12-2018

Aquatic Invasions: Causes, Consequences, And Solutions

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By
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Preface

Invasive species represent a global threat to ecosystems, human health, and the economy. A basic knowledge of invasive species biology is crucial to understand current and future impacts and implications. The purpose of this book is to provide a broad background on invasive species, and also details on specific examples through case studies.

The students in the course Aquatic Invasive Species (MAR 442) at the University of New England in Biddeford, Maine, have researched and reviewed scientific literature to educate readers about these issues. The class, comprised of twelve junior and senior Marine Science, Marine Affairs, Applied Mathematics, and Environmental Sciences students, selected the different topics, presented the material, wrote the chapters, and assembled the final versions into this book. This book cannot be all inclusive, but we think this book will provide an excellent broad overview of the most important aspects of Invasive Species Biology and might stimulate the reader to dive deeper into the material.

Biddeford, Maine, November 2018

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Introduction

To start off our book we want to define several terms that are known to have many different meanings when related to invasive species, to better understand the relationship between different species, non-native species, and their native range expansion. The National Oceanic and Atmospheric Administration (NOAA) defines an invasive species as an organism that causes ecological or economic harm in a new environment where it is not native. This definition lacks explicit mention of human involvement which is needed to specifically set apart the term from another similar term, known as an alien species, as both are similar in regards to the transportation of a species into a new environment, specifically from their native range. The website GreenFacts.org states that an alien species is a species introduced outside its normal distribution (GreenFacts 2018). This definition lacks specification on how, as through natural means is necessary due to it is usually assumed that a non-native species experiences a range expansion. For this book, we use the definition from the Executive Order 13112, an invasive species is an alien species whose introduction does or is likely to cause economic or environmental harm, or harm to human health. A non-native, alien, species with respect to a particular ecosystem, is any species including its seeds, eggs, spores, or other biological material capable of propagating that species, that is not native to that ecosystem. ScienceDirect defines range expansion or contraction, as the result of adaptation of populations in a newly colonized area. This definition is lacking specification as well where natural means is needed again, as the term is similar to another known as expansion. Botanist J.C. Willis in 1922 terms range expansion as organisms reaching areas that they were previously absent from through natural means; where "expansion" is used to denote range changes that took place over evolutionary time without human intervention. We can now use these accurate definitions to take a further look into what characteristics makes a species invasive and how they are affecting our way of life. The common periwinkle, *Littorina littorea,* is a prime example of how these definitions can be applied and expanded on overtime. This species questions the reliability of the definitions which are in place in unison with the overall impacts on humans and the environment that they have had through time. Demonstrating overall how the common periwinkle, *Littorina littorea* is the perfect example of a species that represents our definition for an invasive species.

The common periwinkle was first classified as invasive in Nova Scotia in the early 1800s as a result of rocks used as ballast in shipping (Blackslee 2008). *Littorina littorea* presence has spread throughout Europe and Asia, as well as in North and South America. This species is a successful invasive due to its high reproductive rate of anywhere from 10,000 to 100,000 eggs per year as well as their ability to control competing snail populations through the consumption of fast-growing algae and occupy large amounts of space when large populations are present (Bertness 1984). Eradication methods in areas such as the San Francisco Bay has costed up to $5,976,701, however, in other areas this species is not as viewed as negatively; with little to no costs associated with reducing the population (Estuary 2016). This species has few negative impacts and its presence, in many regions has little to no more of a damaging impact as a native species. *Littorina littorea* have been established for such a large amount of time that they could potentially be viewed as either a non-native species or even a native species, stemming from the time of which populations have been present, as well as the large populations which are seen in the coastal intertidal environments presently. This species has helped us, and will potentially further help, in shaping the definition of an invasive species over time to more specifically account for length of time one has been invasive for, as well as less of an impact over time being seen.

The **ecological impacts** of invasive species can be far-reaching and catastrophic. Native species are often extirpated or entirely eradicated by invaders due to competition or habitat destruction. One such example is the invasive semi-aquatic rodent, Nutria, which has been seen to completely wipe out marshlands in the United States. Nutria eat up to 25% of their body weight per day, feeding almost entirely on the plant life within the marshes they inhabit. This, coupled with their underground burrows, leads to complete destruction of plant matter, increased erosion, and destruction of water containment structures (Evans 1983). The underlying forces at play in the havoc invasive species wreak on their environment typically consist of alterations to the supply and cycling of nutrient, trophic, and mineral resources. These impacts often pervade throughout the food web through trophic interactions with native species and broad-scale changes to the abiotic environment, and may result in an ultimate decrease in the diversity and abundance of aquatic communities. Figure 1 offers a conceptual model of the variety of impacts that invasive species of a given trophic level often have on other trophic levels within the invaded ecosystem (Gallardo et al. 2016).

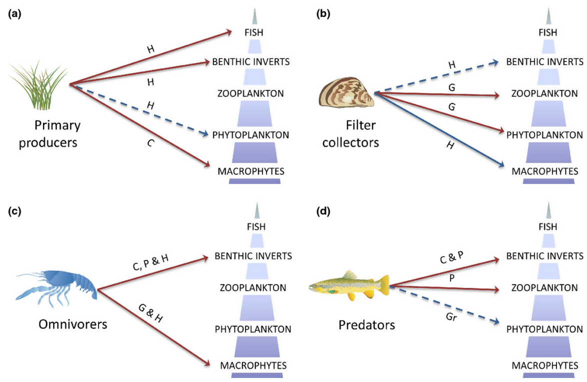

Figure 1: Impacts of invasive species at each of four trophic levels (primary producers, filter feeders, omnivores, and predators) has at each trophic level. Red arrows represent negative effects the species will have on each trophic level, while blue arrows represent positive effects. The main effect(s) of an invasive species towards the given trophic level is defined on each arrow (C, competition, P, predation, G, grazing, Gr, grazer release, H, habitat alteration) (Gallardo et al. 2016).

The impacts of aquatic invasive species can affect the **economy** through both infrastructure and industry in infested areas. Their effects are correlated with the detection of an invasive species, often through specific community outreach programs. Prevention and removal of invasive species hold a large portion of cost allocation due to the potential scale of the invasives range, requiring efforts from multiple communities ranging from barriers, targeted removal, and large-scale eradications. These costs can reach staggering estimates, ranging from hundreds of millions to multiple billions of dollars in economic value. Recovery of the native environment requires as much time as it does funds due to the astonishing ability of invasives to decimate native organismal communities. Invasives commonly go without predation in invasive areas, allowing the species to feed and spread at an unchecked pace, decreasing population numbers as well as diversity, often requiring efforts such as stocking of native species to bring the ecosystem back to normal. In some cases, aiding in the recovery of native environments can again reach costs into the billions. These impacts can be readily seen for example with the invasion of Asian Carp in the U.S., which involve four species that feed on many trophic levels, from producers to consumers, as well as having rapid reproductive rates that are well suited to U.S. waters. The combination of these aspects allow the carp to multiply and spread at a rapid rate and affect the ecosystem and thus the economy more severely as a whole. The primary costs of Asian Carp are seen in the efforts to stop them from moving into the Great Lakes. Efforts attempted include installing three electric barriers meant to deter fish from entering and leaving the Lakes. Initial costs were concluded at nearly $6 million, though an additional $275 million (CSG Midwest, 2012) has been proposed to improve upon the existing structure. A more in-depth analysis of the effects of Asian Carp will be discussed in further chapters. Another example of a species with a high economic impact is the Eurasian Watermilfoil, *Myriophyllum spicatum.* In the United States alone it costs $400 million to deal with the cost of damages and removal of this species and if you broke it down it would cost around $2,000 per hectare. Milfoil causes economic impacts in recreation, tourism, and real estate, but there are also costs in removal methods. This plant can decrease property values by 8% and land values by 13% (Michigan Tech). These losses can be seen in a study conducted in Vermont showing that shoreline property owners could lose up to $12,000 (Maine.gov). Also, due to the nature of this plant it could be problematic for recreation because it could get caught around a boat engine, make fishing more difficult, and deter tourists from recreating. Removal costs can also add up if you consider how often the methods need to be applied to an infested area. It's also important to note that chemical controls using herbicides may kill both invasive and native milfoil, which may have different impacts on the loss of the native species.

Cultural impoverishment due to invasive species are closely related to their ecological impacts. Culture includes the customary beliefs, social forms, and material traits of a racial, religious, or social group. Many cultures can be affected by invasive species by enriching it or impoverishing it, however the latter is more often the case. When an invasive species disrupts ecological systems, it often displaces, by predation or competition, locally important species. It can also deplete important resources quickly by not allowing these resources time to replenish due to the lack of a natural predator to keep its population in check. Diminishment of these resources can lead to a decline in income for fishing industries. There may also be a loss of tourism, or a decrease in recreational activities whether it be due to a loss of species, or implementation of restrictions on activities in an effort to decrease the spread of invasives. Resources may often be culturally significant to local people. These resources do not have a chance to reestablish in their native range depriving people of long-lived traditions of important sources of food, rituals, or medicines. However, there have been cases where invasive species have become accepted by the local people and integrated into local industries although this is often not without damage to other parts of the economy or to ecological systems. This book will describe different invasive species and how culture can be affected by these invasive species in the ways described above.

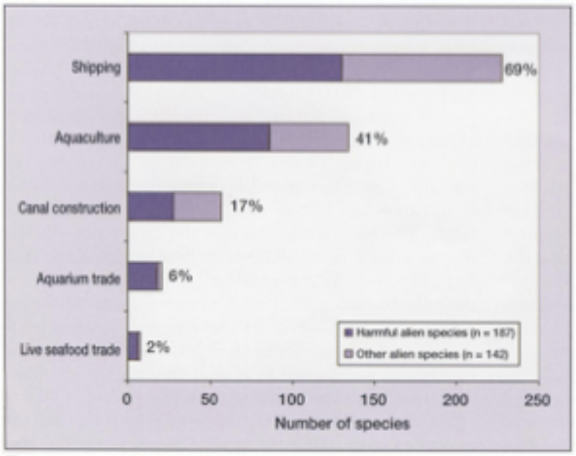

Fig. 2. The most common methods of introduction for invasive aquatic species. The dark purple bars show the number of harmful alien species introduced by the method on the y axis, while the light purple bars show the number of other alien species that may not necessarily be harmful. (Figure from Molnar et al. 2008)

There are many **vectors** which can transport species from their native range to new locations where they could become invasive. For the purpose of this book, we focus on vectors for invasive species that are human caused. Any natural phenomenon such as a storm that carries species long distances would be considered to cause a range expansion rather than an invasion. Some common vectors include shipping, aquaculture, canal construction, the aquarium trade, and the live seafood trade. The first vector mentioned, shipping, can be divided into travel by ballast water transfer and hull fouling. In ballast water transfer, a ship will take in water after it has dropped off cargo to balance the ship and mimic the weight of that cargo. At some point they will need to release the water, which may contain species that are not native in that area. Hull fouling on the other hand is when species attach themselves to the outside surface of a ship and may be removed from the ship in a non-native area. The zebra mussel is a good example of transport through shipping because they have both attached themselves to the hulls of the ship and have been transported in ballast water, although the likelihood of survival is much greater in ballast water. The mussels will typically be living in the water that gets taken in as ballast water and at the time are in the larval life stage; this means they are difficult to detect due to their tiny size. They mature in the ballast water during their free ride to the United States, and are fully matured by the time the water is dumped into the port location. Because they are now mature adults, they are capable of surviving in the new environment.

The second vector mentioned, aquaculture, is when non-native species are farmed as food because of their economic value. Farmed species can escape from pens, or hitch a ride on nets and other aquaculture related materials and become invasive. The Asian Carp is an example of a species that has become invasive in the US due to aquaculture practices. The third most common vector for invasive species mentioned is construction of canals. Large canals like the Panama Canal and the Suez canal enable species to move from one large water body to another via the connecting canal. For example, the lionfish was able to spread into the Mediterranean Sea through the Suez Canal (University of Plymouth 2016). The fourth vector of transport is the aquarium trade, when our aquatic pets or plants used in aquarium tanks are released into non-native areas. This transport could occur intentionally or unintentionally which can be observed when looking at the example of the Goldfish. The last vector mentioned is the live seafood trade, which is where species could attach themselves to the food we harvest and be introduced to a new area that they could cause harm to with their invasion. Also, any species we do use for food may escape and invade an area and become an issue. An example of a species that has been introduced through the live food trade is the Chinese Mitten crab. These five common methods and the number of alien species they have each produced are highlighted in Figure 2. Many of these methods of transport are also outlined in the chapters that follow.

The Asian clam is a perfect example of pathways for introduction, as they have multiple transportation mechanisms that can be examined when trying to better understand how these invasive species rapidly spread throughout the U.S. Initial Asian clam establishment in North America is thought to be due to transoceanic ballast water exchange and Chinese immigration of a food resources. With rapid, long distance colonization through ballast/bilge/engine water transport; food resource trade; bait release; aquarium industry; and anthropogenic mediated hitchhiking, allowing the Asian clam to quickly spread throughout the United States (New York Invasive Species Information 2018). Currently it inhabits water bodies in nearly all 50 States and throughout New York. As human activity is likely to be the key to the dispersal of this invasive species, whether it be through bait bucket introductions, accidental introductions associated with imported aquaculture species, and intentional introductions by people who buy them as a food item in markets (New York Invasive Species Information 2018). Along with larval clams' ability to attach to vegetation and floating debris for long distance dispersal. Though transportation of these juveniles is more likely to be carried in bilge and livewell water in boats and on vegetation attached to anchors and trailers or in sediments left on anchors (New York Invasive Species Information 2018). The only other significant dispersal agent is thought to be passive movement via water currents. Where there remains some question regarding transport by water fowl. Though some might say that birds are not considered to be significant distribution vectors, as transportation on the feathers and feet of water birds can be seen as a secondary transport vector for these tiny creatures (New York Invasive Species Information 2018).

What makes a species invasive? Why are they successful?

Upon introduction to foreign regions, invasive species have the ability to adapt to their new environment which can lead to the colonization and spread to other areas. Invasive success may be due to various determinants such as high reproductive, survival, and dispersal rates, rapid reproduction and growth, and long lifespans. An individual that produces many offspring multiple times within their lifetime coupled with the offsprings' ability to reach sexual maturity in a short timespan can lead to exponential population growth. Most important among the factors though is having a generalistic lifestyle. This allows individuals to tolerate a wide range of conditions such as fluctuating temperatures, salinities, and air and pollutant exposure. Without this tolerability, a species would not be able to thrive in their introduced environments and reproduce at such a successful rate. An excellent example of tolerance can be found in the species hydrilla. Hydrilla can tolerate a wide range of temperatures from 0 to 27 degrees C. It can also withstand up to 7% salinity which allows it to grow in estuaries (Twilley and Barko 1990) . Its most unique tolerance, however, is that of low light conditions. Hydrilla can grow in very turbid waters that receive light at only 1% of surface sunlight conditions (Ramey 2001), and is able to begin photosynthesis early in the morning when light is low. This enables it to obtain large amounts of carbon dioxide that is available in the water before the CO_2 is absorbed by other plants (US Fish and Wildlife Service).

Genetic factors contribute to invasive success as well such as with genetic variability, phenotypic plasticity, and epigenetics. In some cases greater genetic variability resulting from breeding between two separate invasion fronts or between an invasive and native species of the same genus can result in invasive success (Shi et al. 2018). Other cases suggest that less genetic variability can lead to invasive success due to a reduction in intraspecific aggression and an increase in interspecific dominance (Tsutsui et al. 2000). These contradicting studies prove the complexity of what ensures the establishment of the invasive species in affected areas.

Role of climate change

As the climate changes due to the presence of unprecedented levels of greenhouse gases in the atmosphere, aquatic ecosystems change dramatically. The warming of the earth's surface results in changes in surface water temperatures, salinity, pH and weather patterns across the globe. Further, increased frequency and severity of tropical storms resulting from climate change can directly increase the spread of invasive species. Due to their adaptability and plasticity, aquatic invasive species are typically tolerant of these physical and chemical changes and the rapid rate at which they are occurring, resulting in range expansion and sometimes increased productivity. This ability to adapt quickly to changes in the ecosystem enables invasive species further in outcompeting native species, thus amplifying their impact on the invaded area. A prime example of the effect that climate change can have on invasive species populations is that of the *Styela clava*, sea squirts, which have proven to thrive in warming waters.

Sea squirts are able to survive in water between 2 and 23°C, but are unable to reproduce in temperatures below 15°C (Dijkstra et al. 2017). These thermal barriers historically inhibit the spread of the invasive sea squirt, limiting both the areas and time of year in which they are able to thrive. With warming ocean temperatures, recruitment of invasive sea squirts is projected to increase while that of native sea squirts is likely to decline. Further, this recruitment is expected to occur earlier in the year with warming waters, thus allowing the invader to have more time to feed, grow and reproduce. While there is no significant difference between the rate of growth among native and invasive sea squirts in moderate water temperatures, as temperatures increase the invasive species is able to increase its growth rate (Figure 3), and therefore outcompete the native species even more successfully (Stachowicz et al. 2018). The more sea surface temperatures increase by, the larger the gap will become in the survivability and success of invasive and native species. A change in just 2°C is projected to double the rate of reproduction of the invasive sea squirts which will only increase the severity of their invasions.

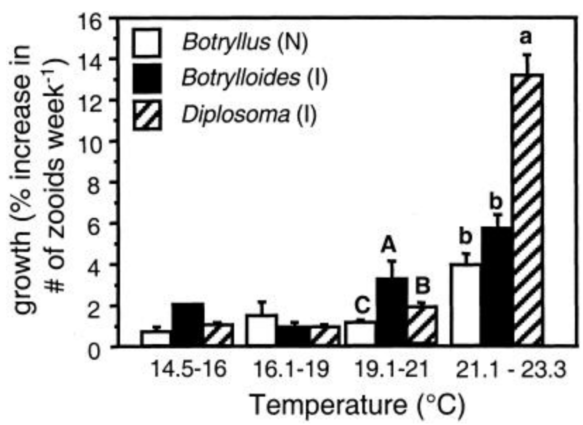

Figure 3: comparative growth rate among two invasive species of sea squirts, *Botrylloides* and *Dipolosoma*, and one native species, *Botryllus*, in varying temperatures. Figure from Stachowicz et al. 2018

Similar trends in response to climate change can be seen among many aquatic invasive species, as will be discussed in detail in the case studies to follow.

Prevention, Detection, and Solutions:

Preventing invasives from becoming established, detecting them early into their introduction, and applying effective practices to remove the invaders is the key solution to avoiding the negative impacts of invasive marine species. Invasive species are often extremely difficult to eradicate from an environment once they have been established, with control effort and costs rising exponentially as the invasion progresses (Taylor 2004). Figure 4 demonstrates the importance of prevention and early detection, as the cost of controlling an invasive species increases the longer the population has been established. The figure also illustrates the interactions of species abundance over time, and the types of solutions used at a given point in the species establishment. Once the abundance approaches the limits of the environment, control costs peak, and reactive control measures are the only feasible response, focusing on limiting further spread, and repairing any damage caused (EDDMapS 2018). Therefore, the most practical solution, economically and ecologically, to the threat of aquatic invasive species is to prevent their introduction entirely (Hulme 2009).

Prevention methods vary depending on the target species, however there are some common methods in use generally to prevent a wide array of invasions. These methods include focused regulations on high-risk transport vectors, such as mandatory mid-ocean ballast water exchange, and extended citizen education and involvement (Hulme 2009, Taylor 2004). Overall, prevention methods are largely focused on areas with a high rate of invasives, such as ports, and regions close to a spreading invasion (Elith 2009).

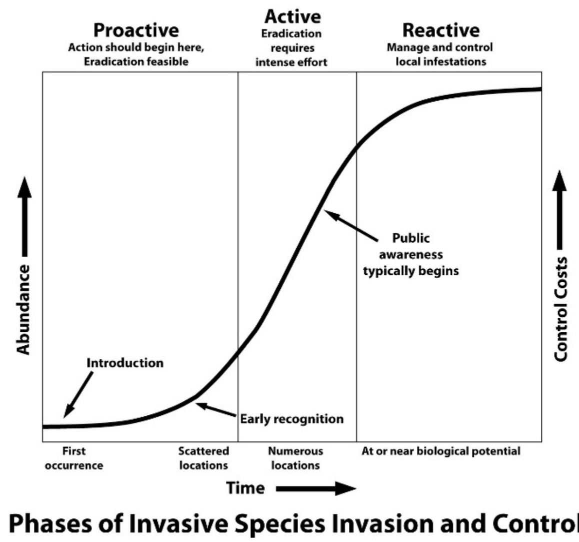

Figure 4: Relative cost of controlling an invasive species, as a function of species abundance and the time since establishment of the population. Also noted are relative milestones in an invasion, and the types of control methods used at a given period in the invasion. (Figure from EDDMapS program)

Similarly, early detection of invasives is crucial to effective control and removal, as often it is only practical to eradicate an invasive species is early in its introduction. Species can be detected physically, such as in community surveys and research projects; using molecular biology techniques, such as environmental DNA (eDNA); or physiologically, a series of novel methods which rely on the differences in invasives and natives biochemistry (Delaney 2008, Jerde 2010, Asner 2008).

Finally, should prevention and early eradication methods fail, there are a number of traditional removal and extermination methods used on aquatic invasive species. One of the most common, though not necessarily efficient, is large-scale cullings and hunts (Taylor 2004). These tend to be both labor and economically intensive operations, which are only effective of a limited number of species, typically those in large, tightly grouped clusters which lack another nearby population for re-introduction (Elith 2009). Another method which has had greater success is targeted and enhanced citizen involvement, such as that utilized to combat lionfish in the Gulf of Mexico (Scyphers et al. 2015). Citizen involvement reduces both the financial and labor costs, as citizens often volunteer their time in these projects, and can offer a large workforce to accomplish tasks rapidly. A species against which many removal methods have been employed is the Brazilian waterweed, *Egeria densa*, an invasive aquatic plant which has spread through a large portion of the southern coastal United States. Researchers and landowners alike have employed a variety of mechanical, manual, chemical, and biological control methods to remove this species from lakes and waterways (Anderson and Hoshovsky 2000). Mechanical methods include using rakes, boat-attached cutting blades, and rotovation of the bottom substrate to pull sections of *E. densa* from the bottom, allowing native species a chance to repopulate (Anderson and Hoshovsky 2000). These methods are risky, as *E. densa* is capable of reproducing by fragmentation, meaning any broken stem, root, or leaf parts left in the water are capable of sprouting into an adult plant, similar to Purple Loosestrife (*Lythrum salicaria*), as will be discussed later (WAPMS 2003). Manual removal methods are the simplest, and the most difficult, as this involves removing the invasive species by hand a small section at a time. This labor-intensive removal method is most practical for small, shallow bodies of water, with a large recreational user population from which to draw a volunteer workforce (CDBW 2000). Otherwise, these operations become expensive, as workers need to be hired, and deeper waters require the use of specialized equipment, such as SCUBA gear, to remove plants from the bottom (Gibbons et al. 1999). Similarly, chemical control methods can be effective if used correctly on certain types of waterways, but can be hazardous if used incorrectly (Anderson and Hoshovsky 2000). Chemical controls such as herbicides and pesticides are often non-selective poisons which will damage native populations along with the target invasive species. Also due to the human health risk chemical controls are heavily regulated and enforced requiring a trained professional to administer the agent in many regions. Finally, biological controls have met with some success depending on the target species (Bonar et. al, 1993). These biological methods involve the controlled introduction of one or multiple additional species , which will act as a limiting factor on the invasive species. Most often, these species are a predator of the invasive species, such as the sterilized triploid grass carp, which have been used to successfully as a control on populations of Brazilian waterweed (Bonar et. al, 1993). Other successful biological controls will be discussed at greater length with regards to Purple Loosestrife.

Overall, the most effective response to an invasive species is to prevent the species from being introduced or established in new territory. In order to avoid establishment, early detection by removal projects and agencies is key. If, against all efforts, a species becomes established, there are a variety of control methods available to control and eliminate invasives.

Management and Policy

Under the public trust doctrine, most submerged lands are being held in trust by the government for the benefit of the public. Natural resource managers and policy-makers are responsible for managing and protecting our oceans, coasts and Great Lakes.

In the United States, numerous federal agencies including Departments of Agriculture, Commerce, Defense, Homeland Security, Interior, and Transportation share responsibilities regarding invasive species (CRS 2017). Management must consider the objectives of all stakeholder groups. This includes consideration towards potential solution approaches for identifying cost-effective or efficient resource investments for invasion management (Epanchin-Niell 2017). Decision-makers, to ensure appropriate levels of invasion management to achieve social objectives, must evaluate complex trade-offs to determine what actions will achieve the best outcomes for the public (Epanchin-Niell 2017).

Executive Orders (EO), which govern federal agencies, have been put in place to emphasize the need for management and policy at the national level. Executive Order 11987: *Exotic Organisms*, issued by President Jimmy Carter in 1977, required Federal agencies to restrict the introduction and importation of exotic species (USDA 2018). Upon revoking EO 11987 in 1999, President Clinton issued Executive Order 13112: *Invasive Species*, establishing the National Invasive Species Council (NISC) and defined alien species as "any species, including its seeds, eggs, spores or biological material capable of propagating that species, that is not native to that ecosystem…[which] does or is likely to cause economic or environmental harm or harm to human health" (USDA 2018).

The National Invasive Species Council provides high-level inter-departmental coordination of federal invasive species actions and works with other federal and nonfederal groups to address invasive species issues at the national level (CRS 2017). NISC delineates seven duties: (1) prepare, revise, and issue a national invasive species management plan, (2) draft the inter-departmental invasive species performance budget, (3) oversee implementation of Executive Order 13112, and review progress under the under the NISC Management Plan and Executive Order 13112, (4) encourage planning and action at local, tribal, state, regional and ecosystem-based level to achieve strategic goals, (5) work with CEQ to develop guidance for federal agencies pursuant to NEPA, (6) work with the Department of State to provide input for international invasive species standards and cooperation, and (7) facilitate development of a coordinated network among federal agencies to document, evaluate, and monitor invasive species (CRS 2017).

Most recently, in 2016 President Obama amended President Clinton's Executive Order with EO 13751: *Safeguarding the Nation from the Impacts of Invasive Species*, expanding the efforts related to invasive species and membership of the Council, and clarifies the operations of such Council, incorporates considerations of human health, climate change, and technological innovation (USDA 2018).

> "Despite efforts to achieve high-level interdepartmental coordination, comprehensive legislation on the treatment of invasive species has never been enacted, and no single law provides coordination among federal agencies. Instead, the current legal framework is largely governed by a patchwork of laws, regulations, policies, and programs. Some laws are tailored to individual species or narrowly focused on what is affected by the species. Other laws have a broader intended purpose and may only peripherally address invasive species. Some laws, although they do not directly address invasive species control or prevention, may limit such introductions" (CRS 2017).

Figures 1, 2, and 3. Compilation of Major Federal Agencies and Laws Governing Invasive Species (Congressional Research Service 2017)

Appendix A. Major Federal Agencies and Laws Governing Invasive Species

Agency	Major Responsibilities and Activities	Selected Authorities, as amended
Department of Agriculture		
Animal and Plant Health Inspection Service (APHIS)	Protects U.S. agriculture from domestic and foreign pests and diseases, responds to domestic animal and plant health problems, and facilitates agricultural trade. As part of its regulatory framework, APHIS has oversight of animal and plant health, including the prevention of foreign diseases and pests, eradication and containment of such problems domestically.	As amended: Animal Health Protection Act (7 U.S.C. §§8301-8322); Plant Health Protection Act (7 U.S.C. §§7701-7721); Agricultural Bioterrorism Act (7 U.S.C. §8401); Animal Damage Control Act (7 U.S.C. §§426 *et seq.*); Federal Seed Act (7 U.S.C. §§1551 *et seq.*); Federal Noxious Weed Act (7 U.S.C. §2814); Noxious Weed Control and Eradication Act of 2004 (7 U.S.C. §§7781-7786); National Environmental Policy Act (42 U.S.C. §§4321 *et seq.*); among other authorities,
USDA's Research, Education, and Economics agencies: Agricultural Research Service (ARS), Economic Research Service (ERS), and National Institute of Food and Agriculture (NIFA).	ARS is USDA's chief scientific in-house research agency. Provides scientific and technical support for its regulatory agencies. ERS is USDA's economic research agency, and supports invasive species efforts through its various research programs. NIFA coordinates and administers federal funding of land grant and other institutions to conduct agricultural and food research, and education activities, including research on invasive species.	Numerous laws dating to the Department of Agriculture Organic Act of 1862 (7 U.S.C. §2201 note), up through and including various omnibus farm bill laws.
Farm Service Agency (FSA)	In managing the Conservation Reserve Program (CRP), requires all participants to control weeds (including noxious weeds), insects, pests, and other undesirable species on enrolled lands.	Provisions governing CRP (16 U.S.C. §§3838a, 3832), as amended; National Environmental Policy Act (42 U.S.C. §§4321 *et seq.*).
Foreign Agricultural Service (FAS)	Works with APHIS, helps provide invasive species technical assistance to foreign countries.	See laws and statutes under APHIS.
Forest Service (FS)	Manages invasive activities on 193 million acres of national forests and grasslands, as well as supports activities outside the United States.	As amended: Organic Administration Act of 1897 (16 U.S.C. §551); Multiple-Use Sustained-Yield Act (16 U.S.C. §§528-531); Forest and Rangeland Renewable Resources Planning Act (16 U.S.C. §§1671 *et seq.*), as amended by the National Forest Management Act (16 U.S.C. §1604); Federal Noxious Weed Act (7 U.S.C. §2814); Public Rangelands Improvement Act (43 U.S.C. §§1901 *et seq.*); Federal Land Policy and Management Act (43 U.S.C. §1701 *et seq.*); Hawaii Tropical Forest Recovery Act (16 U.S.C. §4503(note)); Cooperative Forestry Assistance Act (16 U.S.C. §§2101-2111); sections of the International Forestry Cooperation Act (16 U.S.C. §4501(b)); National Environmental Policy Act (42 U.S.C. §§4321 *et seq.*); among other laws.

Agency	Major Responsibilities and Activities	Selected Authorities, as amended
Natural Resources Conservation Service (NRCS)	Provides technical assistance to cooperating landowners and federal agencies (such as the Forest Service and Bureau of Land Management) to adopt conservation practices on agricultural land, including rangeland, and promotes conservation planning through many of its farmland conservation programs.	As amended: Soil Conservation and Domestic Allotment Act (16 U.S.C. §590(a)-590(f)); also farmland conservation provisions in various omnibus farm bill laws (e.g., Food Security Act (16 U.S.C. §3839aa-3839aa-8); Federal Agriculture Improvement and Reform Act of 1996 (16 U.S.C. §3836a); National Environmental Policy Act (42 U.S.C. §§4321 *et seq.*).
Department of Commerce		
National Oceanic and Atmospheric Administration (NOAA)	Administers a variety of programs aimed at expanding and coordinating prevention, early detection, rapid response, control, and monitoring programs nationwide, among other roles and responsibilities. NOAA is also the statutory co-chair of both the interagency Aquatic Nuisance Species (ANS) Task Force and National Invasive Species Council (NISC).	As amended: Nonindigenous Aquatic Nuisance Prevention and Control Act (16 U.S.C. §4701, *et seq.*); Endangered Species Act (16 U.S.C. §§1531-1543); Fishery Conservation and Management Act (16 U.S.C. §§1801-1882); Coastal Zone Management Act (16 U.S.C. §§1451 *et seq.*); Interjurisdictional Fisheries Act 1986 (16 U.S.C. §§4101 *et seq.*); National Environmental Policy Act (42 U.S.C. §§4321 *et seq.*).
Department of Defense		
U.S. Army Corps of Engineers (USACE)	Maintains programs that address subcategories of invasive species, and provides guidance and research assistance on invasive species control strategies. Provides support to states for aquatic plant management and funds control of invasive aquatic plants in certain southeastern states.	As amended: Nonindigenous Aquatic Nuisance Prevention and Control Act (16 U.S.C. §§4701, *et seq.*), Rivers and Harbors Appropriation Act, as amended (33 U.S.C. §403); Water Resources Development Act (§3061); and National Environmental Policy Act (42 U.S.C. §§4321 *et seq.*).
Department of Health and Human Service (HHS)	Within HHS, the Centers for Disease Control and Prevention (CDC) address zoonotic and emerging diseases. In addition, the National Institute of Health (NIH) supports zoonotic and bioterrorism preparedness research.	Homeland Security Act of 2002 (6 U.S.C. §§101 *et seq.*); sections of the Public Health Service Act (42 U.S.C. §201 *et seq.*) and other public health authorities.
Department of Homeland Security		
U.S. Coast Guard	Responsible for developing and implementing a ballast water management program to prevent the unintentional introduction/dispersal of nonindigenous aquatic species from ship ballast water	As amended: Nonindigenous Aquatic Nuisance Prevention and Control Act (16 U.S.C. §§4701, *et seq.*); Federal Water Pollution Control Act of 1948 (also known as Clean Water Act, 33 U.S.C. §§1251-1376); National Environmental Policy Act (42 U.S.C. §§4321 *et seq.*).
Customs and Border Protection (CBP)	Responsible for border protection and facilitating lawful international trade and travel. Works with other federal agencies to enforce laws prohibiting or limiting the entry of invasive species.	Homeland Security Act of 2002 (6 U.S.C. §§101 *et seq.*); Tariff Act (19 U.S.C. §§1202-1654).
Federal Emergency Management Agency's (FEMA)	Works with other federal, state, tribal, and local authorities to control and eradicate outbreaks of animal/zoonotic disease, exotic plant pests, or invasive plant pest infestations; also contributes to the protection of natural and cultural resources.	Homeland Security Act of 2002 (6 U.S.C. §§101 *et seq.*); National Environmental Policy Act (42 U.S.C. §§4321 *et seq.*); among other authorities.

Agency	Major Responsibilities and Activities	Selected Authorities, as amended
Immigration & Customs Enforcement (ICE)	DHS' principal investigative arm, responsible for border control, customs, trade and immigration.	Homeland Security Act of 2002 (6 U.S.C. §§101 *et seq.*).
Department of the Interior		
Bureau of Indian Affairs (BIA)	Helps support the management of non-native species on Indian lands through its exotic weed eradication and other programs.	As amended: Federal Noxious Weed Act (7 U.S.C. §2814); National Environmental Policy Act (42 U.S.C. §§4321 *et seq.*); among other authorities..
Bureau of Land Management (BLM)	Controls for non-native and invasive plants on land it manages, primarily in western states and Alaska.	Federal Land Policy and Management Act of 1976 (43 U.S.C. §§1701 *et seq.*); National Environmental Policy Act (42 U.S.C. §§4321 *et seq.*); among other authorities.
Bureau of Reclamation (BOR)	Conducts research, prevention, detection, and controls to address pests of aquatic systems such as reservoirs, canals, pipelines, and rivers.	Reclamation Act of 1902 (43 U.S.C. §391h), Fish and Wildlife Coordination Act, as amended (16 U.S.C. §§661-667e; the Act of March 10, 1934; Ch. 55; 48 Stat. 401); National Environmental Policy Act (42 U.S.C. §§4321 *et seq.*).
Fish and Wildlife Service (FWS)	Works to conserve, protect, and enhance fish, wildlife, plants and their habitats. Works to prevent the introduction and spread of invasive species, and on controlling established non-native species, often working with other agencies (USDA, NOAA, and CBP). Maintains programs covering fisheries, endangered species, habitat conservation, refuge operations and maintenance, and international affairs.	As amended: Lacey Act (18 U.S.C. §§42-43; 16 U.S.C. §§3371-3378); Endangered Species Act (16 U.S.C. §1531-1543); Nonindigenous Aquatic Nuisance Prevention and Control Act (16 U.S.C. §§4701, *et seq.*); Wild Bird Conservation Act (16 U.S.C. §§4901, *et seq.*); Hawaii Tropical Forest Recovery Act (16 U.S.C. §4503(note)); National Environmental Policy Act (42 U.S.C. §§4321 *et seq.*); among other authorities.
Geological Survey (USGS)	Supports efforts to identify, document, disseminate, and integrate information about the nation's biological resource, including nonindigenous species.	Organic Act of March 3, 1879 (43 U.S.C. 31); Fish and Wildlife Resources Cooperative Agreements (16 U.S.C. §753 a); Agreements to Implement the Convention on Great Lakes Fisheries between the United States and Canada (16 U.S.C. §§931-939); Clean Water Act (33 U.S.C. §§1251-1387); among other authorities.
National Park Service (NPS)	Uses an integrated pest management approach to manage exotic species, and targets specific sites or species. Regulates fishing on its lands and prohibits the possession or use of certain bait for fishing.	As amended: National Park System (16 U.S.C. §§1 *et seq.*; 16 U.S.C. §594); Endangered Species Act (16 U.S.C. §1531 *et seq.*); Noxious Weed Control and Eradication Act (7 U.S.C. §§7781-7786); Plant Protection Act (7 U.S.C. §7701 *et seq.*); National Invasive Species Act (16 U.S.C. 4701); Nonindigenous Aquatic Nuisance Prevention and Control Act (16 U.S.C. §§4701); Animal Damage Control Act (7 U.S.C. §§426-426c); and National Environmental Policy Act (42 U.S.C. §§4321 *et seq.*); among other authorities.

State and local management agendas are more active than federal agencies, simply because such specified ecosystem data is held in the experts at the local level. The Department of State helps develop U.S. foreign policy on invasive species and present the U.S. position and policies within an international context, including conventions, regional initiatives and bilateral agreements (CRS 2017). The Department of State works with federal agencies, states, tribes, nongovernmental organizations, and the private sector to participate in projects, initiatives and workshops on invasive species to raise awareness, share data and information, and to build regional and global capacity to address invasive species prevention and management (CRS 2017).

Decision-makers and resource managers should utilize the threat scoring system provided by the Ecological Society of America in Panel 1 to analyze aquatic invasions on an ad-hoc, species-by-species basis to ensure efficient management response.

Panel 1. Threat scoring system

Each species in our assessment was assigned a score for each of the following categories (where data allowed), to indicate the magnitude of the threat it poses to native biodiversity. The scoring system was devised so that it could be applied consistently to different types of species and to those living in marine, freshwater, and terrestrial habitats.

Ecological impact
- 4 – Disrupts entire ecosystem processes with wider abiotic influences
- 3 – Disrupts multiple species, some wider ecosystem function, and/or keystone species or species of high conservation value (eg threatened species)
- 2 – Disrupts single species with little or no wider ecosystem impact
- 1 – Little or no disruption
- U – Unknown or not enough information to determine score

Geographic extent
- 4 – Multi-ecoregion
- 3 – Ecoregion
- 2 – Local ecosystem/sub-ecoregion
- 1 – Single site
- U – Unknown or not enough information to determine score

Invasive potential
- 4 – Currently/recently spreading rapidly (doubling in < 10 years) and/or high potential for future rapid spread
- 3 – Currently/recently spreading less rapidly and/or potential for future less rapid spread
- 2 – Established/present, but not currently spreading and high potential for future spread
- 1 – Established/present, but not currently spreading and/or low potential for future spread
- U – Unknown or not enough information to determine score

Management difficulty
- 4 – Irreversible and/or cannot be contained or controlled
- 3 – Reversible with difficulty and/or can be controlled with significant ongoing management
- 2 – Reversible with some difficulty and/or can be controlled with periodic management
- 1 – Easily reversible, with no ongoing management necessary (eradication)
- U – Unknown or not enough information to determine score

Panel 1. Assessing the Global Threat of Invasive Species to Marine Biodiversity. From: Molnar et al. 2008.

As outlined in the introduction, aquatic invasive species - defined as alien species whose introduction does or is likely to cause economic, environmental or harm to human health - can be transported through a variety of vectors, most commonly shipping and aquaculture. These species are successful invaders due to varying physiological attributes, environmental conditions, lack of predators, and more. Aquatic invasive species pose severe economic, ecological and cultural threats. Even though these species may be difficult to remove, there are management efforts in place to eradicate or mitigate the presence of these aquatic invaders.

Every species is different therefore managers and policy makers need to evaluate invasions on an species-by-species basis to ensure proper and efficient decision making. Many species, found within our case studies below, provide further insight into the specific causes, consequences and solutions of marine invasions.

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Case Studies

The introduction provided a broader overview on the multiple definitions of invasive species, the ecological, economical and cultural impacts of invasive species, as well as the various vectors that enable species to be transported, the reasons why some species are more prone to become invasive than others, the effects of climate change, and finally, management and policy issues. The following section will provide multiple case studies of aquatic invasive species in many different phyla to highlight the topics introduced and described in the introduction above.

Asian Carp; *Hypophthalmichthys nobilis, Ctenopharyngodon idella, Hypophthalmusmicthys molitrix,* and *Mylopharyngodon piceus*

Everett Pierce

Physiology and Phylogeny

Asian carp are a ray-finned bony fish classified under the family Cyprinid, native to rivers, streams, and lakes in Asia. The most commonly known species are *Hypophthalmichthys nobilis* (bighead carp), *Ctenopharyngodon idella* (grass carp), *Hypophthalmichthys molitrix* (silver carp), and *Mylopharyngodon piceus* (black carp), which are now proliferating rivers, streams, and lakes in the U.S. These carp can be classified by their feeding behavior; bighead and silver carp are filter feeders, while grass and black carp are omnivorous, feeding on plant matter, snails, and small fish. All four of these species are fast growers, growing up to 10 inches a year, and reach sizes ranging from 50 to 110 lbs[1]. Asian carp are extremely robust, able to tolerate temperatures ranging from 3 to 30°C[1], and can populate extremely quickly, having multiple reproductive cycles a year with hundreds of thousands of eggs per cycle. A unique trait of silver carp is their uncanny ability to leap into the air when spooked. This has developed as a hazard to boaters who must avoid getting injured by the flying fish as their boats pass over schools of carp.

Origins

Water treatment plants take in wastewater, which then go through a multi-step cleaning process to then be reused. This water enters the plant with a large concentration of nutrients that are also vital to the success of plankton, which take in the nutrients and bloom, creating eutrophication events. These events are classified by a large bloom, succeeded by a large die-off of plankton. The blooms have the potential to cause problems, as some plankton create toxins that in normal quantities are not harmful, however when the population of plankton increases, the concentration of these toxins grow with them. These toxins are then transferred with the "treated" water to be used by the public, potentially poisoning a large number of people. The issue of eutrophication works in conjunction with the rapid growth of algae and other aquatic plant species, which clog waterways and contribute the long list of issues. To combat this, Asian carp species were brought to the water treatment plants in1963[2] (originally in the southern U.S.) to feed on blooming phytoplankton and reduces their numbers to a less harmful concentration. This solution is not flawless, however, as the carp were quick to take advantage of regular flooding and

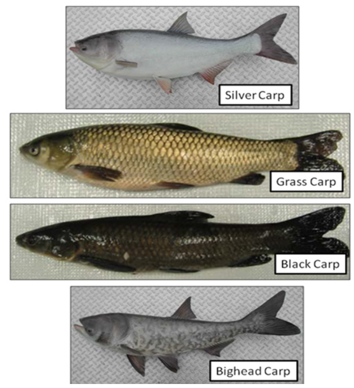

Figure 1- Top to Bottom; Silver, Grass, Black, and Bighead Carp. Figure from: http://www.lakescientist.com/asian-carp/

Figure 3- Silver carp filtering plankton from the water column. Figure from: http://www.prairiestateoutdoors.com/pso/article/taking_on_asian_carp_with_pills_lure_of_sex

escape, spreading north up the Mississippi River.

Effectiveness as an Invader

As with most invading species, the Asian carp invaders face little to no predation in their new-found territories, largely due to their superior size to native species in the U.S. This combined with their rapid growth, maturation, and reproduction rates makes them extremely suited to thrive. Not only do these fish have the capability to survive, they have the internal arsenal to strip a body of water of sustenance, both planktonic and non. Carp average a consumption rate of 5-20% of their body weight per day, meaning that in a 24-hour period, a 100lb fish could consume up to 20lbs of microscopic organisms. This rapid feeding rate is combined with an extremely rapid reproduction rate, with both sexes maturing between 3 and 6 years old and females able to produce over a million eggs in a year. Asian carp are also extremely hardy, able to tolerate temperatures ranging from 3 to 30 degrees C[1].

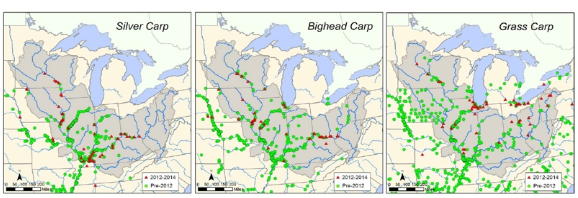

Figure 2- Left to Right; The progression of Silver, Bighead, and Grass carp between 2012 and 2014 is displayed by red, with pre-2012 locations in green. Figure from: https://fw.ky.gov/Fish/Pages/Asian-Carp-Information.aspx

Consequences (economic, ecological, and cultural)

Ecological

The Laurentian Great lakes, being the largest lake system in the world, house a very diverse ecosystem with hundreds of species of fish, plants, mollusks, and crustaceans[3]. Unfortunately, all these classifications can find themselves prey to Asian carp. Grass and Black carp are opportunistic omnivores, feeding on dead organisms as well as live snails, small fish, and vegetation. Silver and Bighead carp are filter feeders, sifting zooplankton and phytoplankton out of the water in large gulps. Between these 4 species, a large portion of the food chain finds themselves prey. Native species are not always affected directly due to the broad diets of the carp species. All four species of invasive carp attack the base of food chains, feeding on the plankton and plants, as well as low tier consumers, thus reducing the stability of the entire chain and stripping the environments of nutrients at the lowest level of consumption. These effects damage the ecosystem by removing sustenance for native species that are unable to compete with the invader's population size. The damage done to afflicted ecosystems can spread as native species migrate in the search for reliable food sources, introducing new species through range expansions.

Economic

The daunting effect carp species can have on native species stirs motivation for those affected. To stop the front of carp moving towards a fishery worth an annual $7 billion, methods such as electric shock barriers, fish kills, and targeted removal have been explored.

Electric shock barriers entail establishing an electrically charged barrier that deters movement both in to and out of a specific area. These plans went into place in 2002 in Romeoville, Illinois. The original was a demonstration barrier, though an updated long-term version was implemented in 2008. The barriers consist of electrodes strung along the bottom connected by lines to a control house, which emits a DC current that is meant to deter by agitation through the fish's lateral line[4]. This method is considered to be one of the last lines of defense, though has potentially been proven unsuccessful, as an 8lb Silver carp was caught past the barrier, a mere 6 miles from Lake Michigan. The

Corp of Engineers as issued a proposal improving the existing 3 electrical barriers with sound barriers and a modified channel, budgeting at $275 million. This proposal is backed by a last resort plan that is to build a solid barrier separating the lake from the river, though that is estimated at a 25-year build time. The original electric barrier was estimated to cost between 4 and 9 billion, on top of the estimated $275 million[5] for improvements. This totals $9,275,000,000 in costs to deter 4 species of fish.

Figure 4- Right; Diagram displaying the 3 electric barriers and their orientation to Lake Michigan and the Mississippi River. Figure from: www.lrc.usace.army.mil/Missions/Civil-Works-Projects/ANS-Portal/Barrier/.

Targeted removal is any method involving removing specifically carp from a body of water. This can mean through fishing, netting, or stunning to remove Asian carp without removing native fish species. These methods do have some positive outlook, as some companies are collecting Asian carp and shipping the, to Asia to satisfy Asia's demand for the fish as a food source. The removal of carp is also showing potential benefit in the states, as the St. Louis Zoo is examining the carp as a potential food source for its animals. The first results were promising, though required some nutrient supplementation[6]. The estimated start costs for collecting and shipping carp overseas is $2.5 million[7], increasing costs from $9,275,000,000 to $9,295,000,000.

Fish kills are a method of completely exterminating a body or section of water, though this results in the extermination of all species, including native variants. Fish kills are completed through electric shock, draining of the body of water, or chemical extermination. This option is mainly applicable to small bodies of water that can easily be re-stocked with native species.

These efforts are inadequate for completely solving the problem, though are instead efforts to aid in stopping the carp from spreading, primarily to the Great Lakes. The estimated cost of these prevention plans totaled reaches nearly $10 billion in costs, which is small compared to the $70 billion in value brought every decade by the Great Lakes alone.

<u>Cultural</u>

Asian carp have affected culture somewhat differently, as the presence of the carp has created an interesting new culture in the Midwest. The emergence of competitions to see who can catch and kill the largest number of silver carp has created enough of a scene to draw the attention of the National Geographic[8], who did a T.V. show on the invasion and the competitions. The silver carp are targeted for their jumping, which is a startle response to loud stimulants, causing the fish to jump meters out of the water. The competitor's venter out in boats armed with helmets, bats, and nets, aiming to catch and kill as many of the carp as possible while hopefully avoiding injury themselves, as piloting a boat over a school of silver carp can result in injuries ranging from bruising to concussion.

<u>Climate Change</u>

Climate change in itself does not necessarily escalate the invasion, though it also does not aid in stopping it. Carp, being extremely temperature tolerable, are not overly affected by a warming climate, though over time the change in temperature may expand their range into areas they would not be able to inhabit currently.

Solutions

As mentioned above, the front of the carp invasion is where the more important management and solution efforts are taking place. To stop the front, multiple ideas have been considered, with the most shocking being the idea of stringing electric cables across the river creating a barrier that stops fish from both entering and leaving the Great Lakes. The same idea is applied to the sound barriers, which use certain pitches of sound to target species from crossing that area. Fish kills are another consideration; however, these are only applicable to smaller bodies of water that can be restocked with native species once the carp have been eradicated. The fish kills primarily use either draining of the body of water, or chemicals to kill off all species, then replacing the fish with native variants.

The primary methods that have been applied are the electric barriers, along with targeted removal and spread of awareness of the invasiveness of carp. The method of electrical barriers has been effective, though as mentioned above, a breach in the barrier may have taken place, though experts are unsure as to whether the fish crossed the barrier or was released past it. The potential upgrade of the system may be a solution to the solution, however if that also fails, a plan to build a solid barrier between the systems is being considered.

Conclusion

In conclusion, the voluntary introduction of Asian Carp has proven to be a decision costing multiple billions of dollars, and a massive loss of native life. The damage done is massive, though the efforts of local communities and government are working to stop, and hopefully reverse the affects.

From 1963 to now, the carp have spread from the Southern U.S to the Northern, striping the native environment of sustenance on the most sensitive level, the bottom. The effects of the carp are being met with severe rebuttal, spending multiple billions to place technology and tools to slow the carp from spreading into the Great Lakes and ruining an industry worth $7 billion in economic value. The methodology applied has been primarily effective, though recent events are showing the efforts may need updating to be truly successful.

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Sea Lamprey, *Petromyzon marinus*

McGowan, Maeve

The sea lamprey, also referred to as great sea lampreys, lake lampreys or lamprey eels, is a parasitic fish distinguishable by its leathery, cylindrical body and wide oral disc or "sucker" that is in place of their mouth (Figure 1).

Figure 1: Sea lamprey (*Petromyzon marinus).* Figure from https://www.outdoorsnews.com/2017/10/09/sea-lamprey-numbers-mysteriously-rising-lake-superior-lake-erie/

This mouth is surrounded by an abundance of small, sharp teeth which with its single rasping tongue the lamprey to attaches to its prey and creates a hole in the flesh of the fish. This species of lamprey, the largest found in the Great Lakes, can reach up to two feet in length. The sea lamprey has no paired fins but does have seven distinct gill openings on each side of its body, as well as two large, functioning eyes [(1)]. Its color ranges from blue-black to grey with lighter shades underneath. While its physical and behavioral traits allow the sea lamprey to be a successful parasite in its natural habitat range, its invasion elsewhere has proven to be devastating.

The presence of the sea lamprey in the Great Lakes, where it has become widely invasive and destructive, was first noted in the 1830's in Lake Ontario. This blood-sucking critter is native to the Atlantic Ocean and while anadromous, historically spends most of its life cycle in saltwater. However, since being introduced to the Great Lakes, the sea lamprey has adapted to spending the entirety of its life in freshwater. Like many aquatic invasive species, the introduction of the sea lamprey can be linked to the shipping industry, in this case through the development of locks and canals [(2)]. The initial introduction of the lamprey has been linked to the development of the Erie Canal through which the species accessed Lake Ontario. Prior to extending to the other Great Lakes, the invasion of the sea lamprey remained isolated in Lake Ontario for nearly a century, not making its way to Lake Erie until 1921 following the modification of the Welland Canal, which connects the Great Lakes to Lake Ontario. After expanding its range to Lake Erie, the spread of the sea lamprey became far more rapid, reaching Lake Huron, Michigan and Superior in 1932, 1934 and 1938, respectively (Figure 2).

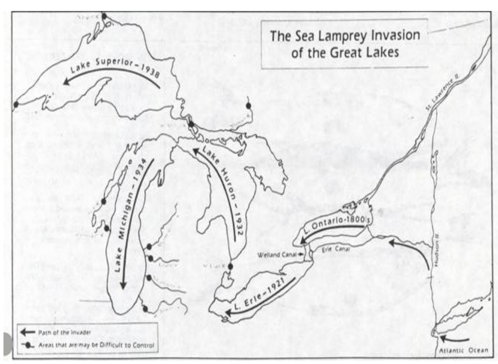

Figure 2: invasion of the sea lamprey. Figure from https://facestaff.cbu.edu/~seisen/PetromyzonMarinus.htm

Impacts

In the Great Lakes, the sea lamprey targets large fish species, including lake trout, salmon, rainbow trout, chubs, catfish, and others. In the Atlantic, sea lampreys are considered to be parasitic rather than strictly predatory as they do not frequently kill their hosts. In the Great Lakes, however, hosts of sea lamprey have no such fate. While losing blood to the lamprey can kill the host fish, they may also die following the detachment of the lamprey. The wound left by the lamprey (Figure 3) makes the fish highly susceptible to disease and other parasites, contributing to the low survival rates of lamprey attacks of only one in seven. In its adult life time, a single lamprey can consume on average 39 pounds of fish. This stage in their life cycle occurs for 12-20 months, followed by the upstream migration of the adult lamprey to spawn and then die. Although reproduction is initiated by male and female lampreys aligning their cloacal openings, fertilization occurs externally. A single lamprey can lay 35,000 to 100,000 eggs, which may be fertilized by more than one male. After hatching, these eggs are swept downstream and bury in silt or sediment where they remain for anywhere from three to 17 years. The larvae then develop into adults and migrate upstream where the parasitic phase begins.

Figure 3: Wound left on lake trout by sea lamprey. Figure from https://phys.org/news/2017-10-vampiric-silver-lamprey.html

The reproductive behavior of the sea lamprey is one of the traits that makes it so successful as an invasive species. Its high fecundity, with each female laying 35,000 to 100,000 eggs, allows its population to increase rapidly with each generation. Furthermore, because fertilization occurs externally thus allowing multiple males to father one brood, there is opportunity for increased genetic diversity within each population. Because the lamprey is anadromous, it is able to tolerate variation in salinity, which likely contributes to the species adaptation to live in different water types than historically typical, which in change has allowed for their establishment in the Great Lakes. Another factor that has enabled the sea lamprey to be such a successful invasive species in the Great Lakes is the lack of natural predators. Although there are other species of lampreys native to the Great Lakes, including the chestnut lamprey (*Ichthyomyzon castaneus),* the northern brook lamprey (*Ichthyomyzon fossor),* the silver lamprey (*Ichthyomyzon unicuspis)* and the American brook lamprey (*Lampetra appendix)*, none of them are as large or aggressive as the sea lamprey, making native species unfit to compete with them or prey on them. Further, because the large fish species in the Great Lakes are adapted to live with less aggressive lampreys, they do not have adequate defensive mechanisms against the sea lamprey. By causing such drastic decline to populations of large fish, sea lamprey has resulted in loss of biodiversity.

Beyond the ecological impacts resulting from the invasion of the sea lamprey there have been substantial economic and cultural impacts as well. The success and stability of the fishing industry is crucial to the economic success of the Great Lake states, yet this stability has been challenged by the sea lamprey. Prior to the invasion of the sea lamprey, the United States and Canada collectively harvested approximately 15 million pounds in the upper Great Lakes annually [(2)]. By the 1960's, once the sea lamprey had become well established, the catch of lake trout averaged 300,000 pounds, only 2% of the previous average. This decline in fish not only impacts commercial fishing but also recreational fishing, thus expanding the scope of the species' effect to from the economic realm to the cultural.

By inhibiting recreational fishing, the invasion of the sea lamprey has disrupted the way in which individuals interact with the Great Lakes. Not only has the invasion of sea lamprey and the resulting loss of fish lead to cultural loss in terms of recreational fishing, it has also impaired the ability of the federal government to fulfill tribal community obligations. Certain tribal communities have rights to a given amount of fish within the Great Lakes, but with an extreme decline in fish, resources must be allocated among all groups that face the loss, and as is historically consistent, tribal communities are likely to not receive what they are owed.

Although the invasion of the sea lamprey has introduced a plentitude of problems to the Great Lakes and all the stakeholders concerned with the stability of fish stocks, the management of this invasive species has actually been tremendously successful. As with most management processes, there has been trial and error with determining the most effective manner to regulate the sea lamprey's population. The use of electrical barriers was once the primary method to keep sea lampreys from fish spawning sites, yet selectivity of these barriers presented an issue and resulted in increased mortality of many of the fish they intended to protect. In 1986, barriers that prevented lamprey entrance but allowed for the passage of other fish were designed. Although this methodology is effective in terms of protecting spawning fish, it does not protect adult fish altogether nor does it control the population of the sea lamprey. In attempt to develop chemical control methods to actually reduce the population of the parasite, scientists tested 6,000 different compounds. While many were found to be either ineffective on the sea lamprey or to also affect other species, the search ended in 1959 when 3-trifluoromethyl-4-nitrophenol (TFM) was discovered. TFM was found to be effective and selective enough to be implemented into sea lamprey control management, and is now used regularly [(2)]. Sometimes Bayluscide, a similar compound, is added to TFM in order to increase its effectiveness as a "lampricide". It is said that due to selectivity, lampricides are not impactful on the environment other than the pests they target, yet it has been found that the additive Bayluscide is toxic to mollusks while TFM impacts mayflies (*Hexagenia sp.)* [(3)]. Based on the wide implementation of lampricides into the integrated management plan for controlling the sea lamprey population in the Great Lakes, it is evident that the ramifications of these chemicals, like their impacts on other species, have been deemed insignificant relative to the impacts of sea lamprey. Other components of the integrated management include the use of barriers, traps, the spaying of male lampreys and the use of pheromones and alarm cues. Barriers and traps are used to restrict lamprey access to specific areas, typically those in which fish are spawning, as mentioned previously. By harvesting pheromones and alarm cues from lampreys and then releasing them in strategic areas, lampreys can be lured towards lampricides or deterred from spawning grounds. Thus far, the integrated management methodology has been wildly successful in controlling sea lamprey populations which have decreased by 90-95% from their peak in the 1950's [(4)]. Although this management is certainly a success story relative to the cases of many aquatic invasive species, there are two factors that may potentially disrupt this success: the impact of climate change and emergence of resistance to lampricide.

Sea lamprey have a higher preferred temperature (18°C) than that of their preferred hosts, lake trout (10°C), and as a result are likely capable of only becoming more successful as the climate continues to change and waters warm. Warmer waters expand the season in which sea lampreys are able to grow and because larger lampreys prey on more fish, warmer waters may increase the amount of trout impacted. Further, as waters warm, more areas become within the preferred thermal range of sea lampreys [5]. Additionally, there is a concern that continued use of lampricides will result in immunity of sea lampreys to TFM. Despite this concern, TFM is still actively used as a part of the integrated management plan due to its effectiveness.

The invasion of the sea lamprey, while once devastating to the Great Lakes, their ecosystems and economies, now stands as a remarkable success story of invasive species control. The success of the sea lamprey integrated management plan can be largely attributed to the amount of energy and resources that have been allocated to the program, being a top priority for the Great Lakes for many years. This case study reflects that even when an invasive species has become widely established and destructive in an ecosystem, mitigation efforts can still be successful.

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Chinese Mitten Crab, *Eriocheir sinensis*

Corey Ackerson

The Chinese mitten crab, *Eriocheir sinensis*, is native to regions of Northeast and Southeast Asia. Predators of the Chinese mitten crab in their native range include organisms such as birds and large fish. These crabs are named for their 'furry' claws that resemble mittens. Their anatomy consists of a smooth round carapace which is approximately three inches in width. They can be distinguishable from other crustaceans, by means other than their claws, by four spines on each side of their carapace as well as a notch between their eyes [4].

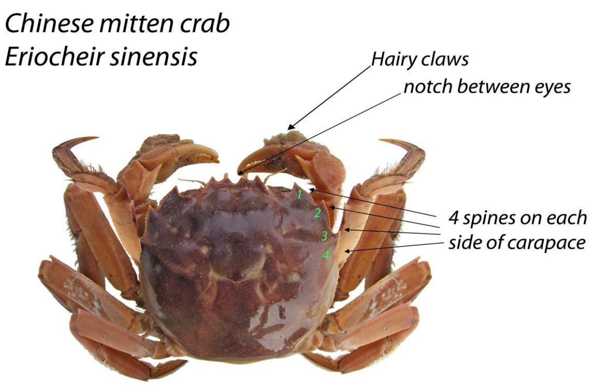

Figure 1: This image shows the basic anatomy of *Eriocheir sinensis* including the key identifying features that this organism possesses. (https://www.freshwaterfishingblog.com/wp-content/uploads/ChineseMittenCrab.jpg)

Eriocheir sinensis are invasive to many aquatic regions throughout Europe as well as to San Francisco in the United States. These organisms were first identified as an invasive species to Germany in 1912. It is suggested that these organisms were brought to regions of Germany unintentionally through means of shipping and the exchange of ballast water in the transport of goods between regions. Chinese mitten crabs are most commonly transported to non-native regions through ballast water exchange, aquaculture, intentional placement, and larval migration up river systems respectively [5]. These methods of transport, being both intentional and unintentional, have resulted in the alteration of diversity and ecosystem health to be witnessed throughout history. Humans are directly responsible for all cases of invasions of these species throughout the globe, other than that of larval migration up river systems; some would disagree however and say that there is a correlation between this migration and human activity.

Why are *Eriocheir sinensis* successful invaders/ Transport

Chinese mitten crabs are successful invaders as a result of their fast reproductive rates, ability to outcompete natives organisms, as well as destructive behavior in these environments. *Eriocheir sinensis* outcompete native populations of crustaceans, as well as mussel and crayfish populations in the ecosystems which they invade for both food and space. Having a fast rate of reproduction, producing 250,000 to 1 million eggs per brood, populations of Chinese mitten crabs are able to invade and take over new ecosystems quite rapidly and deplete the resources which are available for the native species that are present. The population of these organisms destroy the integrity of ecosystems by the burrowing behavior which they partake in in banks and streams. As these crabs dig into the substrate of these regions, the integrity of the stream decreases and erosion can occur as a result [4]. The presence of *Eriocheir sinensis*, can dramatically alter natural environments over long periods of time as a result of all of the impacts which they can have.

The first invasion of *Eriocheir sinensis* in the U.S. was documented in 1965 in the Great Lakes. These organisms were likely brought to these regions through intentional release as a food source to these waters or by unintentional shipping transport into these areas [5]. The only current self-sustaining population in the United States is located in the San Francisco Bay of California. This population has a large impact on the fishing industry by means of decreasing larval egg populations of native fish, destroying traps, stealing bait from traps, and clogging water operation facilities. Millions of these organisms continue to be captured, however, actions taken to eradicate this species have been unsuccessful [1]. Spread of these species outside of the Bays of California has however been successful and evidence of this self-sustaining populations of this species has not been found far outside out this region throughout the United States.

The spread of *Eriocheir sinensis* is a growing concern due to this species being host to *Paragonimus westermani*, a parasitic oriental lung fluke. The presence of this lung fluke in *Eriocheir sinensis* is damaging to native species populations, as well as humans, since consuming these crustaceans or organisms which have consumed these organisms can pass this parasite between trophic levels. Symptoms of consumption of *Paragonimus westermani* in humans include paragonimiasis, side effects similar to pneumonia or the flu which can be long lasting, as well as lesions to the stomach and lungs [8]. The presence of *Eriocheir sinensis* has a great impact on the success of the fishing industry due to the presence of the parasitic oriental lung fluke these crustaceans are host to. The oriental lung fluke causes damage and potential death to marine and terrestrial organisms when they are passed through the exchange of energy between trophic levels of organisms of the same, as well as different, species.

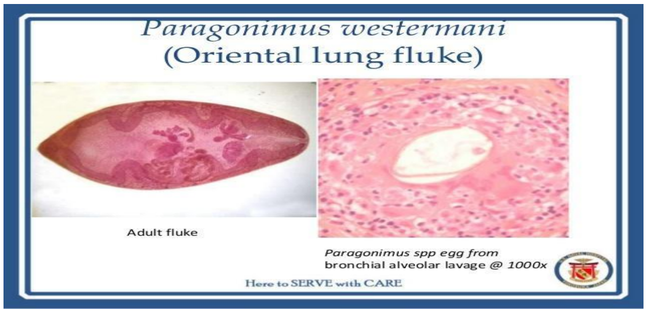

Figure 2: Shape and structure of *Paragonimus westermani*, a parasitic oriental lung fluke which can be found in *Eriocheir sinensis*. (http://image.slidesharecdn.com)

Cultural Impacts

Paragonimus westermani has an impact on the culture seen in human populations, particularly in Asia, since the Chinese mitten crab is consumed as a delicacy in Asian culture. The consumption of these crabs with the presence of the parasite can cause sickness if not cooked and prepared properly. Large amounts of hydrocarbons and metals present in *Eriocheir sinensis* raises concern for consumption due to the greater levels of pollutants in waters of areas which this species is commonly found. Increased levels of pollutants overtime can disrupt culture if these organisms become linked with illness and are no longer consumed. Chinese mitten crabs can also show an effect on culture from the burrowing activity which they partake in causing damage to coastlines and beach fronts [7]. This damage impacts the tourist industry, which many beach fronts and coastlines are centered around.

Ecological Impacts

The ecological impacts of *Eriocheir sinensis* are witnessed through the level of damage which they have on the health of stream and bank environments with the burrowing activity which they partake in [3]. This activity results in erosion, habitat loss and damage, weakening of dams, and decrease in diversity as a result. The effect of this species on the food chain as a result of being a host to the oriental lung fluke greatly impacts the diversity and ecological health which is seen in marine systems in a negative sense as well [4].

Economic Impacts

In terms of economics, *Eriocheir sinensis*, have both positive and negative impacts. The damage that this species has on coastlines and the fishing industry is costly. Most of this cost is seen in the prevention of the spread of this species into new environments outside of the regions which it has already invaded [7]. It is predicted that overtime that *Eriocheir sinensis* will spread far outside of the regions of the environments which it has currently invaded as a result of climate change and warming waters. In the Iberian Peninsula, research has been conducted using past and present rate of *Eriocheir sinensis* spread to predict rates of future spread. This species is predicted to continue to thrive in Iberian waters and other environments which have been invaded by this species as well as it is predicted this species will further its spread outside of these regions as temperatures increase further. Figure 2 shows the predicted suitable area for Chinese mitten crabs (b) and other crustaceans in the presence of varying degrees of greenhouse gases. This spread will continue to cost regions financial strain to combat the damage this species conducts to coastlines. A positive impact this species has on the economy, however, is the potential which it has in the seafood industry. If Chinese mitten crabs were to be consumed by humans in the regions which they invade, they could potentially create a large amount of profit for this industry [2].

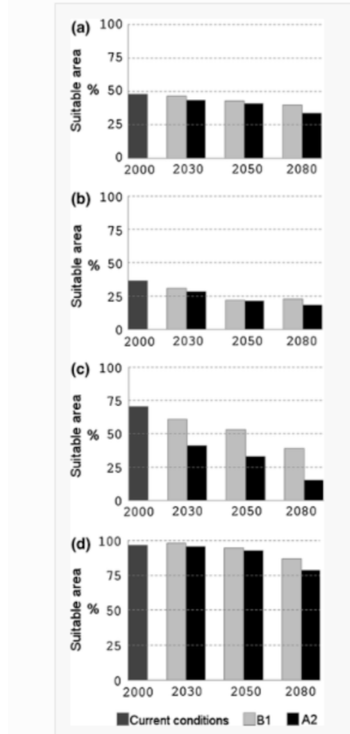

Figure 3: This figure explains the predicted range of crustaceans as a result of the climate change trends of the past, present, and future. This figure shows the suitable range in *Eriocheir sinensis* (b) currently, if high greenhouse gas emission scenarios occur (dark grey) and low greenhouse gas emissions occur. Other crustaceans are shown for comparison purposes. [2].

Policy/Management

Management of this species can be conducted by cleaning off boats and equipment before transferring between different bodies of water. Preventing the spread of this species to new areas and waters is crucial in order to decrease the ecological, economical, and cultural impact which this species has. Reporting any findings of these species to local management groups is important as well in order to combat the spread of Chinese mitten crabs through early action means. Catching this species and eradicating the presence is much more feasible when its presence is still novel to an ecosystem; once a species is well established however this is much more difficult to achieve. The Federal Lacey Act of 1900 has been put into place to prevent the spread of

Chinese mitten crabs by humans by making the import of eggs and Chinese mitten crabs into the United States, from any outside country, illegal [9]. Utilizing prevention tactics to limit the impact of Chinese mitten crabs can limit future impact and damage towards natural ecosystem health and flow.

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Northern Pacific Seastar, *Asterias amurensis*

Nicole Scherer

Introduction: The Pacific Seastar has been known to originally inhabit waters in far North Pacific areas. These regions surrounding Japan, Russia, North China, and Korea are known to go through 'bust and boom' cycles reaching high abundance and then rapid decline. The Northern Pacific Seastar (*Asterias amurensis*) can grow up to 50 cm in diameter. It is yellow with red and purple pigmentation on its five arms, and has a small central disk as seen in Figure 1 [6].

Figure 1. Dorsal view of the Northern Pacific Seastar, also known as *Asterias amurensis*. http://www.loveourlakes.net.au/portfolio/northern-pacific-seastar-monitoring-program/

Its distinctive characteristic is the upturned tips which are not found on other species of stars[1]. The undersides are completely yellow and arms are unevenly covered with small, jagged-edged spines. These spines line the groove in which the tube feet lie, and join up at the mouth in a fan-like shape [1].

Larva can remain in the water column for about 120 days before they finally settle and undergo metamorphosis into an adult seastar. It takes a larva as little as 41 days to about 120 days, from the time of fertilization, to develop into an adult seastar [1]. This process is all dependent upon the temperature of the water in which the seastar is developing; the warmer the water, the faster the rate of development. The average lifespan of a seastar is around 10 years, although many seastar species are able to live to about the age of 50.

Transportation: The Northern Pacific Seastar has now successfully invaded the southern coasts of Australia, and has the potential to move as far north as the Sydney Bay. The specimen has been brought to Southeastern Australia, including Tasmania and Victoria, where it was first detected in Port Phillip as seen in Figure 2 [7].

Figure 2. The rapid increase of the Northern Pacific Seastar's range on the southern coasts of Australia.

They can be transported through the live food trade, specifically where the seastar is transported via seawater in the live fish trade [1]. Ship ballast water is another way for the star to be transported, as the larvae can be distributed through ballast water. Ship hull fouling distributes the Northern Pacific Seastar on ship hulls. Translocation of machinery and equipment can unintentionally transfer the seastar via recreational boats. Transportation of habitat material is another way that the seastar can be brought to new habitats. This can be through Scallop longlines, spat bags, oyster lines, and salmon cages [1]. Larvae can also be transported locally by water currents.

What Makes This Species Invasive: While the Northern Pacific Seastar prefers water temperatures of 7-10°C, it has adapted to the warmer Australian waters of 22°C [5]. It is typically found in shallow waters of protected coasts and is not found on reefs or in areas with high wave action. The seastar is capable of tolerating many temperatures and a wide range of salinities. The maximum temperature for the Northern Pacific Seastar is 25°C and the minimum is 0°C [1]. The salinity range for this species is between 18.7 and 41ppt, while the maximum depth at which individuals have been found is 220m [1]. The Northern Pacific Seastar also has a voracious appetite, allowing it to adapt to eating many different species such as bivalves, gastropod molluscs, barnacles, crabs, crustaceans, worms, echinoderms, ascidians, sea urchins, sea squirts, and other seastars [1]. The seastar will also eat its own kind if food sources become too exhaustive [1].

The Northern Pacific Seastar's reproduction strategies can also be examined as it can reproduce both sexually and asexually. Where at the age of about 12 months, the female is able to reproduce 20 million eggs [1]. Though all of these characteristics contribute to the invasiveness of the species, the main reason is due to the fact that they have the potential for separation and regeneration. Meaning, that if any part of their body was to be cut off such as their arm, it would be able to regrow that specific body part back. Another reason would be the low predation rates of the seastar, however, they may occasionally be eaten by Japanese sun stars and king crabs. For example, in Alaska king crabs are known to feed on this species in laboratory settings [2]. Triton snails have also shown a preference for this species, as opposed to feeding on other marine life.

Ecological Impacts: The Northern Pacific Seastar is considered a serious pest of native marine organisms, as it is a voracious feeder, preferring mussels, scallops and clams [5]. Eating almost anything it can find, including dead fish and fish waste. The Northern Pacific Seastar has the potential to establish large populations in new areas. Estimates made in Port Phillip Bay (where they were first detected), indicate that numbers reached as much as 12 million individuals in two years, which leads to competition for space [5]. The seastar also, monopolizes resources which leads to a decline in mollusks, crustaceans, and echinoderms populations overall. It is implicated in the decline of the critically endangered Spotted Handfish in Tasmania It preys on handfish egg masses, and on the sea squirts (ascidians) that handfish use to spawn on [5]. The seastar is also considered a mariculture pest, settling on scallop longlines, spat bags, mussel and oyster lines, and salmon cages [5]. Leading to oyster production on some marine farms in Southeastern Tasmania to be affected by this insatiable creature.

Economic impacts: The negative economic effects of Northern Pacific Seastars are extensive. In their native habitat of Japan, they have devastated the shellfish industry. In Australia, the economic effects of the species are still being fully evaluated, but it is thought that if their spread continues the soft sediment communities along the coast of Australia may be compromised [5]. It is evident that several fisheries have been negatively impacted, due to there being an estimated 1 billion-dollar loss in the industry in Tasmania [5]. Since these fishing industries are important to the economy of the region, several "seastar hunting days" have been organized in which several thousand sea stars have been removed from the coasts [5]. Northern Pacific seastars are also on the Global Invasive Species Database's list of the "100 Worst Invasive Species" [5]. Though, there are mostly only negative economic impacts, a positive economic impact could be to create an industry where these seastars will be hunted, caught and dried to sell as souvenirs.

Climate Change: Due to climatic warming, the Northern Pacific Seastar is a potential high-risk invader of the sub-Antarctic and Antarctic. To assess the potential range expansion of this seastar to the Southern Ocean as it warms, researchers investigated the bioclimatic envelope of the adult and larval life stages. Specifically, analyzing the distribution of adult Northern Pacific Seastars with respect to present-day and future climate scenarios using habitat temperature data to construct species distribution models (SDMs) [2]. To integrate the physiological response of the dispersive phase, researchers determined the thermal envelope of larval development to assess their performance in present-day and future thermal regimes and the potential for success of this seastar in poleward latitudes, as seen in Figure 3. [2].

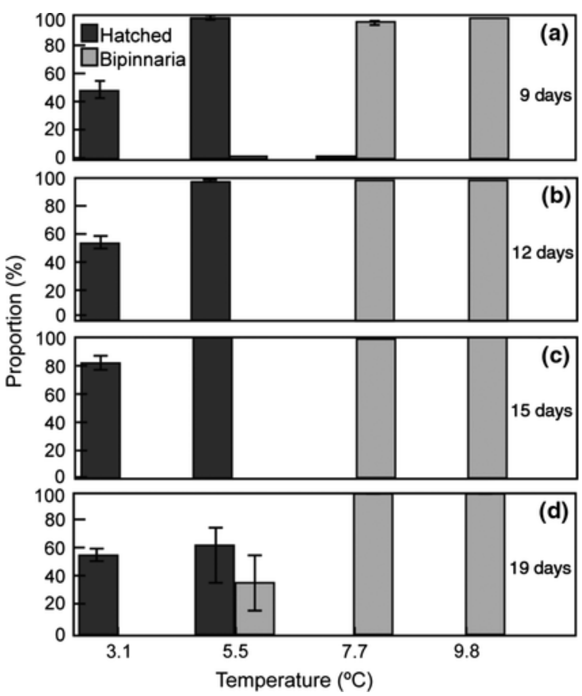

Figure 3. The SDM indicated that the thermal 'niche' of the adult stage correlates with a 0-17°C and 1-22.5°C range, in winter and summer, respectively. Figure from Byrne, 2016.

As the ocean warms, the range of the Northern Pacific Seastar in Australia will constrict, while more southern latitudes will have conditions favorable for range expansion as seen in Figure 4 [2].

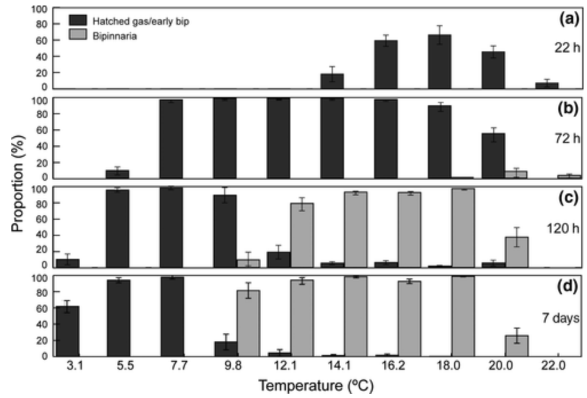

Figure 4. The optimal thermal range for survival of pelagic stages was 3.5-19.2°C with a lower and upper critical limit of 2.6 and 20.3°C, respectively. Figure from Byrne, 2016.

The results show that the seastar faces a decline in its current invasive range while more favorable conditions at higher latitudes of both larval and adult stages to the Southern Ocean, along with an introduction onto New Zealand's coasts is to be expected [2].

Prevention: A two-year study was undertaken for the Department of Environment and Heritage (Australia), by the Commonwealth Scientific and Industrial Research Organization (CSIRO) to identify and rank introduced marine species found outside and within Australian waters [1]. All of the non-native potential target species identified in this report are ranked as high, medium and low priority, based on their invasion and impact potentials. The Northern Pacific Seastar is identified as one of the ten most damaging potential domestic target species, based on overall impact potential (economic and environmental) [1]. A hazard ranking of potential domestic target species based on invasion potential from infected to uninfected bioregions identifies the Northern Pacific Seastar as a 'medium priority species,' as these species have a reasonably high impact and invasion potential [1].

Management: Information about this species has been distributed throughout coastal Australia to educate the community and encourage the reporting of sightings, Legislation has also been enacted in New Zealand to prevent discharge of ballast water taken from the Derwent Estuary and Port Phillip Bay, as these were the areas in Australia where the Northern Pacific Seastar has been reported during its spawning season [1]. Poisons such as quick lime are also available, but are not specific to the Northern Pacific Seastar as they could add damage to the natural marine community and are not economically practical [1].

Other possible control measures are being researched, for example genetic manipulation which involves inserting or changing genes which would eventually sterilize the seastar and kill its young [2]. Another method that has proven to be unsuccessful is the manual removal of seastars by hand, through the use of divers. Though, little success has been seen on aquaculture farms specifically around oyster racks and grow-up trays, and in the intertidal using dip nets or poles with a long nail on the end to spike the seastars [1]. Dredging is unlikely to have a significant impact on this seastar's population as well. Due to in the Derwent River, populations are at an estimated 30 million in 1998 leaving a significant impact to the river's ecosystem [1]. Unlike in Japan where scallop culture techniques can be used, by removing the seastars through the use of scallop dredges and traps before reseeding, and through use of the rope trawls after reseeding [1]. While seastars reinvade the cleared areas, a significant number of scallops can be harvested by the end of the three-year period.

Trapping has also resulted in limited success, as most seastars were caught within the first 24-48 hours, with larger individuals dominating the catches [1]. Using traps at the perimeter of an area manually cleared of these creatures, was not successful in preventing seastars from reinvading the area. In fact, they were found to migrate rapidly and persistently into the trapped area. Even commercial harvesting of the Northern Pacific Seaster for fertilizer has met with limited success. For example, seastars collected in mid-1993 were used for composting trials carried out by the Department of Agricultural Science at the University of Tasmania; where they could be made into satisfactory organic mulch suitable for application to agricultural soils [1]. However, commercial exploitation of these seastars seems remote, and despite the success of several small scale attempts to produce fertilizers, there appears little interest in utilizing this source.

New Research Related to Solutions on the Topic: This research and technology found on the management of the Crown of Thorns can be used for the Northern Pacific Seastar as well. For years, custodians of Australia's Great Barrier Reef have been fighting and largely losing, a war against an alien like invader, the crown-of-thorns seastar, as seen in Figure 5 [4].

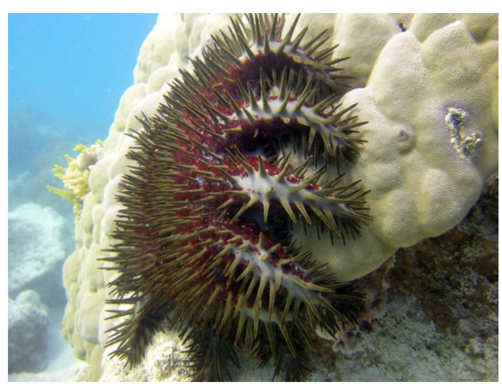

Figure 5. Displays the dorsal view of the Crown of Thorns, also known as *Acanthaster planci*. https://www.scientificamerican.com/article/a-starfish-killing-artificially-intelligent-robot-is-set-to-patrol-the-great-barrier-reef/

However, a solution to this problem is known as the COTSbot, an autonomous underwater drone that can seek and destroy individual seastars. Developed by robotics researchers at Queensland University of Technology in Australia, in the winter of 2016. Artificially intelligent, it correctly identified its target 99.4 percent of the time in laboratory tests [3]. One of the main researchers on the project stated, it's now so good it even ignores our 3-D-printed decoys and targets only live seastars [4].

Another positive is, the vehicle's tank is able to carry enough poison to kill more than 200 seastars in one 4-8-hour mission [3]. Leading to, a fleet of COTSbots supplementing the efforts of human divers who currently remove or poison the seastars by hand, and can't operate during bad weather or high currents [3]. They could also be useful at night when seastars are more active, but swimming is prohibited. The vehicle's tank carries enough poison to kill more than 200 seastars in one 4-8-hour mission, as rapid pace is key because even one seastar can spawn millions of young. The COTSbot travels underwater about 3 feet above the coral, scanning for COTS (crown-of-thorns seastar). It has five independent thrusters to stabilize itself and a camera. Along with, an onboard image-processing capability that allows it to recognize COTS through YouTube video analysis, by using its robotic arm to administer the lethal injection. When the robot spots a crown-of-thorns seastar, its needle-capped pneumatic arm lowers and injects 10 milliliters of poisonous bile salts into the echinoderm, as seen in Figure 6 [4].

Figure 6. Displays the specific features associated with the COTSbot drone.
https://www.scientificamerican.com/article/a-starfish-killing-artificially-intelligent-robot-is-set-to-patrol-the-great-barrier-reef/

The compounds effectively digest the animal from the inside, giving the poisoned seastar only 24 hours until indomitable death, leaving no opportunity for separation and regeneration. A survival tactic that is known to be one of their most promising characteristics, leading towards their vast and extensive populations.

Conclusion: The Northern Pacific Seastar is an invasive species adapted to the warm waters of the Southern Australian coast. Commonly found near protected areas far off these coasts, where there is little wave action. In these areas they can survive at large depths. The seastars are known to be voracious predators with a varied diet, essentially eating any type of animal that they encounter, which allows for the species to be an invasive species in some areas and an obligate predator in others. Allowing this species to have the potential for ecological and economic harm in its introduced range, due to the seastar being well established and abundantly widespread, leading to eradication being nearly impossible. However, prevention and control measures are being implemented to stop this important and detrimental species from establishing in new waters, though none appear to be successful after numerous attempts.

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Five Invasive Tunicates: *Ciona intestinalis, Styela clava, Didemnum vexillum, Botryllus schlosseri,* and *Botrylloides violaceous*

Allison Mills

What are tunicates, exactly?

Tunicates are a unique marine invertebrate that have a rubbery or hard outer coat with two siphons used to draw water into and out of the body, making them filter feeders. Tunicates are extraordinarily ancient creatures. Researchers suspect they first appeared over 500 million years ago[13].

Tunicates can range in size, color and diversity of structure[5]. Colonial sizes range from microscopic zooids to a few meters in length[5]. Solitary tunicate sizes range from one millimeter to 20 centimeters in length[5]. These marine creatures are typically found attached to substrate in sheltered areas, such as rocks, eelgrass, seaweeds, other animals, or man-made structure[13].

Tunicates come from the invertebrate phyla which is distinguishable by the lack of a backbone, unlike humans who are vertebrates with a spinal cord encased in a hard, protective vertebral column[13]. Tunicates are also considered chordates (phylum chordata) due to the presence of a swimming tail, notochord and gill slits during their larval stage[13]. After finding a substrate to grow on, the backbone eventually dissolves, and the tunicate absorbs its cerebral ganglion, which was previously used to control movement[13].

There are two general body types for marine tunicates: solitary or colonial[13]. Solitary tunicates can look like cylindrical fingers, with two siphons on the top[13]. Colonial tunicates are colonies made up of many microscopic tunicates (zooids) that can form encrusting sheets or mats along substrate[13]. Tunicates are one of the most common marine invertebrates, with around 3,000 species[5].

5 Invasive Tunicates

The following analysis of five invasive tunicates will provide a deeper understanding of the specific transportation, impacts, and management and policy of various solitary and colonial species. The list of five is composed of the:

A) Vase Tunicate, *Ciona intestinalis*: solitary

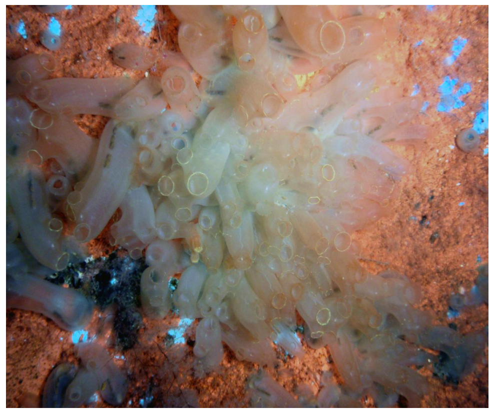

Figure 1. Vase Tunicate. Courtesy of Fisheries and Oceans Canada. http://www.dfo-mpo.gc.ca/species-especes/profiles-profils/invasivetunicates-tuniciersenvahissants-eng.html

DID YOU KNOW: Tunicates are the *only* sessile chordate[13]. These unique marine creatures therefore bridge the gap between vertebrates and invertebrates. Humans and tunicates share a common bond[13]: Tunicates are more closely related to us than to other invertebrates.

B) Clubbed Tunicate, *Styela clava*: solitary

Figure 2. Clubbed Tunicate. Courtesy of Fisheries and Oceans Canada. http://www.dfo-mpo.gc.ca/species-especes/profiles-profils/invasivetunicates-tuniciersenvahissants-eng.html

C) Pancake Batter, or Sea Vomit. *Didemnum vexillum*: colonial

Figure 3. Pancake Batter Tunicate. Also called: *Didemnum*, colonial tunicate, ascidian, and the blog. Courtesy of Fisheries and Oceans Canada. http://www.dfo-mpo.gc.ca/species-especes/profiles-profils/invasivetunicates-tuniciersenvahissants-eng.html

D) Golden Star Tunicate, *Botryllus schlosseri*: colonial

Figure 4. Golden Star Tunicate. Courtesy of Fisheries and Oceans Canada. http://www.dfo-mpo.gc.ca/species-especes/profiles-profils/invasivetunicates-tuniciersenvahissants-eng.html

E) Orange Sheath, or Violet Tunicate: colonial

Figure 5. Orange Sheath Tunicate in Odiorne Point State Park, Rye, NH. Courtesy of Jessica Rosenkrantz. https://www.flickr.com/photos/jrosenk/27435756295

Causes, *Introduction and Transportation*

The vase tunicate originated from Northern Europe, has been seen invading the East Coast thus far, and is expected along the West Coast[16]. Although original mode of dissemination is unclear, scientists believe the species regional dispersal is due to hull fouling of slow moving vessels within many coastal areas[16].

The clubbed tunicate, native to Eastern Asia, has invaded the Pacific and part of the eastern Atlantic Coast[2]. It first arrived in these areas by commercial oyster shipping, but it's proposed that secondary spread occurred through aquaculture, fisheries gear fouling, and recreational boating[2].

Sea vomit, or more commonly known as the pancake batter tunicate, is suspected to be native to Japan[12]. It was found in the Pacific Coast and more recently in 2013 off the coast of Parrsboro, Nova Scotia[12]. The sea vomit tunicate was disseminated through ballast water, tanks of water that improve stability, balance and trim for ships and often get released[7].

The infamous golden star tunicate has invaded every continent except Antarctica and is native to the Mediterranean Sea[3]. The golden star's geographic extent is multi-regional, unlike the other invasive tunicates. Although the mode of dissemination is unclear for this tunicate, it is speculated that it is through reproductive fragmentation; ballast water transportation is unlikely for the golden star tunicate because of their short larval cycle[3].

The orange sheath or violet tunicate is native to Asia and has invaded the western Pacific through hull fouling[17], the growth of marine organisms on immersed artificial structures, such as ships, navigational instruments and aquaculture cages[11].

According to Greg Ruiz from the Smithsonian Environmental Research Center, hull fouling and ballast water are the <u>two most significant vectors</u> for tunicates, followed by accidental introductions from the oyster industry, and other accidental introductions[9].

What Makes Tunicates Successful Invaders?

Tunicates are protected from potential predation with their hard-protective tunicate which can mitigate predation in nonnative areas, in turn contributing to their invasive success[5]. They also tolerate a wide range of temperatures and salinities[5]. The majority of invasive tunicates are fast growing species (even more than other chordates) and can reproduce and release more than 10,000 eggs at a very early age (eight to ten weeks old)[5]. Tunicates have evolved a variety of amazing reproductive strategies, combining both asexual and sexual reproduction strategies that promote very rapid expansion of populations[14].

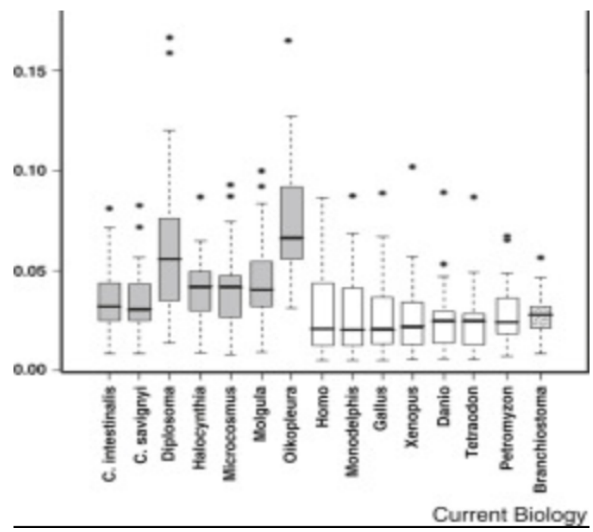

Figure 6. Evolutionary rates of tunicates are much faster than those of other chordates.[1]

Some tunicates, including the invasive violet tunicate, possess thick noxious skins that predators cannot consume[5]. Some utilize a chemical release strategy which hinders other organisms to attach properly to substrate surfaces, making these species more vulnerable to being removed by water currents[5]. Tunicates release a secretion that allows them to more easily adhere to substrate[5]. Tunicates show promise as sources of chemicals which may be applied in the treatment of cancers and other medical conditions[14].

Consequences, *Impacts*

Despite the wide range of morphology and geographic extent, their impacts generally reign similar all-around. Since tunicates are filter feeders, they are natural competitors for other filter feeders for food and space, which alters natural community dynamics[16]. Tunicates also alter gene pools of native species through crossbreeding, shifting predator/prey relationships and potentially spreading disease and/or parasites[16].

> "If this tunicate problem continues, our ecosystem could be significantly impacted. Tunicates are master filter feeders, which means they would remove plankton that power the entire food chain. The nano- and picoplankton are the main contributors to marine productivity and biomass. They are a major base of the food web. If the tunicate population grows then the nano- and picoplankton will not be as available for other organisms such as mussels, clams, and fish[8]."

Disturbance of essential nutrient cycles can also occur from the presence of tunicates. "Much of the nitrogen, phosphorus, and carbon are pulled into the tunicates and are not recycled into the ocean, but the ocean floor,"[8] increasing competition for food and nutrients for the native species.

The vase tunicate is mostly composed of water, and in dense groups can add substantial weight to boats, which results in increased maintenance costs and decreased boat speed and maneuverability[8]. The clubbed tunicate - our second solitary tunicate - is considered a serious threat to long-term economic viability of the shellfish industry off Prince Edward Island (PEI)[8]. In this area, mussel lines and floating docks have been weighed down by the growth of the tunicate, making them immensely difficult to lift from the water[16].

The golden star tunicate, similar to the vase as well as the orange sheath tunicate, is mostly composed of water[12]. It quickly grows over other plants and animals, depriving them of food, sunlight and oxygen. The chemical release discussed in *What Makes Tunicates Successful Invaders*, which is dispersed by the orange sheath tunicate, is harmful to shellfish harvesters, aquaculture farmers, and benthic aquatic organism[5]. The tunicate's chemical strategy can result in economic, ecological and cultural damages.

The pancake batter, or sea vomit, tunicate has been found on eelgrass along the coast of Maine and Massachusetts. This heavily concerns scientists because eelgrass is a critical habitat for the early life stages of shellfish and fish important for the culture, economy and ecology of the area. The presence of the pancake batter tunicate may not allow these species to survive there[3]. Many of the aquatic species being pushed out by invasive tunicates are of cultural and historical value to these areas[3].

Colonial tunicates have a short larval phase and settle quickly, thus allowing them to grow fast[9]. They also reproduce both sexually and asexually, which allows them to spread farther[9]. Unlike colonial species, the solitary tunicates can be easier to manage since they reproduce only sexually and do not bud[9].

Aquaculture farms in Nova Scotia and Prince Edward Island (PEI) have reported decreased size of harvested mussels, increased harvesting costs due to tunicate removal, and water quality issues on fish farms[16]. "Tunicates may serve as marine pollution indicators for monitoring the release of industrial and/or radioactive wastes into the marine environment. Their ability to accumulate certain trace elements from the seawater can be employed in order to define a suitable organism as indicator for some specific pollutants."[19] These livelihoods and cultures are at risk from the presence of invasive tunicates.

When *Didemnum* was discovered in New Zealand, a great deal of money was spent to prevent the invasion from spreading, but it continued nonetheless[9]. In coastal Alaskan communities, when tunicates were not monitored and controlled, it had severe adverse impacts on planktonic organisms who are the foundation of the food web[9]. Less plankton abundance from the invading filter feeders can drop the salmon populations, as salmon are dependent on native organisms that consume plankton[9].

There are three major research gaps that need to be filled in order to properly handle their impacts, including identify vector pressures, identify source population, and social marketing with boaters, fishermen and social scientists[9].

Overall, coastal waters are especially susceptible to tunicate invasion since ballast water, fouling of ship hulls, and aquaculture are the three most important vectors[9].

The Role of Climate Change

There is a lack of research relating the effects of climate change on tunicates. Extended seasons mean they can more quickly transform ecosystems by pushing aside native species[10]. It is presumed "as the ocean grows warmer, it is important to monitor [tunicates] distribution and range expansion. This will help in preventing and managing it's spread."[5]

Solutions, Management & Policy

Managers focus on prevention, detection, and solution. Prevention practices are focused on cleaning and inspection of boats and vessels[16]. To control the spread of tunicates, it is essential that boat hulls and gear undergo visual inspection and be cleaned regularly by letting air dry for at least 48 hours[16]. To prevent the spread of living fragments, water inside boats needs to be drained[16]. Antifouling pants are practical in preventing settlement of tunicates[16]. In the worst case scenario when invasive tunicates have established a population within an area, removal from wharves, piers, and man-made structures is important[16].

It has been widely recognized that local expertise is most efficient in management of invasive species. Some affected U.S. states and regions have invasive tunicate species management programs. The Washington Department of Fish & Wildlife's Invasive Tunicate Species Management Program was established by legislators to prevent the introduction and spread of these species[7]. Surveys and monitoring are effective for early detection, to mitigate or ideally eradicate recently established population before they spread[16]. But, education and outreach remain debatably one of the most effective ways to stop the spread of invasive species.

There are policy and laws in place regulating ballast water exchange and boat inspections that enforce citizens to maintain awareness of invasive tunicates and to mitigate their change of secondary dissemination. Washington is the only state with an active invasive tunicate management program[9]. The Fish & Wildlife Service is one of the major national agencies that reports on the activities and outcomes of invasive species.

The 2014 Fish and Wildlife Service, western panel, *Invasive Tunicate Report* lays out four management plans they believe would be most effective in mitigating the species abundance: designing a biofouling vector management plan, design a pro-active policy framework, design a re-active management framework for a vector event, and design a re-active management framework for established recognized pests[16]. Along with these management strategies was outreach, including campaigns and interacting with existing stakeholder groups[16].

Panel 1. Threat scoring system, created by the Ecological Society of America in 2014, that managers can use to prioritize actions and decisions[1]. Utilizing the panel, managers, educators, and citizens can determine the threat of invasive tunicates in a given area.

Panel 1. Threat scoring system

Each species in our assessment was assigned a score for each of the following categories (where data allowed), to indicate the magnitude of the threat it poses to native biodiversity. The scoring system was devised so that it could be applied consistently to different types of species and to those living in marine, freshwater, and terrestrial habitats.

Ecological impact
- 4 – Disrupts entire ecosystem processes with wider abiotic influences
- 3 – Disrupts multiple species, some wider ecosystem function, and/or keystone species or species of high conservation value (eg threatened species)
- 2 – Disrupts single species with little or no wider ecosystem impact
- 1 – Little or no disruption
- U – Unknown or not enough information to determine score

Geographic extent
- 4 – Multi-ecoregion
- 3 – Ecoregion
- 2 – Local ecosystem/sub-ecoregion
- 1 – Single site
- U – Unknown or not enough information to determine score

Invasive potential
- 4 – Currently/recently spreading rapidly (doubling in < 10 years) and/or high potential for future rapid spread
- 3 – Currently/recently spreading less rapidly and/or potential for future less rapid spread
- 2 – Established/present, but not currently spreading and high potential for future spread
- 1 – Established/present, but not currently spreading and/or low potential for future spread
- U – Unknown or not enough information to determine score

Management difficulty
- 4 – Irreversible and/or cannot be contained or controlled
- 3 – Reversible with difficulty and/or can be controlled with significant ongoing management
- 2 – Reversible with some difficulty and/or can be controlled with periodic management
- 1 – Easily reversible, with no ongoing management necessary (eradication)
- U – Unknown or not enough information to determine score

Overall, these five invasive tunicates pose a multi-ecoregional geographic threat, reaching every continent besides Antarctica, yet few managers and legislators have yet to call the shots for the presence of these invaders. They have an ecological impact of 3, disrupting multiple species and many ecosystem functions. Invasive tunicates move out native species and utilize their fast growth to filter feed massive amounts of plankton, essential for native species, out of the system. Able to tolerate a wide range of salinities and temperatures partnered with the impending impacts of climate change, they have an invasive potential of 3. As seen in *Management & Policy* tunicates have a management difficulty of 3, because they are reversible and manageable with difficulty, and can be confined with ongoing, exhaustive management.

In conclusion, regardless of these generalizations for these five invasive tunicates, it is recommended that tunicates are evaluated on an individual species, adhoc basis to ensure accurate analysis of geographic extent, invasive potential, and management difficulty that is able to lead to effective solutions. After analysis of these species economic, cultural and ecological harm, mandatory development of regional and coastal state plans is recommended through legislation. Detailed management strategies will allow regions to be prepared, educated, and acting with precaution for these marine invasions.

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The New Zealand Mud Snail, *Potamopyrgus antipodarum*

Nikki Volosin

Background

The New Zealand Mud Snail (*Potamopyrgus antipodarum*) is a small freshwater snail, measuring an average of 5mm long and varies in color from gray to dark brown and light brown. It has 7 or 8 whorls; a complete 360 degree turn in the spiral of a mollusc shell[3].

This snail is native to New Zealand and the surrounding islands, but now inhabits the USA and several other parts of the world such as Europe. The mud snail has several important qualities that will be introduced below that have made it a successful invasive species around the world. To understand how this species came to be such an efficacious invader in the United States, its traits, introduction and impacts must be investigated.

The best environment for the mud snail is one where there is high primary productivity, constant temperatures, and constant flow[4]. However, the New Zealand mud snail is extremely tolerant of many different conditions including a wide range of benthic habitats, changes in salinity, and a range of temperatures. Benthic habitats for the mud snail include silt, sand, gravel, cobbles and vegetation[3]. They are typically found in slow moving water, but these waters can include lakes, reservoirs, and brackish water estuaries[3].The quality of water can vary as well, which can include turbid and degraded conditions, including sewage[2]. The mud snail can tolerate a range of salinities with a salinity of about 12 ppt as their maximum[3]. Temperatures tolerated range between zero degrees Celsius and 28 degrees Celsius[3].

One of the mud snails most effective capabilities is its ability to reproduce

Image 1. New Zealand mud snails compared to a penny. Image from http://www.michiganradio.org/post/volunteer-anglers-help-monitor-rivers-invasive-mudsnail

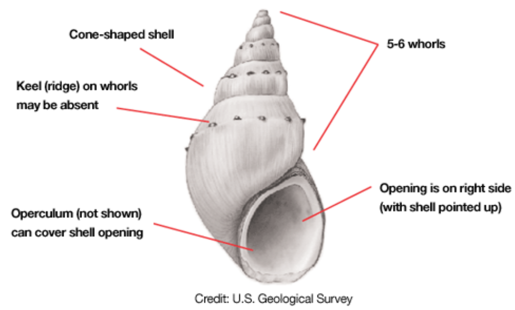

Image 2. Diagram of New Zealand mud snail. Image from http://www.seagrant.umn.edu/ais/newzealand_mudsnail

Image 3. Close-up image of mud snail. Image from https://en.wikipedia.org/wiki/New_Zealand_mud_snail

asexually, also called parthenogenesis. Parthenogenesis allows females to reproduce without the need to find a male. Although this is beneficial, without a male a female will only pass on her DNA, therefore all offspring produced asexually are clones and lack genetic variation. When a female reaches maturity, around 6-9 months she will produce about 20 to 120 embryos every three months during warmer seasons[3]. Although this is a much smaller amount than other aquatic species, the lack of need to find a male, and short maturation time allows the mud snail to reproduce rapidly and quickly invade new areas.

Introduction and Transportation

The first introduction of the New Zealand mud snail into the US most likely occurred with a shipment of trout eggs into Snake River in Idaho, where these eggs were used for sport-fishing hatchery operations. Believed to have occurred in the 1980s, this is only one of two introductions of the species in the US. This population is the first of two genetic types of mud snails in the US and is therefore known as Clone 1.

The second introduction created populations in three Great Lakes: Erie, Michigan and Superior. This population is made up of all cloned females and are known as Clone 2 mud snails. Both populations have spread rapidly into several surrounding states and into relatively untouched areas such as Yellowstone National park. Mud snails can easily spread not only through locomotion, but also through attachment to recreational equipment such as boats, fishing gear, boot, and clothing. Local species can also spread the mud snail by the consummation and excretion of the mud snail into new areas. Mud snails have been documented to survive passage through the digestive tracts of fish populations while also doing damage to their health by causing depletion in nutrition[8].

Table 4: Summary of critical physiological tolerances of New Zealand mud snails, Potamopyrgus antipodarum (*adapted from Mackie and Claudi 2010).*

Parameter	No Potential for Adult Survival	Little Potential for Egg Development	Moderate Potential for Nuisance Infestation	High Potential for Massive Infestation
Calcium (mg Ca/L)	<2	2-4	4-7	7-?
pH	<6.0?	6.0-6.8	6.9-7.5	7.5-8.5?
Alkalinity (mg CaCO/L)	<10	10-50	50-100	100-350
Hardness (mg $CaCO_3$/L)	<10	10-50	50-100	100-350
Temperature (°C)	<0, >35	0-15, 30-35	15-20, 26-30	20-26
Conductivity (µS/cm)	<25, >46,000	25-200, 25,000-46,000	200-1,200, 9,000-25,000	1,200-9,000
TDS (mg/L)	<17, >30,800	17-130, 16,800-30,800	130-800, 6,000-16,800	800-6,000
Salinity (‰)	<0.01, >30	15.0-30.0	0.1-2.0, 5-15	2.0-5.0

Table 1. Table of physiological tolerances for mud snail. From Therriault et al. (2010)

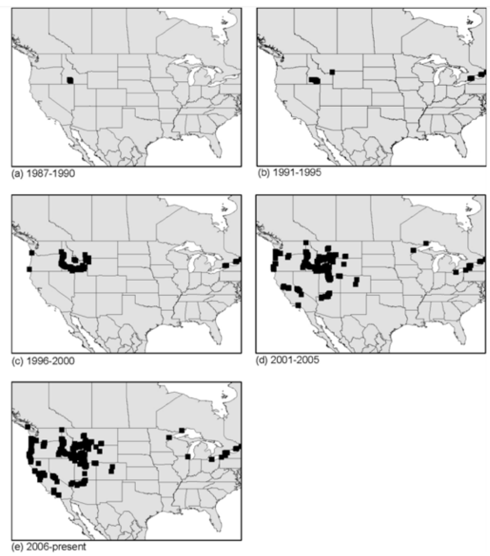

Image 4. Rapid growth mud snail populations in the United States. From **https://seagrant.oregonstate.edu/sites/seagrant.oregonstate.edu/files/invasive-species/toolkit/nz_mudsnail.pdf**

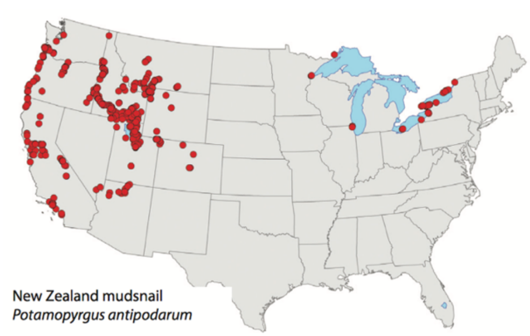

Image 5. Current mud snail populations in the United States. From **https://seagrant.oregonstate.edu/sites/seagrant.oregonstate.edu/files/invasive-**

Impacts

Due to their small size the New Zealand mudsnail has gone reasonably unnoticed and their impacts in the US thus far have been minimal. The most severe economic has been a result of funding for research and education about mud snal invasions. It is suggested that the mud snail could affect recreational fisheries, and impact local Chinook Salmon populations which are an important part of the tribal religion, culture, and the diet of native Pacific Northwest tribes.

Due to a lack of research and knowledge on the ecological impacts of the mud snail, many ecological impacts can be deduced from several other invasive species studies by comparing them to invaders who also feed at the same trophic level. It is hypothesized that because mud snails can consume up to 95% of primary food sources, they may outcompete other native aquatic invertebrates and they may also alter ecology[2]. A study of the Gibbon and Madison rivers in Greater Yellowstone confirmed this hypothesis when researchers determined that 25%-50% of the macroninvertebrates were mudsnails and the areas that the occupied has a decreased number of native mayflies, stoneflies, and caddisflies[2]. These are all imporant insects to the diets of salmonoids and several bird species[2] .

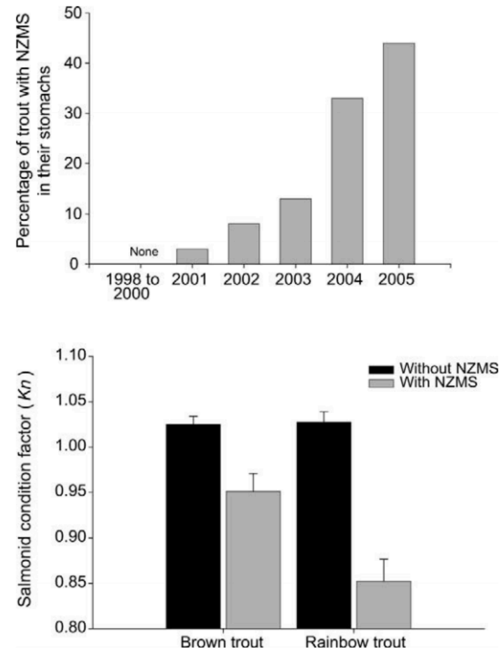

FIGURE 2.—New Zealand mud snail (NZMS) occurrence in brown trout and rainbow trout stomachs and associated condition (K_n) of fish collected from the Green River, Utah, downstream from Flaming Gorge Dam after NZMS invasion in 2001: **(A)** percentage of fish (species combined) that consumed NZMSs and **(B)** mean (±SE) K_n of fish that did or did not consume NZMSs.

Figure 1. Effects of mud snail ingestion on trout in Utah. From Goldberg et al. (2013)

Detection, Prevention, and Solutions

A prevalent issue regarding mud snails, is that once a population has been established, it is nearly impossible to remove them. Therefore, managing established populations and preventing further spread is a high priority. To keep populations from spreading there must be thorough decontamination protocols. This must extend to recreational activities, commercial activities, and other proceedings that may require people or equipment to come into contact with the species such as habitat

Image 6. Informative pamphlets on invasive mud snails. From https://www.northcountryinvasives.org/outreach-publications--signs.html

restoration, flood protection, and road maintenance. This can be done by tourists, locals, citizen scientists, researchers, or anyone who may use the bodies of water infested with the mud snail.

To implement such protocols, it is important to be able to determine where current populations are established. Whether it is in an area where there are known sightings, or in areas where the possibility of a mud snail population is likely, methods for detecting these small creatures is important for managing their expeditiously growing populations. Environmental DNA (eDNA) can be collected from many different sources, and can be used to detect even very small populations of mud snails in water. Researchers have found that as few as one individual in 1.5 L of water for 2 days could be detected[4]. After snail removal eDNA remained detectable for up to 21 to 44 days[4]. This method confirmed the presence of New Zealand mud snail eDNA at densities as low as 11 to 144 snails/m^2 when applied in the environment[4].

Management and Policy

There are many states already that recognize the New Zealand mud snail as a threat, despite there being little known about their economic, ecological, and cultural damages. In the western US there are policies that specifically prohibit importation, possession and transport of the mud snail. Some states have quarantined bodies of water and closed off fishing access to stop the spread of the species. Other states address the species in aquatic nuisance species management plans. There have also been local efforts to inform citizens using infested bodies of water to check all gear, and wash, before entering another body of water.

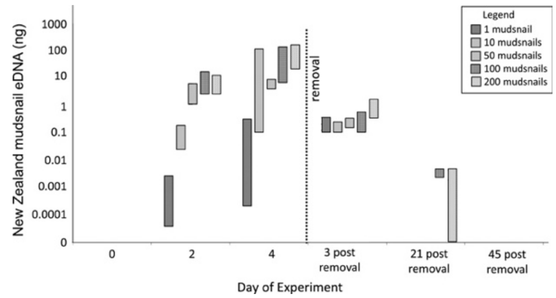

Figure 2. eDNA experiment with mud snail. From Goldberg C et al (2013)

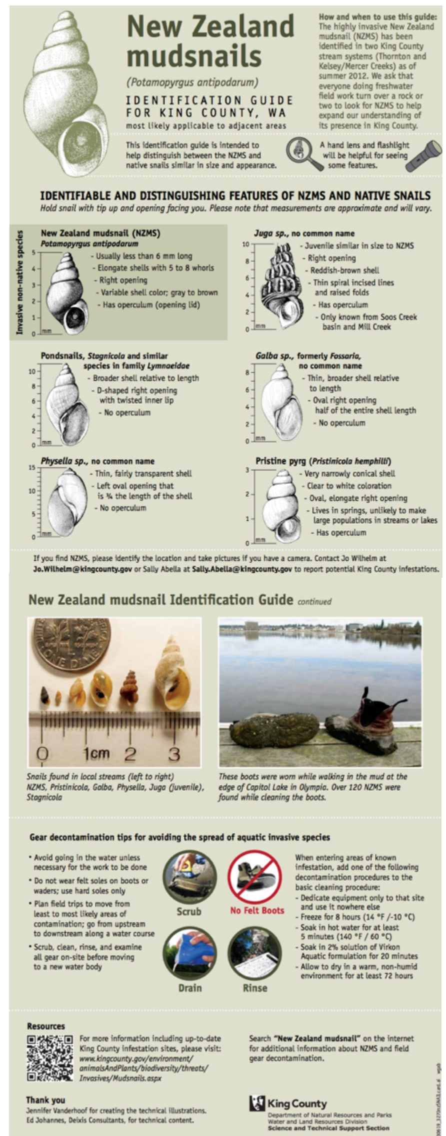

Image 7. Identification guides for mud snails. From https://www.kingcounty.gov/services/environment/animals-and-plants/biodiversity/threats/Invasives/Mudsnails.aspx & https://www.northcountryinvasives.org/outreach-publications--signs.html

Climate Change

As bodies of water warm due to climate change, the environment the mud snail now occupies will change. Since the mud snail can only tolerate an upper temperature limit of 28 degrees Celsius it must move to waters that do not exceed this limit. Warming waters may cause the mud snails to move more northward where waters are cooler, but it is difficult to determine future scenarios for the mud snail. There are only two clones of the mud snail in the United States, and if they cannot adapt to changing temperatures, or move quickly enough, it is likely that entire populations will die due to lack of genetic variation. However, in its native range and other parts of the world, there are males which have created more of a genetic diversity.

New Zealand mud snails are commonly afflicted with trematode parasites which occur more frequently in warmer, shallower water than cooler, deeper water. An increase in temperatures could also correlate with an increase in trematode infections because of their preference for warm water. However, the mud snail has a method to cope with these parasites. Sexual reproduction has become more prevalent for the mud snail in shallower waters where trematodes are more prevalent. This increases genetic diversity and allows for adaptations that may better survive parasitic attacks. In places like the United States however, where sexual reproduction is impossible because of a lack of males, a parasitic infection could be disastrous for the mud snail. These infections though, would benefit local aquatic populations and the citizens who depend on them.

Specifically prohibit importation, possession and transport of NZ mud snails:
- California
- Colorado
- Kansas
- Montana
- Utah
- Washington
- Wyoming

Do not allow to be imported, possessed, or transported without prior authorization through a state permit system:
- Alaska
- Hawaii
- Idaho
- Nevada
- Oregon

Quarantine and fishing access closure:
- Colorado
- California

Image 8. Trematode parasite which frequently infects mud snails in shallower waters. From Wikipedia.

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Purple Loosestrife, *Lythrum salicaria*

Jillian Henrichon

Purple loosestrife, *L. salicaria,* is a flowering wetland plant native to Asia and Europe. It has purple flowers arranged in 'spikes' that typically grow 4-10 feet tall (Fig 1 a) and in clumps of 30-50 stems (Fig 1 b)[6]. Purple loosestrife typically flowers early July through September[10]. It was first introduced to the Northeast United States in the early 1800's, but did not become officially established in the US until about 1830. Today, it has spread to become widely distributed across most states of the northern United States. Purple loosestrife has become an invasive plant of high concern in the United States, however it is also an excellent example of the possible success of biological control methods. Most cases where biological control has been explored have either been unsuccessful or resulted in new invasive species being released. However, biological control methods for purple loosestrife have not created any new invasive species and have been efficient enough to keep populations in check, though will not be enough to eliminate those populations[10].

Fig. 1a. Purple loosestrife flowers display a "spike" formation. Figure from Liz West at https://www.gardeningknowhow.com/plant-problems/weeds/purple-loosestrife-info.htm

Fig. 1b. Growth of purple loosestrife in clumps. Figure from https://www.maine.gov/dacf/php/gotpests/weeds/purple-loosestrife.htm

Introduction to the U.S.

Purple loosestrife was first introduced to the Northeast United States in the 1800's, but by now it has spread to become widely distributed across most states of the northern United States. In order to help track its spread, the online 'Early Detection and Distribution Mapping System' (or EDDMapS for short) allows citizens to report sightings by county and then maps the distribution accordingly. Purple loosestrife has been reported 23 times in York county, Maine alone (Fig 2)[3]. Although some purple loosestrife was introduced accidentally via dry ship ballast, most of its introduction was intentional. The intentional introduction was primarily for ornamental purposes as the plant has beautiful purple flowers and was useful for beekeeping[9], however purple loosestrife was also introduced for its desirable medicinal properties that are not present in native related species such as Winged loosestrife, *Lythrum alatum*[8].

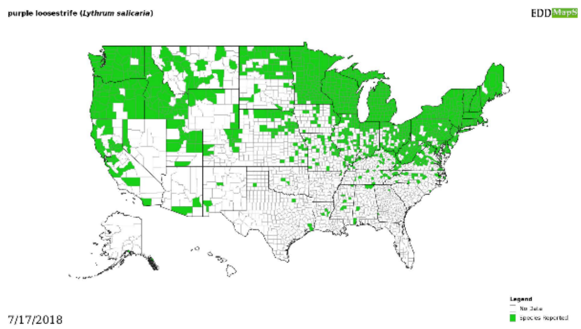

Fig. 2. Distribution of purple loosestrife throughout the US is shown in green. Figure from http://www.eddmaps.org/.

What Makes It Invasive?

Several factors make purple loosestrife a successful competitor of native wetland plants. One of these factors is that the species' flowers are showy, produce large quantities of nectar, and are short tubed. These three elements work in tandem to make them ideal for pollinators, and high pollination rates facilitates rapid spread. Another reason purple loosestrife is so successful is that its seeds germinate within 3-4 days; which is much quicker than average for native plants. Lastly, the production of seeds is extraordinarily high; each plant can produce between one and three million. Due to this sheer volume of purple loosestrife seeds in comparison to other native plants', seed banks tend to become dominated by purple loosestrife seeds, allowing growth of many more purple loosestrife individuals than native individuals[4].

One more factor that likely aided in the success of the purple loosestrife is its ability to hybridize with the native loosestrife congener winged loosestrife, *Lythrum alatum*. This ability was first suspected when the genomes of the two were found to be compatible enough for hybridization, and some populations of purple loosestrife in Minnesota were found to express unique morphological characteristics unseen in native European populations. A study by Houghton-Thompson et al in 2005[5] proved introgression was occurring between the two species. Additionally, pollinator visitation was significantly reduced in a winged loosestrife patch near a purple loosestrife patch over a two-year period[2]. More research is needed to conclude whether the uptake of genes from winged loosestrife made purple loosestrife more successful, however it is likely that the incorporation of unique genes that code for morphology adapted for this area was more helpful than harmful.

Impacts

Ecological

Purple loosestrife has many negative ecological impacts. As already touched upon, its successful reproduction rates enable it to crowd out and displace many wetland native plants. For example, purple loosestrife is able to completely displace narrowleaf cattail (*Typha angustifolia*) within four years[7]. Not only does purple loosestrife outcompete native plants, but it is not suitable habitat for wetland birds and other species- thus it drastically reduces available habitat for these species. In the Montezuma National Wildlife Refuge of western New York, purple loosestrife was deemed unsuitable habitat after a study concluded that not one of over 100 nesting pairs of black terns (*Chlidonias niger*) were reported nesting in the purple loosestrife. Furthermore, the local population of black terns in that area went extinct in 1987; the same time when the purple loosestrife population exploded. Many other species such as Pied-Billed Grebes (*Podilymbus podiceps*), Virginia Rail (*Rallus limicola*) and the American Bittern (*Botaurus lentiginosus)* also avoided purple loosestrife for both nesting and foraging[1].

Purple loosestrife can also disrupt the ecological functions of a wetland. Its leaves tend to fall off and decompose in the autumn, while most other native wetland plants shed leaves in the springtime. Purple loosestrife leaves also tend to decompose rapidly. This increases the nutrients an abnormal amount and can contribute to eutrophication of waters downstream[1]. Eutrophication of waters may have direct impact on people by harming the fishing industry; if nutrient levels are too high, then algae can become excessively successful. Increases in plant biomass lead to a decrease of dissolved oxygen in the water, and these conditions are unfavorable for survival of fish species that are economically and culturally important to us[1].

Economic/ Cultural

Purple loosestrife does not directly affect any species of great economic importance to humans, however $229 million is estimated to be spent annually on the control of this species. This money is spent because purple loosestrife indirectly impacts the fishing industry and overall water quality through eutrophication, and because it affects the culture of birdwatching by reducing available habitat for songbirds[13]. While purple loosestrife does not seem to be a highly valued component of modern US medicines, it does have a cultural impact in that it is used for a variety of medicinal purposes and was brought to the US for those purposes. Purple loosestrife can be made into a tea and used for diarrhea or other chronic intestinal issues. It can also be used externally to help with eczema, varicose veins, bleeding gums, and hemorrhoids[8].

Role of Climate Change

Purple loosestrife will likely continue to be successful as the climate changes. Clinal variation in its seasonal initiation of flowering has been observed; as latitude increases, the time until initial flowering decreases, but it was noted that these flowers were smaller in size than those at lower latitudes that took longer to initiate flowering (see Fig 3). These geographic patterns show that this species can adapt to a variety of climactic selective pressures and has balanced trade-offs of reproductive success and energy expenditure. As climate warms, purple loosestrife will likely be able to spend more energy on larger flowers at higher latitudes[11].

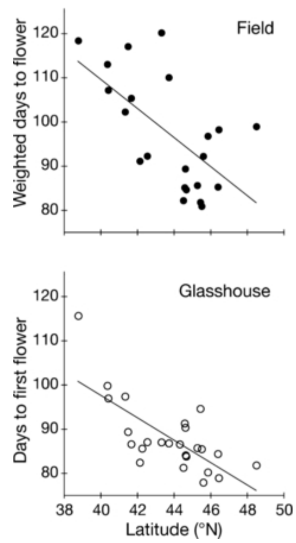

Fig. 3. Clinal variation in seasonal initiation of flowering of purple loosestrife. (Figure from Montague et al 2008)

Detection, Prevention and Solutions

A variety of solutions (physical, chemical and biological) have been attempted for control of purple loosestrife, most of which are largely ineffective. Most physical methods of control such as pulling, mowing, flooding the invaded area, disking, and burning are only effective on small patches. Chemical methods, mostly the use of herbicide, can be more dangerous than helpful because these herbicides can kill nearby natives as well. This then creates open space for more purple loosestrife, or even other invasive species like common reed (*Phragmites australis*) to further expand. Any of the methods that require killing the plant will result in high levels of leaf litter on the ground, which then creates unsuitable conditions for the growth of native plants[12].

In terms of detection, the Early Detection and Distribution Mapping System program is a wonderful tool- ordinary citizens of any US state as well as Canada can report sightings to the organization and they will be added by county, allowing for a continually updated map. There are many other ways for citizens to easily report purple loosestrife sightings as well- Ontario Canada has a toll free invading species hotline and a handful of websites[12]. Preventing further spread of *L. salicaria* is imperative to slowing its impacts. Prevention methods include reporting its presence when noticed so detected patches can be eradicated, staying on designated trails when hiking, inspecting for seeds and cleaning seeds from clothing, pets, vehicles and other equipment after use in an invaded location, and educating the public to use native plants instead of ornamentals in their gardens[12]. Minnesota has an aquatic invasive species law that requires cleaning mud, plants and animals from boats and trailers, draining water related equipment before leaving a water access area, and proper disposal of unwanted bait[9].

The most effective control method so far has been biological control- the release of another species that is a natural predator/ consumer of the problem species. Biological control can be dangerous as the species released is usually not native to the area and could become invasive itself. In the case of purple loosestrife, the potential impacts of using biological control was intensely studied between 1987 and 1991 in both Europe and the United States. All candidate species were put on "feeding trials" to see how they would affect over 50 native or commercially/agriculturally important plant species. Eventually, the four species were chosen that would have the smallest impacts to other native/ important plant species while effectively chowing down on the purple loosestrife[15]. These four are two species of leaf-eating beetle *Galerucella pusilla* (Fig 4a) and *G. calmariensis* (Fig 4b), a flower feeding weevil *Nanophyes marmoratus* and a root boring weevil *Hylobius transversovittatus*[10].

Fig. 4a. *Galerucella pusilla* on a purple loosestrife leaf. Image from http://baza.biomap.pl/en/taxon/species-galerucella_pusilla/photos_rc

Fig. 4b. *G. calmariensis* on a purple loosestrife leaf. Image from http://www.purpleloosestrife.uconn.edu/BioControl.php#

The two beetle species are native to Europe and Asia and were first introduced in 1992. When presented with 50 other native plants including species related to purple loosestrife, scientists observed that the beetles only fed on purple loosestrife, with the only other potential host being the winged loosestrife, *Lythrum alatum.* Even so, the beetles would avoid winged loosestrife if given a choice. *Hylobius transversovittatus* is native to Europe and was also introduced in 1992. It has two other potential hosts besides purple loosestrife: winged loosestrife and swamp loosestrife, *Decodon verticillatus,* but again will avoid using the natives as a food source if purple loosestrife is an option[14]. The introduction of these four species has been effective (see Fig 5 a and b) and has not caused significant damage to natives. In Minnesota, residents can even obtain beetle rearing kits to take care of patches of purple loosestrife near their own property[10].

Fig. 5a. Pigs Eye Lake, St. Paul Minnesota, 2000: pre-biocontrol invasion of purple loosestrife. Figure from https://www.dnr.state.mn.us/invasives/aquaticplants/purpleloosestrife/biocontrol.html

Fig 5b. Pigs Eye Lake St. Paul 2004- post biocontrol, purple loosestrife is nearly eliminated. Figure from https://www.dnr.state.mn.us/invasives/aquaticplants/purpleloosestrife/biocontrol.html

Conclusion

The success of biological control methods in the management of purple loosestrife has been incredible. However, it is of paramount importance that citizens continue to prevent its spread by methods mentioned above and by reporting new patches to invasive species specialists and to EDDMapS, especially because it is still relatively unknown how continued hybridization with native congeners and other forces like climate change may strengthen purple loosestrife or facilitate its spread.

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Goldfish, *Carassius auratus*

Melissa Carmichael

Introduction

The Goldfish is a common find in many aquarium tanks around the world. These fish can be the typical orange color, but can also be cream, brown, or olive colored. These colorful common pets are becoming more prominent in our water bodies. These fish can pose a significant threat to native species, the ecosystem, and our economy. As the Goldfish invasion continues it is important to find ways to manage the problem and prevent them from spreading even more.

Transportation

Goldfish are native to Asia and their introduction began in the 1600's and are thought to be one of the first invasive fish species to reach North America. They are now established throughout the United States, Canada, Australia, and Europe. These fish were first introduced by the settlers of North America because they wanted to add to the fish fauna. However, the more prominent form of transportation today is through the aquarium trade. Goldfish are a common pet throughout the world and they are relatively easy to care for. Unfortunately, they aren't the most interesting pet to have and people lose interest in them. When people no longer want to deal with their fish tank they will dump its contents into a waterbody thinking there will be no harm in such actions. Also, people will accidentally introduce goldfish into an ecosystem by flushing the fish assuming that they are dead or will die during the flushing process. As more Goldfish occupy a waterbody a new form of introduction is emerging. Anglers are now accidentally introducing Goldfish into water bodies because they misidentify them and use them as bait.

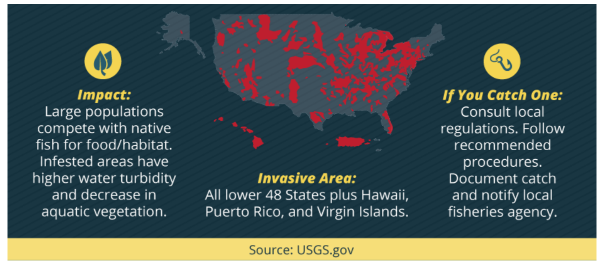

Figure 1: Distribution map of goldfish in the United States. (Figure from https://www.fix.com/blog/invasive-fish-species-guide/)

Why are they Successful?

Goldfish are a very hardy species and have the typical characteristics of an invasive species. The first thing that makes them successful is the fact that they can eat a large variety of species which can impact native populations. The Goldfish also lack natural predators in many of their introduced locations. They are also able to grow very quickly and reach a very large size that is not typically seen in confined aquarium tanks. Also, Goldfish can lay up to 40,000 eggs, which is a lot more than a Rainbow Trout which can lay between 400 to 3,000 eggs. [11] That fact is also concerning considering most of the eggs do survive and reach reproductive age. Goldfish are also successful invaders because they are capable of hybridization. For example, in Australia Goldfish are capable of mating with Common Carp, another invasive species in Australia, to produce a hybrid that has traits that allow them to be better invaders.[8]

Figure 2: The different variation in size of the goldfish and their range of growth (Figure from https://www.bbc.com/news/blogs-news-from-elsewhere-33254630)

Ecological Impacts

Once introduced, the Goldfish can quickly dominate the area and cause a variety of ecological impacts, however, there isn't much research available on these impacts quite yet. One way that is known to cause issues to the environment is through their natural behaviors. Goldfish are omnivorous and are benthic feeders which allows them to disrupt sediments, affect turbidity, impact macrophytes, and possibly revive Cyanobacteria through their gut processes.[2] It's also important to know that goldfish grow based on how much space they have. In aquariums goldfish are only capable of growing to the size of their tank, so in the wild they have an almost unlimited amount of space to grow into. As they grow in size they consume more food which impacts the species that are being consumed and decreases the food supply for other native species.

Goldfish can also directly impact native species by affecting their health, Naturally, Goldfish carry a number of diseases, parasites, and/or bacteria; when introduced to native species they could make the population sick and possibly decrease their populations. Two of the most common things the goldfish carry is the Koi Herpesvirus and the Myxozoan bacteria.

Economic Impacts

A cheap aquarium fish can prove to have a lot bigger impact economically once they are invasive. For example, the voracious eaters may diminish a native species that is associated with a local industry. Also, they are super expensive to remove due to the difficulty of removal and the cost of removal techniques. Different removal methods can have different costs and if the removal was ineffective the first time it may cost more for each successive attempt at removal. For example, West Medical Lake in Washington is infested with Goldfish and the state spent approximately $150,000 to remove them. [1]

Cultural Impacts

There is very little known about how invasive Goldfish can have a cultural impact. However, native species are being impacted by these invasive fish. This means there could be a culture surrounding them, like if there is a fishing industry surrounding a native fish. Also, certain environments that are being impacted could be culturally important to an area.

The Role of Climate Change

With climate change, many parts of the planet are getting warmer and warmer. This can prove to be problematic because it could increase the Goldfish problem by allowing them to become even more successful. Goldfish are able to excel in a wide range of temperatures, but they excel especially well in temperatures above 65˚F. With the warming it is likely that more waters will be able to reach 65˚F or a higher temperature creating more habitable areas for the Goldfish. [4]

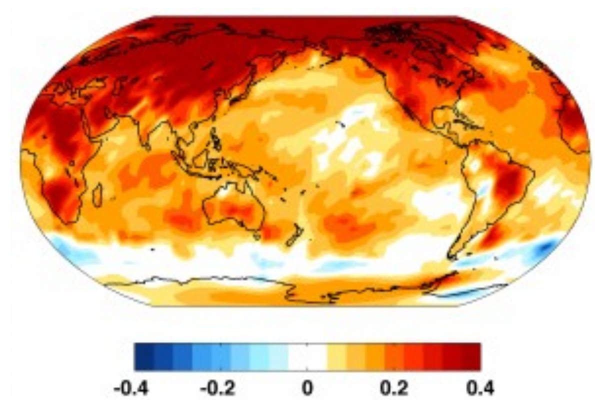

Figure 3: Map showing the increasing temperatures of water over the past 50 years (Figure from https://www.washington.edu/news/2016/05/30/deep-old-water-explains-why-antarctic-ocean-hasnt-warmed/)

Prevention, Detection, and Solutions

The methods that are suggested for prevention, detection, and solutions are simple ones that everyday people could follow, but they focus more on the introduction and spread of the species. The basic suggestion is to not dump your aquarium into a water body and instead give your fish to a responsible party. Also, scientists suggest that people should not even flush their fish because there is a chance of survival. If a fish is sick and no one wants to care for it anymore, it is suggested that the goldfish be put in an ice slurry, which is the most humane way to kill the fish. There is also the rule that people need to check their boats, trailers, and gear and remove anything attached when they come out of a waterbody and go into a new one to stop the spread.

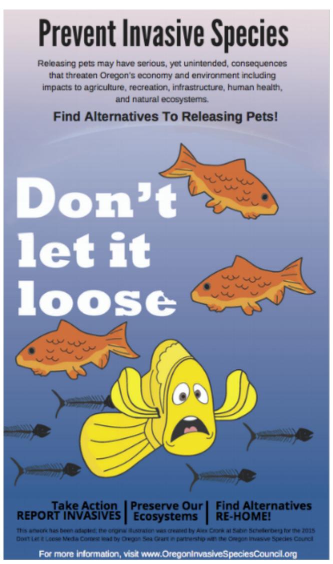

Figure 4: Poster/handout about not releasing Goldfish produced by the Oregon Invasive Species Council (Figure from https://www.oregoninvasivespeciescouncil.org/dont-let-it-loose/)

Management and Policy

There are a few different management strategies used in the case of Goldfish. One method is electroshock. This method would temporarily paralyze all fish in the water so people could go around and pick out all the goldfish by hand. The same concept is also utilized in draining a waterbody and netting where they pick out the Goldfish manually. Another method that is being used is the chemical rotenone. This chemical kills all gilled fish species in the water body, which also impacts native species, so they have to restock the waterbody with the native species after.

After the Goldfish have been obtained there are a few different options as to what can be done with them. One option is to freeze the fish to kill them and then the frozen fish could be studied. Another option is to repurpose the Goldfish and put them into aquaponic systems. Lastly, some people have begun using the fish as food for animals like one rehabilitation center uses them to feed the birds. There has also been some cases where people will eat the Goldfish, but that does not seem to be a widespread occurrence.

Through research there are also other ways in which people are trying to control the Goldfish where they try to understand the different life qualities of the fish. One study conducted in Australia on the Vasse River identified wetlands as a vital area for the species. Wetlands are valuable to the Goldfish for spawning grounds where the fish mate and lay eggs. In the study it is suggested that a barrier is created between the River and the wetland that only allows a one way passage that would trap the fish. This study also mentioned that it is important to understand that Goldfish have high cognitive abilities meaning they are capable of learning capture methods and evading them. Knowing this means that when controlling or managing the Goldfish people have to be aware of this and work on a method that will lead the Goldfish in regardless. For example, drawing them into a food source is a way to counteract their cognitive abilities.[2]

There are laws in place that pertain to the goldfish problem. For example, the state of Maine makes it illegal to keep Goldfish outside due to the risk of escape. It is also common that many states make it illegal to dump anything into the water.

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Comb Jellies, *Mnemiopsis leidiy* and *Beroe sp.*

Nicholas Paolini

Mnemiopsis leidiy, commonly referred to as the Warty Sea Jelly or the Sea Walnut (Figure 1), is a Ctenophore native to the Atlantic coasts of North and South America. Sea Walnuts have a walnut-shaped bell, and are covered in wart-like bumps, which is where it gets its name. It has eight rows of cilia that refract ambient light, and is bioluminescent. These jellies are planktonic, generally found to be anywhere from 100-120mm in its native habitat. Since the Sea Walnut is a Ctenophore and not a Cnidarian, it does not have any stinging cells, like other sea jellies would. The Sea Walnut prefers to inhabit subtropical to tropical estuaries. They are hermaphroditic, and can produce 2-3,000 eggs per day. The diet of a Sea Walnut consists of zooplankton, copepods, fish larvae and other ctenophores.[1]

In 1982, the Sea Walnut was found in the Black Sea during a routine weekly water check, where it is thought to have been brought over in merchant ship ballast water. It was then found in the Caspian Sea in 1999,

Figure 1: Mnemiopsis leidiy. Picture taken at the New England Aquarium by Steven G. Johnson.

where it most likely traveled via the Unified Deep Water System of European Russia. Since then, it has used the Mediterranean Basin and the Northwest Atlantic to travel to numerous other waterways, including the Baltic Sea and the North Sea.[2]

The Sea Walnut is the perfect invader for these waterways since there is only one species of comb jelly native to these waterways, the Sea Gooseberry, *Pleurobrachia bachia*. The Sea Gooseberry previously had kept its own populations in check via cannibalism, meaning that there was no need for any natural Ctenophore predators in this area. In fact, there is only one natural Sea Walnut predator known on Earth. The Sea Walnut has also excelled due to the fact that it can tolerate a wide range of environmental factors. It can handle temperatures from 4-32°C and salinities from 3-39%.[3] Due to these factors, it can easily survive in practically any waterway it travels to. This, coupled with the fact that it can produce so many eggs without needing a mate, means it is feasible that just one Sea Walnut can start an entire new population.

After its introduction to the Black Sea, the Sea Walnut has completely altered the food web and disrupted the way of life for fisheries along the sea. The Sea Walnut has depleted the non-gelatinous phytoplankton

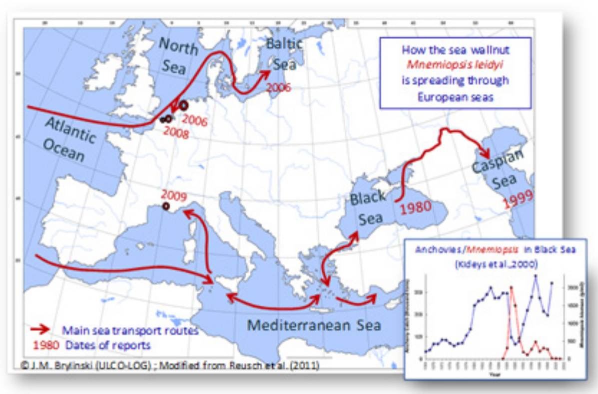

Figure 2: Main sea transport route of the Sea Walnut. Figure taken from ILVO's Mnemiopsis Ecology, Monitoring Observation project. https://www.ilvo.vlaandren.be/memo/EN/Home/tabid/5229/Default.aspx

populations in the waters it has been introduced to. This has caused a decrease in the anchovy and larger fish populations due to lack of food. Ultimately, lack of larger predators leads to phytoplankton blooms due to the fact that the primary producers are no longer being consumed. This lack of larger organisms has led to the collapse of the Turkish fishing industry and the Baltic Sea anchovy industry, causing an estimated $300 million USD loss.[1]

Right before the year 2000, another Ctenophore, *Beroe sp.*, the Cigar Comb Jelly, was also introduced to the Black Sea via ballast water of cargo ships. The Cigar Comb Jelly is transparent and can reach sizes of up to 150mm. The Cigar Comb Jelly was also native to the Atlantic coasts of North and South America and is believed to have taken the same routes as the Sea Walnut once it arrived in the Black Sea, quickly spreading all over Europe's waterways. However, the Cigar Comb Jellies are actually the Sea Walnuts only known predators, and have gone on to eat a sizeable proportion of the Sea Walnuts in Europe.

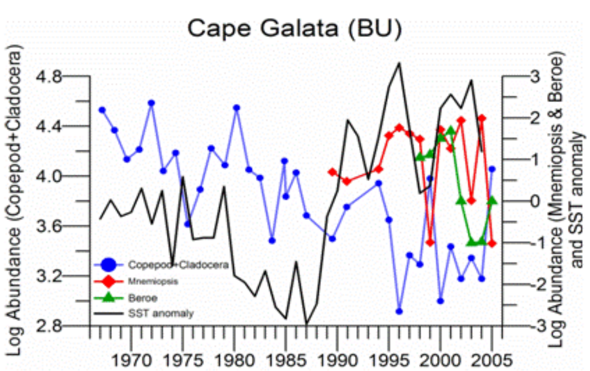

Figure 3: Population sizes of native copepods along with Mnemiopsis and Beroe in Cape Galata (Bulgaria) from 1965-2005. From Kamburska et al. 2006.

Since its introduction, the Cigar Comb Jelly has fed almost exclusively on Sea Walnuts, and their population has steadily decreased throughout Europe. At one point, the Cigar Comb Jellies had eaten so many Sea Walnuts that they almost caused themselves to go extinct due to lack of prey.[4] There have been no reported negative impacts to the natural ecosystem in the waters they have been introduced to. There has also been a trend of more non-gelatinous phytoplankton, and decreased eutrophication in the waterways. This leads to the question of whether the Cigar Comb Jelly is just a non-native species, and not an invasive species like the Sea Walnut.

Not much is currently being done to regulate the populations of Ctenophores in European waterways. They are difficult to manage due to their size and reproductive rates. There is heavy monitoring of population sizes, but it is widely accepted that these organisms will always be a part of these waterways now that they have established populations there. The Invasive Species Specialist Group suggests that the only viable method of eradicating *Mnemiopsis leidyi* is to continue to introduce more predators to the invaded areas.[6] The idea of introducing more species is one that is often met with much concern, due to how unpredictable the outcome could be. In the case of the Sea Walnut, this might be a viable option since their predators have already been introduced to the waters, and have shown no ecological harm thus far. This is just one example of how important it is to enforce and implement laws to regulate water transfer among continents. Ballast water exchange laws need to be put in place and enforced so that organisms like these are not being released into new habitats, and destroying them.

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Lionfish, *Pterios volitans*

Olivia Carpenter

Lionfish are an exotic and beautiful fish that catches the eyes of many aquatic enthusiasts for a multitude of reasons. Aside from their striking appearance, they are recognized as being the poster children for invaders of the sea due to their invasive success. Native to the Indo-Pacific, lionfish have been thriving in their non-native environments since their point of introduction to the Eastern Coast of the United States, Caribbean, and Mediterranean. For over a decade they have contributed to the damage and loss of reef habitats and the depletion of fish populations. This in turn has significantly impacted the ecology and economy of affected areas, however it hasn't been until recent years that things have begun to turn around. There have been many attempts to manage the lionfish populations, but none have been as successful hunting lionfish for human consumption. The inclusion of lionfish on the menu has provided cultural enrichment in participating areas and lionfish populations have noticeably declined, proving that human predation on lionfish is a viable way of controlling the invasive species.

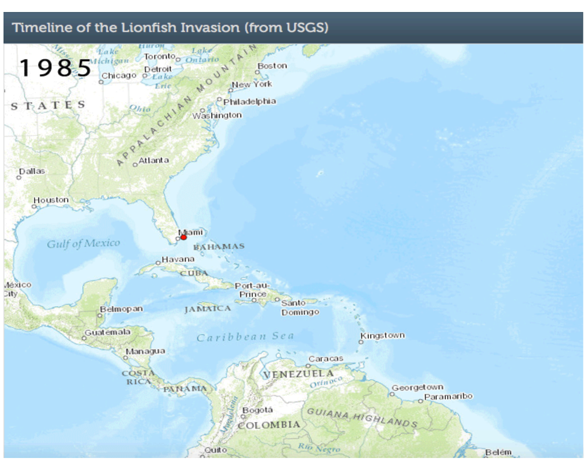

Figure 1. Lionfish population off coast of Florida in 1985 [from an animated timeline of the lionfish invasion on http://lionfish.gcfi.org/index.php]

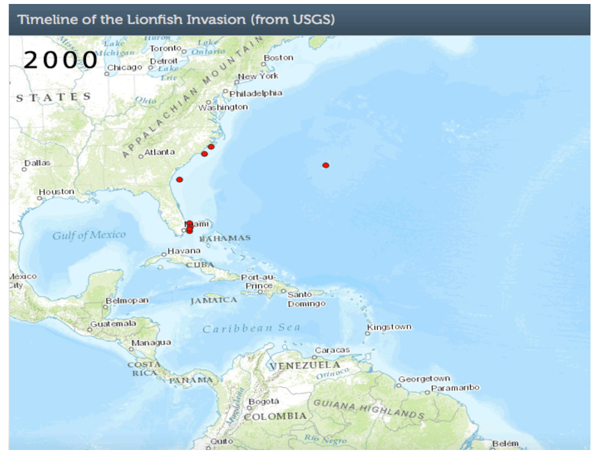

Figure 2. Lionfish dispersal in 2001 [from an animated timeline of the lionfish invasion on http://lionfish.gcfi.org/index.php]

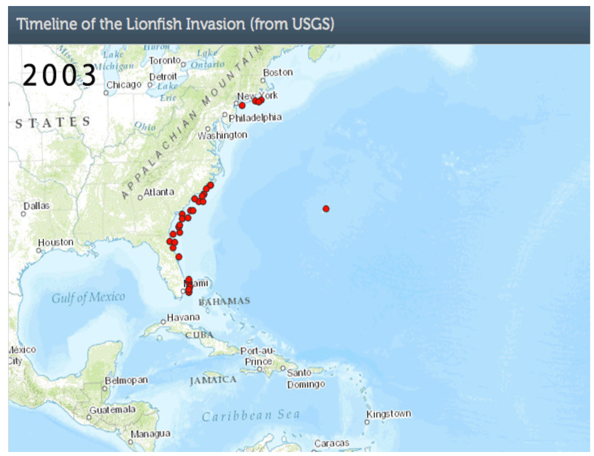

Figure 3. Lionfish spread by 2003 [from an animated timeline of the lionfish invasion on http://lionfish.gcfi.org/index.php]

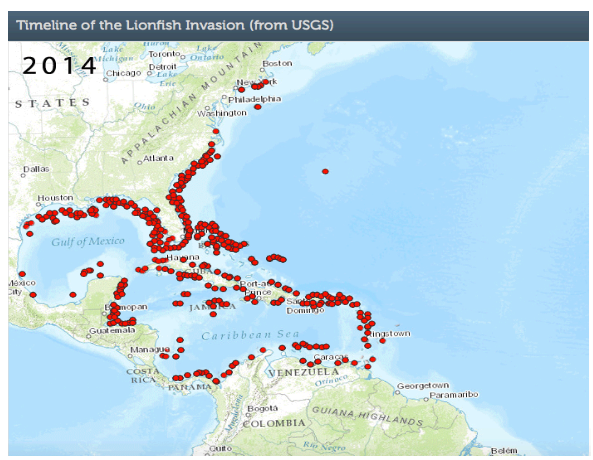

Figure 4. Lionfish invasion in 2014 [from an animated timeline of the lionfish invasion on http://lionfish.gcfi.org/index.php]

Although there is not much known about their mode of introduction, it is speculated that they were introduced via the aquarium trade due to the attraction of aquarium enthusiasts to the fish's beauty. However, aquarium owners didn't realize lionfish require heavy maintenance due to their varied diet and need for spacious tanks so it's suspected that they proved too difficult for their owners and were improperly disposed down toilets or thrown in the non-native parts of the ocean. Scientists have also hypothesized that Hurricane Andrew caused accidental release from aquarium breakages[6]; seeing that the first recorded lionfish observation was off the coast of Florida in 1985 and was possibly a result of the hurricane. However, it wasn't until 2001 that populations began to grow exponentially, spreading north of North Carolina and south through tip of Florida. By 2008 they had reached the Caribbean and began to rapidly spread across the sea. In 1992, the lionfish were first detected off the shores of Israel and in 2013 they were observed in Lebanon, marking the beginning their invasion of the Mediterranean Sea[5].

Lionfish have been able to successfully invade these areas due to a combination of different factors. Though slow moving, these fish are aggressive and fiercely territorial. Not only are they able to outcompete most native species for space, but they also have the capability of consuming a wide variety of fish. When dissected, the stomachs of lionfish contained as many as fifty different species at one time due to their stomach's ability to "expand up to 30 times its normal size[2]". The lionfish have primarily colonized reef habitats due to the warm climate and abundant food sources. Another factor enabling the invasive success of the lionfish is the lack of natural predators. This may be due to deterrence caused by large venomous spines on their fins, which serve as a defense mechanism against attackers. In their native waters, lionfish have few to no natural predators as well so little is known on how their populations are kept in check. However, in invading areas, the lack of predation on lionfish coupled with their rapid reproduction and long lifespan enables population growth. They have high fecundity rates and a relatively short maturation period as a single lionfish can spawn over two million eggs per year, each egg having the ability to reach sexual maturity within the year.

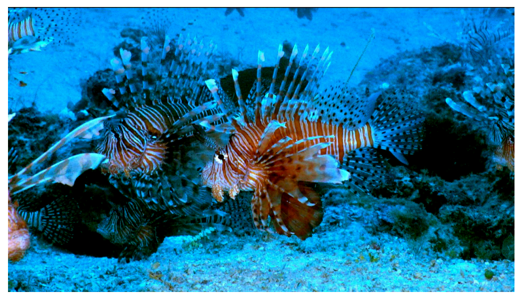

Figure 5. Lionfish invasion of reef habitat [from http://aamboceanservice.blob.core.windows.net/ocea oceanser-prod/caribbean-mapping/video/lionfish-splash.jpg]

Invasions of lionfish have been detrimental to the ecology of affected areas. Due to the ability of lionfish to consume up to one hundred species of fish, there is heavy predation on native fish[3]. In just two years, increased lionfish abundance correlated with a 65% decline in the biomass of the lionfish's 42 Atlantic prey fishes[3]. Fish populations have continued to decline significantly since 2012, throwing off the biological balance of these reef systems. With few native fish species now remaining to control algae populations, subsequent increased algae growth will allow them to outcompete coral reefs for space, thus ultimately causing coral reef populations to decrease. Not only do lionfish perturb coral reef populations by throwing off the balance of the system, but they also cause physical disturbances contributing to reef destruction.

Decreased biomass has also had a significant economic impact, as fishing industries aren't able to supply fish that are experiencing a decline in population. Groupers, snappers, and shrimp, have long been the heart of fishing industries located on the southern coasts of the United States but unfortunately, these species are among the many that are heavily preyed upon by lionfish, resulting in serious implications for fisheries in affected areas. Large-scale impacts include government-funded institutions researching general information about the species as well as management tools and techniques to eradicate the invader. In contrast, small-scale economic value on the citizen level is impacted as well due to the divers that invest in the equipment needed to remove lionfish in management attempts.

Figure 6. Lionfish dish served at a restaurant [from http://media2.fdncms.com/orlando/imager/u/original/2445336/lionfish.jpg]

Regardless of all the negative impacts derived from the introduction and spread of lionfish, there has been cultural enrichment in the invaded areas and even to some extent on a global scale. Due to wide recognition as the invasive poster child, lionfish has been immersed in the media, having been featured on various news broadcasting and Hollywood shows. It has gained publicity for not only its impact on the environment and rapid spread, but also for its claim to fame appearance. Lionfish have been regarded as one of many tourist attractions inhabiting coral reef systems, where people observe their remarkable striped patterns and uniquely fanned out spiny fins.

Though media coverage and tourist engagement have contributed to cultural change around the lionfish, the greatest impact has resulted from the recent discovery of being able to consume them. Lionfish have had the capacity to substitute many of the affected marketable fish such as groupers on the menu. This has greatly encouraged management to be focused on hunting the fish using spears and puncture-resistant tubes for containment, enabling divers to avoid being stabbed by the venomous barbs[4]. Though there is concern for ciguatera food poisoning, the result of toxin consumption contained in venomous fish, it has been proven unlikely to be contracted if prepared properly. Lionfish preparation is much simpler than that of puffer fish, another toxic fish that has long been consumed by humans in countries such as Japan. Due to the confinement of the venom within spines located on the anterior dorsal and pelvic fins, there is low risk of contaminating the meat and the spines just need to be cut while carefully avoiding contact with the skin in the process. This contrasts the difficulty of preparing the puffer fish, which has a venomous sack located internally near vital meat, so one wrong cut penetrating the sack upon removal will contaminate the meat of the entire individual. Once the spines have been clipped off, the remaining process follows that similar to grouper fish. Claims from areas marketing lionfish say that the meat is just as tender and delicious when compared to other cooked fish, making it a viable food source for others to follow.

Lionfish hunting introduces a method of population control, which has led to the start of population decline in participating areas. Whether it is to provide meat for buyers such as restaurant owners, or for mass culling outings, hunting methods have proved to be relatively successful in the management of lionfish within recent years. In Florida a derby competition is held, offering a win-win-win to the environment that's losing the harmful invader, participants who receive money for the most amounts of catches, and hosts who are primarily restaurant owners paying a flat cost to the labor of one for the labor of all. Other management methods such attempting to train sharks to prey on lionfish have conversely fallen short of success.

The beginnings of a management success story, these sustainable hunting methods have led to the start of lionfish population declination in participating areas. If all invaded areas introduced routine lionfish expeditions into management forces, then perhaps there would be observations the steady decline of lionfish populations. This would lead to protecting ecological biomass, save on economic investments, and ultimately enrich culture through the introduction of lionfish in daily cuisines.

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Lake Trout, *Salvelinus namaycush*

Kady Winsor

The "invasiveness" of a species is easy to conceptualize in the case of a nonnative crab which can be seen decimating local commercial fisheries, or a plant which proliferates to such an extent that waterways become impassable, but there are some invasive species which have been introduced so far back in history that society has lost sight of the damage they are causing. Such species are important to consider in discussions of aquatic invasions because they present unique challenges to study and management. Trout are a prime example of these species, as sport fishing is considered by many to be a traditional pastime throughout North America. Although many species of trout are found throughout the continent, few are truly native within their current ranges, and many of these non-native species should be regarded as invasive.

The salmonid family comprises 225 species in 11 genera ranging from salmon to trout and char. Although many species are considered "trout" in the common vernacular, these species are incredibly diverse and span three different genera[(2)]. Trout species are held in high esteem by anglers, who devoted extensive time and effort to translocating them across the northern hemisphere in the late 19th and early 20th centuries [(4)]. So extensive were these translocations that very few parts of the United States are uninhabited by trout. For example, Yellowstone National Park, an iconic model for conservation in the United States, is home to four species of introduced, potentially invasive trout species and only one species of native trout [(3)]. Unlike lionfish, which have established a notorious presence in Atlantic waters in the past decade, many of these trout species were introduced so long ago that few people can remember a time when they were not present. This presents a challenge to removal efforts, as such initiatives can be perceived as a threat to angling as a cultural institution among Americans [(4)]. Further complicating the management of trout as invasive species, many trout species have been introduced to areas which are relatively proximal to their native range. While it is a straightforward process to list and manage internationally invasive species at high levels of government, many species of trout have been translocated to areas within the country, sometimes even within a state or county. This means that management must be applicable on a very localized scale, and it may be challenging to publicize information effectively when invasions are localized and difficult to trace.

One example which is representative of many of the problems caused by invasive trout species, and the challenges to their management, is that of the lake trout, *Salvelinus namaycush,* in Yellowstone Lake. Introduced to nearby lakes by the United States Fish Commission in the late 19th century, lake trout were illegally translocated to Yellowstone Lake at some point in the late 20th century, where the first documented catch of a lake trout occurred in 1994[(3)]. This introduction has contributed to a substantial decline in populations of native cutthroat trout, *Oncorhynchus Clarki bouvieri,* largely due to direct predator-prey interactions [(5)]. Lake trout are piscivorous and grow to much larger sizes than cutthroat trout, making them a particularly effective predator of the native species [(6)]. This results in declining populations of cutthroat trout, a less piscivorous species which is responsible for keeping smaller aquatic species' populations in check, as demonstrated in figure 1. Furthermore, as lake trout generally inhabit greater depths than cutthroat trout, they are less susceptible to avian predation and are therefore are an ineffective substitute for cutthroat trout as prey for other species.

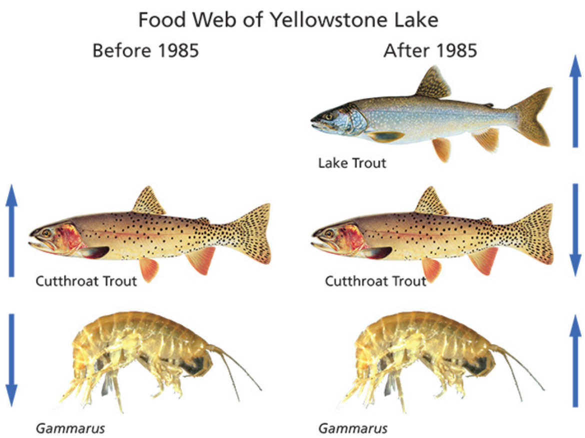

Figure 1. Diagram demonstrating the change in trophic interactions within the Yellowstone Lake ecosystem following lake trout introduction
Source: National Parks Service
https://home.nps.gov/media/photo/view.htm?id=80A11A21-1DD8-B71B-0B1815EDD9DAC06A&utm_source=Photo&utm_medium=website&utm_campaign=experience_more

The lake trout-driven decline in cutthroat trout populations is more than just the loss of a keystone species in the Yellowstone Lake ecosystem, it is also a major economic stress on the region. In a 1995 report to the director of the National Parks Service calculated the nominal value of each individual cutthroat trout in Yellowstone Lake at $72.63 [6]. It is further suggested in the same report that if lake trout populations were not controlled, the resulting decline in cutthroat trout would cause a $27,507,700 decline in annual sportfishing revenue for the local economy. These figures both speak to the considerable economic value of cutthroat trout. Their cultural value, though harder to quantify, is also substantial. In response to the threat that they pose to native cutthroat trout, the Yellowstone Lake ecosystem, and the human community which depends on the continued presence of cutthroat trout, the national parks service has commenced an aggressive gillnetting operation to remove lake trout, resulting in the removal of over two million lake trout from Yellowstone Lake since its start in 1994 [3].

Although lake trout are being managed in Yellowstone Lake with relative success, they are unlikely to be completely eradicated. In other bodies of water with greater connectivity, invasive trout are even more difficult to remove. One potential method of eradicating lake trout is electrofishing, which is labor intensive and requires a long-term investment to ensure success. Even when electrofishing is conducted alongside gillnetting and over a multi-year time span, it may not be possible to fully remove the invasive species. Birchell reports that electrofishing for brook trout in Reader Creek, Utah was successful in removing between 50 and 100% of invasive trout, but the low end of this estimate, and its substantial range, suggest that this method would be insufficient to completely eradicate this invasive population [1]. Lake trout gillnetting in Yellowstone Lake has allowed the cutthroat trout population to recover to a minimal extent but given that this program has been taking place for over twenty years while still yielding high catch rates in the present day, it seems unlikely that lake trout could ever be fully removed through this method [3].

What makes trout so unique as invasive species, especially those which were intentionally introduced, is that in many instances the groups driving removal of invasive trout are the very same ones which were initially responsible for their introductions. Throughout North America, anglers have begun to realize the harm that invasive trout cause to native fish populations, and have been leading the charge in their removal, and habitat restoration to support native [4]. It may not be feasible to entirely remove invasive trout from the full extent of their range, but there is hope that they may be managed sufficiently to allow native species to gain a foothold and reestablish themselves as dominant fauna in the landscape.

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Zebra Mussel,
Dressina polymorpha

Hannah Crull

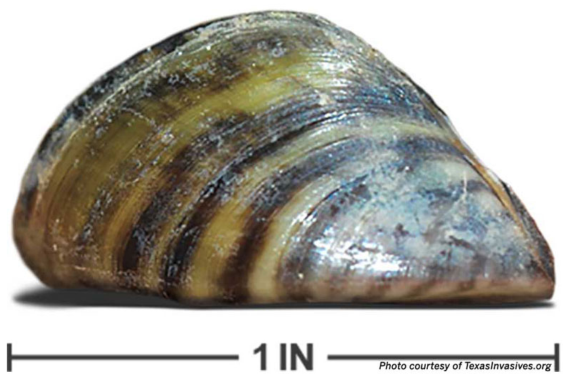


Figure 1: Fully grown adult zebra mussel (texasinvasives.org)

Species Introduction:
Zebra Mussels (*Dressina polymorpha*) are an invasive species which is heavily featured in the public awareness, and as such is a good demonstration of the facts and effects of a well-known invasive species. Zebra mussels are a small, freshwater bivalve, averaging 50 mm or smaller in length[10]. They are filter feeders, obtaining nutrients and oxygen by siphoning nearby water, and removing dissolved particulates and gases. Zebra mussels are named for the distinctive striped pattern on their shell, which distinguished them from the larger, and also invasive, quagga mussel. Zebra mussels are considered an invasive species in American waterways. They have significant ecological and economic impacts, are not native to the regions in which they are now found, and are spread predominantly by human-mediated vectors (shipping, boats, canals)[8].

Figure 2: Zebra mussels washed ashore at Lake Erie Bay City (courtesy of the Great Lakes Environmental Research Lab)

Transport
Zebra Mussels were originally native to the Black, Caspian, and Azov seas of Eurasia[2]. They initially spread outside of these bodies of water in the later 1700's, invading waterways throughout Europe between 1790-1867[8]. In 1940, they were discovered in Scandinavia and the USSR[8]. Prior to this, the spread of zebra mussels was slow and largely restricted to Western Europe. However, in the early 1900s, cargo ships transitioned from solid ballast to ballast water, increasing the probability of transporting live organisms[8]. Zebra mussels first appeared in North America in 1986, when they were introduced to Lake St. Clair/Detroit River[6]. It is thought that they were transported by ballast water from cargo ships arriving from the Black sea[8]. In 1991, zebra mussels were detected in the Hudson River, thought to have been spread through the Erie Canal in their larval form[8]. Since then, zebra mussels have invaded a wide variety of North American waterways[6]. Across the country, zebra mussels continue to be spread largely unintentionally, by attachment and fouling of smaller recreational vessels and gear. In some cases, zebra mussels were deliberately introduced to new territory in an attempt to improve water clarity, especially in man-made bodies of water that are popular for recreation[9]. Zebra mussels spread more

rapidly and successfully in the United States than Canada, with more than half of America's waterways being infested or at risk of infestation by 1994 (Figure 3) [8].

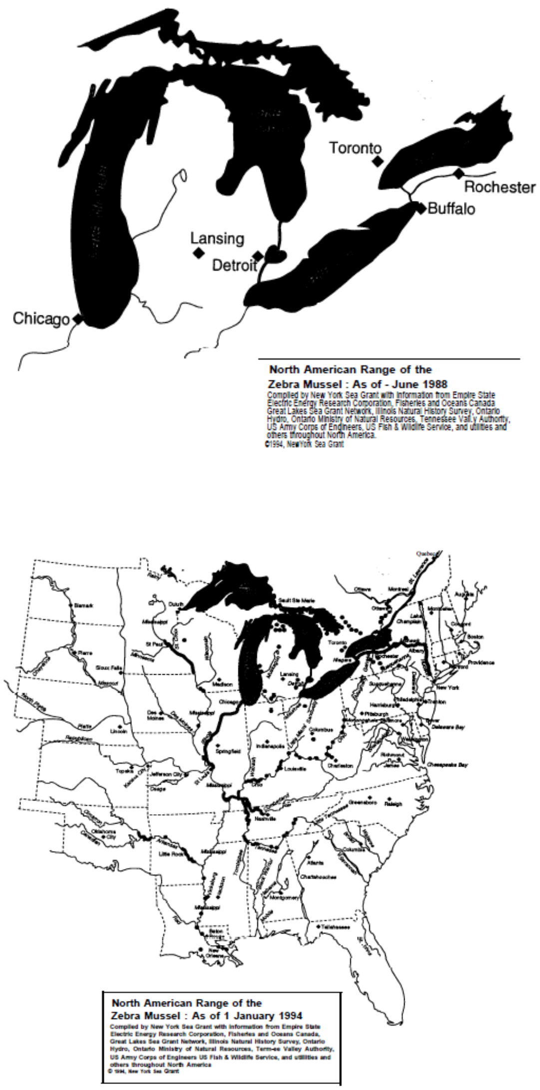


Figure 3A and B: The rapid increase of Zebra mussel range in American waterways, over 6 years. A) the estimated range of Zebra mussels in North America in June, 1988 and B) the estimated range of zebra mussels in North America in January, 1994[8].

Why are they successful?

Zebra mussels are extremely successful as an invasive species due to several physiological traits and adaptations. Zebra mussels, like many bivalves, can survive transport out of water for days by closing their shell[8]. This allows them to be transported over land on boats, trailers, and gear, until they are introduced to a new body of water. They can also attach to other organisms for transport, either mobile aquatic organisms which may travel to new bodies of water, or aquatic plants. Plants are easily snagged on boat propellers, and may then be transported to another body of water, spreading the attached zebra mussels as well[8].

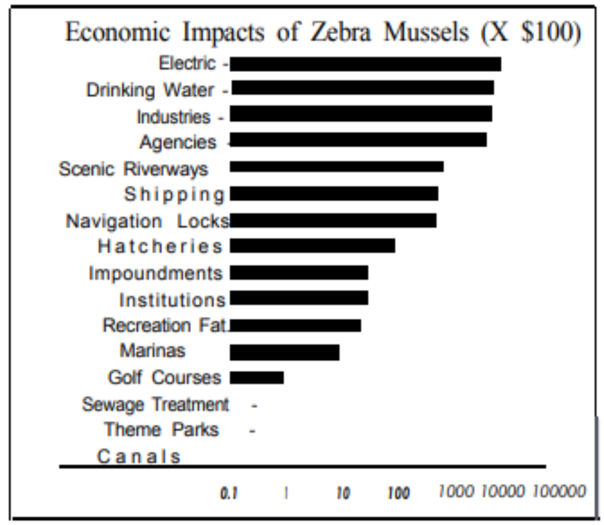
Zebra mussels have high physiological tolerances for temperature, oxygen, and pollution. They can survive water temperatures between 0-30^{o}C, with an optimal spawning temperature of 16-18^{o}C[6]. They adapted to the temperature conditions of North America rapidly, following their initial introduction[6]. Zebra mussels also have a high reproductive rate, with a single female producing one million eggs annually[2]. Combined with the bivalve life cycle, which includes a planktonic larval stage, this elevated reproduction allows for rapid and thorough invasion of large portions of a body of water[1]. As the larvae can move, being planktonic rather than sedentary like the adult phase, they are able to travel away from the initial spawning grounds, throughout a body of water, and even out into rivers and streams which connect to the main waterway[1].

Finally, zebra mussels have been more successful in North America than in Europe due to the timing of their introduction. European populations of zebra mussels have been kept in check by high pollution in European rivers and waterways[8]. However, when American waters cleared during the 60s-70s, it improved conditions for founding populations to establish and spread[8].

Impacts:

The most significant impacts of zebra mussels are ecological and economic. Ecologically, the majority of damage from zebra mussels is from their feeding method, which is more effective than the filtration of native species. Zebra mussels, with their rapid reproduction, can attain a much larger population with the same space and available resources[6]. The current population of zebra mussels in the Hudson river basin can filter the entire water content in 2-4 days[2]. In comparison, it takes native filter feeders 2-3 months to do the same[2]. Filtering the water in this way results in the oligotrophication of infested lakes and streams, reducing the available nutrients and oxygen for other species, which they easily and swiftly outcompete[8].

Zebra mussels also have a significant economic impact, as they can be harmful to industry and civilian water use. Mitigating the effects of the Great Lakes invasion cost an estimated $5 billion between 1993 and 1999[5]. The hydropower industry alone accounted for an estimated $3.1 billion of this, removing and preventing zebra mussels from attaching and fouling dams[5]. The primary expense arising from zebra mussels is removal from infrastructure and equipment, especially as, in heavily infested areas, the mussels must be fully removed routinely[5]. Removal of colonies which block water intake and outlet pipes incurs a wide range of costs across many industries and unexpected users, such as fish hatcheries, golf courses, marinas, public institutions, and agricultural irrigation[7]. Aquaculture and fisheries are also impacted by the decreased nutrient levels mentioned above. Fisheries of recreational and consumer catches are threatened by the decreased nutrients and biodiversity resulting from the monopolization of the base of the food chain by zebra mussels, threatening the sports fishing industry of the great lakes[7]. Similarly, many hatcheries and other aquaculture ventures rely on natural nutrients and oxygen for their operations, which can be jeopardized by the depleted food supply[7]. Finally, a significant cost is felt by the users of infested waters, as they now shoulder the burden of inspecting, cleaning, and maintaining their watercraft and equipment to a level which was not previously expected[5]. These costs spread throughout the local economy, creating widespread disruption and damage to local businesses.



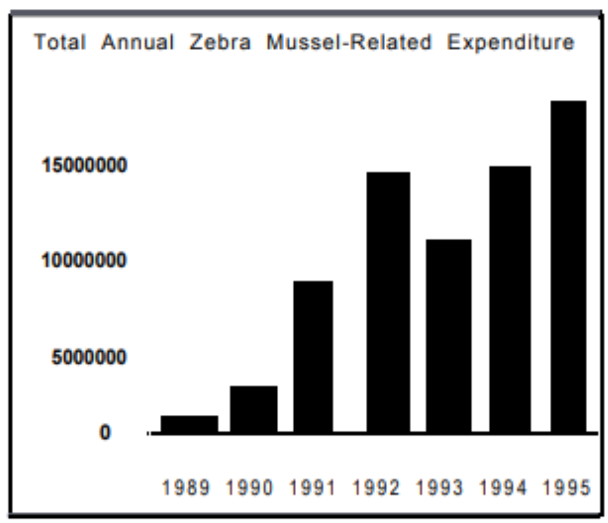


Figure 4A and B: A) Summary of total economic impact by water category of zebra mussels in the Great lakes (note logarithmic scale), and B) total annual zebra mussel expenses in the Great Lakes by year, 1989-1995[7]

Zebra mussels have limited impacts on local culture where they are established. They result in the closing of swimming and fishing areas due to the risk of spread from gear and clothes. There is also a minor human health risk, as zebra mussels have extremely sharp edges to their shells, which can cut unsuspecting visitors[11]. Additionally, zebra mussels have a negative impact on the recreational use of waterways, as the increased labor and costs for cleaning and inspecting equipment presents a barrier to many water users. Recreational boaters, for example, must spend a great deal of time and labor thoroughly inspecting their hulls, propellers, and trailers for any sign of attached aquatic life before they are permitted to take their craft out of an infested area[11]. This additional labor becomes more trouble than it's worth for many boat owners, who are more likely to take their craft to a different, non-infested waterway, or simply leave it in the same body of water, where they may have previously frequented many waterways.

One positive cultural impact did arise from the zebra mussel invasion. Due to their ubiquitous harm, and the relative ease of identifying the primary introduction vector, a unified protocol and policy has been implemented across the entirety of the great lakes ports and harbors[4]. This protocol required the agreement of several state and local governments, as well as agreements with Canadian provincial governments[4]. The specifics of this policy will be discussed at greater length below, but the point stands, zebra mussels managed a level of political unity that is rare in the United States[3].

Detection, Solutions, and Prevention

In-person detection is the most common method of identification, and is largely accomplished by sailors, workers at shipyards/marinas, civilian boat owners, swimmers, recreational fishermen, and the coast guard[8]. Other methods, such as environmental DNA, have also been implemented to detect zebra mussels in at-risk waterways.

There has been minimal success in removing or mitigating the effects of zebra mussels once they have been established. Several removal methods have been attempted, including civilian-led culling hunts, application of benthic mats to smother the mussels, water drawdowns to expose the bottom and dry out any attached organisms, applying UV light to prevent larvae from entering pipes, as well as several chemical controls[4]. These methods have met with limited success, especially as none of the current methods are selective enough to target only zebra mussels, harming the native species as well, and then requiring restocking or restoration programs afterwards to return the ecosystem to normal[4].

Figure 5: Zebra mussels attached to a boat rudder removes from Lake Austin, Texas (Photo courtesy of Colorado River Alliance)

The greatest limitation on zebra mussel spread is actually an environmental factor, rather than any human interference. Zebra Mussel larvae abundance decreases sharply below 18^{o}C, indicating that the larvae die at low temperature conditions[6]. This means that they cannot establish breeding populations in colder climates where the breeding season temperature is unfavorable, preventing the spread of zebra mussels into northern latitudes[8]. Internationally, this limitation can be seen, as the infestation in North America shows limited success in Canadian waterways. Extremes of temperature shifts are, therefore, one of the few limiting factors to the spread of zebra mussels[9]. However, with the moderating effects of climate change, winter temperature drops will decrease, allowing the species to spread north into waters which were previously too cold for reproduction.

Figure 6: A common sign posted at infested waters to remind boaters of cleaning and draining regulations for trailered boats and equipment (courtesy of Lake Havasu State Park, https://d2umhuunwbec1r.cloudfront.net/gallery/asp-archive/Parks/LAHA/index.html).

Regardless, there have been several strategies implemented to reduce the spread of zebra mussels from human vectors. Following recent studies on areas of high risk and key areas for spread, there has been an increased focus of prevention and containment efforts on streams and headwaters leading to other reservoirs, bodies of water, or water basins, as it is a significant vector for transport of planktonic larvae[1]. There have also been enhanced cleaning protocols and inspection requirements for trailered boats and across-state transport, as shown in Figure 6, which have become mandatory in many states[9]. Finally, there is mandatory mid-transit ballast water exchange for cargo ships prior to entering Great Lakes[3]. These strategies have been implemented in many places, and have become key to management and regulations in infested areas.

Current Management, Policy

As mentioned previously, a significant proportion of management efforts have been focused on preventing increased spread of zebra mussels, by limiting potential transport vectors. These include two major policies: a legal requirement to effectively and thoroughly clean and inspect boats, trailers, and other recreational equipment leaving infested areas, and mandatory mid-ocean ballast water exchange prior to entry into the great lakes. These policies are supported by several laws and regulations, each of which carry fines or penalties for non-compliance.

For example, the Great Lakes Port regulations, involves a collection of laws, policies, and regulations from the federal government, international governing bodies, the US Coast Guard, seven individual states, and the environmental protection agency. Ballast water exchange was first required by congress in 1990 for all vessels entering the great lakes, as was expanded in 1996 to include any ships entering an American port, and in 2006 with increased regulations for the Great Lakes[3]. This most recent set of regulations gave the US Coast Guard the authority to board and inspect every incoming vessel before they enter the great lakes, to ensure compliance[3].

Another set of regulations is Virginia State Department of Game and Inland Fisheries (VDGIF), regulation 4 VAC15-30-40: Importation requirements, possession and sale of nonnative (exotic) animals[4]. These regulations require that All sampling gear permitted for use in zebra mussel infested waters must be decontaminated, as well as giving the VDGIF authority to inspect and enforce the policies it puts in place[4]. This authority includes the rights to inspect any property in the state of Virginia which is suspected to harbor an invasive species, any presence of which is punishable by up to $25,000 of fines, as well as covering the costs of identification, control, and eradication[4].

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Conclusion

Aquatic invasive species pose a threat to the stability of ecosystems, economies, and cultures that is unique in its severity, resilience, and prominence. With the ever-increasing interconnectedness of the world, there are many pathways through which invasive species are able to spread from one area to another: commercial shipping, aquaculture, aquarium trade, and manmade channels and canals, just to name the most significant. Furthermore, in some instances, aquatic invasive species are released intentionally on the basis of being aesthetically pleasing, serving a role in sport hunting or fishing, or being a biological approach to eradicate other invasive species. The human-initiated spread of invasive species, both intentional and accidental, reflects a lack of understanding regarding the consequences of our actions. As aquatic invasive species become increasingly notorious, there has been a growing effort to research their impacts. These impacts are frequently generalized, leading to a very limited understanding among the general population. Management strategies which are enacted without a sufficient understanding of the unique characteristics of each invasion and the surrounding local environment are rarely effective. This book and the twelve case studies within it explore in detail specific examples of aquatic invasive species and their diverse impacts, in order to challenge the generalization that frequently leads to inaction or ineffective action.

Despite aquatic invasive species being present in North America since the arrival of European settlers in the 1500s, there is a substantial lack of data. The first U.S. laws concerning invasive species were not enacted until the 1900s. Based on the information compiled in the introduction and case studies, the following actions can be taken to mitigate the invasive species problem. First, the lack of one cohesive definition of invasive species must be addressed in order to ensure consistent management decisions and judicial action. The definition most commonly used when designing policies and management was established by Executive Order 13112, which can be revoked by any future administration, making this definition arbitrary through time. Second, it would be beneficial to consistently evaluate the legislation in place to deter and mitigate aquatic invasive species. The efficiency of enforcement and federal guidelines must be analyzed in order to safeguard our environment from these invaders.

Generalization and misinformation concerning invasive species commonly results in paradoxical responses of alarmism and inaction. Removing invasive species and preventing their spread is perceived as an insurmountable challenge. However, cases such as the Lionfish or the Sea Lamprey demonstrate that management, and possibly even eradication, may be possible if the species and source of the introduction can be identified and solutions are rapidly enacted to mitigate the invasion. In both of the aforementioned cases, management of the invasive species was highly prioritized and therefore received extensive funding and attention, which was a key factor in their successful management. These examples reflect that when eradication efforts are localized and tailored to each unique species, they are more likely to be successful. More research is essential to developing a more comprehensive understanding of each individual invasive species, which in turn will allow for more effective responses to current and future invasions. As climate change exacerbates existing invasions and allows species to invade previously unaffected areas, further research will be needed to determine the exact nature of these effects.

Although aquatic invasive species are currently extremely destructive to some areas due to their ability to outcompete native species, damage the environment, and disrupt local economies and cultures, these impacts are only predicted to worsen. As the surface of the earth continues to warm due to unprecedented levels of greenhouse gases being present and actively emitted into the atmosphere, the oceans are absorbing most of this added heat, increasing sea surface temperatures dramatically. Because many aquatic invasive species are inherently more capable of tolerating changes in the environment and a wider range of conditions than native species, they are more likely to survive such shifts. Further, some species, such as invasive tunicates, are predicted to actually be more productive and successful in warmer waters, allowing them to outcompete and displace native species more rapidly than they already do. Mitigating climate change is essential to preventing or reducing the future impact and spread of invasive species. Climate change research and ongoing monitoring of habitats which are susceptible to aquatic species invasions must occur in order to avoid the worst case scenario of these climate change-driven invasions. Establishing a baseline for habitats under threat of invasion, and detecting new invasions early will allow invasive species' population growth to be curtailed before they reach such proliferous levels that eradication becomes impossible, to the great benefit of the local economy, society, and natural environment.

While this book is by no means a complete account of the many unique invasive species which have become established across the globe, the authors believe that knowledge accumulated within this book provides a strong foundation to understand the causes, consequences, and solutions of aquatic species invasions. Our introductory materials reflect a comprehensive review of the existing literature pertaining to the factors associated with most species invasions. Although a great deal of the information discussed in this book is alarming, as it should be given the severity of the impacts of aquatic invasive species, the actions of individuals can make a difference. Ultimately, by remaining informed and by educating others, we can encourage responsible action rooted in environmental stewardship which, in return, will support the stability of the environment.