods (Sousa, 2013).

Four studies (Coughlan et al., 2018; Dos Santos et al., 2014; Gomes et al., 2014; Nogueira et al., 2018) have examined the potency of biochemicals in their effect on the target species in laboratory or field settings. Dos Santos et al. (2014) tested the agricultural chemicals atrazine (ATZ) and Roundup (RD) separately and in combinations. Alone, each chemical negatively affected *C. fluminea* in biotransformations (ATZ) or interfered with the species antioxidant defenses (RD) leading to lipid peroxidation. When the two chemicals were combined, effects either intensified or weakened, with little to no pattern. Gomes et at (2014) evaluated three biocides; cationic polydiallyldimethylammonium chloride (polyDADMAC), potassium chloride, and aluminum sulphate. All three chemicals were found to be promising control methods, with potassium chloride representing the lowest degree of environmental hazard. The organometallic biocide, zinc pyrithione (ZnPT), showed strong toxic effects on *C. fluminea* (Nogueira et al., 2018). ZnPT presence in natural ecosystems was found to be associated with other pyrithiones whose pairings can increase the level of toxic effects to surrounding bivalves. Another study (Coughlan et al., 2018) using a chemical variant looked at the efficacy of dry ice pellets (solid CO_2 at -78 degrees C) to kill *C. fluminea*. Pellets of 9mm had a greater effect than 3mm pellets, while direct contact (water absent) and indirect contact (*C. fluminea* submerged) had similarly successful results. Overall, through direct contact 9mm pellets applied for five minutes had 100% mortality rates, suggesting this method could be an effective control device for rapid management response after first detection.

3. ERADICATION
3.1 METHODS

3.1.1 Round Goby

Attempts at eradication of round gobies have rarely been undertaken, with only one article found on the topic. N'Guyen et al. (2018) evaluated the effectiveness of two methods; removal of eggs, and the removal of adults. The field study conducted, paired with a dynamic population modeling, yielded long term successful outcomes. For the population to be 95% eradicated, both eggs and adults should be removed over a time period of 13 years if the infestation was caught and treated in the early stages, or 18 years for a late start (N'Guyen et al., 2018). Removal of adults was deemed the most feasible, with removal of 57% of adults taking 20 years in an early start model, and 29 years with a late start. N'Guyen et al., (2018) conclude that eradication of the population is only practical when started early and if the population can be isolated, with no further additions of propagules.

3.1.2 Asian Carp

Eradication of Asian carp is almost impossible once a population is established (Malcomson & Goucher, 2013). Early detection of low abundances and rapid response are the main factors favoring eradication potential (Phelps et al. 2017; Wilson et al., 2014).

3.1.3 Asian Clam

Sousa et al. (2013) stated that no eradication method has been successful for established invasive bivalves. Though one study (Coughlan et al., 2018) suggests that it may be possible through the use of dry ice pellets. 100% mortality was observed when applying 9mm dry ice pellets directly to *C. flumeria* for a 5-minute period, with similar results obtained even when the species was submerged in water, gravel, or mud due to the surrounding substrate freezing. More research is still needed, including field tests to determine its practical use.

METHODS

The literature review was conducted with a topic search in multiple databases including; Web of Science, Jstor, and Lakehead University Library, as well as within Journals such as Management of Biological Invasions, and Great Lakes Research. A time restriction of 18 years (2000-2018) and study site location of North America was imposed. Literature was found by searching the common name of each species, round goby, Asian carp, and Asian clam followed by prevention, control, and eradication. Each aspect of invasive species management was searched separately for each species. Once articles were located, they were sorted into columns stating their titles and authors, management methods, and the drawn conclusions. Publications focused on invasive species environmental, economic, or recreational impacts was excluded from this literature review.

Table 1 Summary of Literature Sources

Information Outlet	Description
Web of Science	Online subscription-based scientific citation indexing service originally produced by the Institute for Scientific Information
Jstor	Online scientific citation indexing service containing digitized books, primary sources, and current issues of journals
Lakehead University Library Database	Premier source for peer-reviewed, full-text articles for academic libraries from the world's leading journals.
Management of Biological Invasions	Open access, peer-reviewed international journal focusing on applied research on alien species and biological invasions

RESULTS

Results gathered from the literature review of Great Lakes invasive species management shows variation across all categories of management and species type. Generally, publications focused on the eradication of all three case study species was low compared to prevention and control articles, as shown in Figure 1. Studies for both round goby and Asian clam were focused oncontrol, with few studies covering prevention and eradication. Asian carp was found to have the bulk of articles focused on prevention, with few articles discussing their control or eradication.

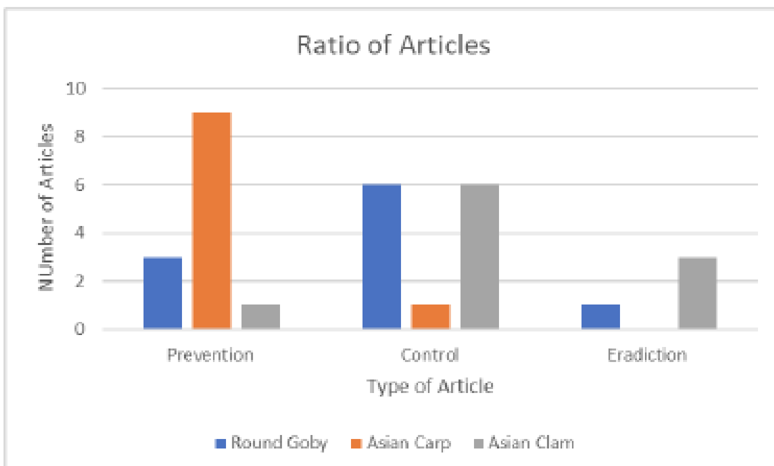

Figure 1 Ratio of Articles

The publishing date of the literature is left skewed, with the majority published between 2013 and 2018, as shown in Figure 2. Prevention had a slightly more uniform spread with publication dates extending back to 2003, though still with a large percent of articles occurring within the last 6 years (2013-2018). Control and eradiation followed the same spread with most articles published over the last 6 years (2013-2018).

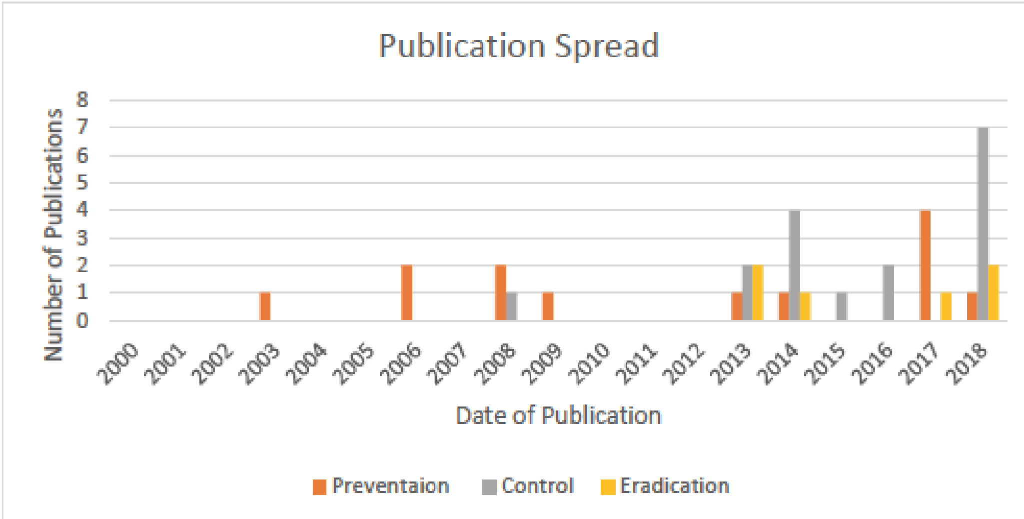

Figure 2 Spread of Article Publications

Table 2 Summary of Round Goby Publications

Species	Author	Category	Method	Approach	Success (Y/N)
Round Goby	Cupp et al. 2018	Control	Chemical	Altering CO2 levels	Yes
	Isabelle-Valenzi & Higgs 2016	Control	Olfactory	Trapping using mating calls	Yes
	Juza et al. 2018	Control	Physical	Removal using fyke and gill nets	No
	N'Geyen et al. 2018	Eradication	Physical	Egg and adult removal	Yes
	Nevers et al. 2018	Prevention	Assessment	eDNA to detect presence and biomass density	Yes
	Schreier & Larson 2008	Control	Chemical	Use of pesticides	Yes
	Wanger et al. 2015	Control	Olfactory	Damage to senses through sismic water gun	No
	Zeyl et al. 2014	Prevention	Assessment	Gonadosomatic index (GSI) to determine reproductive status	Yes

Publications on the round goby present control as the dominate method of management (as shown in Table 2). Both chemical and olfactory methods were used above physical control, which only had one publication reporting an unsuccessful control (Juza et al., 2018). Chemical methods using CO_2 levels and various pesticides found greater success than olfactory with one successful study using mating calls to trap the target species (Wanger et al., 2015). Two assessment methods for the prevention of the round goby were both found to be successful in efficiently detecting the target species. Lastly, one eradiation study had positive results using the physical method of egg and adult removal (N'Geyen et al. 2018). Though this approach is used best within certain situations, it was the only study found to successfully manage the invasive species using a physical technique.

Table 3 Summary of Asian Carp Publications

Species	Author	Category	Method	Approach	Success (Y/N)
Asian Carp	Kokotovich & Andow 2017	Prevention	Policy	Identifying gaps in knowledge and legislation between state Country	Yes (Potential)
	MacNamara et al. 2018	Prevention	Assessment	Mobile hydroacoustics to quantify habitat and depth use	Yes
	Malcomson & Goucher 2013	Prevention	Physical	Electric barrier	Yes
	Pingfu, Wiley, & McNyset	Prevention	Modeling	Genetic algorithm for rule-set prediction (GARP) to model potential range	Yes
	Phelps et al. 2017	Prevention	Policy	Legislation and early detection	Yes
	Rasmussen 2006	Prevention	Policy	Creating regulations and laws	Yes
	Varble & Secchi 2013	Control	Physical	Marketing and consuming the species	Yes (Potential)
	Wilson et al. 2014	Prevention	Assessment	eDNA to detect presence and biomass density	Yes
	Wittmann et al. 2014	Prevention	Assessment	Structured expert judgement forecasting invasions	No

Publications on the species Asian carp present prevention as the dominate management tactic (Table 3). The most common prevention methods were assessment and policy, which had a 100% success rate for all papers using these approaches, with one physical method also finding success (Kokotovich & Andow 2017; MacNamara et al. 2018; Malcomson & Goucher 2013; Pingfu, Wiley, & McNyset; Phelps et al. 2017; Rasmussen 2006; Wilson et al. 2014). One publication found potential positive results with a physical control method of consuming the target species (Varble & Secchi 2013). Overall no studies gathered found negative results.

Table 4 Summary of Asian Clam

Species	Author	Category	Method	Approach	Success (Y/N)
Asian Clam	Colwell et al. 2018	Prevention	Modeling	Open access map for public to create awareness	Yes
	Coughlam et l. 2018	Control/ Eradication	Chemical	Dry ice applied	Yes
	Dos Santos 2014	Control	Chemical	Agricultural chemicals applied	Yes
	Gomes et al. 2014	Control	Chemical	Three biocides applied	Yes
	Nogueira et al. 2018	Control	Chemical	ZnTP compound applied	No
	Pereira et al. 2016	Control	Biological	Predator consumption	Yes
	Smith et al. 2018	Prevention	Assessment	Benthic survey of water body	Yes
	Sousa et al. 2013	Control	Chemical	Chemical applied as reactive and proactive methods	N/A
	Sousa et al. 2013	Control	Physical	Reactive and proactive removals	N/A

Publications on the species Asian clam present control as the dominate management approach (Table 4). Chemical control had the greatest success with three studies finding success using pesticides and other various chemical compounds (Coughlam et al. 2018; Dos Santos, 2014; Gomes et al., 2014). One form of biological control was successful through predator consumption (Pereira et al. 2016). One study found stated two approaches to management through chemical and physical methods but failed to state their effectiveness or lack thereof (Sousa et al., 2018). Two prevention tactics, one using an assessment approach and one focusing on modeling and public awareness both found positive results (Colwell et al. 2018; Smith et al. 2018). Finally, one chemical eradication method, used initially for control of the species was found to also have success in eradicating the target species (Coughlam et al., 2018). Management of invasive species already found and established in areas of the Great Lakes (round goby and Asian clam) were found to have studies focused on the control of the species, with prevention having the second most emphasis (Colwell et al. 2018; Coughlam et l. 2018; Cupp et al. 2018; Dos Santos 2014; Gomes et al. 2014; Isabelle-Valenzi & Higgs 2016; Juza et al. 2018; Nevers et al. 2018; Nogueira et al. 2018; Pereira et al. 2016; Schreier & Larson 2008; Smith et al. 2018; Wanger et al. 2015; Zeyl et al. 2014). Both case study species were also found to be positively affected by chemical control methods, unlike the Asian carp. Species not yet found in the Great Lakes but in adjoining water systems (Asian carp) were found to have studies almost entirely focused on their prevention. With an even ratio of articles using polices as their method of management.

Similarities between general life forms can also be seen when comparing the two target fish species (round goby and Asian carp). Both prominent assessment techniques involve the use of eDNA and the modeling of physical or behavioral characteristics.

DISCUSSION

Although overall several publications were found, there was a clear lack of expertise behind eradication type management for all three case studies. Many studies have pointed out the infeasibility when attempting to remove an entire species once it has been established (Robertson & Gemmell, 2004; Simberloff, 2003; Sousa et al.,2013). The impracticality is attributed to the extreme cost and logistical difficulties in targeting a single species (Gaeta et al., 2012; Simberloff, 2003) Before eradication attempts are taken, considerations must be made on the factors surrounding its success. Vander Zanden et al. (2010) highlighted three main factors; the economic and environmental costs of inaction, economic and environmental costs of the eradication process, and the probability of success both in present and future.

The cost of inaction is calculated by the impact the invader would have on the native species, as well as the ecological degradation and loss of ecosystem functions that would occur, ultimately affecting the economy (Epanchin-Neill &Hasting. 2010a). Whereas the cost of eradication in determined by the total cost of the procedure including equipment, the time and physical labor needed to execute the plan, and the potential harm the chosen method will have on the native species and surrounding ecosite (Gaeta et al., 2012). These two costs are readily compared, assessing whether a passive or active method is best suited for the situation. A successful eradication attempt is estimated by the susceptibility of that area receiving another invasion, determined through the degree of isolation and frequency of human interaction, in addition to the probability that all members of the invaded population were removed (Sousa et al., 2013).

The impracticality of eradication is suggested by the many studies documenting failed attempts, for example, the zebra mussel eradication in 2008 that applied 22 tons of copper sulfate pentahydrate and resulted in little mitigation of the target species and massive fish mortality rates (Sousa et al., 2013). Though opposingly there have also been many success stories (Gaeta et al. 2012; Robertson & Gemmell, 2004; Simberloff, 2003). With multiple management tactics accomplishing in their goals, it begs the question as to why we see so little eradication attempts within the great lakes? The answer is multitiered. Firstly, the degree of isolation is an influential factor. The majority of successful publications have been on small localized populations, on islands for example, or communities limited to "habitat islands" (Robertson & Gemmell, 2004). Areas with well-defined perimeters and within a manageable area of undertaking have the greatest chance of complete eradication. This trait cannot be seen in the great lakes. All five of the lakes are joined to one another with each branching out into major tributaries and eventually smaller inland lakes. Atop its connectivity, human interaction and recreational use is extraordinary. Imports, the fishing industry, and leisure activities connected to over 40 million people living in its basin make this freshwater system one the most heavily used and economically important in the world (Malcolmson & Goucher, 2013; Sousa et al., 2013). Therefore, it is impractical to attempt to isolate and near impossible to ensure the target species will not return.

Secondly, the impact of management actions, both environmental and economic, would in most cases fail to outweigh the benefits of complete eradication (Thresher et al., 2018). The risk of further degradation and unintentional mortality of nontarget species through intrusive physical and chemical applications overshadows the level of destruction the sole invasive species causes (Thresher et al., 2018). To avoid these risks, extensive studies and tests must be run to ensure the management action is accurate and precise, followed by the execution of the chosen strategy. Both testing and actual implementation have a high price tag with demands for the equipment/supplies and labour (Simberloff, 2003). Not to mention the extended time periods most studies require to find a solid solution.

Lastly, the agreement of whether to eradicate and the means of doing so is seldom straight forward. Multiple parties with differing views and objectives create barriers for cooperation, sometimes resulting in parties not being seen as equal (Simerloff, 2003). Government agencies, environmental groups, local citizens committees, and various others, depending on the context of the situation, must all come together to coordinate the most effective plan that tries to meet all parties' objectives (Simerloff, 2003).

With all opposing factors surrounding the reality of eradication programs, it is clear why this study found so little publications on this method of management for both established and possibly invading species. The next option once eradication has been ruled-out is to control the population. Containing the species to tolerable levels is seen as the most feasible approach once a species is established (Dragicevic, 2018; Gaeta et al., 2012; Simberloff, 2003; Thresher et al. 2018).

As control is considered the most practical method of invasive species management ((Buyukahakin et al. 2014), it can explain the skewed ratio of articles favouring control efforts found for both round goby and Asian clam case studies. Determining the means of control when eradication is no longer feasible is multi-objective. The most optimal management strategies are based on components such as the invasion dynamic, the analysis of the spread and performance of the species in their native range and how they may respond to the new ecosystems. Other important components include the cost of control and the estimate of damages caused by the invasion (Buyukahakin et al. 2014; Epanchin-Neill & Hasting, 2010a).

Managing for control is first broken down into two categories; the strategies and methods needed (Epanchin-Neill & Hasting, 2010a). Strategies are determined through the when, where, and how the methods are applied. Whereas the methods for control are derived from the researched invasion dynamics and are focused on the killing and prevention tactics needed to stop the spread (Epanchin-Neill & Hasting, 2010a). These tactics are classified as methods such as physical, chemical, or biological control. An understanding of each invasive specie's dynamics is vital to choose the appropriate strategy and method (Buyukahakin et al. 2014). The determination of costs is measured by either the total area treated, number of organisms needing to be removed, or the cost needed to achieve a predetermined level of control. The potential damage is attributed to the amount of land invaded, the number of individual organisms, or the total density of the species (Epanchin-Neill & Hasting, 2010a).

Researching the biology of each invader can lead to a potential overlap in previously managed invasive species. Such similarities can give hints to specific management methods that may have a greater chance of success. For example, the prolific invader *Dreissena polymorpha* (zebra mussel) is detected by methods like eDNA and has rapid-response methods like extreme temperature exposure, similarly seen in Asian clam management (Amberg et al., 2019; Coughlam et al., 2018; Luoma, 2018). Other similarities can be seen in species within the class Osteichthyes (bony-fish), such as the round goby. Physical methods have proven effective for fish control, giving the idea that similar methods may work when Asian carp do find their way into the Great Lakes (Isabelle-Valenzi & Higgs, 2016; N'Geyen et al., 2018; Wittmann et al., 2014).

While considered most practical and with studies finding similarities in management methods between invaders, it begs the question as to why control methods are not uniform for those grouped species, such as clams and mussels, or bony-fish. If scientific analysis proves certain treatments are effective, why are they not universally used? This can be explained by the complex social structure that is environmental management. Firstly, the gaps in current legislation and scientific knowledge are inefficient at implementing seamless and rapid management efforts. Coupled with insufficient funding, this decreases the likelihood of expansive invasive species control (Epanchin-Neill et al, 2010b). Secondly, the goals and objectives of managers, environmental organizations, and cultural groups play a large role in the types of methods deemed adequate for each species and geographic area (Shine & Doody, 2011). Varying uses of the affected area, species of high concern, and government priorities create issues in the fluidity of management action. Finally, the creation of management mosaics creates additional cooperation and direct impacts on the management of adjoining landscapes (Shine & Doody, 2011). Management mosaics refers to when the landscape is divided into private properties or areas that of which are under different managers (Epanchin-Neill et al. 2010b). Each mosaic piece is controlled by its manager, whose decision then directly influences its neighbours. For example, a landowner may choose to ignore the presence of an invasive species on its property, creating a source population that could spread across jurisdictional boundaries (Epanchin-Neill et al., 2010b).

The complexity of control actions, though in most cases is still the most reasonable and common method of management across publications, is still second to that of prevention methods. Multiple articles stated the need for and efficiency of monitoring and preventative actions.

Prevention methods can take multiple forms, all of which can be generally grouped into risk assessments and policy frameworks. Risk assessments, in all their variations, rely solely on the research done for each invading species (Malcolmson & Goucher 2013; Messing & Wright 2006; Sousa et al. 2013; Phelps 2017). Information on biology fuels the forecasting of risk analyses, risk characterizations (Allen et al., 2006), and structured expert judgments (Wittmann et al, 2014) which enable the creation of preventative strategies, such as integrated pest management (Colwell et al. 2018; Phelps et al. 2017: Sousa et al. 2013). Novel prevention techniques are constantly being developed to help resolve the level of effort required to complete these types of risk assessments and preventative strategies. For example, Graham et al. (2008) suggested the use of cyberinfrastructure to compile and share the known material or successful tactics, making management of these species more efficient. These assessments create crude estimates of their potential damage and indirect impacts. Such estimates have become the base for policy responses (Hoagland & Jin, 2006). Policy is an essential element in the world of invasive species prevention.

The creation of policy through governments is the most proactive method of invasive species management (Malcolmson & Goucher, 2013). Policies have the power to support and further current prevention measures as well as create laws that prohibit the introduction of invasive species, which is essential to combat the issue. Many studies reference the need of greater and more strict regulations to be put into place (Pyke et al., 2008; Zabin et al., 2018; Kokotovich & Andow 2017).

Though policies are far from perfect, many laws, as mentioned above, are based on the estimates of strictly economic damage (Hoagland & Jin, 2006). Little consideration is given to ecosystem services, social perceiving's of each invader, as well the number of species to be included or the size of the landscape that should be covered under the regulations for it be effective (Leung et al., 2002). Though this is easier said than done, as seen with management actions to control invasive species, the ability to smoothly enact cohesive prevention is disrupted by management mosaics and the values of invested organizations and citizens (Epanchin-Neill et al. 2010b; Shine & Doody, 2011).

At the broadest scale, coordination between federal, provincial and municipal governments must occur to adhere seamless compliance on all levels. Federal and provincial governments must also work together with agencies and bilateral organizations (Malcolmson & Goucher 2013). Municipal governments must work with varying ownership at the landscape level. Analogous to control method setbacks, creating unified efforts across divided management areas proves a challenge for all local scales (Epanchin-Neill et al. 2010b; Kalnicky et al., 2018). As well as the inclusion of objectives and values of free independent organizations is a challenge all levels of government must take on.

Citizen education and involvement are key in the success preventative actions as recreation have been linked as a direct contributor to the spread of invasive species (Kalnicky et al., 2018; Van Riper et al., 2018). The creation of educational outreach programs aims to form pro-environmental behaviour either through informational interventions, changing the population's attitude, or structural interventions, using policies to give motivations or encouragement to act in the desired manner (Kalnicky et al., 2018).

Legal and educational actions focused on or including the great lakes have been taken by both border provinces and states. In Canada, the creation of An Invasive Alien Species Strategy for Canada in 2004 stated four priorities “prevention of new invasions, early detection of new invaders if prevention fails, rapid response to new invaders, and management of established and spreading invaders (containment, eradication, and control).” (Climate Change Canada, 2017). The federal government also includes invasive species measures in the Fisheries Act 1985 (Government of Canada, 1985). The Fisheries and Aquaculture Ministries produced an action plan in 2004 to address the treat of aquatic invasive species (Canadian Council of Fisheries and Aquaculture Ministers, 2004). Ontario specifically passed the Invasive Species Act in 2015 in which restrictions, enforcement and response plans are listed (Government of Canada, 2015). Ontario also constructed the Ontario Invasive Species Strategic Plan in 2012 (Ontario Ministry of Natural Resources, 2012), with adjoining policies enacted by the Ministry of Natural Resources and Forestry. The United States has similar Federal legislation, with the Alien Species Prevention and Enforcement Act of 1992, as well as several others (Ericson, 1985). All bordering states have their own specific rules and regulations for invasive species. All jurisdictions are home to multiple outreach programs through non-profit agencies, universities, and government-funded organizations. For example, the Ontario Invading Species Awareness Program (OFAH, 1992), or the New York Invasive Species Council (New York State, 2008). Partnerships within countries have shown to be strong with all provinces and territories joining forces on the Canadian Council on Invasive Species, and collaborative efforts of multiple organizations through the U.S. Fish and Wildlife Service. Internationally, The Commission for Environmental Cooperation which encompasses all nations within North American (Canada, United States of America, and Mexico) and funded for the coordination of programs such as the North American Invasive Species Network and public information forums or platforms to promote education (CCIS,2018; Commission for Environmental Cooperation, 2018).

Though with scientific articles backing the promotion of prevention method, and multiple government and non-government groups coming together to halt invasions and educate the public, very little prevention publications were found on the case studies.

Improvements in management practices can be achieved for each method of management. Creating open access to literature and past research, for example, could eliminate duplicated studies and increase the reaction time when eradication or control tactics are needed. International polices that encompass all variables which influence the introduction of invasive species could help reduce the number of gaps in legislation and create stronger legal prevention strategies. Finally, further funding and support towards public outreach programs is vital to improve not only prevention efforts but increase the response time needed for eradication and control management.

CONCLUSION

The great lakes have been subject to invading alien species for decades. The case studies were chosen to represent the state of management, for the most part, reflect the current understandings of those management methods. Eradication tactics, known to only be successful through isolated, small populations with generous funding, is infeasible for the great lakes. With the fewest number of publications found, it is clear that managers of the great lake's region understand the extreme undertaking eradication processes involve and have focused efforts in control. Management of established species, such as the round goby and Asian clam used in the case study, is most practically managed by controlling the population size and spread. Halting the spread of invasive populations works almost identically as prevention methods. Both control and prevention have been shown to be undoubtedly the most reasonable and effective methods through both case study examples and literature.

Overall the management of established and potentially invasive species in the great lakes is reasonable given the current understandings of management strategies. With an emphasis on prevention, improvements can be made through conjunctive policies between Canada and the United States. Cohesive legislation within countries is not enough when both regions have an equal impact on the ecosystem. Additionally, outreach initiatives towards the general public should continue to be of focus, as education plays a vital role in the stop of invasive species. Finally, current and future research on species biology and management methods should be readily available to scientists and technicians undertaking the issue to eliminate repeated findings and create rapid management.

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