4-2021

Who Invited You? The Complex Story Of Aquatic Invasive Species

Shaylee A. Amidon

Colin J. Birch

Sierra E. Brown

Kaitlyn E. Butts

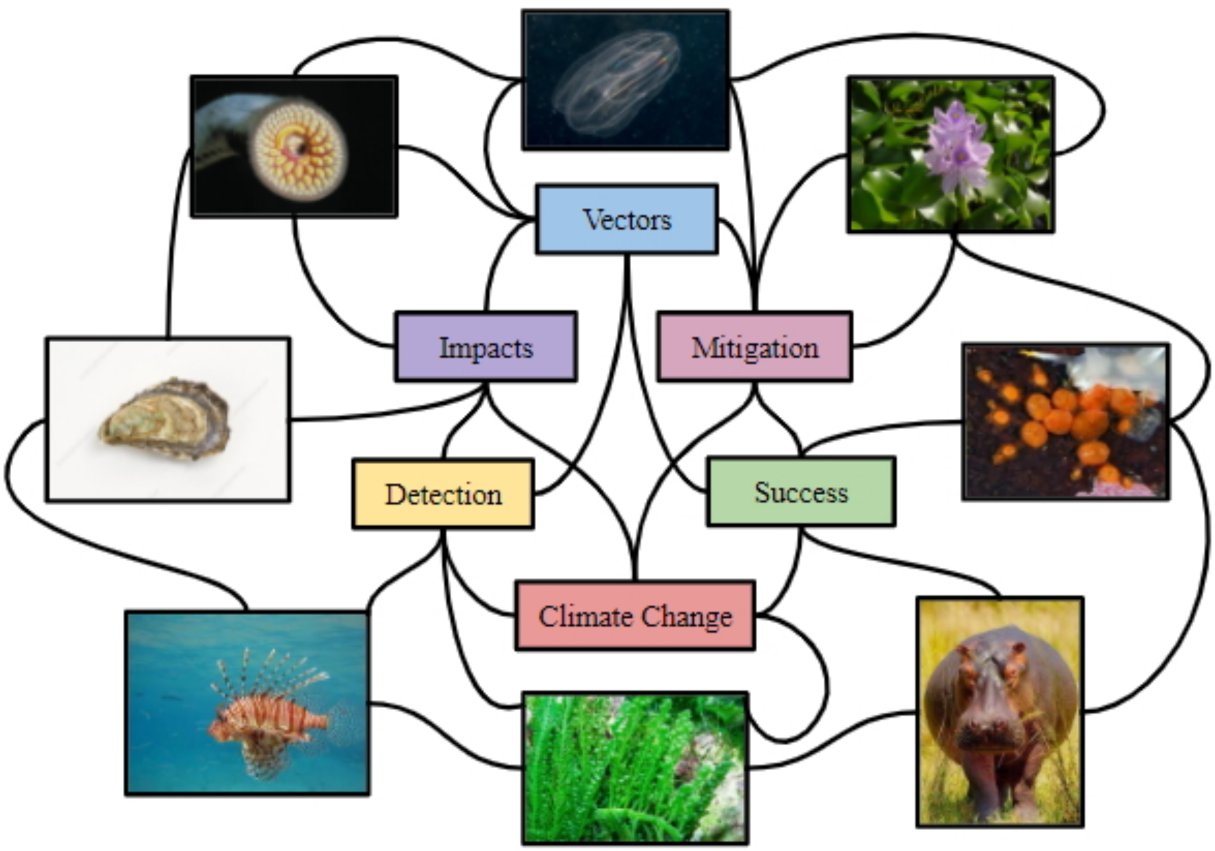
Abbigail L. Felix

See next page for additional authors

Creator
Shaylee A. Amidon, Colin J. Birch, Sierra E. Brown, Kaitlyn E. Butts, Abbigail L. Felix, Samuel S. Fuller, Edwin Gao, Emily M. Lewis, Alexandra Michaud, Doyle M. Proto, Bradley N. Spear, George H. Wales, Hannah M. Welch, Conor F. Wiley, Kristen S. Wurth, and Markus Frederich

Who Invited You?

The Complex Story of Aquatic Invasive Species



By: Shaylee A. Amidon, Colin J. Birch, Sierra E. Brown, Kaitlyn E. Butts, Abbigail L. Felix, Samuel S. Fuller, Edwin Gao, Emily M. Lewis, Alexandra Michaud, Doyle M. Proto, Bradley N. Spear, George H. Wales, Hannah M. Welch, Conor F. Wiley, Kristen S. Wurth, and Markus Frederich Ph.D.

Cover page design by Sierra Brown and Kristen Wurth, using images from:
https://www.pinterest.com/pin/613263674237987631/
https://www.sciencephoto.com/media/132578/view/pacific-oyster
https://oceana.org/blog/invasive-lionfish-are-delicious-%E2%80%94-it-safe-eat-them-6
https://cisr.ucr.edu/invasive-species/caulerpa-taxifolia-or-killer-alga
https://www.britannica.com/animal/lamprey
https://d1o50x50snmhul.cloudfront.net/wp-content/uploads/2016/09/27104355/morski-orah-mnemiopsis-leidyi-2.jpg
https://en.wikipedia.org/wiki/Eichhornia_crassipes
https://racerocks.ca/category/species/subphylum-urochordata

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 fifteen junior and senior Marine Science, Marine Affairs, Animal Behavior, 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, April 2021

Table of Contents

Introduction

Authors: Hannah Welch & Colin Birch
Edited by: Doyle Proto

The idea of an invasive species is a relatively new concept in the science of biology. Humans have been aiding the invasion of many species throughout society. Many species that seem so integral in our current environments have started out as invasive species, which includes honeybees, horses, & sheep. While it is true that human interaction has caused a large number of invasive species throughout history, the impacts of these critters has been a topic not discussed in great detail until the 20th century. One of the first scientists to really talk about the concept of invasive species as a whole was Charles Elton. Elton was a biologist in the early 20th century and was uniquely interested in the interactions an organism has in its environments. In 1958, Elton published, "*The ecology of invasions by animals and plants*" which was one of the first books dedicated to invasive species as a whole. Some credit this book to being responsible for launching invasive ecology into mainstream science. Interest for invasive species has been growing steadily ever since the 50's. This book still has great interest and is cited 105.7 times every year. Invasive species really started to get the spotlight throughout the 80s as many larger scientific organizations started to spread public awareness around invasives. At this time, many governments around the world started to define and place laws and restrictions around invasive species. One major example is the Wildlife and Countryside Act of 1981 in Great Britain which banned any introduction of any animal not naturally occurring. While both biological science and many governments are now recognizing the threat of invasive species, they are an extremely huge effort and require lots of attention and work to avoid the detriments to our ecosystem.

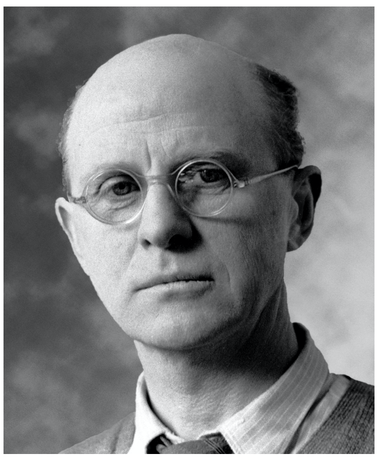


Figure 1.1 Charles S. Elton first coined the term "invasive species" https://biology4095.science.blog/2020/02/22/elton-and-ecology/

There is no generally accepted definition for an invasive species. Some describe it as simply an organism that is not indigenous, or native, to a particular area. Others specify that their spread *can* have beneficial aspects, however an invasive species must adversely affect the invaded habitats and bioregions, causing ecological, environmental, and/or economic damage. To narrow it down further, some exclude any organism that has not been introduced by humans. For our purposes, we will be looking exclusively at aquatic invasive species which we define as any aquatic species who is not native to a specific area and causes harm to that native ecosystem. These harmful effects can be either ecological, environmental or economical, and we will consider both human and non-human means of introduction.

One of the main reasons that invasive species are such an issue is that they are often very successful in their new environment. The fact that they are in a new environment isn't much of a threat, but oftentimes invasive species tend to outcompete and can drastically alter an environment because of how well they do. There are a variety of factors that are considered when talking about the success of invasive species. The main reason that they are so successful is because they can outcompete other organisms and take away a lot of the available resources. Since invasives are introduced to a brand new ecosystem, many of the native prey don't have a chance to adapt to the new predator. For the same reason invasives tend to also have no natural predators in the new environment to keep them in check meaning their voracious eating habits go unchecked. While not a standard for all invasives, it is common to see that they have a larger tolerance for various environmental conditions then their native counterparts. This can include salinity, temperature, light levels etc. There are also many cases where human interaction is continuing to help the invasives takeover. Because humans are often the reason for their introduction to an environment it is not uncommon to see more and more individuals brought in using the same vectors. One example of an invasive that is incredibly successful due to all of these reasons is the green crab. They can outcompete their native counterparts, have no natural predators, and can better tolerate colder temperatures than natives (USDA). Combining all these factors together means that many invasive species besides just green crabs are very hard to control after they've settled in an 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

Figure 1.2 Threat scoring system table; from Molnar et al. 2008

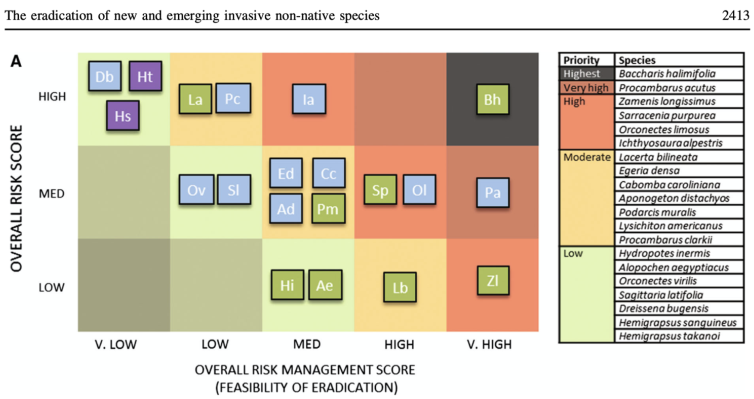
There are many reasons invasive species are problematic. It is estimated that 42% of threatened and endangered organisms are at risk because of invasive species, so clearly they can have a profound, negative impact on biodiversity (Prism, 2018). Analyzing the threat of invasive species globally then requires global databases, however most datasets are local or regional. A study conducted to assess the global threat of invasive species to marine biodiversity then developed a new database. This consists of a simple, quantified threat-scoring index which has been key in objectively comparing marine invasive species worldwide (Molnar, 2014). They developed a threat scoring system based on several existing threat classification systems and each invasive species can be assigned to score for the following categories: ecological impact, geographic extent, invasive potential, and management difficulty. "Ecological impact scores measure the severity of the impact of a species on the viability and integrity of native species and natural biodiversity" (Molnar, 2014). For example, the green algae *Caulerpa taxifolia* was assigned the highest ecological impact score of 4, based on its ability to outcompete native species and reduce overall biodiversity. On the other hand, sea slug *Godiva quadricolor* was given a lower score of 2 because it's only known impact as feeding on other sea slugs, with no wider effects documented. In the Atlantic area, it was found about 60 species associated with high impacts (index score of 3 or 4) (Castro, 2017). The authors even noted this is believed to be an underestimate. Since species are often introduced in new areas for their economic or ecological benefits, assessing the impacts of a potential invasive species can be critical in this decision-making process.

Invasive species can also have a dramatic impact on local communities as they may clog or contaminate waterways, impact recreational opportunities, and interfere with waterfront property. Economically, money is poured into control, removal, and prevention efforts. In Japan, the Northern Pacific Sea Star has wiped out their bivalve populations and ultimately cost the mariculture industry millions of dollars in control measures and losses from predation. Overall, it is estimated that generally, invasive species cost the U.S. upwards of $138 billion dollars per year (Prism, 2018). Many invasive species also impact the welfare of human beings. Invasive species can negatively impact human health by infecting humans with new diseases, serving as vectors for existing diseases, or causing wounds through bites, stings, allergens, or other toxins (Mazza et al. 2014). Their negative impacts are even expected to "intensify in the near future due to the increased opportunities of invasions associated with climate change, the augmented pathways of introductions and the synergic effects of climate change" (Seebens, 2021).

Climate change is expected to facilitate the spread and establishment of many invasive species and creates new opportunities for other non-native ones to become invasive. In fact, a 2020 study predicts that the number of established alien species will increase by 36% between 2005 and 2050 (Seebens, 2021). By nature, invasive species pose a greater threat to areas sensitive to climate change as they can reduce the resilience of natural habitats, agricultural systems and urban areas to climate change. As temperatures increase, many species will be able to increase their invasive range. Lionfish for example, are a tropical fish currently invasive in North America all the way up to the Carolinas. Occasionally in the summer, there have been sightings of juveniles off the coast of Rhode Island. This is not included in their range since they cannot survive the winters in New England waters, however as sea temperatures climb they have the potential to continue to spread more and more northwards. Additionally, the spiking sea temperatures cause sea ice to melt which, in turn, opens up access to more shipping routes. For example, emerging Arctic shipping passages due to melting ice caps will greatly reduce the time taken for ships to travel from Asia to Europe. This will increase the risk of alien species surviving the journey and increases the opportunity for more species to be introduced to more areas across the globe via ballast water.

About 80% of international trade, in terms of volume, is carried by sea (Castro, 2017). Shipping routes connect coastal regions worldwide, making ballast water a major vector, or mode of introduction, for species transportation and spread of invasive species. Ballast water is used to adjust the draught and trim of a ship to improve manoeuvrability and stability with an estimated 3–10 billion tons of ballast water transferred globally each year (Castro, 2017). Other highly cited vectors for introduction and spread of invasive species in the Atlantic are biofouling and aquaculture. Many times, the introduction of an invasive species is unintentional, like in the instance of ballast water and biofouling. However, sometimes these species are actually brought to a new area on purpose. Oftentimes they are introduced as a form of pest control while other times they may be brought in as pets or decorative displays. For example, in 1949, five cats were brought to Marion Island, a part of South Africa in the southern Indian Ocean. The cats were introduced as pest control for mice. By 1977, about 3,400 cats were living on the island, endangering the local bird population (Adams, 2021). Once an invasive species is introduced, even intentionally, they can cause unforeseen harm and pose significant challenges to eradicate.

Given how dangerous and prevalent invasive species are in many of our current environments, strategies to maintain and eradicate invasives are incredibly important. One of the first steps to taking care of invasive species involves detection and monitoring. Before any removal or eradication efforts are implemented, it's important to have a rough estimate of the number of invasives present and the amount of damage they do. Invasives can be categorized on the threat that they pose to an ecosystem along with the likelihood of eradication (Booy, 2017). This strategy allows efforts to be maximised around invasives that are most worthwhile to remove. There are a variety of strategies used to monitor invasive species in an area. Different types of tagging may be done to track specific individuals to locate where the invasives go and how far their range extends. Some common strategies include either radio or satellite tags to get real time read on invasive locations. Invasives are also often monitored through low tech strategies such as sending in observers into the field to survey an area. Cameras and traps are also used to get a lot of information without as much effort. Lastly eDNA can be analyzed to determine all of the species in an environment up to the last 30 days. eDNA is affected by environmental conditions and in harsher climates might not be as reliable.



Priority	Species
Highest	*Baccharis halimifolia*
Very high	*Procambarus acutus*
High	*Zamenis longissimus*
	Sarracenia purpurea
	Orconectes limosus
	Ichthyosaura alpestris
Moderate	*Lacerta bilineata*
	Egeria densa
	Cabomba caroliniana
	Aponogeton distachyos
	Podarcis muralis
	Lysichiton americanus
	Procambarus clarkii
Low	*Hydropotes inermis*
	Alopochen aegyptiacus
	Orconectes virilis
	Sagittaria latifolia
	Dreissena bugensis
	Hemigrapsus sanguineus
	Hemigrapsus takanoi

Figure 1.3 Diagram showing the feasibility of eradication compared to the risk score of multiple high priority invasive species. (Booy 2007)

Because of how big of threats invasive species tend to be to their environments, removal and eradication seem like the obvious answer. While it is very imperative that invasive species are controlled and removed for delicate ecosystems, invasives can be very difficult to handle. Because invasives tend to be very successful in new environments, they can reproduce and spread out at extremely quick rates making eradication more difficult as invasives are left alone. Another issue is that because invasives do so much damage to native species and ecosystems as a whole, many eradication strategies are too disruptive for the now fragile ecosystems. Despite these challenges, a variety of unique strategies are constantly being created and implemented to try and remove invasive species. While many strategies exist, most removal efforts can be placed in one of three categories: mechanical, biological, or chemical (USDA). Mechanical mitigation refers to any process where the invasive is being physically removed from the environment. This strategy is most common in invasive plants because machines can help to mow down or cultivate plants with ease. Biological refers to using other organisms to try and control the invasive species. Often a new can predator is introduced to control the invasive population, but the risk of this species becoming uncontrollable is present. Lastly chemical methods refer to any strategy that involves toxins or chemicals introduced into an environment to kill off an invasive. A common example of this is herbicides which can be used to kill off plant populations. The risk of these chemicals are that they may also harm the environment, although some specific pesticides have been developed that only take out the target species. Even if mitigation efforts cannot fully eradicate an invasive, they can control their populations to provide relief to the ecosystems giving them a chance to recover.

<u>References:</u>

Adams, T. Invasive Species - The Damage They Do, and How We Can Stop Them. 2021. https://wildlifetree.com/blogs/sustainable-living/invasive-species-the-damage-they-do-and-how-we-can-stop-them.

Castro, Maria Cecilia T. de, Fileman TW, Hall-Spencer JM. Invasive species in the northeastern and southwestern Atlantic Ocean: A review. Marine Pollution Bulletin 2017 Mar 15,;116(1-2):41-7.

Mazza G, Tricarico E, Genovesi P, Gherardi F. Biological invaders are threats to human health: An overview. Ethology, Ecology & Evolution 2014 Jul 3,;26(2-3):112-29.

Molnar JL, Rebecca L Gamboa, Carmen Revenga, Mark D Spalding. Assessing the global threat of invasive species to marine biodiversity. Frontiers in Ecology and the Environment 2008 ;6(9):485-92.

Prism, S. Why Should We Care About Invasive Species [Internet]; c2018. Available from: https://www.sleloinvasives.org/invasives/what-is-an-invasive-species/.

Seebens H, Bacher S, Blackburn TM, Capinha C, Dawson W, Dullinger S, Genovesi P, Hulme PE, Kleunen M, Kühn I, et al. Projecting the continental accumulation of alien species through to 2050. Global Change Biology 2021 Mar;27(5):970-82.

Booy, O., Mill, A., & Roy, H. (2017, May 15). Risk management to prioritise the eradication of new and emerging invasive non-native species. Retrieved April 19, 2021, from https://link.springer.com/article/10.1007/s10530-017-1451-z

Impacts of Invasive Aquatic Species

Authors: Doyle Proto & Abbigail Felix

Edited by: Bradley Spear

<u>Introduction</u>

Invasive species, by this book's definition, must have some effect on their non-native habitat which is called an impact. Impacts of an invasive species can cause damage to different sectors of society like the economy, the environment, human health, and recreation. Economic impacts can occur at many scales from disruptions to local businesses to being responsible for the loss of billions of dollars across the globe. Ecological and environmental impacts can directly influence the physical habitat, or the interactions between participants in an ecosystem. This can be observed in invasive species destroying native populations of prey or altering the physical layout of an environment. Impacts to human health typically occur when people live near areas overrun with invasive species. Some populations of invasive species can produce or carry toxins, wastes, or diseases with adverse effects on humans (Mazza *et al.,* 2014). Invasive species can have other direct impacts on humans such as affecting recreational activities by physically disrupting areas where they take place. Defining and measuring the impact of a species can help us to determine appropriate mitigation techniques and prioritize species with high impact potentials.

One of the ways impact potentials can be determined is completing a risk assessment of a species. Risk assessments use research into the genetic, reproductive, behavioral, and physical characteristics of the target species to determine possible impacts. Risk assessments allow important factors that make a species successful to be weighed against each other (Keller *et al*., 2011). Risk assessments are important for governments and communities to be able to understand the level of damage an invasive species can present. In addition to illustrating what options communities have in addressing these invasive species, risk assessments help to determine an order of importance. Currently most risk assessment systems do not consider the feasibility of mitigation and eradication techniques when comparing invasive species only the level of risk they pose (Booy *et al*., 2017). The Non-Native Risk Management scheme (NNRM) is one of the only risk assessment systems that considers these factors and many others. The NNRM judges the mitigation of invasives on seven measures including, effectiveness, practicality, cost, impact, acceptability, and likelihood of reinvasion. Each category receives a score from 1 (Negative: i.e., ineffective) to 5 (Positive: i.e., effective). A similar assessment model was discussed in the introduction chapter which described a threat scoring system. This system examined the ecological impact, geographic extent, invasive potential, and management difficulty (Molnar 2014). Both assessments are useful and should be utilized to identify the scope of an invasive.

The need for the management of a species is directly dependent on the impacts of a species. For this reason, organizations also use density-impact curves to determine the relationship between the population density of a species and its economic impact including both natural impact and cost of mitigation. The model assumes that if the economic impact of an invasion is a function of the population density, any decrease in impact of removing individuals will depend on the density at the time. The researchers examined three possible nonlinear curves; low-threshold (I), high-threshold (IV), and S-shaped (II), as well as a linear relationship (Yokomizo *et al.,* 2009). In the low-threshold curve, the economic impact of the species remains high until there is a significant reduction in the population. In the high-threshold curve, the species' impact remains low until the population becomes massive, then we see a sharp increase in impact. The S-shaped curve is defined by the economic impact of a species increasing quickly at an intermediate population density (Yokomizo *et al.,* 2009). The curve itself is based off a mathematical model that considers year to year growth rates and management efforts to determine density (Yokomizo *et al.,* 2009).

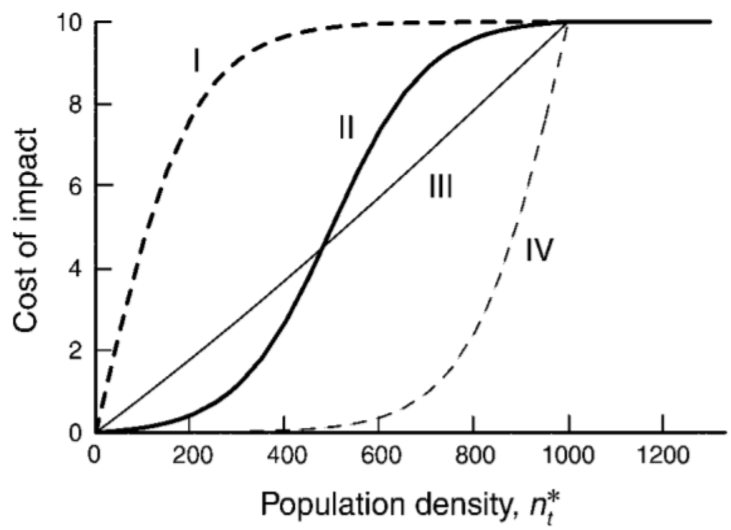


Figure 1. Example of possible density-impact curves. Population density is located on the X axis while cost of impact is on the Y. Three non-linear curves: curve I is a low-threshold curve, curve II is a S-shaped curve, IV is a high-threshold curve and curve III is a linear curve (Yokomizo *et al.*, 2009).

If the assumed density-impact curve is incorrect, organizations and governmental bodies could potentially waste precious resources. Density-impact curves are especially important for invaders that have high economic impact at low density and low economic impact at high density. High impact, low density species are extremely dangerous and must be handled immediately. Their populations inflict the same level of impact as significantly larger populations while also being more difficult to find. If a previously discovered species of this caliber was assigned a density-impact curve, organizations experiencing new invasions would be able to allocate necessary resources to mitigate impacts more effectively. Low impact, high density invasive species become too numerous to realistically manage and can be a general annoyance to the public. Although they may not significantly impact the local economy, they may overrun ecosystems and affect human health. Moreover, the simultaneous mitigation of all invasive species would require more resources than is afforded to such efforts currently and would inefficiently divide resources between different priority species. Once obtained, this information suggests a logical path through invasions focusing on species with the highest impact potential first.

<u>Types of Impact</u>

Impacts of invasive species are not equal. Some have developed behavioral and physiological adaptations that allow them to create drastic impacts to non-native regions. Governments tend to get involved in countering invasive species when they have a significant negative effect on the local or national economy or human health. A good example of this is when commercial fisheries started losing money in the Great Lakes due to sea lampreys (see sea lamprey case study). Specific organizations, like Marine Invader Monitoring and Information Collaborative, or MIMIC, in New England, monitor ecological effects of invasive species, but very

Figure 2. Nutria are semi-aquatic rodents native to South America. They have been introduced to several areas through fur farms. They are similar in stature to beavers with a less pronounced tail.
https://www.tn.gov/twra/wildlife/mammals/medium/coypu-nutria.html

little of the public cares unless they see impacts on recreational ability. The level of impact a species inflicts and who is harmed determines how fast a response is mounted if at all.

Economic

The overall global economic impact of invasive species is difficult to calculate with it being more common to analyze impacts on a regional and species basis. The organizations that track this data are usually attempting to calculate its effects, and costs, on local industries, recreation, and environment. Determining the exact effects of the invasive species can also be difficult sometimes, but direct damage is the easiest to estimate. Direct damage is damage or losses that can be directly attributed to the species in question. This can be destroying aqua-crops, biofouling that slows down cargo vessels, destroying a local ecosystem that is popular with tourists, and the costs related to removing them from a region. Those who tabulate the costs of invasive species and the economists who write the economic reports about their effect tend to not focus on any of the ecological effects.

Nutria, also known by its common name Coypu and scientific name *Myocastor coypus,* is a semi-aquatic rodent found within the Patagonia region of South America. They have an appearance somewhere between that of a beaver and a rat (*See figure 2)*. They live by eating the stems and roots of plants found in marshes. They dig burrows into riverbanks where they live and care for young. They are primarily nocturnal, but they will forage for food during the day when it is scarce. They were intentionally introduced to different regions as a replacement for beaver in fur farms.

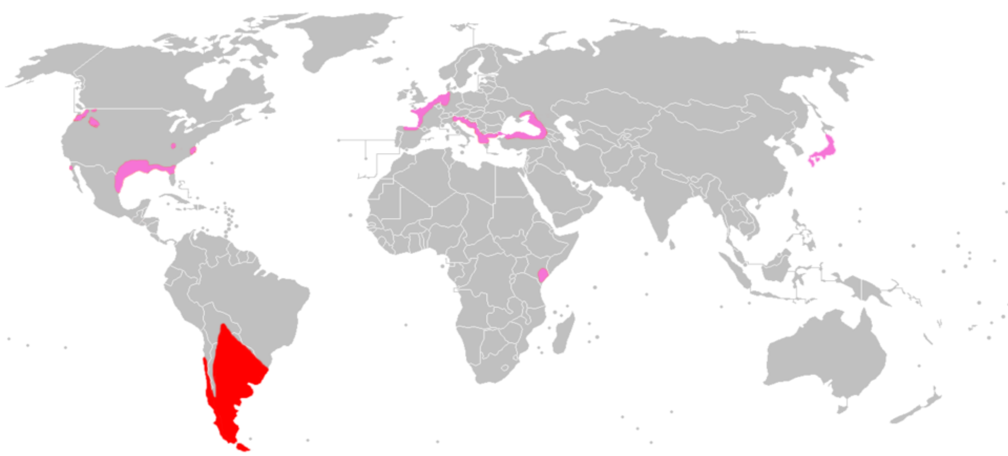


Figure 3. In red is the native range of Nutria, a medium sized aquatic rodent. In pink are the places where they have been introduced through fur farms and other vectors.
https://commons.wikimedia.org/wiki/File:Mapa_Myocastor_coypus.png

However, many of these failed and nutria were released into local environments. This was the reason for their introduction to Dorchester County, Maryland in 1943. They were released at some point after this and have proliferated within the Chesapeake Bay. They have been destroying vulnerable marshlands via burrows and a consumption of the roots that hold them together. It is estimated that they could have collectively caused losses exceeding $35 million annually in loss of productivity and jobs (US FWS). Currently the only large collection of nutria on the United States East Coast is in an area surrounding Maryland. Therefore, the US Fish and Wildlife Service has launched the Chesapeake Bay Nutria Eradication Project. The project was launched in 2002 and as of 2016 they have potentially removed all nutria from 1/4 of 1,000,000 acres on Delmarva Peninsula (US FWS).

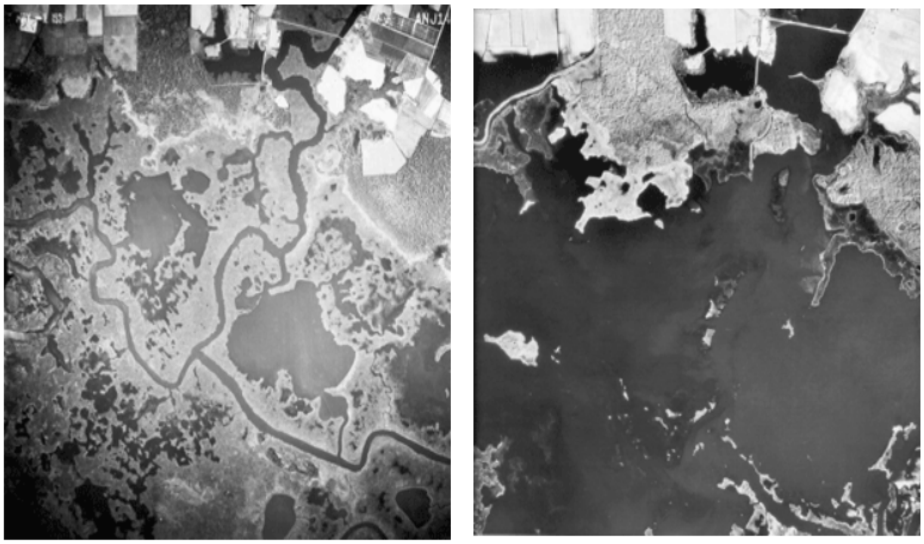


Figure 4. Two pictures showcasing some of the destruction caused by invasive Nutria. The picture on the left was taken in 1939. The one on the right was taken in 1989. (US FWS, 2016)

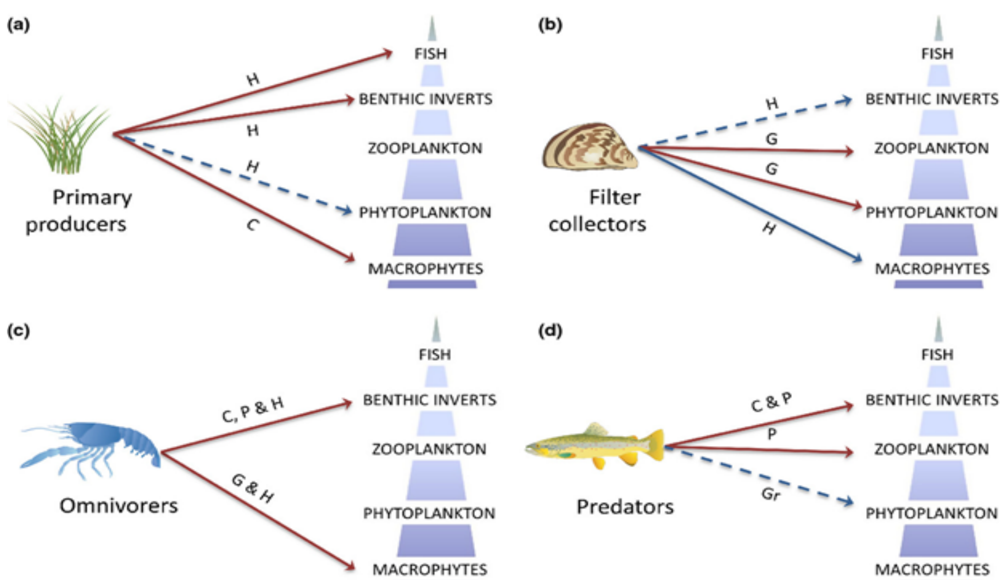


Figure 3. The arrows represent what level of the ecosystem the organism is affecting and whether it has a negative (Red continuous arrow) or positive (Blue dashed arrow) impact. (Gallardo *et al*. 2016)
Direct ecological impacts: C = Competition, P = Predation, G = Grazing, Gr = Grazer release
Physicochemical impacts: H = Habitat alteration

Ecology

A cumulative study was performed on literature about invasive species. Researchers were attempting to quantify the effect of the following five groups of organisms: fish, benthic invertebrate, zooplankton, phytoplankton, and macrophytes (Gallardo *et al.* 2016). They were aiming to deduce which of these groups had the greatest impact on the ecosystems they are present in. Out of all of them, it was found macrophytes were the most destructive group. Macrophytes can greatly alter the habitats they invade. Habitat alterations can be crowding the water column with their roots or not providing sufficient shelter for organisms in the environment (Gallardo *et al.* 2016). Of course, any invasive organism will alter their new habitat to better suit their needs. Macrophytes due to their size and complexity can outcompete most native phytoplankton and other native macrophytes. When they out compete the natives, it fundamentally changes the local food web leaving many other organisms without a source of food. Interestingly, the group with the least negative effects and some possible positives were the benthic filter feeders (Gallardo *et al.* 2016). Benthic filter feeders come to form reefs where none existed before. This means that some of their negative effects are offset by increases in biodiversity that occur with reef construction.

The paper "Invasion dynamics of the white piranha (*Serrasalmus brandtii*) in a Neotropical river basin" investigates the dispersal of the aforementioned white piranha or *S. brandtii* through DNA barcoding analysis of the invasive population using COI and 16S gene markers (Teixeira *et al.,* 2020). *S. brandtii* poses a significant threat in many regards as it is a voracious invasive predator. They can mutilate large finfish when feeding and will even attack fishermen if given the opportunity. The invasion of this region has been facilitated by the construction of hydroelectric dams and the filling of their reservoirs. These man-made structures provide them a habitat to breed in before feeding in the river basin at large (Teixeira *et al.,* 2020). It is also clear that they were introduced several times to the river basin as noted by haplotype analysis (Teixeira *et al.,* 2020).

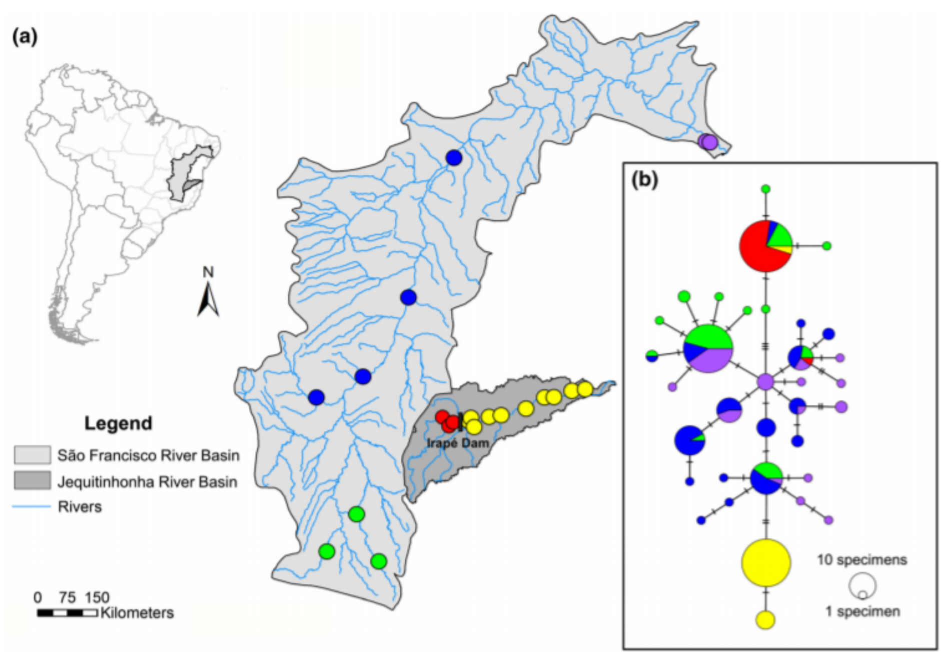


Figure 4. (A) in the figure above the geographical distribution of the different S. Brandtii and (b) the haploid distribution of each population relation to each other (Teixeira *et al*., 2020).

<u>Human Health Impacts</u>

Invasive species also have more direct impacts on human life, especially our health. Although critical, studies of human health impacts of invasives were lacking until the 2000s. A scientist, Giuseppe Mazza, and his research team examined current articles on human health impacts. They describe four categories of hazards to human health including causing disease or infections, exposing humans to direct injury, injury by other mechanism, and other effects to livelihood (Mazza *et al.,* 2014). Invasives can be pathogens or infections themselves as well as being vectors for pathogens to new environments. Direct injuries from invasives can be bites or stings, allergens, biotoxins, and toxicants. Invasives may also cause injury or psychological disorders through other mechanisms as "invasive species" can come from any family or genus of living organism (*See figure 7)*. Other effects to human health include indirect effects such as polluting water supplies or destroying food sources (Mazza *et al.,* 2014).

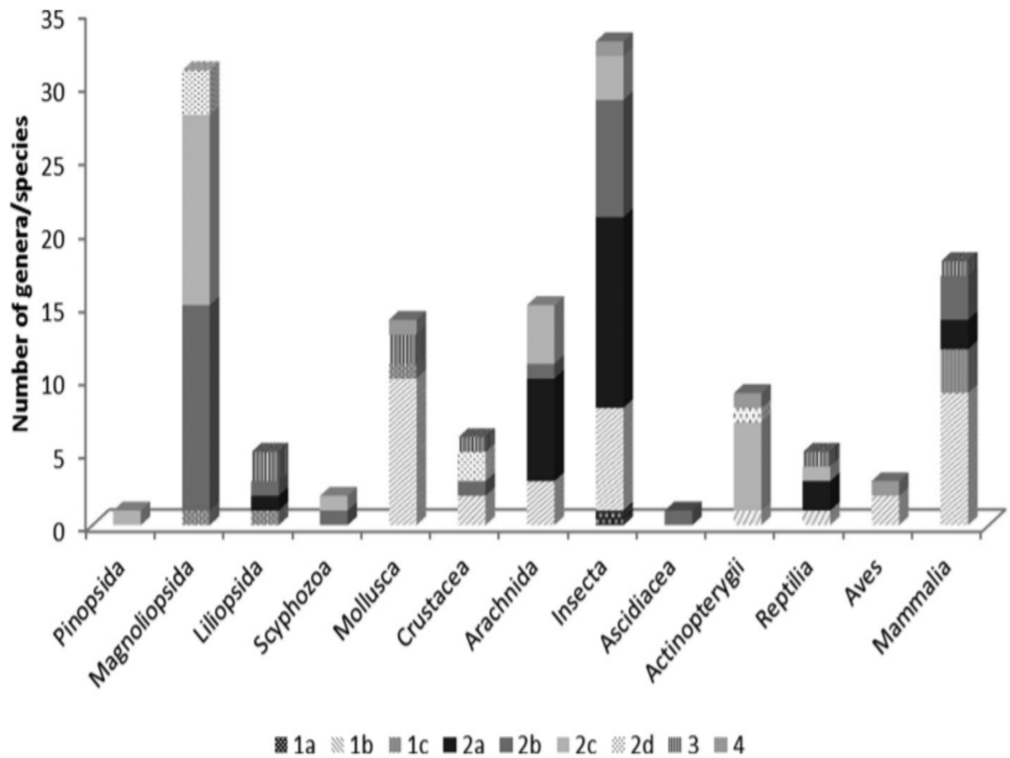


Figure 5. Number of genera/species for the categories and subcategories of hazard to human health. 1a: are pathogens/parasites, 1b: are vectors for pathogens/parasites, 1c: favor pathogens/parasites and/or their vectors, 2a: bites and stings, 2b: allergens, 2c: biotoxins, 2d: toxicants, 3: facilitate injuries, death, and psychological diseases through other mechanisms, 4: have other negative effects on human livelihood. The X axis shows families of invasive species which shows any species has invasive potential (Mazza *et al.*, 2014).

The impact of invasive species can span over generations as some toxins settle into the sediment and cause spikes in concentration when it is disturbed. Other toxins are produced on demand or after an organism dies such as with many species of algae. In these cases, we can see a significant drop in negative effects to human health when the impact of the invasive species is reduced. Benjamin Jones, an economist from the University of Mexico, studied a perfect example of this in Michigan using birth data from 2005 to 2015. Jones was studying the effect of blue-green algal blooms on infant health, specifically birth weight (Jones, 2019). Blue-green algal blooms produce a toxin called microcystin that impairs embryonic development in mammals. Microcystin can become a problem if directly ingested, inhaled, consumed in tainted seafood, or touches the skin. These may occur through drinking water, recreation, and simply breathing in contaminated water droplets dispersed by the wind. An increase in algal blooms seemed to be correlated with an

Figure 6. Blue-green algae bloom (bright green mass) near the shore. Blue-green algal bloods released a toxic that negatively affect fetal mammals. https://newenglandboating.com/blue-green-algae-blooms-widespread-on-long-island/

increase in invasive zebra mussel populations (Jones, 2019).

Figure 7. Zebra mussel out of water. As filter feeders, Zebra mussels can cause a lack of organism and nutrients in the water. https://www.northcentralpa.com/life/harmful-zebra-mussels-invade-raystown-lake/article_bbd2d8c2-8c5c-11eb-9126-4f1513569e0e.html

Zebra mussels were introduced to Michigan through ballast water in the mid-1980s. The mussels use reverse filtering to strip nutrients from the water. They ingest all types of algae except for the harmful blue-green Microcystis variety (Jones, 2019). This in turn reduces competition for the algae and causes an increase in frequency and severity of blue-green blooms. Increased nutrients from agricultural runoff already increases the frequency of total algal blooms, but reduced competition allows blue-green algae to flourish. Jones examined a specific die-off of zebra mussels in Gull Lake, Michigan which caused a sudden drop in microcystin concentration. After the concentration decreased, Gull Lake counties saw a decrease in low birth weight of newborns which also reduced hospitalization costs. Although microcystin levels in Gull Lake never reached dangerous concentrations according to the US EPA (0.3 µg =L) and WHO (1 µg =L), the drop in concentration obviously had positive effects on people nearby (Jones, 2019). It also shows that invasive zebra mussels were clearly responsible for increasing the negative human health impacts of blue-green algae. Impacts to human health can be deadly whether they are direct such as an attack, or indirect such as reducing competition of toxic organisms.

Recreation

Humans utilize bodies of water such as lakes and rivers for recreational fishing, boating, and swimming as well as tourism. Invasive species can cause changes to the physical environment such as oysters making it uncomfortable to walk in mud flats or hyacinths clogging waterways. However, as mentioned in the human health section, some invaders release toxins that are dangerous for humans at high concentrations leading to some recreational sites shutting down until the invasive populations are removed. An article by Ryan Sharp details a survey provided to the community to examine public knowledge, perceptions, and attitudes towards aquatic invasive species and management strategies (Sharp et al., 2017). Recreation has proven to be a viable vector for the transportation of many invasive species as people move boats to multiple bodies of water within a short timeframe without rinsing the hulls. The public tends to ignore aquatic invasives unless there are direct negative effects to their lives. The results from the survey showed that more on-site education is needed to ensure users respect restrictions and closures necessary to mitigate or eradicate invasive species (Sharp et al., 2017). Recreation can be severely impacted by invasives which can also cause the public to care about overarching impacts of species.

In Massachusetts, the water chestnut has taken over waterways, especially Mystic River. Water chestnuts are an invasive aquatic plant that forms mats at the surface of the water which block out 95% of sunlight (Jennings, 2004). Volunteers from the community have spent days pulling water chestnut plants by hand as the plants have made it impossible to swim or boat in the area. The water chestnuts also produce barbed nuts (*See figure 10)* that have been known to penetrate the sole of shoes. Water chestnuts are an example of each type of impact previously described. The plants degrade the environment through outcompeting native plants. Water chestnuts are a direct hazard to human health due to

Figure 8. Invasive water chestnut flipped over to expose barbed seeds (circled in red) and roots. Water chestnuts are proving to be quite a problem in a number of states including Massachusetts.
https://www.michigan.gov/images/invasives/waterchestnutwithseed_502730_7.jpg

their nuts and indirect by causing water pollution as a result of trapping organic matter (Jennings, 2019). They even have economic impacts from reducing shoreline property value and the cost of management. All these impacts are critical to a response. However, threats to recreation specifically increased the amount of community members supporting and participating in the mitigation of this invasive.

Exceptions

In many definitions of invasive species, it is a prerequisite that the organism in question have harmful impacts in any of the categories previously discussed. If the definition of an invasive species is stretched to include species that are just foreign to a region, then there are quite a lot of them. Some species inhabit foreign lands with no tangible effect on their environment, some may even have positive effects, but it is important to emphasize that most of them are harmful. A great example of this is in the Wadden Sea and the invasive red algae *Gracilaria vermiculophylla*. This ecosystem spans between the Netherlands, Denmark, and Germany on the northern coast of central Europe. The Wadden Sea region is known for its particularly low biodiversity. As invasive species were introduced through the years, they began to enrich its biodiversity by providing either shelter or acting as food sources (van Ginnekin & de Vries, 2018). *G. vermiculophylla* has provided the latter to a native species of snail called *Littorina brevicula*. This small benefit however is not enough to justify their continued presence in this environment. However, this does present an opportunity to get rid of *G. vermiculophylla* using *L. brevicula*. The snails could be bred in large numbers and released in the worst affected areas of the Wadden Sea (van Ginnekin & de Vries, 2018). The snails are a native species which means the biocontrol would not lead to another, more dangerous invasive on top of the algae.

In some cases, invasive species can fill vacant niches within an ecosystem or help by bolstering another important species. This can be observed in the round gobies that have invaded the Great Lakes. The round goby has had a positive impact on the Great Lakes ecosystem as a food source. The lake sturgeon, an important keystone species, likes snacking on the small fish (Jacobs *et al.,* 2017). The newly found treat has resulted in a far more robust diet for the predator fish than before the introduction of the round goby. A more diverse diet has allowed the sturgeon to eat more and in turn grow more which permits them to reproduce more than before (Jacobs *et al.,* 2017). Although this is promising, it is important to note that the positive interaction between the round gobies and lake sturgeon are one of many in which the gobies are involved.

Figure 9. The invasive round goby has become a common meal for the sturgeon of the great Lakes.

https://commons.wikimedia.org/wiki/File:Hand_with_a_round_goby_4.jpg

Conclusion

Impacts of an invasive species can be extensive and include effects on the ecosystem, economy, human health, and recreation. Quantifying these impacts can prove difficult, but critical to future mitigation plans. Numbers of invasive species have skyrocketed across the globe due to increased shipping and other human interactions such as climate change which only enhances these impacts. This extensively highlights the deep connection mankind has to its environment. When it is disrupted, it greatly affects how humans can live their lives. There are also those nonnative species who do not have such dire impacts. With radical changes to the Earth's climate, it becomes important to analyze the impact level of invasive species to determine when governments, communities, and people can afford to intervene.

References

Chesapeake Bay Field Office | Northeast Region, U.S. Fish and Wildlife Service. https://www.fws.gov/chesapeakenutriaproject/index.html. Accessed 28 Mar. 2021.

Conservation Conundrum: When Invasive Species Benefit Native Species. Catalyst, https://cusjc.ca/catalyst/project/draft-invasive-native-species-relationships/. Accessed 31 Mar. 2021.

Gallardo, B., Clavero, M., Sánchez, MI., Vilà, M. 2016. Global ecological impacts of invasive species in aquatic ecosystems. Glob Change Biol. 22(1):151–163.

Gribben, PE., Byers, JE., Wright, JT., Glasby, TM. 2013. Positive versus negative effects of an invasive ecosystem engineer on different components of a marine ecosystem. Oikos. 122(6):816–824.

Jacobs, GR., Bruestle, EL., Hussey, A., Gorsky, D., Fisk, A. 2017. Invasive species alter ontogenetic shifts in the trophic ecology of Lake Sturgeon (*Acipenser fulvescens*) in the Niagara River and Lake Ontario. *Biol Invasions* 19**,** 1533–1546.

Jennings, K. 2004. Invasion Biology Introduced Species Summary Project - Columbia University. http://www.columbia.edu/itc/cerc/danoff-burg/invasion_bio/inv_spp_summ/Trapa_natans.html.

Jones, BA. 2019. Infant health impacts of freshwater algal blooms: Evidence from an invasive species natural experiment. Journal of Environmental Economics and Management. 96:36–59.

Katsanevakis, S., Wallentinus, I., Zenetos, A., Leppäkoski, E., Çinar, ME., Oztürk, B., Grabowski, M., Golani, D., Cardoso, AC. 2014. Impacts of invasive alien marine species on ecosystem services and biodiversity: a pan-European review. AI. 9(4):391–423.

Keller, RP., Kocev, D., Džeroski, S. 2011. Trait-based risk assessment for invasive species: high performance across diverse taxonomic groups, geographic ranges, and machine learning/statistical tools. Diversity and Distributions. 17(3):451–461.

Lovell, SJ., Stone, SF., Fernandez, L. 2006. The Economic Impacts of Aquatic Invasive Species: A Review of the Literature. Agric resour econ rev. 35(1):195–208.

Mazza, G., Tricarico, E., Genovesi, P., Gherardi, F. 2014. Biological invaders are threats to human health: an overview. Ethology Ecology & Evolution. 26(2–3):112–129.

Sharp, RL., Cleckner, LB., DePillo, S. 2017. The impact of on-site educational outreach on recreational users' perceptions of aquatic invasive species and their management. Environmental Education Research. 23(8):1200–1210.

Southwick, R., Foster-Turley, P. 2016. U.S. Fish and Wildlife Service. [accessed 2021 Mar 28]. https://www.fws.gov/chesapeakenutriaproject/nutria_affect.html#:~:text=The%20predicted%20impact%20of%20nutria,this%20already%20economically%20embattled%20sector.

Teixeira, DF., Neto, FRA., Gomes, LC., Beheregaray, LB., Carvalho, DC. 2020. Invasion dynamics of the white piranha (*Serrasalmus brandtii*) in a Neotropical river basin. Biol Invasions. 22(3):983–995.

van Ginneken, V. & de Vries E. 2018. The Global Dispersal of the Non-Endemic Invasive Red Alga Gracilaria vermiculophylla in the Ecosystems of the Euro-Asia Coastal Waters Including the Wadden Sea Unesco World Heritage Coastal Area: Awful or Awesome? Oceanography & Fisheries. 8(1): 555727.

Yokomizo, H., Possingham, HP., Thomas, MB., Buckley, YM. 2009. Managing the impact of invasive species: the value of knowing the density–impact curve. Ecological Applications. 19(2):376–386.

Success and Opportunity

Authors: Shaylee Amidon, Kaitlyn Butts & Alexandra Michaud

Edited by: Harry Wales

Introduction : What Does "Successful" Mean?

What does "Successful" mean? There are plenty of definitions out there that would fit one species but not fit the other. Just like the term "Invasive" there are interchangeable definitions that fit the majority but not the minority. The overall, and most accepted definition, of "Successful" is the ability to not only survive but thrive in an environment. How we determine a species' successfulness is determined by not only their characteristics and traits, but by the circumstances of their created opportunity. Opportunities would include the weaknesses in pre-existing communities, such as, diseases, fragile food webs, among other things that are easily disturbed by outward forces.

Why Does Success Matter?

Success matters because of four main reasons: (1) longevity, (2) mapping/triaging, (3) mitigation and eradication, and (4) develops preventive measures. Determining the longevity of an invasive community will help determine their success in the native community. Showing the success of an invasive community will allow the mapping/triaging of the "at-risk" environments and communities. Determining and demonstrating how an invasive community is successful will give insights to possible mitigation and eradication techniques that can be used to help the native community and environment. Finally, by showing the success of an invasive community we can learn from them and develop preventative measures for neighboring, uninvaded locations so that the invasive community cannot destroy them.

Overview of Chapter

Located in this chapter are two key points of success for invasive species that will go into more depth with sub-key points. This chapter will cover traits of success and created opportunities. Through traits of success, you will learn about reproduction rates and strategies, predator/prey relationships, and tolerance ranges. In created opportunities you will learn about disease outbreaks, natural disasters, and global warming. Each of these topics help invasive species become successful in the native environment, however note that not every species will use every point and for some it doesn't work out. Examples will be given in each subject.

Traits of Success

A lot of species can become invasive, some are more likely to because of traits they possess. These traits of success can be the difference between a non-native species and an invasive species. In this section the types of traits for success will be explained.

Reproduction Rates and Strategies

Reproduction is one of the major factors in the success of an invasive species, if a species can reproduce fast and efficiently there is a greater chance they will be a majorly invasive species. One such strategy is hermaphroditism, where the species have both types of sex gametes. This leads to success because they can mate with any other individual they come across. An example for a species that is hermaphroditic is the sea walnut (*Mnemiopsis leidyi*), the sea walnut also has the ability to self inseminate which leads to further success as they only need one individual to build a population.

Another type of reproduction strategy is fragmentation which is a type of asexual reproduction where a piece of the parent organism breaks off and can grow a new organism. Types of organisms that use fragmentation include: fungi, molds, lichens, worms, acoel flatworms, sponges, and sea stars. Specific species that use fragmentation include: the orange sheath tunicate (*Botrylloides violaceus*) and the common water hyacinth (*Eichhornia crassipes*).

Fast reproduction and fast maturation rates both also have a large impact on success. If you can reproduce fast there is a higher chance that some of your offspring will survive till maturity. Fast maturation also has a large effect on success because the fast rate means that more offspring will survive until maturity as well.

Predator/Prey Dynamics & Diet

Diet and predator and prey dynamics play into success in an invasive species because it dictates how the species eats and survives. If the invasive is considered prey they lack a natural predator which increases their success. If the invasive species has a wide diet it leads to a higher success rate because they have a bigger supply of food. If one food source runs out they can eat the next.

Tolerance Ranges

Tolerance ranges include: temperature, salinity, oxygen levels, and pollutant levels. Species that have higher tolerances will have higher success because there is a bigger number of environments they can live in. One example of a species with a high tolerance is the common water hyacinth (*Eichhornia crassipes*) which can live in polluted water (Danoff-Burg JA, 2002). Another example is the Sea Walnut (*Mnemiopsis leidyi*) which has a large temperature tolerance (4-31℃) and large salinity tolerance (3-39%) (Aquarium of the Pacific, 2021).

Created Opportunities

While certain organisms are more fit for invasion than others, there are events which allow species to compete in new areas. In this chapter these events will be called “created opportunities,” and they include both man made opportunities as well as nature based ones. It’s important to also understand that while some of these events may be natural they are exacerbated by human influence. The opportunities that will be addressed in this section include disease outbreaks, natural disasters, and global warming.

Disease Outbreak

Diseases and sickness are a powerful method for invasion, and they come from five major groups; bacteria, viruses, fungi, protozoa, and worms (Janeway et al., 2001). Typically, unintentional, success of many invading species can be attributed to the use of diseases. The most iconic example is humans, seen by the colonization of the Americas with the introduction of European illnesses (smallpox, sexually transmitted diseases, etc.). The introduction of European people came with a number of illnesses, all of which the Europeans were accustomed to. The Native Americans on the other hand, were not. They lacked an immunity, and this led to the annihilation of their tribes.

The same is seen with other organisms, both on land and in the water. In terms of aquatic examples, the zebra mussel (*Dreissena polymorpha*) was introduced to the Great Lakes and brought with it a parasitic roundworm (*Bucephalus polymorphus*). The roundworm is known for living within freshwater cyprinids during its immature stages, and therefore causes a lot of damage to those populations and subsequent populations that depend on them (Crowl et al., 2008). These shifts in ecosystem allow openings for invasive species to enter and take hold. On land, the most common example is the chestnut blight (*Cryphonectria parasitica*). Originally native to Asia, it came over with the Chinese chestnut tree. This blight has since then decimated the American chestnut tree population, allowing invasive, faster growing species to take their place (Anagnostakis, 1987).

Natural Disasters and Human Destruction

Similar to the introduction of disease, though arguably faster, natural disasters can create openings for invasive species. This is easier to imagine terrestrially, so we'll look at that first. Imagine a forest fire; the dry foliage on the ground from seasons past and a lack of rainfall can create the perfect fire-starting kit. With a single bolt of lightning, the land can go up in flames. These events can and do destroy many acres of land. This leads to the death of many, if not all, organisms in the area. Once the fire dies the land is suddenly open, and a large amount of nutrients are now available from the decaying remains of the environment. This allows species that would typically have a hard time getting established a front row spot in the area. Organisms that require a long time to grow and mature won't be able to reestablish themselves.

Similarly, natural disasters occur in the ocean: tsunamis, hurricanes, earthquakes, submarine landslides, etc. These events can also lead to a partial or total collapse in ecosystems, allowing invasive or non-native species to move in and take the space.

On top of all this, humans can create their own "natural disasters." The building of oil rigs, drilling, the dumping of waste into water in mass quantities: these can also have similar effects as natural disasters. It can all be summed up as an event that causes the collapse of an ecosystem, either partially or completely, allowing non-native species to move in and establish in the area.

Global Warming

Climate change exacerbates every topic mentioned above from disease spread to frequency of natural disasters. The focus of this section, will instead be on the change in the ocean's chemistry and its effect on creating opportunities for invasion. The effect of climate change is two fold; first, it can expand the ranges necessary for other species to invade, and two, it can wipe out species that are more sensitive to changes in the water chemistry, opening niches that can be taken by non-native species.

It's no secret that climate change is increasing the ambient temperature of the ocean. Many species, including the flattened crab (*Halicarcinus planatus*), are sensitive to colder temperatures, but with the increase in warmth Antarctica is not far from seeing its first invasive species (Aronson et al., 2015). The increase in temperature will also see the death of many sensitive species. Coral have already been hit by the warming waters, but those who have remained resilient may fall victim to the rise in temperature. Reef building corals rely on algae called zooxanthellae to gain nutrients, and in return the zooxanthellae are protected by the coral. If temperatures continue to rise, as we've already seen, more corals will be forced to expel their algae (the phenomenon known as coral bleaching) and eventually die. The corals are not only important as a species, but also as an environment to many other nursery fish and organisms. Climate change has the capability to rewrite major ecosystems, allowing non-native species to become invasive.

Conclusion

The success of an organism is defined by its ability to thrive in its environment, but what allows them to be successful is a combination of the organisms' characteristics as well as the abiotic and biotic factors of the environment. This chapter highlights the common characteristics of successful invasive species as well as common events that lead to opportunities of invasion. These successful attributes are only enhanced by the relationship between humans and the environment.

References

Anagnostakis Sandra L. 1987. Chestnut Blight: The Classical Problem of an Introduced Pathogen, Mycologia, 79:1, 23-37. [accessed 2021 Mar 16] DOI: 10.1080/00275514.1987.12025367

Aquarium of the Pacific. 2021. Comb Jelly (Sea Walnut). Aquarium of the Pacific. [accessed 2021 Mar 16]. https://www.aquariumofpacific.org/onlinelearningcenter/species/comb_jelly/.

Aronson Richard B, Frederich Markus, Price Rick, Thatje Sven. 2015. Prospects for the return of shell-crushing crabs to Antarctica. Journal of Biogeography. 42:1-7 [accessed 2021 Apr 12]

Janeway CA Jr, Travers P, Walport M, et al. 2001. Infectious agents and how they cause disease. Immunobiology: The Immune System in Health and Disease. 5th edition. [accessed 2021 Mar 16]

Tina Tennessen. 2011 Sep. 5 Invasive Species You Should Know. Ocean Find Your Blue. [accessed 2021 Mar 16]. https://ocean.si.edu/ocean-life/5-invasive-species-you-should-know.

Crowl, T.A., Crist, T.O., Parmenter, R.R., Belovsky, G. and Lugo, A.E. 2008. The spread of invasive species and infectious disease as drivers of ecosystem change. Frontiers in Ecology and the Environment, 6: 238-246. [accessed 2021 Mar 16]. https://doi.org/10.1890/070151

NRDC. May 14, 2018. Melissa Denchack, "Water Pollution: Everything You Need to Know." {accessed 2021 Mar 16]. https://www.nrdc.org/stories/water-pollution-everything-you-need-know#categories

Danoff-Burg DJA. Invasion Biology Introduced Species Summary Project - Columbia University. [accessed 2021 Mar 20]. http://www.columbia.edu/itc/cerc/danoff-burg/invasion_bio/inv_spp_summ/water%252520hyacinth.html

Vectors

Authors: Sam Fuller and Harry Wales

Edited by: Hannah Welch

Introduction

There are many ways for invasive species to travel into areas that they are not native to, whether it is intentionally or unintentionally introduced by humans. Vectors are a pathway or route in which non-native species are introduced into new environments. Vectors can be classified as either natural or human-mediated. Natural vectors can include wind, currents, attaching to a different species unintentionally, and any other forms of dispersal that can happen naturally. Human-mediated vectors are either intentional or unintentional. Intentional vectors are from a deliberate movement of a species by humans. Some examples of intentional vectors include, biological control organisms and the pet trade. Unintentional on the other hand is inadvertent movement of species as a byproduct of human activity. Some examples of this are ballast water and recreational watercraft. These two human mediated vectors are responsible for lots of invasive species being introduced into nonnative lands.

Ballast Water

Ballast water is one of the major pathways for the introduction of native species into nonnative lands. Ballast water could either be fresh or salt water held in the ballast tanks and cargo of ships. Ballast water is pumped into ballast tanks when a ship has delivered cargo. It is then transported to the next port where the ship picks up more cargo. When a ship does this, they release water or take on ballast water at each port. The release of ballast water is one of the major introduction pathways for invasive species in the north Atlantic.

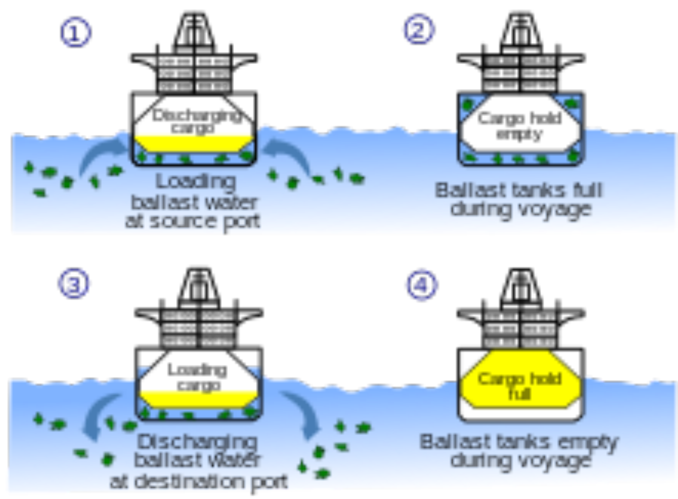


Figure 1: How Ballast water is transported from port to port. (https://www.danfoss.com/en/service-and-support/case-stories/dcs/how-to-comply-with-new-ballast-water-regulation/)

Aquaculture

Moving onto another vector that has a lot of impact is aquaculture. All over the world, nonnative species are farmed for food as bait. Animals can actually be in aquaculture systems because of lack of suitable over pond overflow pipes, pond overflow due to flood events, equipment failures, and transportation and dropping of animals in other bodies of water by predatory birds (Nichols 2018). A common method that people have started to use to address this risk is to prevent the siting of aquaculture in certain floodplains. Many states have put forth requirements that aquaculture facilities be designed to guard against predation from other animals. If non-native fish are not allowed to be there from an aquaculture site, states risk those specimens entering state waters. (Nichols 2018).

Similarly to aquaculture, mariculture is also a pathway for nonnative species to enter a new environment. Mariculture is simply aquaculture that is practiced in the ocean. Species may be cultivated in locations in which they are not native for economic reasons, but if they were to escape, they could cause harm to their new environment. Similar to aquaculture, escapes can occur in mariculture, usually due to poor facility maintenance, strong storms, adverse weather events, currents, and destruction of nets or cages by boats and marine life (Nichols 2018).

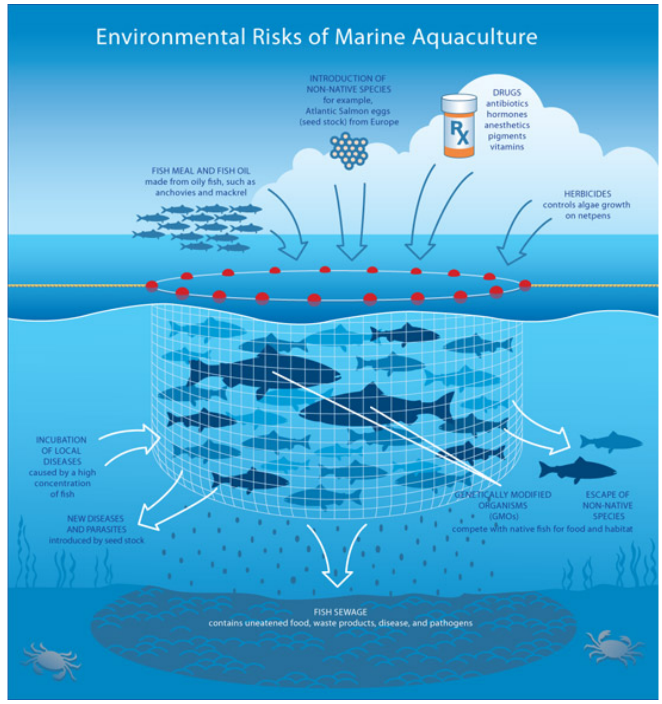


Figure 2: How marine aquaculture results for the introduction of nonnative species by fish sewage, fish escaping, and the introduction of local diseases. (https://forloveofwater.org/programs/aquaculture-in-the-great-lakes/)

Aquarium and Pet Trade

One of the main vectors that has been on the rise over the past few years have been the release of pets. Thousands of exotic pets are shipped internationally every year (Lockwood et al. 2019). This high volume of transportation is bound to result in escapes of species in a new environment. The excotic pet trade now ranks as one of the biggest primary causes of the spread of invasive species (Roth 2019). While some animals may escape in transport, the majority are released by their owners. Aquatic plants, reptiles, amphibians, and fish are being released because they are either or too hard to take care of, too expensive to take care of, or they live too long. They can also escape from their enclosures; the lionfish is known for escaping from an aquarium because of a hurricane. Access to these exotic pets is also on the rise. There has been an increase in non-traditional marketplaces such as websites, trade shows, and social media (Roth 2019).

Biocontrol

Biological control organisms, or biocontrol organisms, are organisms that are introduced to an environment in order to control another organism (NYISRI). This practice is often used in agricultural settings, and is meant to reduce pest populations. There are a few different approaches to this technique, the first of which, and the most common, is classical biological control. This method involves bringing natural predators to deal with an invasive species (NYISRI). The second method is called augmentation. This involves identifying natural predators of pests that are already present in the ecosystem. Once that is accomplished, these organisms are reared and are given augmentative releases to boost the population (NYISRI). And the last method is conservation. In this one, conserving and promoting the native natural predators already present in the system is the main goal (NYISRI)

On paper, the idea of biological control organisms sounds like a good idea. It removes a pest or an invasive species without the need to rely on harmful chemicals. But without proper risk assessment, this practice can go horribly wrong. A very famous example is the cane toad. The cane toad was released in Australia in 1935, in an attempt to control the population of cane beetles that were destroying cane crops (National Museum of Australia). Unfortunately, the cane toad did not prey on the beetles, but thrived in their new environment. They outcompete native species, as well as exuding a poison that kills other native species (National Museum of Australia). This is one of the many examples of how introducing a new species to control another, often leads to two pests being present in the environment.

Tourism

Another vector that does not get a lot of recognition but is responsible for many of the invasive species being introduced is tourism. An example is the Galapagos Island, because the Galapagos Island is very vulnerable to invasive species and their ecosystems are very isolated. So far, there have been 1,579 introduced species that have been documented on the island, and 98% of them arrived via humans. More than 70% of the species have arrived after the 1970s, when the Galapagos Island first became a tourist destination for humans. Furthermore, on average, there have been about 27 new invasive species being introduced there per year for the past 40 years (Baldwin 2018). The most common invasive species that was introduced to the Galapagos Islands are plants and insects, and only a few vertebrates. Recently, the number of flights to the Galapagos Island has increased, from 74 flights in a week in 2010, and 107 flights in a week in 2015. More and more people have been traveling to the Galapagos which means more new invasive species will most likely be introduced (Garnett and Granda 2017). With this happening, the Galapagos island is changing everyday, including the tourism aspect of it as well.

Non-human Vectors

Although most vectors come from humans, either intentionally or unintentionally, there are some non-human vectors as well, even though they are not as prominent. Some of these vectors are wind, currents, as well as other species carrying another species on them, and all of them can contain marine debris. They are usually short distance, compared to ballast water, which can transport species between continents. An example of marina debris was actually in Japan in March 2011. When the wind currents scattered debris from the Southeast all the way to Alaska that actually arrived on an Oregon beach, which brought nonnative species from the Southeast all the way to Oregon (Murray Maximenko and Lippiatt 2018)

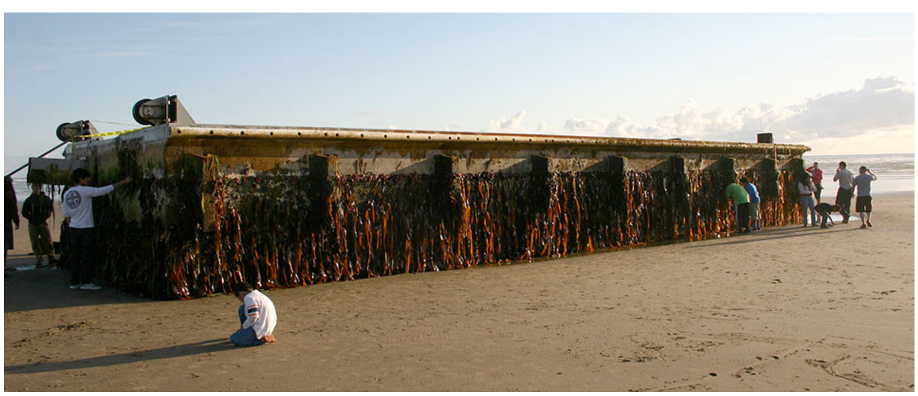


Figure 3: Japanese Tsunami Marine Debris ending all the way in Oregon. Attached was buoys, sports balls, signs, and more that came from Japanese Marine Debris (https://oceanservice.noaa.gov/aa-updates/japan-tsunami-marine-debris.html)

Conclusion

In conclusion, there are many types of vectors for how invasive species can get to ecosystems that they are not native to. Most of the time, invasive species get to areas where they do not belong by man made (humans), but there are some non-human vectors that contribute to this as well. It is important to understand these types of vectors to see how these species are brought into areas where they are not native, and to see if climate change is negatively or positively affecting these non-native species.

References:

Baldwin G. How tourism impacts ocean health: Invasive species — sea going green. Seagoinggreen.org. 2018 Apr 10 [accessed 2021 Apr 4]. https://www.seagoinggreen.org/blog/2018/how-tourism-impacts-ocean-health-invasive-species

Driver: Intentional and unintentional introduction of invasive and non-native species. Eopugetsound.org. [accessed 2021 Apr 4]. https://www.eopugetsound.org/science-review/section-6-driver-intentional-and-unintentional-introduction-invasive-and-non-native

Garnett S, Toral-Granda V. Galapagos species are threatened by the very tourists who flock to see them. The Conversation. 2017 Oct 30 [accessed 2021 Apr 4]. http://theconversation.com/galapagos-species-are-threatened-by-the-very-tourists-who-flock-to-see-them-86392

Invasive species - methods of introduction, Alaska Department of Fish and game. Alaska.gov. [accessed 2021 Apr 4]. https://www.adfg.alaska.gov/index.cfm?adfg=invasive.pathways

Murray CC, Maximenko N, Lippiatt S. The influx of marine debris from the Great Japan Tsunami of 2011 to North American shorelines. Marine pollution bulletin. 2018;132:26–32.

National Museum of Australia. Introduction of cane toads. National Museum of Australia; [accessed 2021 Apr 5]. https://www.nma.gov.au/defining-moments/resources/introduction-of-cane-toads

Roth A. 2019 Jul. Why you should never release exotic pets into the wild. National Geographic (July).

Detection and monitoring of aquatic invasive species

Author: Bradley Spear

Introduction

Invasive species can be potentially dangerous organisms that are prevalent in many ecosystems around the world. The definition of what constitutes an invasive species can vary depending on the viewpoint. The important aspect is that these invaders disrupt ecosystems and can cause multiple types of damage to our shared world. Highlighting the immense importance to be able to maintain or eradicate a problem when one arises.

The concept of an invading non indigenous organism is relatively new in science. The strategies to combat these invaders is an ever evolving process. One of the first steps and most important combative strategies against invaders, is knowing where they are located and the quantity. This is where the methodologies of detection and monitoring step in. The proper procedures of detecting an invader allows mitigation efforts to be maximized and valuable resources allocated correctly.

High Density

There are a variety of efforts used to detect and monitor invasive species in a specific area. Before beginning the explanation of these methods, the concept of species density is important. Detection of an organism depends heavily on if it occurs in high or low densities. When a species is at a moderate to high density it is usually easier to observe. The most basic form of detection would be to use the naked eye to observe and count in field studies. If the species is difficult to locate or is harder to catch with just a rod and reel than other methods can be applied.

In figure 1, a method called electrofishing can be seen. This is where probes are inserted into the water that emit an electric charge to stun the fish. This causes the fish to float to the surface where they can easily be scooped up in a net. A study by Peterson attempted to estimate the abundance of stream-dwelling salmonids by using electrofishing. The organisms under study were the bull trout, *Salvelinus confluentus* and the cutthroat trout, *Oncorhynchus clarki lewisi.* The cutthroat trout can be an invasive species that impacts river biodiversity. Their results "suggest that most electrofishing-removal-based estimates of fish abundance are likely to be biased and that these biases are related to stream characteristics, fish species, and size. We suggest that biologists regard electrofishing-removal-based estimates as biased indices" (Peterson, 2003). This study shows that in order for electrofishing to be effective the

Figure 1. Electrofishing in action. https://www.seabreeze.com.au/News/Fishing/Electro-Fishing-the-friendly-way-to-fish_8996375.aspx Date accessed: April 8th 2021.

methodologies must be area specific and parameters need to be defined to increase success. The researchers encourage future scientists to measure the efficiency of their sampling methods to avoid introducing systematic errors into their data.

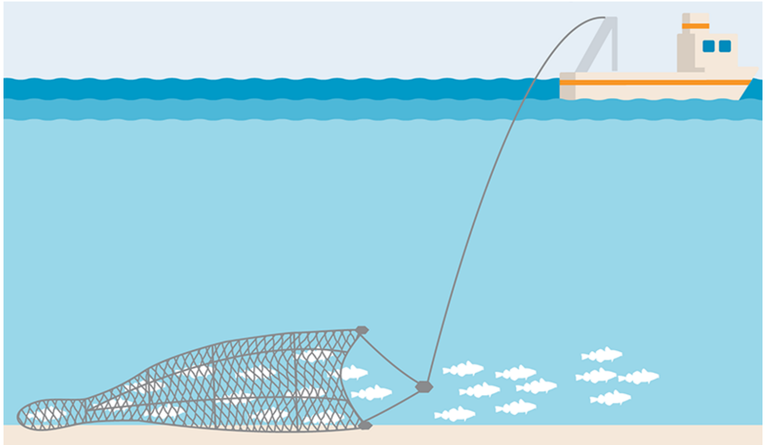


Figure 2. An example of bottom trawling. https://www.msc.org/what-we-are-doing/our-approach/fishing-methods-and-gear-types/demersal-or-bottom-trawls Date accessed: April 8th 2021.

Another method that is used to detect species at high densities is called trawling. This is where a large net is dragged behind a boat either along the bottom or in the water column depending on the desired species. This method is a good way to cover a lot of ground but isn't as effective in targeting specific species. There is unwanted bycatch and some habitat destruction that occurs.

A study by Fabrizio titled ''Assessing prey fish populations in Lake Michigan" used trawling techniques in their methods. The Lake Michigan fish community has been monitored since the 1960s with bottom trawls, and midwater trawls. Estimates of total fish density as well as densities of the invaded rainbow smelt *Osmerus mordax* were calculated. "Rainbow smelt vertical distributions were found to vary with lake depth and time of day. Because Lake Michigan fishes are both demersal and pelagic, a single sampling method cannot be used to completely describe characteristics of the fish community" (Fabrizio 1997). This study highlights the importance of choosing the correct method to survey the species under study and how to monitor potentially harmful or invading species.

Figure 3. Two kids operating a beach seine. https://www.floridagofishing.com/fishing-beach-seining.html, Date accessed: April 8th 2021.

If the target species is closer to the shoreline, with a max depth of a couple meters, then a beach seine could be applied. This can be seen in figure 3 where two kids are holding a pole with a long net attached. One kid would walk out into the deeper water, then would walk parallel to the shore to begin to urge the fish to go closer to shore. The other kid will stay in place as the kid in the deep water pivots the net and will herd the fish towards the net and the shore. The net is then dragged up on shore to do the analysis.

What if the species under study is rare and the time spent using a net to capture them would be an invaluable use of time? Another method of detection and sampling is the Fyke net. The fyke net doesn't require constant attention and can be left out. See figure 4 for an example. The trap consists of a long cylindrical netting bag usually with several netting cones fitted inside the netting cylinder to make entry easy and exit difficult. This net is then mounted on rigid rings or other rigid framework and fixed on the sea bed by anchors, ballast or stakes It also has wings or leaders to help guide the fish towards the entrance of the bag. These are usually placed in areas that have a current or flow to the water that can help facilitate the fish into the net where they get trapped in the end. There is "very little environmental impact with this gear as it is usually done on a small scale. The only seabed impact would be the interaction between the stakes or anchors with the seabed. These are usually in areas of fairly mobile sea beds being tidal or intertidal where any impact is quickly dissipated by the tidal movements. By-catch is minimal and any unwanted by-catch can usually be released alive." (Sea fish, 2021) The use of baited traps and nets can be used for benthic species such as crawfish. Where they can crawl into the cage but can't crawl back out.

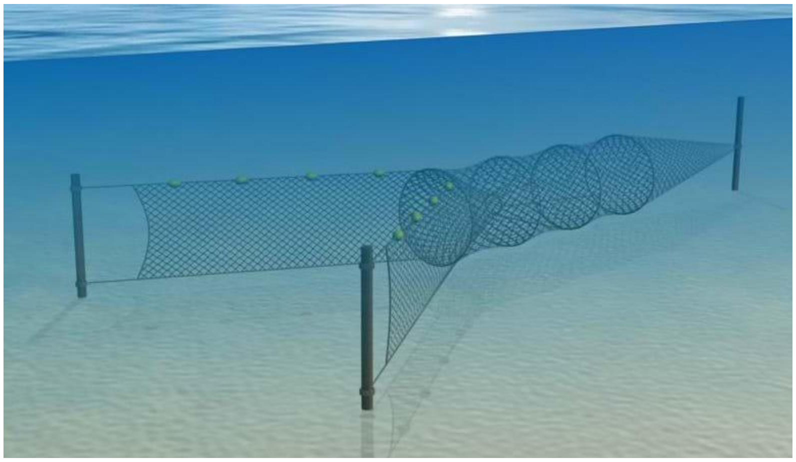


Figure 4. Example of a fyke net anchored to the sediment. https://www.seafish.org/responsible-sourcing/fishing-gear-database/gear/fyke-net/Date accessed: April 8th 2021.

One method that doesn't require constant attention and can be applied to species occurring in either, high or low densities would be the use of global positioning systems (GPS) or satellite tags. "Time and space constrain the ability of biologists to make direct observations on animals, but the development of electronic tagging tools (i.e. biotelemetry and biologging devices) has provided a method for remote monitoring of free-living animals (Cooke et al. 2004)." Allowing the researchers to track the organism and record its position over time. See figure 5 for satellite tag example. Remote monitoring of organisms with tags that transmit data remotely or log them for future reference can contribute key knowledge about invasive organisms. Most of the electronic tags deployed are usually utilized for, "characterizing spatial ecology, identifying species interactions, assessing risk potential and analyzing management options" (Cooke et al. 2004). Electronic tags have great potential for the development or reevaluation of invasion management procedures. "The behavioral and physiological data that are useful for answering the fundamental questions about animal invasions can be obtained from free-living animals using electronic tags. Such information is especially useful for developing and implementing management strategies that aim to assess the consequences of invasive animals at various stages of an invasion" (Blackburn et al. 2011).

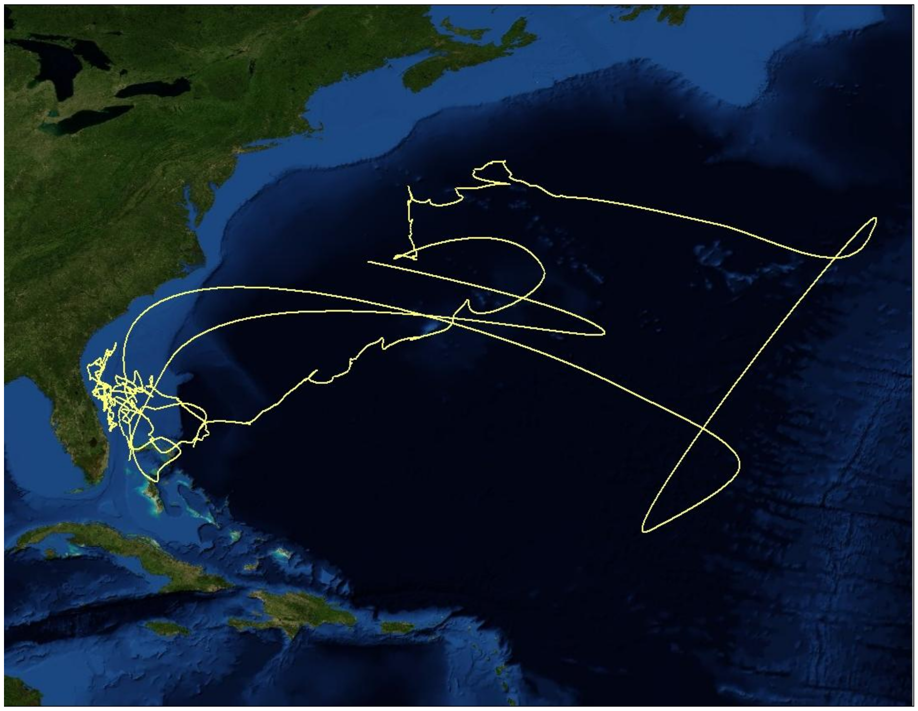


Figure 5. Shows a tiger shark migration, tracked with satellite tags and mapped by a computer program, in the Bahamas, by a research team. This shark traveled as far as 8,000 km round trip. https://blog.nationalgeographic.org/2014/01/16/electronic-tagging-and-tracking-marine-animals-supports-conservation/.

Low Density

The probability of detecting a rare species is typically low in any environment, but particularly low in aquatic environments. Organisms are able to hide beneath the water's surface and in the various structures underneath. Effective management of recently introduced nonindigenous species, requires the detection of populations at low density. For rare species, the low detection probability of net and trap tools often leads to an error. Possibly concluding a species is absent when it is actually present.

"In the case of rare or low density species, the only solutions are to increase sampling effort or change to a detection tool with greater detection probability. However, with traditional surveillance tools, increases in sampling effort sufficient to achieve a useful detection probability is often infeasible" (McDonald 2004).

Introducing eDNA. What is eDNA? Environmental DNA is DNA that is collected from a variety of environmental samples such as soil, seawater, snow or even air rather than directly sampled from an individual organism. As various organisms interact with the environment, DNA is expelled or sloughed off and that then accumulates in their surroundings.

A study by Mahon in 2011 demonstrated the efficacy of environmental DNA as a detection tool in aquatic environments. It was titled, 'detection of rare aquatic species using environmental DNA'. The study describes the application of environmental DNA as an effective surveillance method for rare fishes in a large river and canal complex. They show that it is "more sensitive than traditional tools, has no risk of harming the species under study, and effort can feasibly be increased for species management" (Mahon, 2011). The study demonstrates the usefulness of eDNA surveillance with a case involving two species of Asian carps, silver carp and bighead carp which have caused harm to fisheries, recreational use of waterways, and human safety as they have invaded much of North America's Mississippi River basin. "Both carp species now threaten to invade the Great Lakes through a set of human-built waterways in and near the city of Chicago, Illinois, which connects the Mississippi River basin and the Great Lakes-St. Lawrence River basin" (Garvey *et al*. 2010). Specifically, they targeted eDNA at locations on the thought to be leading edge of invasion, and compared that to the detection capabilities between standard fisheries methods of electro fishing and rod sampling.

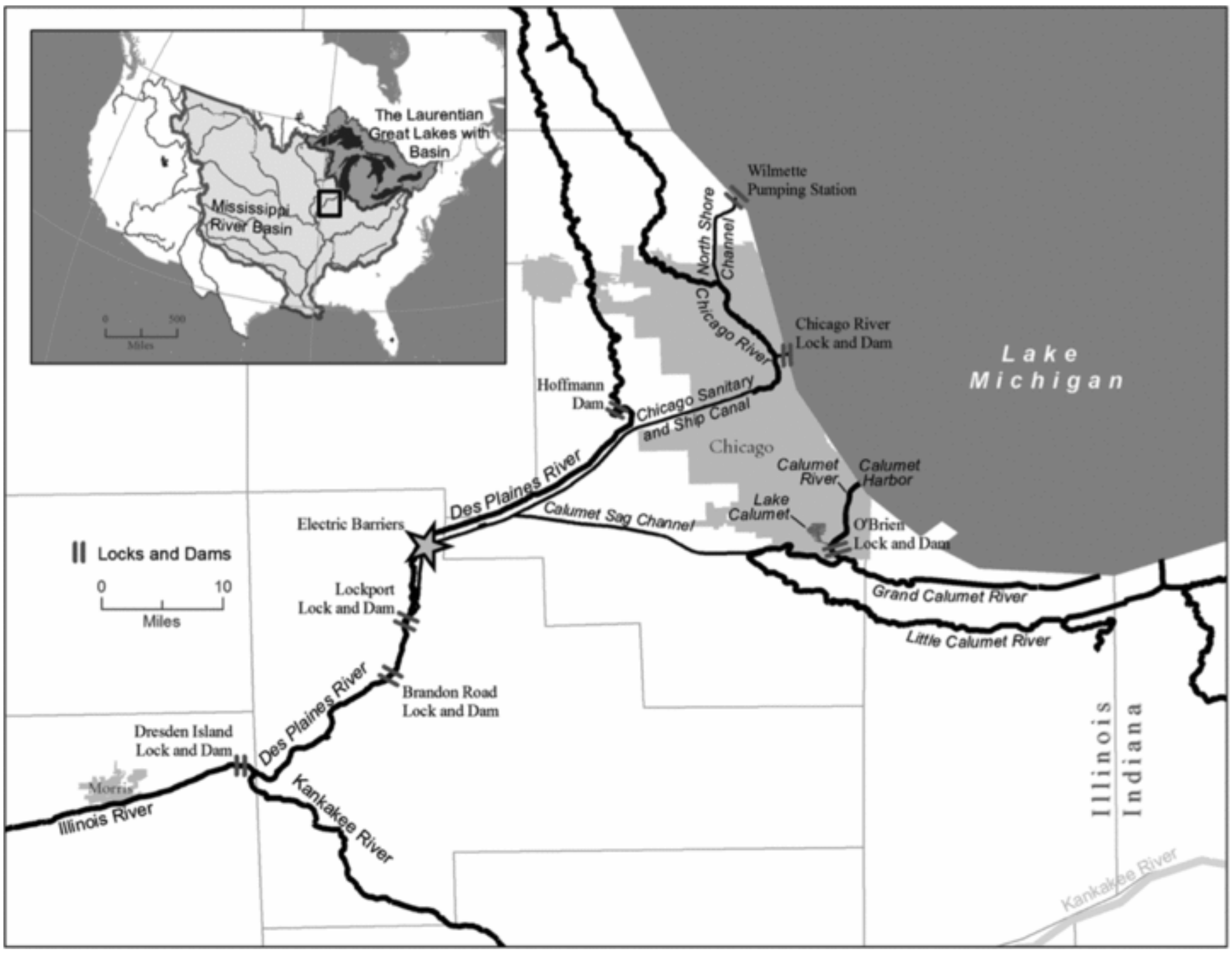


Figure 1 shows the Connection of the Great Lakes which is in the top right of the image and the Mississippi River basins which is in the bottom left. The electric barriers are represented by the star. The sampling was occurring mostly above the star in the tributaries. https://conbio.onlinelibrary.wiley.com/doi/10.1111/j.1755-263X.2010.00158.x

In the early 1970s, bighead and silver carp escaped fish farms in Arkansas in the southern Mississippi River basin. Upstream range expansion of bighead and silver carp in the Illinois River and its tributaries is ongoing. Water samples, from along the rivers, were analyzed with molecular markers designed for *the carp,* using publicly available sequence information from GenBank. To ensure species specificity, they targeted short fragments of the mitochondrial d-loop region and then used PCR to amplify. Then they used BLAST or Basic Local Alignment Search Tool; to compare the markers to all available sequence data, including those of closely related species and nontarget species common to the Chicago area water system.

"The results showed far more advanced invasion fronts for each species. Invasion fronts detected with eDNA surveillance suggest that both species of carps are north of electric barriers installed to prevent fish passage, making clear that management actions to prevent invasions of Lake Michigan and the other Great Lakes are much more urgent than suggested by traditional fisheries methods" (Mahon, 2011). The use of eDNA monitoring methods will have broad research and management applications in all types of aquatic environments, freshwater, estuarine, and marine ecosystems for threatened, endangered and invasive species.

<u>Conclusion</u>

In the case of invading, non indigenous, species that can potentially cause harm there are important aspects to consider. One aspect is knowing the extent of the invasion not only temporally but spatially as well. The only way to do this is by having proper detection and monitoring strategies in place. It's important to keep in mind that invasions should be dealt with on a case by case basis, to ensure an adequate response. Each location should be researched thoroughly, so the proper monitoring technique can be applied. As shown earlier in the chapter, its critical to distinguish if something like electrofishing is going to be the most efficient method. The researchers encouraged future scientists to measure the efficiency of their sampling methods to avoid introducing systematic errors. Detection and monitoring methods aid in characterizing spatial ecology, identifying species interactions, assessing risk potentials, and reevaluating invasion management procedures. The information given is especially useful for the initiation and implementation of management strategies that aim to contain and control invasions.

<u>References:</u>

Andrew R. Mahon, Christopher L. Jerde W. Lindsay Chadderton David M. Lodge "Sight-unseen" detection of rare aquatic species using environmental DNA: 04 January 2011 https: //doi.org/10.1111/j.1755-263X.2010.00158.x

Blackburn TM, Pyšek P, Bacher S, Carlton JT, Duncan RP, Jarošík V, Wilson JRU, Richardson DM (2011) A proposed unified framework for biological invasions. Trends Ecol Evol 26:333–339

Cooke SJ, Hinch SG, Wikelski M, Andrews RD, Kuchel LJ, Wolcott TG, Butler PJ (2004) Biotelemetry: a mechanistic approach to ecology. Trends Ecol Evol 19:334–343

Fisheries Research, Volume 33, Issues 1–3, 1997, Pages 37-54, https://doi.org/10.1016/S0165-7836(97)00061-1.(https://www.sciencedirect.com/science/article/pii/S0165783697000611)

Garvey, J., Ickes B., Zigler S. (2010) Challenges in merging fisheries research and management: the upper Mississippi River experience. *Hydrobiologia* **160**, 125–144.

James T. Peterson, Russell F. Thurow & John W. Guzevich (2004) An Evaluation of Multipass Electrofishing for Estimating the Abundance of Stream-Dwelling Salmonids, Transactions of the American Fisheries Society, 133:2, 462-475, DOI: 10.1577/03-044

Joel C. Hoffman, John R. Kelly, Anett S. Trebitz, Greg S. Peterson, and Corlis W. West, Effort and potential efficiencies for aquatic non-native species early detection Canadian Journal of Fisheries and Aquatic Sciences 23 November 2011 https://doi.org/10.1139/f2011-117

Magnuson, J.J., Benson B.J., McLain A.S. (1994) Insights on species richness and turnover from long-term ecological research: fishes in north temperate lakes. *Am Zool* 34, 437–451.

Mary C. Fabrizio, Assessing prey fish populations in Lake Michigan: comparison of simultaneous acoustic-midwater trawling with bottom trawling,

McDonald, L.L. (2004) Sampling rare populations. Pages 11–42 in W.L. Thompson, editors. *Sampling rare or elusive species*. Island Press, New York.

Mitigating Aquatic Invasive Species

Authors: Emily Lewis and Sierra Brown

Edited by: Kristen Wurth

Introduction

In the context of invasive species, mitigation refers to reducing the impact of an invasive species, either before or after an introduction occurs. This can be done using three mechanisms, including biological, chemical, and mechanical. Mitigation is used in order to control a species that has invaded an area. If mitigation does not work, eradication could be an option. Eradication is when you completely eliminate the invasive species from that area. The point of these two methods is to get populations of invasive species under control to bring back the stability of the environment prior to the invasion. This is important because it keeps the ecosystem stable enough that no native species would be under threat of being removed from that area by a species that should not be there or a species that is also native to the area.

These two methods can be depicted on what is known as an "invasion curve". It shows the progression of invasive species. It shows what can be done to stop or control an invasion as it progresses. As time goes on the cost of controlling an invasive species increases while the chances of removing a species decrease. It shows that the only time eradication is really a possibility is when the species has just been introduced to a new area and there are only a few organisms present. Once they begin to reproduce it gets harder and harder to get the species under control.

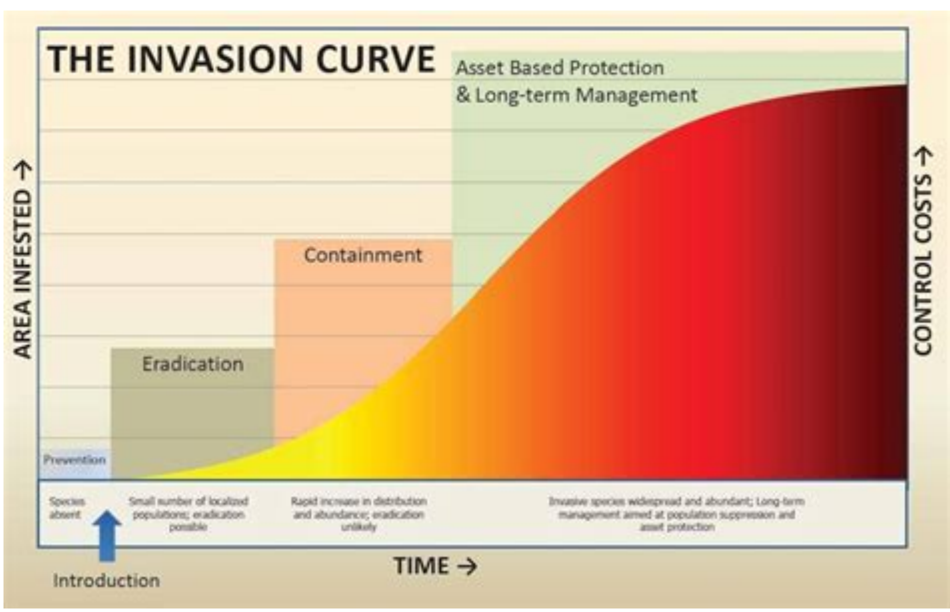


Figure 1: Invasion curve showing what can be done after an introduction of a species. Available: https://www.evergladescisma.org/what-we-do/

Biological Mechanisms

Biological mechanisms are when an organism is used to control an invasive species by predation or competition. One example of a biological mechanism using predation is the control of lionfish populations by introducing sharks as predators. Sharks typically do not prey upon the lionfish due to their spines. These spines inject venom into the predator, causing pain that will last for days. However, divers are now catching lionfish and feeding them to sharks. The sharks are able to safely avoid the spikes of the lionfish if they begin eating the fish at the mouth side rather than the tail side (Fears, 2014). Feeding these fish to the sharks creates a search image for the shark to associate the lionfish with food. They will then actually seek out the lionfish on their own, thereby decreasing their populations and beginning to get their numbers in check.

Figure 2: Diver feeding a lionfish to a shark.
Available: https://sharkswimmers.wordpress.com/2012/03/08/another-reason-to-protect-sharks/

Humans are also a biological mechanism for the mitigation of lionfish. People are now diving for lionfish to catch them and use them as food. These fish are only venomous, not poisonous, so as long as the spines are untouched you can eat these fish without doing any harm to yourself. There are no regulations on the number of lionfish you can catch and bring in on your boat (DEMA, 2014), and in Florida they have challenges to see who can remove the most lionfish from the environment. They allow people to spearfish these lionfish even within areas where spearfishing is not allowed just to allow for their removal (Lionfish Challenge 2021).

As for introducing another organism to help outcompete an invasive species, it is quite a bit more risky than finding a way to prey on the species. This involves taking an organism that preys upon the invasive organism in its natural habitat and introducing it into the environment the other species invaded to add a predator, without having to wait until the species in the area create a search image and recognize it as prey. However, this can create just as many problems as the initial invasive species being introduced. If the predator is not controlled, it could have the potential to become incredibly invasive itself, hence why this tactic of removing an invasive species is barely used.

Chemical Mechanisms

Chemical mechanisms are methods using any sort of chemical, typically liquid, against any invasive species. They are often less expensive and more effective than other methods of mitigation. Since the mid-1970's, researchers in Florida have been working on developing herbicides for aquatic invasive plants along the coastline (Communications). These herbicides were created to be used as single site plant enzyme inhibitors with the intention of being the least harmful to humans and other organisms (Communications). Researchers from the Center for Aquatic and Invasive Plants at the University of Florida have implemented strategies to prevent resistance to the herbicides for aquatic plants (Communications). Some of those strategies are rotating active ingredients when possible, managing invasive plants at low levels to avoid large scale applications, and combining active ingredients if cost effective and selective (Communications).

The use of aquatic herbicides and other chemical mechanisms have the potential to cause a lot of harm when used incorrectly. The release of large amounts of certain chemicals into an ecosystem can kill or at the very least impair all marine wildlife in the area. Lots of research is needed when developing herbicides or other chemical mechanisms to limit the overall effect it has on the environment. The researchers at the University of Florida have been able to develop herbicides that work on hydrilla, water hyacinth, and water lettuce all of which are in invasive species (Communications).

Figure 3: A man spreads herbicide onto aquatic plants to control their spreading.
Available: https://www.killlakeweeds.com/blogs/aquacide-blog/aquatic-herbicide-application-timing-q-a

Mechanical Mechanisms

Mechanical mechanisms are anything that includes trapping of the invasive organism itself or removal of habitat that it lives in. Trapping of organisms has the least amount of side effects on the environment surrounding the invasive species, however, sometimes the only way to remove the species is to completely eradicate the environment to get rid of the species as well. Trapping is a method that is more accepted and can be used on a lot of free swimming invasive species. One species that the trapping method has been used on is the sea lamprey. Sea lampreys are invasive in the St. Mary's River, as well as in the Great Lakes, and have caused a downfall in fish populations. There have been three methods used to reduce the populations of the sea lampreys in these areas. One method is the isolated treatment of sea lamprey rearing areas with lampricide to eradicate the next generation of lampreys. This was a chemical and mechanical mechanism due to seeking out the rearing areas being mechanical and the chemicals being used being a chemical mechanism. The second method is capturing male sea lampreys and sterilizing them using a chemosterilant, which is actually a chemical mechanism because of the sterilization as well as a mechanical mechanism where trapping was involved. The third method was an entirely mechanical method which involved the trapping of reproductive females and makes at the time of spawning in order to reduce the number of offspring that were produced in that spawning event (Bravener, 2011).

Removal of an environment can be disruptive for both native and invasive species. Removing an environment, such as clearing off a rock, dredging on the bottom of the ocean floor, among other ways, it can remove those invasive species and make room for native species to come back in, or it will entirely allow the invasive species to outcompete native species for the remaining habitat and become fully dominant.

Policies and Protocols

Many different policies have been put in place to protect from additional invasive species from being spread. Every state has regulations on what kinds of pets you can have, and some people may have to get permits in order to keep certain animals. This is due to the possibility of the owner not wanting to care for their animal anymore due to many reasons like size or moving homes, or if one escapes, leading to an invasion. There are also laws that are put in place to control the species, or laws that are taken away. One example of this is how pythons have invaded the state of Florida. Burmese pythons were released by people who could no longer house these large snakes, as well as a breeding facility being destroyed by Hurricane Andrew in 1992. This allowed the snakes to develop a breeding population in the local swamps, which has led to massive population growth. Florida has now removed barriers to hunting these organisms, without a permit or hunting license. They have set up incentive programs as well in order to encourage people to participate in removing these invasive snakes from the breeding population. They do have restrictions and guidance on doing this humanely as well (Janos, 2020). Strategic plans are also put into place in order to deal with and control a species after an invasion. In the case of the pythons, pet ownership of these pythons is now illegal, as it prevents owners from releasing their pets after they become too large. Jobs have also been created to eradicate them, known as "python removal agents". The state also began hosting "python competitions" with cash prizes for who kills the most snakes (Janos, 2020). These things being encouraged by the state allow for mitigation and eradication of invasive species to occur.

Conclusion

One of the most effective mitigation tactics against invasive species is a collaborative effort from a range of people and organizations. This is exactly what happened in the early 2000's when the European grapevine moth invaded grapevines and other agricultural fruit plants in northern California (Schartel et al., 2019). With the help of the general public, farmers/growers, researchers, and state and federal government officials this species was completely eradicated within seven years from when it was first identified as a problem (Schartel et al., 2019). Public education and a thorough understanding of the life history and ecological role were also huge factors to effectively mitigating this species (Schartel et al., 2019).

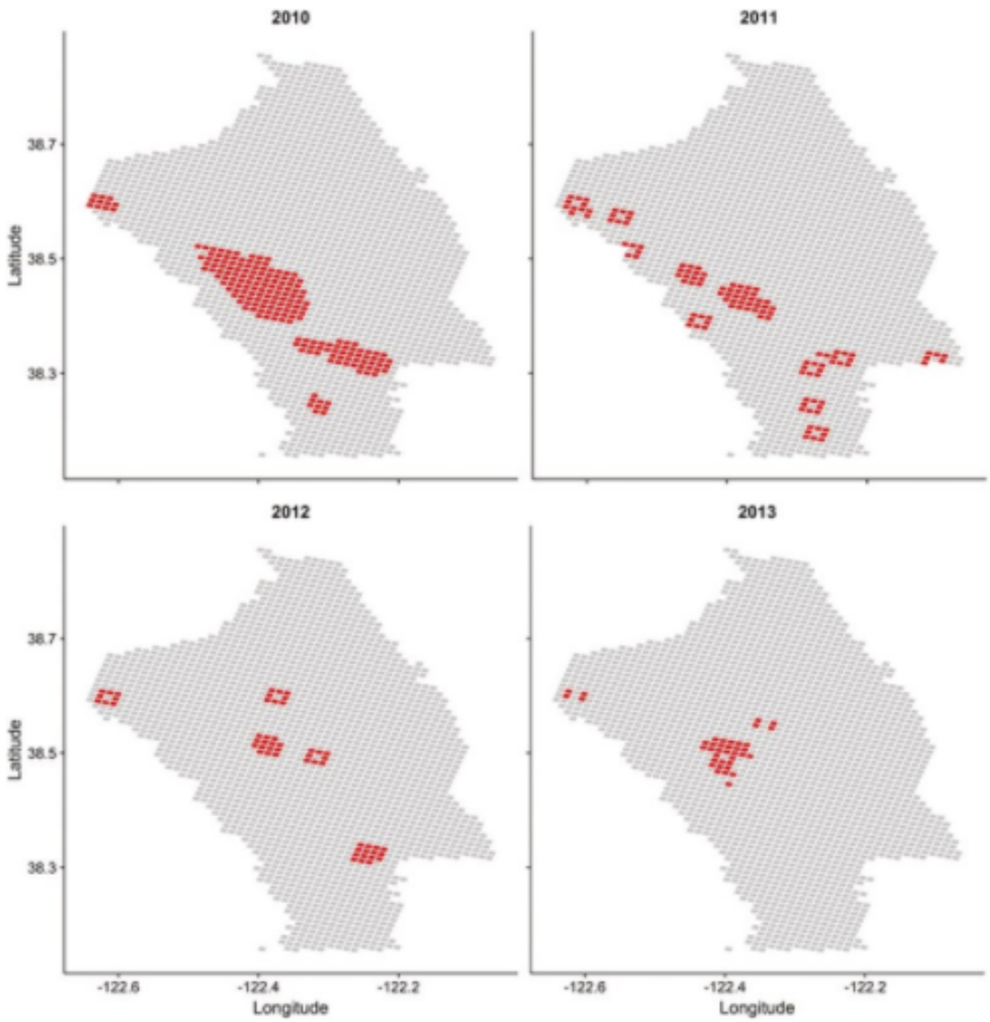


Figure 4: The diminishing European grapevine moth population in Napa County, California over the course of 4 years (Schartel et al., 2019).

The story of the European grapevine moth has taught us that eradication is possible for invasive species. However, the European grapevine moth is a terrestrial species. This leads us to the question of: Is there an example of a successful eradication for an aquatic invasive species? The short answer is no. Due to the nature of aquatic ecosystems, it is in general a lot harder to monitor the whereabouts of individuals for aquatic species. Unfortunately, the presence of an invasive species is only noticed when it affects some type of human activity or industry. We know that aquatic plants can be mitigated using herbicides, but what about other organisms like the European green crab *Carcinus maenas* or tunicate *Botrylloides violaceus*. Is it possible to completely eradicate invasives like these or at the very least mitigate them and stop them from spreading? Does one type of control mechanism work better for each invasive species or is it best to combine different mechanisms? These are all questions that need to be researched and answered.

<u>References:</u>

DEMA. (2014, June 30). REGULATORY ALERT- Florida Lionfish Recreational Regulations. Retrieved April 3, 2021, from https://www.dema.org/news/180002/REGULATORY-ALERT---Florida-Lionfish-Recreational-Regulations.htm

Fears, D. (2014, October 19). Divers try spoon feeding lionfish to sharks, a method that could come back to bite them. Retrieved April 03, 2021, from https://www.washingtonpost.com/national/health-science/divers-feed-invasive-lionfish-to-sharks-but-could-this-come-back-to-bite-them/2014/10/19/32efc18a-547a-11e4-809b-8cc0a295c773_story.html

Janos, A. (2020, February 20). How Burmese Pythons took over the Florida Everglades. Retrieved April 04, 2021, from https://history.com/news/burmese-python-invasion-florida-everglades

Lionfish Challenge 2021. Florida Fish And Wildlife Conservation Commission. [accessed 2021 Mar 21]. https://myfwc.com/fishing/saltwater/recreational/lionfish/challenge/

Communications IFAS. Plant Management in Florida Waters. A Brief History of Aquatic Herbicide Use - Plant Management in Florida Waters - An Integrated Approach - University of Florida, Institute of Food and Agricultural Sciences - UF/IFAS. [accessed 2021 Apr 5]. https://plants.ifas.ufl.edu/manage/control-methods/chemical-control/a-brief-history-of-aquatic-herbicide-use/

Schartel TE, Bayles BR, Cooper ML, Simmons GS, Thomas SM, Varela LG, Daugherty MP. Reconstructing the European Grapevine Moth (Lesidoptera: Tortricidae), Invasion in California: Insights From a Successful Eradication. Annals of the Entomological Society of America. 2019;112(2):107–117. doi:10.1093/aesa/say056

Interconnected Crises: Climate Change and Aquatic Invasive Species

Authors: Kristen Wurth, Conor Wiley

Introduction:

Climate change is the regional and global change of climate patterns that is primarily driven by anthropogenic activities that cause an increase in the overall carbon dioxide content in the atmosphere (NOAA, 2021). Climate change is a process that has had an effect on a multitude of factors within the marine environment including sea level, arctic ice melt, ocean heat content and ocean acidification. These factors are interconnected not only with themselves but also invasive species factors (vectors, success, impacts, mitigation and detection). Sea level rise has been increasing at a steady rate since the 1890's (NOAA, 2021). This increase in sea level has caused flooding and increased erosion, which leads to the destruction of many organisms' habitats (NOAA, 2021). This destruction of habitats opens up ecological niches and depletes native populations, allowing for increased opportunities for non native species to invade (Troost, 2010). Arctic ice melt can also be coupled with sea level rise because of its contribution to overall sea level rise. Arctic ice minimums and extent continues to decrease each year (Figure 1).

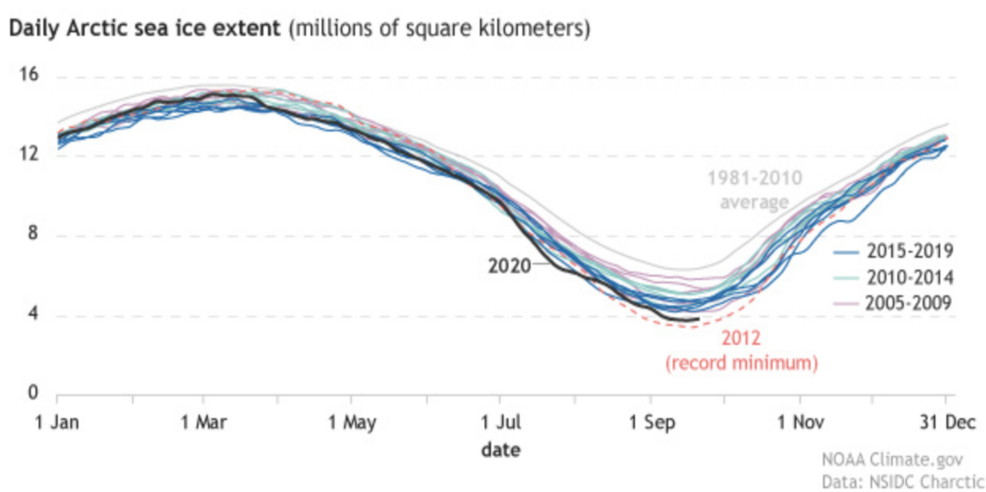


Figure 1. Decrease in Arctic sea ice extent for various years.
Available:https://www.climate.gov/search?search=ocean+acidification

This leads to decreased habitat availability for many species, opening up of shipping vectors and a change in the overall habitat structure. Species that use sea ice for mating, hauling out and hunting struggle, while organisms who don't use sea ice prosper. Species that were originally unable to invade or migrate to Arctic locations due to the obstacle of thick sea ice, now have little to no challenge invading many areas due to melting. As arctic sea ice melts the overall ocean heat content increases due to the fact that the white sea ice has a higher albedo than the dark ocean, causing an higher heat absorption as sea ice melts. This also poses another connection between factors, ocean heat content increase and Arctic sea ice melt. The increase in carbon dioxide and other greenhouse gases also contributes to the increase of ocean heat content (Figure 2).

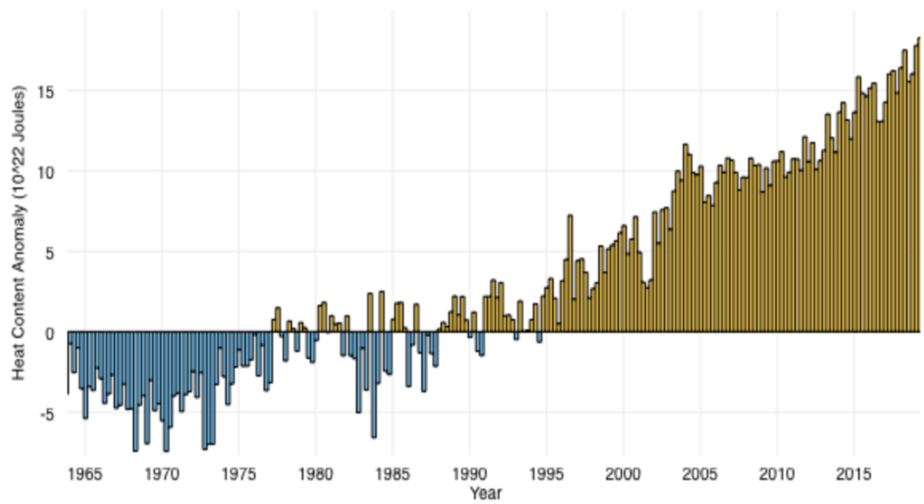


Figure 2. Ocean Heat content (10^{22} Joules) from 1965-2015.
Available:https://www.climate.gov/search?search=ocean+acidification

As ocean heat increases, this causes organisms to migrate, struggle to survive or increase their range expansion, making invasion easier or harder for some species. Finally, ocean acidification is the overall decrease in pH of the world's oceans due to an increase of carbon dioxide in the atmosphere (Figure 3). This poses many threats to both native and invasive organisms' survival seeing that many biological functions are dictated by pH.

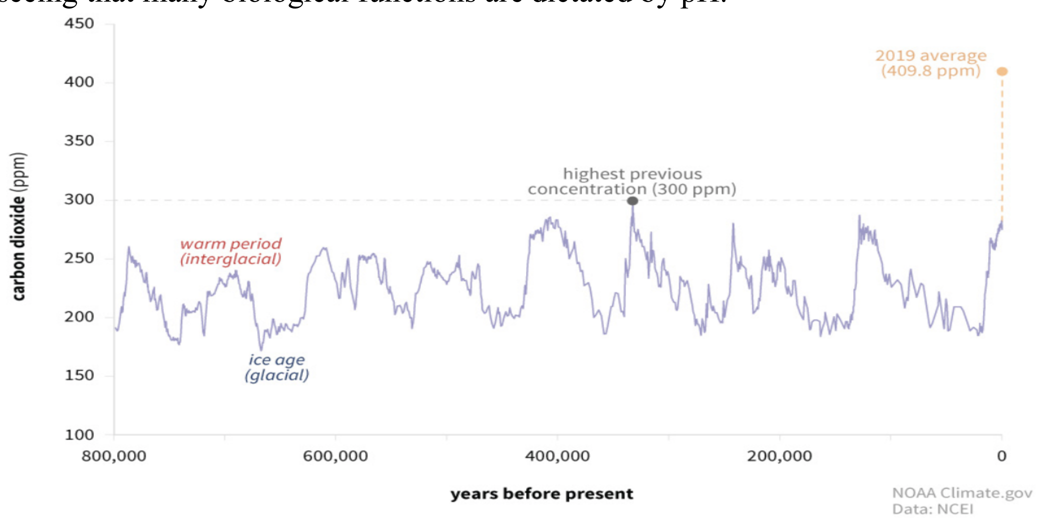


Figure 3. Total carbon dioxide content (ppm) in the atmosphere until present day (2019).
Available: https://www.climate.gov/search?search=ocean+acidification

The connections between climate change and invasive species factors can easily be seen. In previous chapters success, vectors, impacts, mitigation and detection of invasive species were discussed. Climate change factors have an effect on each of these characteristics and needs to be addressed.

Climate Change and Vectors:

Climate change will have significant impacts on the vectors which introduce invasive species to new areas. As described earlier, the most common vectors for invasive species involve shipping and seafaring vessels. As more shipping routes get discovered that connect different ecosystems through shipping, more invasive species from those ecosystems can invade areas previously inaccessible to them by natural means. There is evidence to suggest that climate change will make shipping possible in areas it has not been before, and as a result will allow more invasions to occur. Climate change has contributed to significant amounts of sea ice melt in the Arctic Sea, and experts suggest that the Arctic would be ice-free by 2030 (Chen et al., 2020). This would open up many new shipping routes to use to shorten the distances between locations. A study done in 2020 analyzed a shipping route called the Northeast Passage, an Arctic shipping route which would shorten the distance and time between Europe and northwestern Asia by between 33 and 40 percent (Chen et al., 2020) especially when compared to the Suez Canal. This shipping lane was previously impossible to navigate due to the presence of sea ice, but climate change has contributed to heavy sea ice melt in a very short time. Because of this, the Northeast Passage is predicted to open up for open-water ships in September 2021.

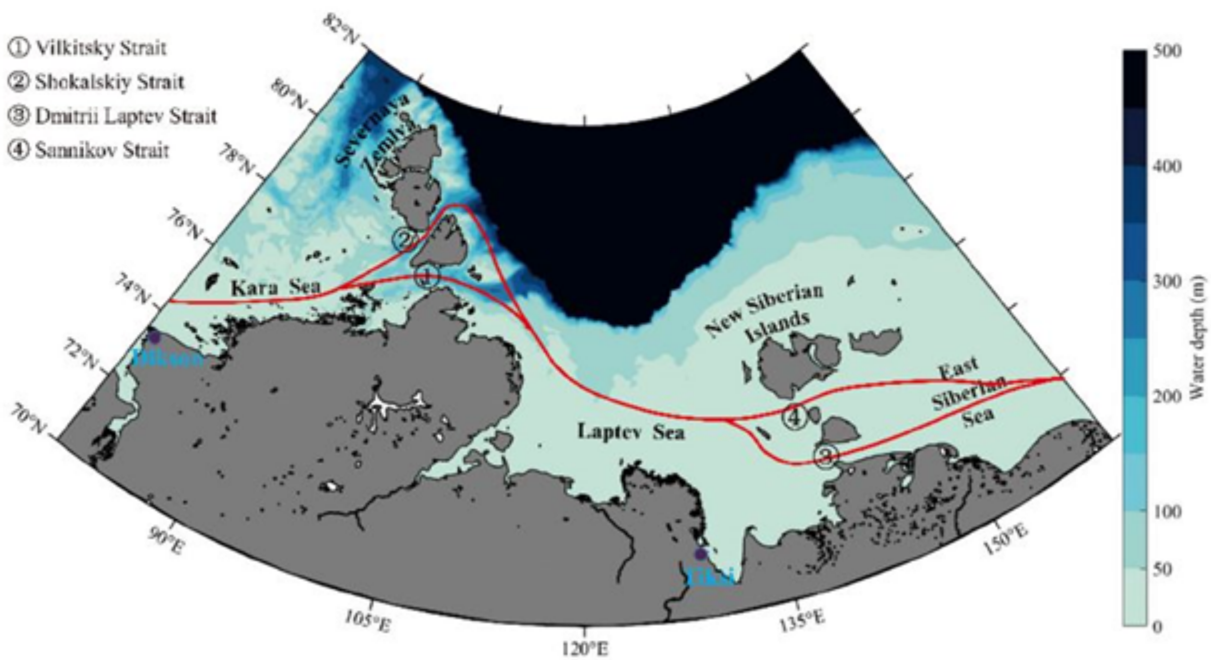


Figure 4. Map of the Northeast Passage in the Arctic with water depth from Chen et al., 2020.

The Northeast Passage's opening will increase the risk of invasions by non-indigenous aquatic species significantly (Chen et al., 2020). These risks specifically come from shipments associated with the following countries: Japan, China, Taiwan, South Korea, and the Philippines. The risk was especially high compared to terrestrial invasive species as there is less difference in the habitats for aquatic invasive species coming from Asian to American waters or vice-versa. Without climate change, the Northeast Passage would not have opened up naturally and these risks would never come to fruition.

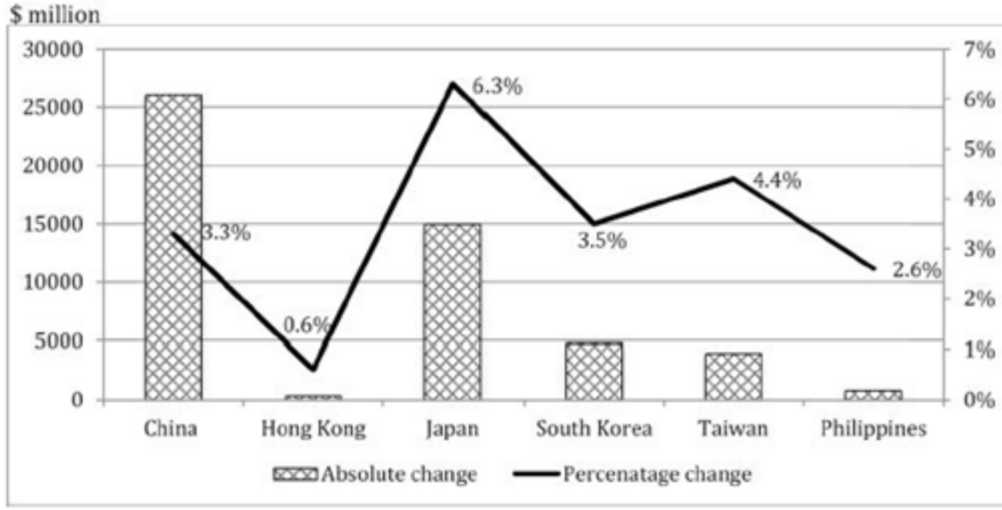


Figure 5. Changes in risk of non-indigenous species spread in the eastern U.S. from Asian-Pacific countries in 2030. The bars represent absolute change in risk by trade volume in dollars. The line represents risk by percentage change in trade.

Climate Change and Ecological Impacts:

Invasive species have several known ecological impacts. Invasive species are the second leading cause, behind anthropogenic actions, of the endangerment and extinction of native species (Simberloff, 2001). One of the major ecological impacts of invasive species is their effect on biodiversity. Invasive species shift native species richness and abundance, causing for both the loss and addition of biodiversity (Troost, 2010). Depending on which ecosystem or habitat that a non native species invades determine the ecological damage that is caused. This ecological damage is also amplified by climate change factors such as increased carbon dioxide, warming temperatures, sea ice melt, ocean acidification and sea level rise. The impacts on biodiversity due to the coupled effects of invasive species and climate change can be observed (Figure 6). Coral reef ecosystems struggle the most with the climate change factor of ocean acidification. Reef building corals lose their zooxanthellae partner, if waters become too acidic causing coral polyps to struggle to survive or die (Kleypas, 2009). This creates a decrease in viable coral reefs, causing native species populations that depend on coral for shelter or food to decline (Kleypas, 2009). In result even more of a pressure is put on declining populations when it comes to interactions with invasive species. This is because native species not only have to struggle to survive with changing conditions, but also the increased competition with other invasive species. The invasive lionfish is an example of an invasive species that thrives in coral reef areas. Not only does the lionfish compete with some reef fish for food but they prey on many reef fish (Raymond, 2015). This invasive predation and pressure of climate change affects biodiversity of the coral reefs (Raymond, 2015).

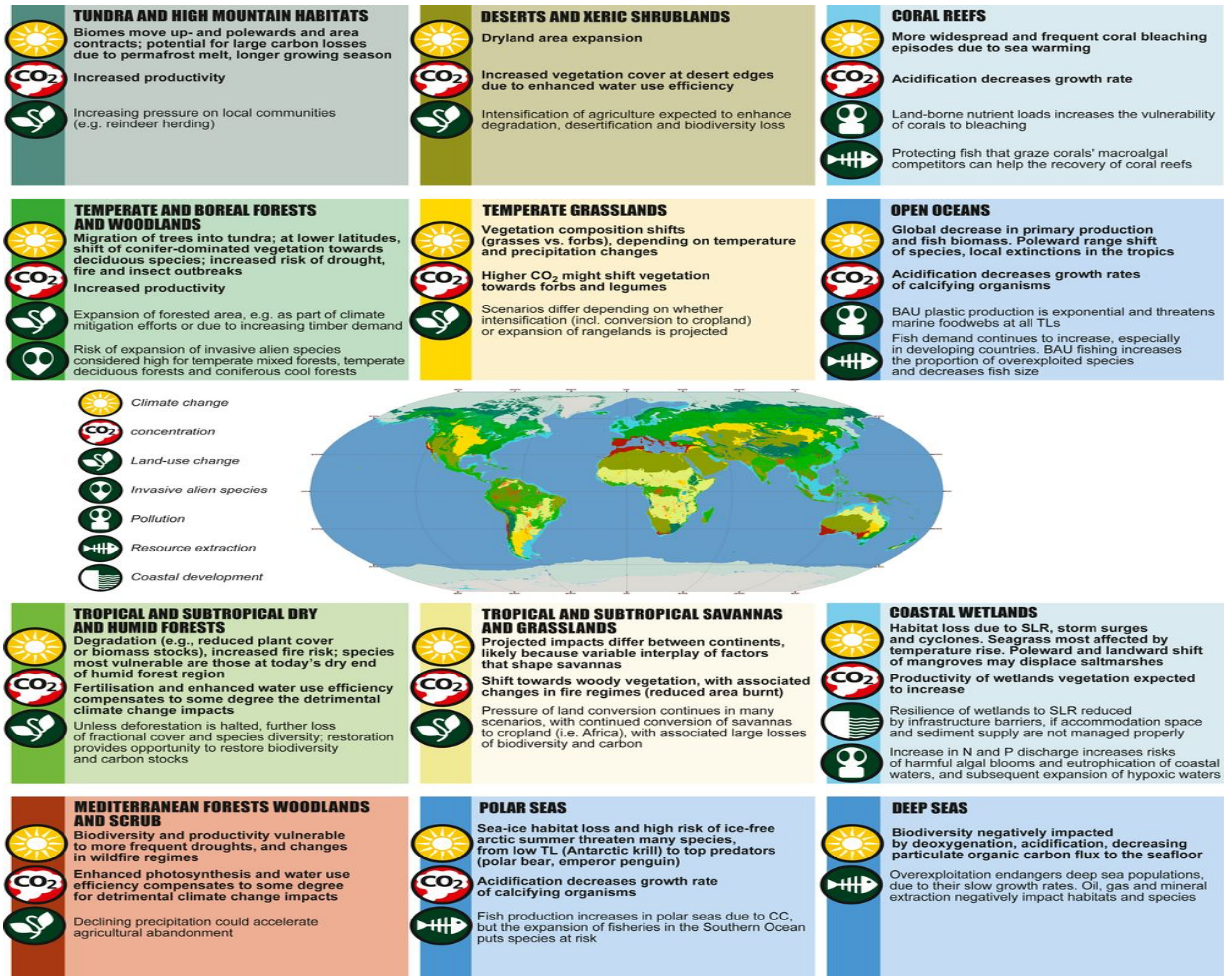


Figure 6. Effects of climate change, pollution, invasive species, carbon dioxide concentration, resource extraction and coastal development on different ecosystems. Available: https://www.pnas.org/content/117/49/30882

Besides biodiversity invasive species also have effects on the abiotic factors within an ecosystem. Invasive species can not only alter water quality and biogeochemical cycles but also do this while sometimes enhancing the impact of other invasive species. An example of this is the zebra mussel (*Dreissena polymorpha)* and Eurasian watermilfoil (*Myriophyllum spicatum*). Both of these species are aquatic invasive species and they affect the water quality and clarity within the area they reside (Simberloff, 2001). Since the zebra mussel is a bivalve species it siphons and filters water, allowing for increased water clarity. Although this might seem like a positive effect, it only enhances the ability for Eurasian milfoil to grow. Eurasian milfoil creates thick mats on the surface of the water, inhibiting other native species to grow and affecting sunlight availability (Olden *et al.,* 2014). This increased growth of Eurasian milfoil also pays back to the zebra mussel by creating more settling substrate for the mussel to settle on (Simberloff, 2001) This becomes a vicious cycle allowing for both the zebra mussel and Eurasian milfoil to prosper into new areas. The climate change factor of increased ocean heat content also contributes to enabling this cycle and growth even more. Since warmer water temperatures are preferred by both zebra mussels and Eurasian milfoil, climate change will only continue to enable invasion of these species (Jilek, 2009). The combination of invasive species and climate change factors causes major ecological changes and damage that will only be enhanced as climate change continues.

Climate Change and Economic Impacts:

The economic impacts of invasive species can be staggering, and climate change will only worsen these impacts. Some of the major economic harm caused by invasive species consist of shutting down fisheries, property damage, removal of desired food organisms, and sometimes actually making workers sick. The primary way climate change will interact with all of these impacts is by making invasive species more successful and more widespread, thereby intensifying all of the impacts those species have on the environment and on the economy. These economic costs often include the costs of preventing or eradicating invasive species. In the years 1999 and 2000, half of the $500,000 used by federal agencies in activities relating to invasive species was used for prevention (Warziniack et al., 2021). That figure will only increase as climate change makes invasions more common and more frequent. For example, invasive harmful algal blooms (HAB) will become more intense due to climate change as the lowering of the ocean's pH benefits many of those algae species (Hall-Spencer & Allen, 2015). In 2008, the sailing competition of the Beijing Olympics was threatened by a blue-green algal bloom, and efforts to dispose of the bloom cost upwards of $100 million.

Figure 7. An image of a barge surrounded by algae in the area where the sailing competition was set to take place. https://www.nytimes.com/2008/07/01/world/asia/01algae.html

Climate Change and Success of Invasive Species:

The environmental changes brought about by climate change will make many invasive species much more successful in invading new areas. Rising water temperatures will widen the range of many tropical invasive species and for species who have strong tolerance to fluctuating temperatures. For example, the invasive strain of the algae species *Caulerpa taxifolia*, which is described in more detail later, is a tropical species known for its relatively strong tolerance to cold water compared to its native strain. Warmer water temperatures will allow this species to enter new areas and outcompete the more environmentally vulnerable native species present. The spiny urchin, *Centrostephanus rodgersii*, became invasive in Tasmania because of the warm water there (Hall-Spencer & Allen, 2015). While other consequences of climate change may be detrimental to this species, it is hypothesized that the benefits *C. rodgersii* will experience with increased water temperatures will outweigh any other effects on this species by climate change.

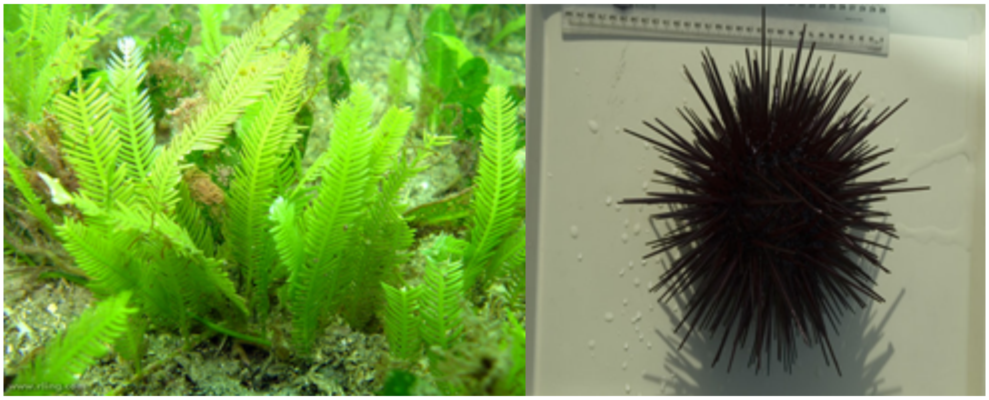


Figure 8. *C. racemosa* (left) and *C. rodgersii* (right), two unrelated invasive species who will both benefit from rising water temperatures as a result of climate change. Available: https://cisr.ucr.edu/invasive-species/caulerpa-taxifolia-or-killer-alga

Ocean acidification will also make life easier for several invasive species. While many species of marine life struggle with lower pH in the water, invasive algae species which form harmful algal blooms will thrive as ocean acidification provides increased CO_2 in the water which stimulates photosynthesis (Hall-Spencer & Allen, 2015). The genus *Ulva* which causes destructive "green tide" algal blooms will form more intense blooms as a result of this. Nutrient limitation resulting from increased CO_2 also leads to higher concentrations of toxin being produced by these blooms, specifically in the species *Pseudo-nitzchia* and *Karenia brevis*. Other invasive species besides algae will benefit as well. In a complicated case, the American slipper limpet, or *Crepidula fornicata*, sees increases in calcification levels in adults at higher levels of CO_2, yet the shell growth of larval individuals is hindered at the same levels. This reduces recruitment of the species and lessens survival rate in larva. As a result, it is difficult to label ocean acidification as a helping or hurting mechanism towards *C. fornicata*. This is an important fact to understand, that different aspects of climate change may not help or hurt invasive species in the same way and understanding the specifics for each species will make handling them more effective.

Climate Change and Detecting Invasives:

Detection of invasive species is now more important than ever. Since climate change aids many invasive species in success or an increased number of vectors, detection efforts are essential to stop the spread of invasive species. Since invasive species and climate change are so intertwined, researchers have begun combining climate models with predicting range expansion of various invasive species. An example is the European Crayfish which is a group of native species to Europe. Unfortunately invasive species like the red swamp crayfish (*Procambarus clarkii*), signal crayfish (*Pacifastacus leniusculus*) and spiny-cheek crayfish (*Orconectes limosus*) have started invading the European crayfishes habitat and spreading disease (Capinha, 2013). The crayfish plague, *Aphanomyces astaci* is a deadly disease that has pushed many European crayfish populations to the status of endangerment or extinction (Capinha, 2013). Researchers created a climate model which showed the future abiotic effects that climate change had on watersheds, temperature and precipitation. This model was coupled with the possible range expansion and habitability of native and invasive crayfish allowed them to understand the future health of the European crayfish (Capinha, 2013). It was concluded that climate suitable areas for native

European crayfish were decreased anywhere from 19% to 72% (Capinha, 2013). This information allows scientists to understand that the European crayfish will be endangered severely in the future and specific actions need to take place.

Another detection method that has been used for the effects of invasive species with climate change is the Dynamic energy budget model (DEB). The DEB was applied to estimating the reproduction and expansion along the southern coast of China, of the invasive black striped mussel (*Mytilopsis sallei*). Satellite data of current sea surface temperature and chlorophyll a concentrations were taken (Sian Tan, 2020). The reason for these specific abiotic factors being looked at is because increased sea surface temperature will allow for an increased range expansion of the mussel and chlorophyll a is the food source of the mussel. Future predictions up to the year of 2046 were modeled for sea surface temperature increases and different percentages of chlorophyll a. It was found that with warming sea surface temperatures the black striped mussels are predicted to expand and prosper up to the southern parts of the Yangtze river where they currently are unable to inhabit because of the cold temperatures (Figure 9). The mussels' expansion will be stopped North of the Yangtze river because of another sea surface temperature barrier. It was also seen that when chlorophyll a concentrations were decreased by 20-30% egg production was no longer viable and anything more than a 10% decrease had a negative effect on the mussels reproduction (Sian Tan, 2020.) By using both an energy model and the tolerance of the black striped mussel for predicting the invasion of a species allows for scientists to take into account the effects of both invasive species and climate change.

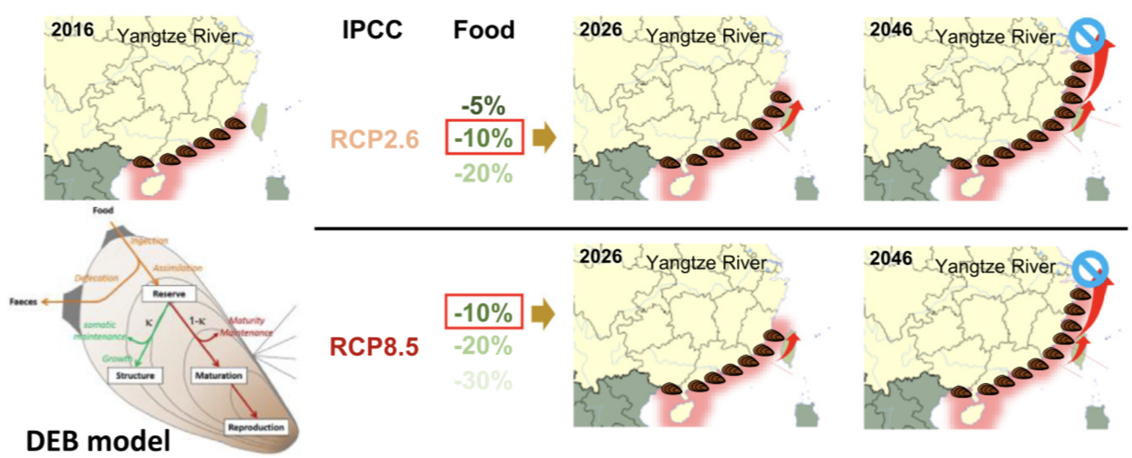


Figure 9: Dynamic Energy Model (DEB) of the chlorophyll a and sea surface temperatures along the southern coast of China. The black striped mussel range expansion is shown based on different conditions and effects of climate change. (Sian Tan, 2020.) Available: https://www.sciencedirect.com/science/article/pii/S0048969720366274

Climate Change and Mitigation/Eradication of Invasive Species:

Naturally, invasive species of all kinds will face similar challenges from climate change as their native counterparts. Due to this, climate change must be considered in the context of how it will help mitigate or eradicate invasive species. As mentioned in previous sections, species like the spiny urchin that benefit from one aspect of climate change (increased temperature) can suffer from another (ocean acidification). The sea star species *Asterias rubens*, an invasive species in Irish waters, sees reduced growth rates and increased pathogen vulnerability at lower pH levels (Hall-Spencer & Allen, 2015). The Pacific oyster, *Crassostrea gigas*, faces similar challenges but does so at an advantage compared to native bivalves which are generally more vulnerable to ocean acidification and other environmental extremes. This is a crucial aspect of mitigating invasive species; finding out which native species will be able to outcompete invasive species in these changing climates. As for total eradication, the best example is the red king crab *Paralithodes camtschaticus*. This crab species invaded the Barents Sea in the Arctic but is expected to die out as a result of ocean acidification which severely limits survival and growth of larval and juvenile crabs. Even this is not entirely a good thing because while the eradication of these crabs is beneficial in mitigating their invasive traits, it is also potentially damaging to the crab fisheries located within both their invasive and native range. In this we must consider the economic and ecological danger of certain invasive species being wiped off the map entirely.

Figure 10. The red king crab, *Paralithodes camtschaticus*, which is invasive in the Barents Sea. This species is severely impacted negatively by ocean acidification. Available:https://oceana.org/sites/default/files/styles/lightbox_full/public/21_0.jpg?itok=O9Gy5tEw

Policy and Management:

In order to take on the many challenges that climate change has posed to invasive species management, current policies and management must be analyzed. Currently invasive species and climate change management are approached as two separate issues. This causes some invasive species policies to negatively impact climate change policies and vice versa. Since invasive species are very hard to manage, especially once they have inhabited an area, this has caused many

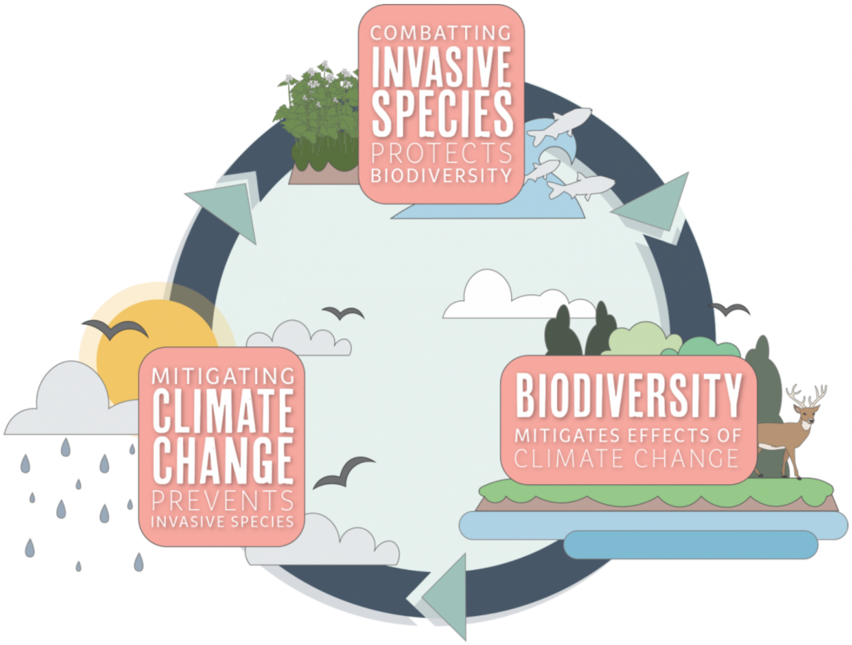


Figure 11. Showing the interconnection of invasive species, biodiversity and climate change. Available: https://www.sleloinvasives.org/reversing-the-positive-feedback-loop/

management and eradication efforts to fail. One of the main obstacles that managers currently face is the lack of funding and staff (Beaury, 2019). As climate change continues, certain aspects of invasive species are also worsening and causing invasive species managers to add to their already long list of species to manage (Beaury, 2019). A new basic framework has been laid out to help managers create new policies and develop mitigation strategies. The framework states that all invasive species and climate change policies should be based on, (1) the characterization of interactions between climate change and invasive species, (2) Identifying where current climate change policies would negatively affect invasive species management, (3) Identifying where policies could benefit from synergies between climate change and invasive species (Pyke, 2008.) All of these aspects should be considered in order to better current policies. By looking at invasive species and climate change policy as one this allows for the possibility of a more productive and effective management, due to the fact that they are deeply interconnected (Figure 11).

Conclusion:

These policies should be only one part of a multi-pronged effort to handle the invasive species problems exacerbated by climate change. Climate change has affected all marine problems, but on the subject of invasive species it has affected their impacts, vectors, survivability, methods of detection and mitigation, and policy making. All of the topics discussed in this paper don't exist in a vacuum, they can and do intersect. This makes understanding each of them essential to solving invasive species problems. Knowing how climate change opens vectors for invasive species is key to understanding how climate change will make them more successful and knowing the details of which invasive species impacts will be made better or worse by climate change is important for creating updated policies to handle them. Going forward, invasive species should be considered during climate change conversations, and climate change should be mentioned in conversation about invasive species. Leaving them separate will only serve to lessen our effectiveness in doing what needs to be done.

References:

Capinha et al. 2013. Effects of Climate Change, Invasive species, and disease on the distribution of Native European Crayfishes. Conservation Biology 27(4) 731-740. doi: 10.1111/cobi.12043

Chen J, Kang S, Chen C, You Q, Du W, Xu M, Zhong X, Zhang W, Chen J. Changes in sea ice and future accessibility along the Arctic Northeast Passage. Global and Planetary Change. 2020;195:103319. doi:10.1016/j.gloplacha.2020.103319

Climate change Maps and Data. NOAA. Available: https://www.climate.gov/maps-data

Hall-Spencer J, Allen R. The impact of CO2 emissions on 'nuisance' marine species. Research and Reports in Biodiversity Studies. 2015:33. doi:10.2147/rrbs.s70357

Jilek J et al. 2009. The effect of Climate change on *Dreissena polymorpha*, a Multiregional Invasive species in North America. University of Michigan. Available: https://deepblue.lib.umich.edu/bitstream/handle/2027.42/64578/Jilek_Sookhai_Yee_Lande_2009.pdf?sequence=1&isAllowed=y

Kleypas J.A et al. 2009. Coral Reefs and Ocean Acidification. Oceanography, Vol. 22, No. 4, pp. 108-117. doi: 64.222.173.1

Nong D, Warziniack T, Countryman AM, Grey EK. Melting Arctic sea ice: Implications for nonindigenous species (NIS) spread in the United States. Environmental Science & Policy. 2019;91:81–91. doi:10.1016/j.envsci.2018.10.013

Nong D, Warziniack T, Countryman AM, Grey EK. Melting Arctic sea ice: Implications for nonindigenous species (NIS) spread in the United States. Environmental Science & Policy. 2019;91:81–91. doi:10.1016/j.envsci.2018.10.013

Olden J.D et al. 2014. Incentivizing the Public to Support Invasive Species Management: Eurasian Milfoil Reduces Lakefront Property Values. PLoS ONE 9(10). doi/10.6084/m9.figshare.1148967.

Raymond W.W et al. 2015. Competitive interactions for shelter between invasive Pacific red Lionfish and naitve Nassau grouper. Environ Biol Fish 98: 57-65. doi 10.1007/s10641-014-0236-9

Simberloff D.A et al. 2001. Biological Invasions: How they are affecting us, and what can we do about them? Western North America Naturalist 61(3) 308-315. doi: 64.222.173.126

Warziniack T, Haight RG, Yemshanov D, Apriesnig JL, Holmes TP, Countryman AM, Rothlisberger JD, Haberland C. Economics of Invasive Species. Invasive Species in Forests and Rangelands of the United States. 2021:305–320. doi:10.1007/978-3-030-45367-1_14

Case studies

The first part of this book 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.

The Hoover Vacuum of the Sea: Introduction of the Invasive Lionfish

Authors: Hannah Welch & Colin Birch
Edited by: Shaylee Amidon

Introduction

According to the World Conservation Union, invasive alien species are the second most significant threat to biodiversity, after habitat loss (Park, 2004). While many species would not be of concern when introduced to a new area or range of distribution, there are certain qualities and circumstances that can create a destructive invader. According to some estimations the major environmental damages, losses, and control measures for invasive species cost the U.S. an average of $138 billion per year and invasive species also threaten nearly half of the species currently protected under the Endangered Species Act (Wurzbacher, 2020). A poster child of marine invaders, the lionfish, has proved to be one of the most successful invasive species in the Northeast over the last several decades. Although it is a tropical fish, the lionfish has already caused a drastic decrease in native fish populations along the Atlantic coast and current control methods are proving insufficient.

Figure 1.1 Animated map of reported lionfish sightings (1985 - 2020). Map created by: U.S. Geological Survey, Nonindigenous Aquatic Species Database. https://www.usgs.gov/media/images/reported-lionfish-sightings-animated-map-1985-2020

Distribution

One of the examples of an invasive species is *Pterois*, commonly known as the lionfish. This poisonous fish is originally native to the South Pacific and Indian Oceans where they are widely distributed from southern Japan to Micronesia, Australia and the Philippines. They can be found in practically all warm marine waters of the tropics and have been located at depths from 1 to 300 feet on hard bottom, mangrove, seagrass, coral, and artificial reefs (US Department of Commerce, N., 2016). *Pterois volitans,* the Red Lionfish, occurs throughout most of Oceania (including the Marshall Islands, New Caledonia and Fiji) east to French Polynesia. *Pterois miles,* nicknamed the Devil Firefish, is from the Indian Ocean and Red Sea, although its range extends to Sumatra.

Currently though, lionfishes can be found all along the Atlantic coast of the U.S. One of the first sightings off the coast of Florida was reported in 1985, but the population quickly became established by the early 2000's. Surveys conducted by Paula Whitfield and her team in 2004 found that lionfish were already as abundant as many native groupers, and second in abundance only to scamp (Whitfield et al, 2007). Lionfishes have now become established in Bermuda, the Bahamas, Columbia, Cuba, the Dominican Republic, Jamaica, Puerto Rico, Turks and Caicos, and the Cayman Islands. There are also reported sightings in Belize, Haiti, U.S. Virgin Islands, Mexico, and Aruba, Curacao, and Bonaire (US Department of Commerce, N., 2016). On the coast, they can be found as far south as Colombia and Venezuela, and as far north as North Carolina. In fact, there have even been sightings off the coast of Rhode Island. These mainly consist of juveniles though, and are limited to the summer months due to the fact that they cannot currently survive New England winters. Recent estimates of lionfish population densities show not only that the populations continue to grow, but some locations are reporting numbers of over 1,000 lionfish per acre (US Department of Commerce, 2016).

Vectors

There are different theories as to what initially introduced the lionfish to the east coast of the U.S. Unlike most invasive species, shipping is not thought to be a cause for the invasion of the lionfish. Some likely alternatives include that they were introduced in the late 1980s by local aquariums or fish hobbyists in Florida. Since lionfish are a popular marine ornamental fish (especially in the U.S.), many believe it to be possible that they were intentionally released into the Atlantic. At-home aquarists have reported intentionally releasing these fish due to how long they live, while they were unaware of how quickly they reproduce and the impacts this would have on the environment. In 1992, it was speculated that the root of the problem was actually only 6 lionfish accidently released from an aquarium during hurricane Andrew (Wurzbacher, 2020). Genetic research supports this theory, but it is likely that many more have been intentionally released by the retired aquarium enthusiasts.

What Makes Them Successful

Several factors contributed to the lionfish's ability to take over the east coast so rapidly. First, lionfish have 13 long venomous dorsal spines, 2 short venomous pelvic spines and 3 venomous anal spines, which all are capable of delivering a venomous sting. The venom is a combination of protein, a neuromuscular toxin and a neurotransmitter called acetylcholine (pronunciation: ah-see-toe-coe'-lean), which may kill or stun predators (US Department of Commerce, N., 2016). As this makes them quite difficult to pray on, they typically have virtually no predators in areas they invade. In addition, they are voracious predators. Samples of lionfish stomach contents in the western Atlantic have shown that they consume more than 50 different species (Gupta, 2009). Not only are they non-selective feeders, but they can consume an impressive quantity as well. Some areas estimate that they have lost up to 90 percent of their native fish population due to the appetite of invasive lionfish (US Department of Commerce, N., 2016). While they are mainly nocturnal, they have been found with full stomachs during the day as well. Their stomachs can even expand up to 30 times their normal size. This, couples with extremely high reproductive rates, makes them the perfect predator. Mature females have an extremely high

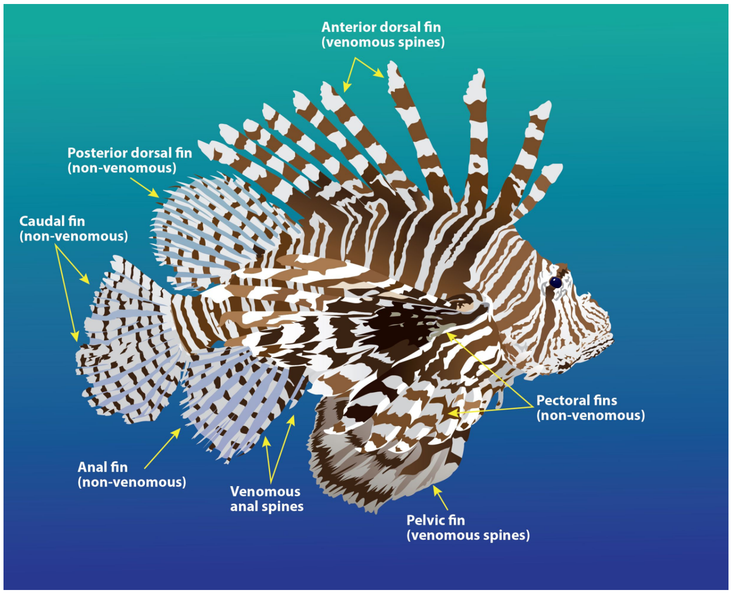


Figure 1.2. Labeled diagram of the lionfish's venomous and non-venomous spines. Figure from: https://www.fisheries.noaa.gov/southeast/ecosystems/impacts-invasive-lionfish

reproductive rate and can spawn every 2-3 days, producing over 2 million eggs per female a year (Wurzbacher, 2020). Another factor to consider is that lionfish now occupy an impressive geographic range and are able to survive in a wide range of habitats and depths. Thus, creating the perfect storm for an invasive species.

Impacts

The impacts of invasive Lionfish are seen most prominently in the species that they consume. Lionfish are voracious predators and they will often consume a large amount and a large variety of native species. Since they have been released into Florida waters in the mid 1980s, they have inhabited multiple habitats including coral reefs, shipwrecks and other benthic marine ecosystems. Lionfish primarily feed on fish and can drastically reduce a reef population of its native species. They are also known to consume important species to coral reefs health. Grazer species such as parrotfish, surgeonfish and tangs are primary prey to lionfish and their removal can severely damage a reef ecosystem. In addition to grazers, there are many species that are considered cleaners that remove detritus and parasites from both the reef and larger animals such as sea turtles or other fish (Albins, 2008). These cleaners are generally safe from predators since they are beneficial, but lionfish will prey on them. Lionfish will consume over 50 different species and can reduce juvenile fish populations by 79% in only 5 weeks (Gupta, 2009). In addition to directly consuming native species, lionfish also indirectly affect other native species through competition. Species like groupers and snappers consume the same prey as lionfish but since lionfish do not have any natural predators in the new environment, they can outcompete larger fish species.

In addition to environmental damage, lionfish have also caused economic and anthropogenic impacts. Because of their venomous spines, lionfish are of serious concern to any humans using waters recreationally. While lionfish stings are generally non-lethal, they can be incredibly painful and cause redness, bruising, and swelling (Lanese, 2019). In rare cases, the venom can cause an extreme reaction such as anaphylaxis shock. In this scenario the symptoms can become more severe and will include fainting, shortness of breath, and cardiac arrest. Despite the low fatality rates of lionfish stings, their presence can be enough to scare people from using recreational beaches and waters (Lanese, 2019). In some countries entire economies are dependent upon fisheries and diving industries. Many fisheries rely on the large biodiversity of coral reefs and since lionfish can consume a large number of fish, many industries are heavily damaged by the presence of lionfish populations. For example, diving is a $2.1 billion dollar industry in the Caribbean and if lionfish continue to damage coral reefs, these waters will no longer be a popular tourist destination (NOAA, 2020).

Monitoring & Mitigation

As far as detection strategies go, there are only a couple methods used to monitor invasive lionfish populations. Oftentimes, details in regard to lionfish range are known due to observer reports. Lionfish populations are often reported to local marine organizations and NOAA has an accurate map that details lionfish range. In many scientific reports, lionfish are monitored through human divers or remote operated vehicles. The main mitigation strategy used to help control lionfish is fishing. Removal efforts currently exist to help mitigate lionfish efforts, but they are not intense enough to fully eradicate invasive lionfish populations. However, the full eradication of lionfish populations is unlikely, because it is both costly and not incredibly efficient. Although full eradication of invasive lionfish isn't likely, fishing does provide relief to native ecosystems. Removing any number of lionfish allows for native species to come back from the harmful impacts of lionfish (Barbour, 2011).

Climate Change

Lionfish have invaded a large amount of the United States east coast and are continuing to expand their range due to the effect of global warming. Lionfish are rarely found outside of waters that are colder than their physiological tolerance. Lionfish cannot live year-round in environments that are not warmer than 16 degrees Celsius (Grieve 2016). Their range is limited to this temperature restriction, but as global temperatures increase these tolerances do not matter as much. Due to their physiological tolerances, lionfish can extend their range during summer months but will have to return during winter months. Lionfish will already extend past their range given a seasonal temperature increase so as global temperatures increase there is no doubt that lionfish will expand their territory. To expand into new territory, lionfish typically require an area that meets their optimal temperature requirement at least 11 months out of the year. In multiple climate change models, lionfish will extend their territory farther north along the Atlantic coast and further inland in previously established areas. In a conservative climate change assessment, it is thought that lionfish will extend their territory at least 6,000 km² further (Grieve 2016). There are no natural predators in the new predicted territory, so it is only fair to assume that if lionfish extend their

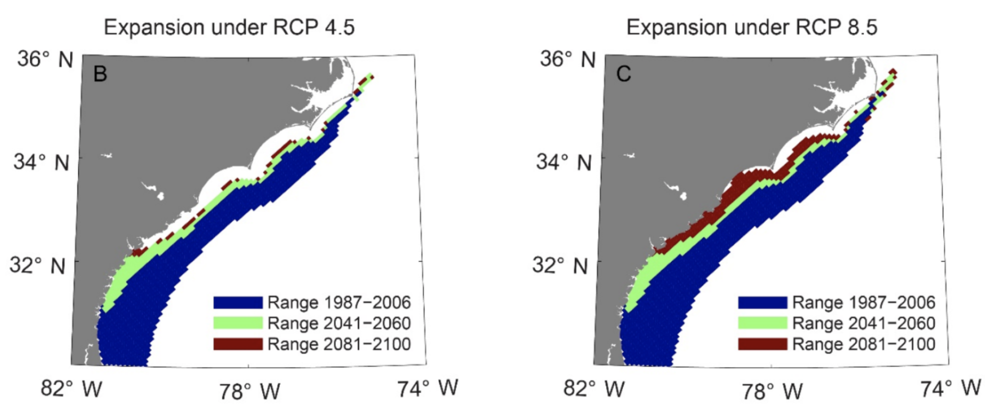


Figure 1.3: Diagram showing range expansion of the lionfish over a 100 year period in a conservative climate change model (right) and a liberal climate change model (left). Figure from: Grieve, B., et al. 2016

range, similar damage will be done to both the environments and economies of the new locations (Grieve 2016). Overall, climate change has shown to aid the agenda of invasives, by both worsening their impacts and making them harder to control, making. With global temperatures increasing at an unprecedented rate, it has become more important than ever to invest in prevention and monitoring methods.

References:

Albins, Mark & Hixon, Mark. (2008). Invasive Indo-Pacific lionfish *Pterois volitans* reduce recruitment of Atlantic coral-reef fishes. Marine Ecology-progress Series. https://www.researchgate.net/publication/250218999_Invasive_Indo-Pacific_lionfish_Pterois_volitans_reduce_recruitment_of_Atlantic_coral-reef_fishes

Whitfield, P.E., Hare, J.A., David, A.W. *et al.* (2007). Abundance estimates of the Indo-Pacific lionfish *Pterois volitans*/*miles* complex in the Western North Atlantic. *Biol Invasions* 9, 53–64. https://doi.org/10.1007/s10530-006-9005-9

Gupta, A. (2009, May 07). Invasion of the lionfish. https://www.smithsonianmag.com/science-nature/invasion-of-the-lionfish-131647135/

Barbour, A., Allen, M., Frazer, T., & Sherman, K. (2011, May 31). Evaluating the potential efficacy of invasive lionfish (*Pterois volitans*) removals. https://journals.plos.org/plosone/article?id=10.1371%2Fjournal.pone.0019666

Grieve, B., Curchitser, E., & Rykaczewski, R. (2016, March 21). Range expansion of the invasive lionfish in the Northwest Atlantic with climate change. https://www.int-res.com/abstracts/meps/v546/p225-237/\

US Department of Commerce, N. (2016, July 28). What is a lionfish? https://oceanservice.noaa.gov/facts/lionfish-facts.html

Lanese, N. (2019, January 17). Lionfish: Beautiful and dangerous invaders. https://www.livescience.com/64533-lionfish.html

Wurzbacher, J. (2020, February 7). The lionfish invasion. https://www.sailorsforthesea.org/programs/ocean-watch/lionfish-invasion

NOAA (2020, March 30.). Impacts of invasive lionfish. https://www.fisheries.noaa.gov/southeast/ecosystems/impacts-invasive-lionfish

Sea Lamprey: The Invader of the Great Lakes

Authors: Sam Fuller, Harry Wales
Edited by: Emily Lewis

Introduction

The sea lamprey (*Petromyzon marinus*) is an invasive species native to the Atlantic Ocean and invasive to the Great Lakes. Sea lampreys are unique from many other fishes, in that they do not have jaws or any sort of bony structures, their skeleton is made of cartilage. These eel-like fishes can get up to 4 feet in length, they latch on and attack using their suction cup mouth to dig their teeth into their prey. Once they are attached, they kill the fish with their sharp teeth and tongue. The sea lampreys feed on the native fish, and when they bite it, it creates an enzyme that causes blood from clotting on the native species they attack.

Figure 1. Suction mouths of the sea lamprey, used to latch onto prey and to consume their blood and other bodily fluids. https://www.britannica.com/animal/lamprey

Distribution

The sea lamprey is native to the Atlantic Ocean, on the North American coast from Newfoundland and Labrador to Florida. They are invasive to the Great Lakes (Lake Huron, Lake Michigan, Lake Superior, Lake Ontario, Lake Erie and their tributaries). The sea lamprey was first discovered in Lake Ontario in 1835, Lake Erie in 1921, Lake Michigan in 1936, Lake Huron in 1937, and Lake Superior in 1938 (Applegate 1950, Emery 1935). While sea lampreys are native to the Atlantic Ocean, and do not have the same destructive effect on the fish found there, they have created havoc in the Great Lakes. This is due to the fact that sea lampreys coevolved with the fish found in the Atlantic, causing the sea lamprey to not kill its host. However, in the Great Lakes, the sea lamprey was not present when the fish found there evolved. They are relatively new predators, and the native fish have no defense mechanisms to protect themselves. In the Great Lakes, sea lampreys can kill up to 40 pounds of fish.

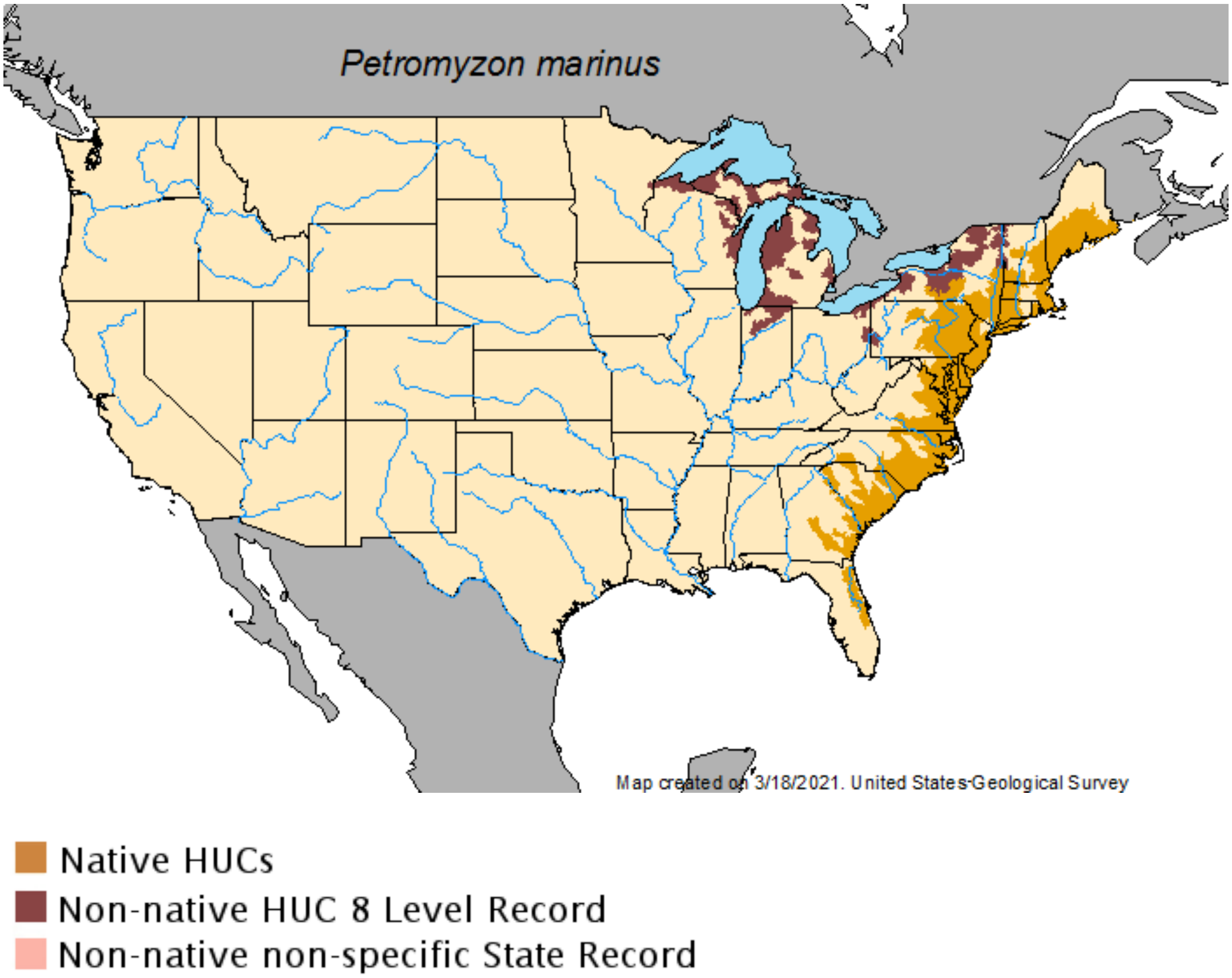


Figure 2. The distribution of sea lamprey in its Hydrologic Unit Codes in its native range, and its nonnative range in the United States. https://www.invasivespeciesinfo.gov/aquatic/fish-and-other-vertebrates/sea-lamprey#cit

<u>Vectors</u>

The sea lamprey was first introduced in Lake Ontario in the 1830s, but there is some controversy surrounding this discovery date. Several researchers believe that the sea lamprey is actually native to Lake Ontario and its tributaries, the Finger Lakes and Lake Champlain. This belief stems from the idea that a relic population from the Pleistocene glaciation was present in the lake already (Smith 1985). While some believe this, the prevailing theory is that the sea lamprey was unknown to Lake Ontario and they were introduced via Atlantic coastal drainages caused by the construction of the Erie Canal (Emery 1985). Despite the confusion on whether or not it is native to Lake Ontario, no one contests that it is not native to the rest of the Great Lakes and its tributaries. The sea lampreys were prevented from entering the rest of the Great Lakes because of Niagara Falls, but the construction of the Welland Canal bypassed it, allowing the Lampreys to move from Lake Ontario to Lake Erie (Aron and Smith 1971). It took over a century for sea lampreys to spread to the rest of the Great Lakes after the construction of the Welland Canal. Improvements made to the canal in 1921 is believed to have been the cause of the spread to the rest of the Great Lakes (Great Lakes Fishery Commission 2019).

Impacts

The introduction of sea lamprey has had a profound impact on the native fish species' as well as introduced game fish. In the Great Lakes, attack and parasitic feeding on native fish species almost always results in the death of the fish, either by tissue and fluid loss or infection (Phillips *et al.* 1982). The introduction of this species as well as their predation, along with water pollution and overfishing, has resulted in the population decline of several large native species. Some of these species include multiple ciscoes, lake trout, and walleye. Because of these factors, there was a collapse of commercial fisheries throughout the Great Lakes in the 1940s and 50s (Lawrie 1970).

Figure 3. Sea lampreys feeding on a fish. https://www.usgs.gov/centers/umesc/science/improving-accuracy-and-precision-predictions-tfm-niclosamide-concentrations?qt-science_center_objects=0#qt-science_center_objects

The sea lamprey has been a menace in its new freshwater habitat. They continually prey on a multitude of species found in the Great Lakes. These species include white sucker (*Catostomus commersoni*), longnose sucker (*Catostomus catostomus*), redhorse (*Moxostoma* spp.), yellow perch (*Perca flavescens*), rainbow trout (*Oncorhynchus mykiss*), burbot (*Lota lota*), channel catfish (*Ictalurus punctatus*), northern pike (*Esox lucius*), and common carp (*Cyprinus carpio*) (Scott and Crossman 1973). The predation of sea lamprey contributes to more than just lower populations. It is one of the main reasons for the extinction of 3 species endemic to the Great Lakes. These species include the longjaw cisco (*Coregonus alpenae*), the deepwater cisco (*C. johannae*), and the blackfin cisco (*C. nigripinnis*) (Miller *et al.* 1989). Lampreys have had such an impact on the native fish population that it helped the success of other invasive species. When the alewife was introduced to the Great Lakes, the population of possible predator species were so low because of the lampreys, it was very successful (Smith and Tribbles 1980). As stated before, the introduction of the sea lamprey also had an impact on introduced game fish. State fish agencies introduced salmon into the great lakes for fishing purposes. Salmon, like the other fish found in the Great Lakes, were subject to sea lampreys parasitic feeding behavior, and resulted in a diminished population.

Sea lampreys have also had a significant impact on humans, the economy, and recreational activities. The sea lamprey, unlike some other invasive species, do not have any effect on human health. They are not known to bite humans, as they can distinguish between cold-blooded and warm-blooded organisms (Hammond Bay Biological Station/VAO News). Unfortunately, the greatest effect the sea lamprey has is on the economy. Lampreys, through predation, have caused the collapse of Great Lakes fisheries and the decline of local economies. A single lamprey can kill upwards of 40 pounds of fish in a lifetime, and there are between 80,000 and 150,000 lampreys found in the Great Lakes. This drop in economic activity has resulted in upwards of 10,000 jobs lost and the diminishing of property values surrounding the Great Lakes.

Mitigation Tactics

There are a couple of methods to try and mitigate the sea lampreys in the Great Lakes. The first method they were doing was to use mechanical weirs and electrical barriers (Smith and Tibbles 1980, Scott and Crossman 1973). In the late 1950s, the sea lamprey was successfully controlled by the lampricide 3-trifluoromethyl-4-nitrophenol (TFM). TFM is a chemical that kills the sea lamprey in their habitats now in the Great Lakes. This technique actually worked, reducing its population by 90% in 1961 when the population was peaking (Scott and Crossman 1973). With this, fisheries have seen some recovery, and they also noticed that the native fishes population was going up. TFM is necessary to control the population of the sea lamprey in the Great Lakes, but the TFM is harmful to some native species, like the walleye, as well as larvae to nonparasitic lamprey species (Becker 1983). As of 1991, the United States and Canada were spending around 8 million dollars for mitigation purposes to control the sea lamprey, and another 12 million dollars to restore the trout population in the Great Lakes (Newman 1991). Another mitigation tactic involves the sterilization of the male sea lamprey. All of the females that they catch are killed, and all the males that are caught are sterilized and released (Bergstedt 2007). They do this tactic to disrupt or "slow down" spawning of the sea lampreys in the Great Lakes, and the stocking of Lamprey-resistant strains of fish. Another mitigation tactic that people did and did not really work out was they would catch the sea lamprey and eat them, but they are incredibly noxious and they are a pest. In fact, England's Henry I died in 1135 because of eating "a surfeit of lampreys."

Despite the lack of interests in sea lampreys as food, mitigation tactics have been mostly successful. Because of the use of pesticides, sea lamprey abundance has dropped by 90-95% (Christie and Goddard 2003). While there is little to no change of total eradication, the population levels have started to reach restoration goals (Negus and Schreiner 2008). Along with this success, some native fish species have started to see an incremental rise in population. These

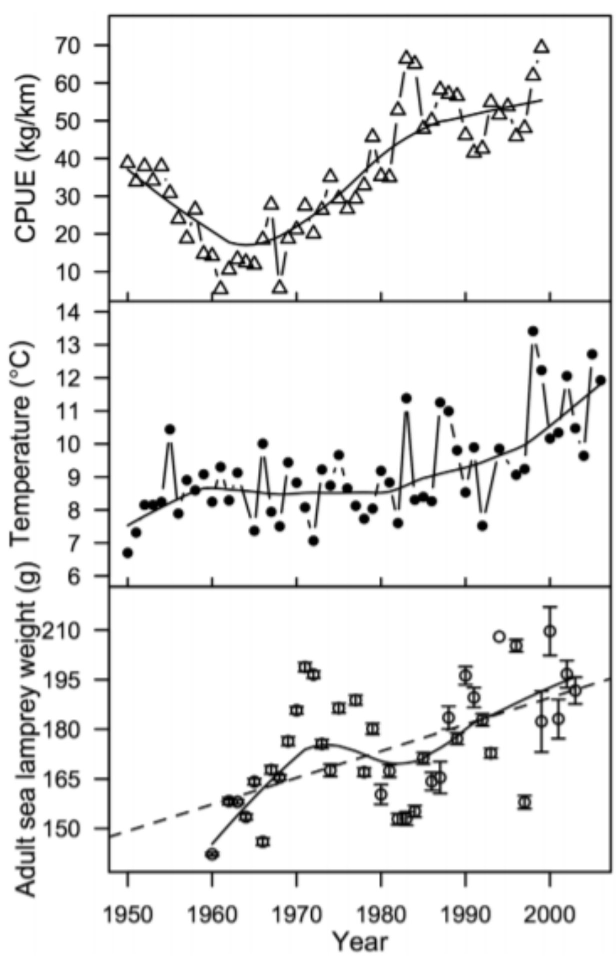


Figure 4. Catch per unit effort (CPUE) of lake trout is the top graph, temperature (℃) is the middle graph, and adult sea lamprey weight (g) is the middle graph. Showing a trend that as temperature rises, so does lamprey weight and CPUE of lake trout. (Cline et al. 2014)

successes do not mean that mitigation tactics have stopped working or will stop in the near future. The increased effects of climate change threaten to undo all the progress that has been made thus far.

Climate Change

The effects of climate change will only increase the sea lampreys' opportunity to devastated The Great Lakes ecosystem. The Great Lakes, especially Lake Superior, surface water temperatures have been rising dramatically since the 1980s. This has caused an increase in sea lamprey size corresponding with a longer growing season of their preferred prey (Cline *et al.* 2014). The warming of waters will directly impact the native fish populations, as it allows for sea lamprey to grow longer and consume more fish. As the ratio of host size to sea lamprey decreases, the direct mortality rate increases (Cline *et al.* 2014).

Conclusion

In conclusion, the sea lamprey is a very impactful invasive species in the great lakes, harming native species, as well as human and the economic aspects. The population of the sea lampreys have been increasing in the great lakes, and will continue to increase. In recent years, there have been different attempts in trying to mitigate the sea lamprey, because this species is very dangerous, now, and it's going to be in the future.

References:

Aron, W.I., and S.H. Smith. 1971. Ship canals and aquatic ecosystems: equilibrium has not been achieved since the Erie, Welland, and Suez canals were built. Science 174:13-20.

Becker, G.C. 1983. Fishes of Wisconsin. University of Wisconsin Press, Madison, WI.

Bergstedt, R.A., and M.B. Twohey. 2007. Research to support sterile-male-release and genetic alteration techniques for sea lamprey control. Journal of Great Lakes Research 33(2):48-69.

Christie GC, Goddard CI. 2003. Sea Lamprey International Symposium (SLIS II): Advances in the Integrated Management of Sea Lamprey in the Great Lakes.Journal of Great Lakes Research 29:1–14.

Cline, T. J., J. F. Kitchell, V. Bennington, G. A. McKinley, E. K. Moody, and B. C. Weidel. 2014. Climate impacts on landlocked sea lamprey: Implications for host-parasite interactions and invasive species management. Ecosphere5(6):68.http://dx.doi.org/10.1890/ES14-00059.1

Emery, L. 1985. Review of fish introduced into the Great Lakes, 1819-1974. Great Lakes Fishery Commission Technical Report, volume 45.

Great Lakes Fishery Commission. Status of Sea Lampreys. [accessed 2021 Mar 21]. http://www.glfc.org/status.php

Lawrie, A.H. 1970. The sea lamprey in the Great Lakes. Transactions of the American Fisheries Society 99:766-775.

Phillips, G.L., W.D. Schmid, and J.C. Underhill. 1982. Fishes of the Minnesota Region. University of Minnesota Press, Minneapolis, MN.

Scott, W.B., and E.J. Crossman. 1973. Freshwater Fishes of Canada. Fisheries Research Board of Canada, Bulletin 184. Ottawa.

Smith, B.R., and J.J. Tibbles. 1980. Sea lamprey (Petromyzon marinus) in Lakes Huron, Michigan, and Superior: history of invasion and control, 1936-78. Canadian Journal of Fisheries and Aquatic Sciences 37(11):1780-1801

Smith, C.L. 1985. The Inland Fishes of New York State. New York State Department of Environmental Conservation, Albany, NY.
VAO Connect. 2019. A Most Dangerous Fish. [accessed 2021 Mar 9]. https://www.youtube.com/watch?v=XqTKZnR9448

Mnemiopsis leidyi: A Means of Success

Authors: Kaitlyn Butts & Alexandra Michaud
Edited by: Sierra Brown

Introduction

Biology

The *Mnemiopsis leidyi*, or as it is more commonly known as the Sea Walnut, is a small Ctenophore. A Ctenophore is an invertebrate that lacks stinging cells and uses its eight rows of fused cilia to move in the water column. Also known as "comb jellies" they are not really Cnidarians due to the lack of stinging cells. However, the government still classifies them as jellyfish. Ctenophores can either have two tentacles or none at all, it depends on their species (Waggoner, 1995).

Figure 1. This is a picture of *Mnemiopsis leidyi*. The image depicts the reflective nature of the cilia on its body, which is what gives it its name the "comb jellyfish." Even though they are referred to as jellyfish, the sea walnut is not a jellyfish, but actually a ctenophore. Individuals in this phylum are more commonly known as comb jellyfish. Capture image found: https://d1o50x50snmhul.cloudfront.net/wp-content/uploads/2016/09/27104355/morski-orah-mnemiopsis-leidyi-2.jpg

M. leidyi is bell shaped with the oral lobes (Mouth) forming the rim of the bell. Their bodies are translucent and white, the digestive system and gonads are visible (Aquarium of Pacific, 2021). On their body are eight bands of cilia that they use to move around the water column, slowly. As the cilia move it gives the *M. leidyi* a refraction effect and it looks like rainbows go across their entire bodies. The maximum length can be between 100-120 mm or 3.9-4.7 in (Aquarium of Pacific, 2021). However, larger sizes have been recorded in the Caspian and Black Seas where they are considered an invasive species.

Instead of catching prey with stinging cells, the *M. leidyi* uses its sticky cells to capture prey, it is a voracious predator and will eat anything given to it. The food of choice is zooplankton, either as eggs and larval forms, other invertebrates and fish, copepods, sea jellies, and other ctenophores (Aquarium of Pacific, 2021). Using it's lobes it opens really wide and then captures its prey once inside. Despite the very large appetite of the *M. leidyi*, they are never full and will continue to eat if given the chance. This has caused great economic and environmental strain where they are considered invasive, discuss more later.

There is a male and female counterpart to reproduce, however it is hermaphroditic and can reproduce with itself (Aquarium of Pacific, 2021). Spawning is more common is the summer and will vary with habitat conditions. Sperm and egg is released into the water column where fertilization will occur, it has been found that internal fertilization is an option for this species too (Aquarium of Pacific, 2021). The larvae will develop rapidly, only taking twenty or so hours to fully mature and sexual maturity can take place within two weeks after hatching. A female can release and or fertilize 2-3,000 eggs per day with the right habitat conditions and food supply (Aquarium of Pacific, 2021).

Figure 2: This map demonstrates the spreading of *M. leidyi* through the European waters where they are considered invasive and detrimental to the ecosystems. They entered through the Mediterranean Sea and have since spread all the way up north. The image also shows where they have been recorded to be seen within the last year, in the grey circles. The map also shows where they are projected to be seen within the coming years, in the white circles.
Capture image found: http://www.flickr.com/photos/zoienvironment/7715398884/

Native Location(s) & Non-Native Location(s)

The *M. leidyi* is native to the East Coasts of both North and South America with a particular concentration in the Chesapeake Bay area of North America. They are non-native, or invasive, in the Black, Caspian, Mediterranean, Baltic, and North Sea.

How Did They Arrive?

The *M. leidyi* were unintentionally transported to European water through ballast water from cargo ships(Aquarium of the Pacific, 2021). Ballast water is the water that the ships suck up in the port and use to help the ships balance while out at sea if there is no cargo. Then when they reach another port to deposit or pick up goods they let that water out into the port that they are in, thus carrying many invasive species all over the world. Ballast water is the only way that *M. leidyi* is known to travel as they do not travel long distances on their own.

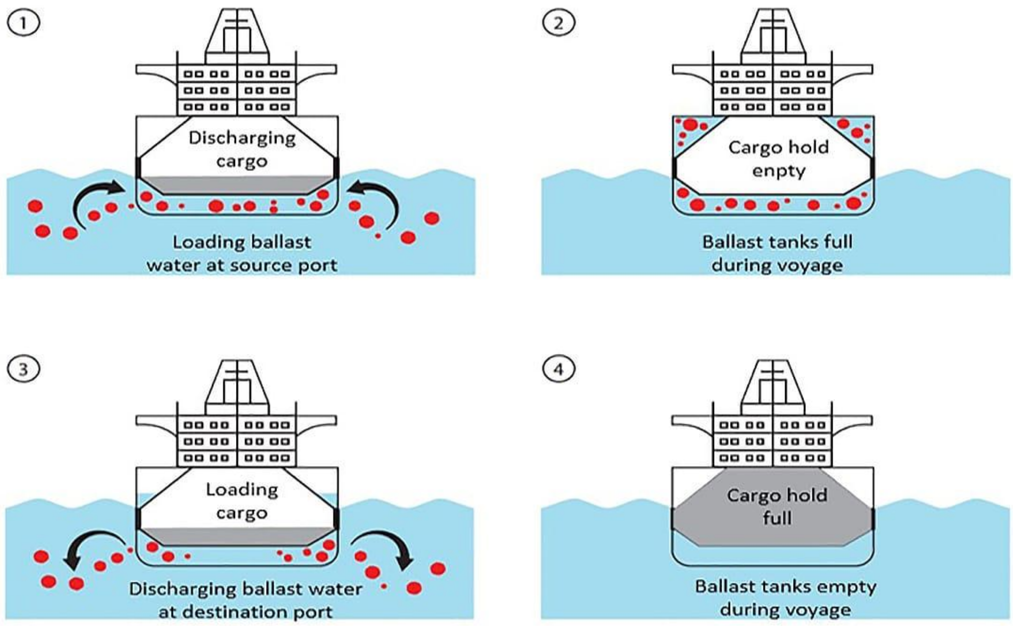


Figure 3: This image displays how the transfer of ballast water works. The first image is the ship taking in water from one port when there is no cargo in the ship to balance out the weight of the ship. The second image is the water all present in the ship. The third image shows the ship dumping out their ballast water before they enter another port which then transfers all of the organisms that they may have picked up from the first port and places them in a new environment, making them invasive. The last image shows the ship full of cargo and thus does not need ballast water to sail,
Capture image found: https://gms-instruments.com/wp-content/uploads/2019/11/Blog_Ballast_Water_Treatment.jpg

Impacts

Environmental

As stated in the Biology section, the *M. leidyi* diet contains zooplankton and they are never satiated. In their non-native habitats they consume the zooplankton that the native commercial fish consume. If there is little to no food for the fish to consume then they will either die out, their populations will decrease, or they will find a new place that supports their populations. *M. leidyi* does not affect the habitat around them, they float and swim in the water column and are not benthic in nature. It's also important to note that in most cases climate change creates a shift in the effects of species on their environments, but *M. leidyi* has not been observed to change in response to climate change (Aquarium of the Pacific, 2021).

Economic

As *M. leidyi* pose no threat to humans or human health, instead they pose a greater threat to us economically. *M. leidyi* has led to the collapse of the local fisheries and led to an economic decline in that specific area as they consume the native commercial fish food supply. A news article by the Huffpost, written by Mark Fischetti discussed how *M. leidyi* harmed fisheries in the Black and Caspian Seas. Fischetti again mentioned about the ever eating *M. leidyi* and how fish populations had a sharp decline due to the lack of their zooplankton.

Attributions of Success

M. leidyi have a number of attributes that make it highly successful in a broad range of ecosystems, including a wide range of tolerances, fast and adaptable reproductive capabilities, and their relationship within predator-prey dynamics. These abilities are what make *M. leidyi* an exceptional case study in the attributes of success among invasive species.

As a gelatinous mass with little internal complexity, *M. leidyi* can withstand temperatures ranging from 4 to 31℃ and salinity ranges of 3‰ to 39‰ (Aquarium of the Pacific, 2021). This means that they can exist in almost every ocean, except for the extreme poles. On top of that, they have the ability to live in both surface and deep waters, areas of hypoxia, and areas of high pollution (Aquarium of the Pacific, 2021). This means that in areas that a number of organisms would be unable to survive in, the sea walnut can maintain its position. With a rise in pollutant production and hypoxic zones, many ecosystems could find themselves under attack by this and other tolerant invasive species.

Like many other invasive species, *M. leidyi* are R strategists. This means that they put more energy into producing massive quantities of offspring rather than the care of a few offspring. The sea walnut is hermaphroditic and capable of self-fertilization as well as internal fertilization, though this is only done in extreme cases. Under normal circumstances, the sea walnut broadcast spawns, releasing 2,000 to 3,000 eggs into the water. These eggs hatch relatively quickly and will be sexually mature after 12 days at the very least (Aquarium of the Pacific, 2021). This makes them capable of creating massive populations in a short amount of time with very few initial samples. Along with this, they can alter their metabolism in times of food shortage, and will even go as far as to reproduce only to eat their young (Aquarium of the Pacific, 2021).

M. leidyi are described as voracious eaters (Aquarium of the Pacific, 2021). As an organism consisting of a nervous system and stomach, they never stop eating. They feed on zooplankton, and occasionally on phytoplankton by accident (Aquarium of the Pacific, 2021). Zooplankton are not an area specific food source, and therefore the sea walnut is capable of inhabiting any location that harbors such organisms. Zooplankton play a vital role in the survival of many lower trophic level species, which support higher trophic levels and human economics. The sea walnut also has few predators, which demonstrates a large issue when it comes to the invading of new areas. These ecosystems do not possess predators for these invaders, and it's a pattern commonly seen among other invasive species.

<u>Monitoring Strategies & Mitigation or Eradication</u>

Very few studies have been published in the monitoring and mitigation of *M. leidyi*. NOAA has been sighted on many invasive species databases, but unfortunately none of the data is publicly available. In terms of monitoring, one paper brought to light the usage of genetic microsatellites to identify the origins of the sea walnut (Reusch et. al., 2010). These methods of identification are important for future prevention of further infestation. If the native location is identified then laws and regulations can be put into place to mitigate the spread from these ports to other areas. For now, mitigation relies on these regulations to prevent the further spreading of *M. leidyi*. In 1997, the ctenophore *Beroe ovata* was accidentally introduced into the Black Sea via ballast water and it was found to feed primarily on *M. leidyi*. This led to a drop in sea walnut populations and then a decrease in *B. ovata* populations as they lost their primary food source (CABI, 2021).

<u>Conclusion</u>

The important takeaway from this case study is the understanding of the economic impact and successful characteristics of *M. leidyi*. This species highlights a number of characteristics shared by other invasive species that allow them to be successful, specifically its wide tolerance levels, and its rapid and adaptable reproduction strategies. The effects this fast-producing species has on coastal economies is detrimental, and something that needs to be watched closely as mitigation methods are sought out.

References:

Aquarium of the Pacific. 2021. Comb Jelly (Sea Walnut). Aquarium of the Pacific. [accessed 2021 Mar 16]. https://www.aquariumofpacific.org/onlinelearningcenter/species/comb_jelly/.

CABI. 2021. Invasive Species Compendium: *Mnemiopsis leidyi* (sea walnut), CAB International. [accessed 2021 Mar 5]. https://www.cabi.org/isc/datasheet/75102#topreventionAndControl

Fischetti M. 2012 Jun 7. Glowing Jellyfish: *Mnemiopsis leidyi* Harming Fisheries In Black, Caspian Seas (VIDEO). Huffpost Science.:1. [accessed 2021 Mar 16]. https://www.huffpost.com/entry/glowing-jellyfish-mnemiop_n_1578441.

REUSCH, THORSTEN B. H., et al. "Microsatellites Reveal Origin and Genetic Diversity of Eurasian Invasions by One of the world's most Notorious Marine Invader, *Mnemiopsis leidyi* (Ctenophora)." *Molecular Ecology*, vol. 19, no. 13, 2010, pp. 2690-2699.

Waggoner B. 1995 Aug 30. Introduction to Ctenophora. Gershwin L, Collins A, editors. Berkeley. [accessed 2021 Mar 16]. https://ucmp.berkeley.edu/cnidaria/ctenophora.html.

Common Water Hyacinth

Author: Shaylee Amidon
Edited by: Kaitlyn Butts

Introduction

Biology

The common water hyacinth (*Eichhornia crassipes*) is a common ornamental, free floating, water plant. This plant forms dense matts on top of many types of freshwater sources. The common water hyacinth can get up to 3 feet in height. The leaves of this plant are rounded, waxy, glossy, and thick, the leaves grow on spongy and inflated petioles that rise out of the water. The flowers have 6 petals and are purple colored with blue and yellow markings; the flowers grow on a thick stalk containing 8 to 15 flowers. The roots are dark in color and are feathery in appearance, the roots are also free floating. This species grows very quickly and reproduces both vegetatively through stolons and from seed pods.

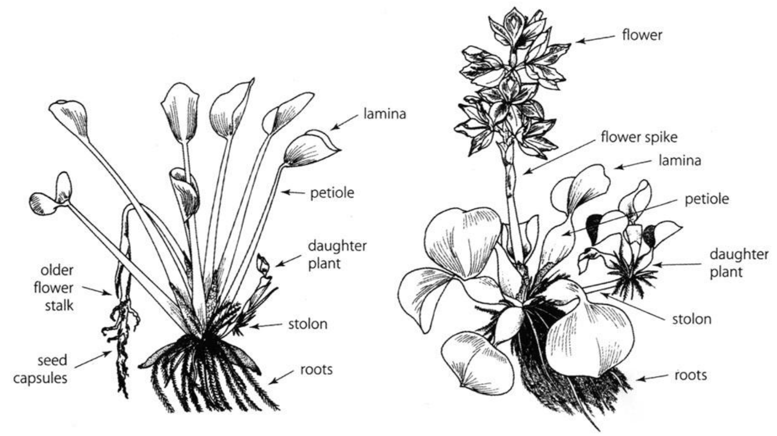


Figure 1. Depiction of the structure of a common water hyacinth https://wiki.nus.edu.sg/display/TAX/Eichhornia+crassipes+-+Water+hyacinth

Native and Invasive Ranges

This species in native to the Amazon basin. The common water hyacinth, however, has spread to many new areas. These areas include: the rest of South America, North America, Asia, and eastern Africa (Danoff-Burg JA, 2002).

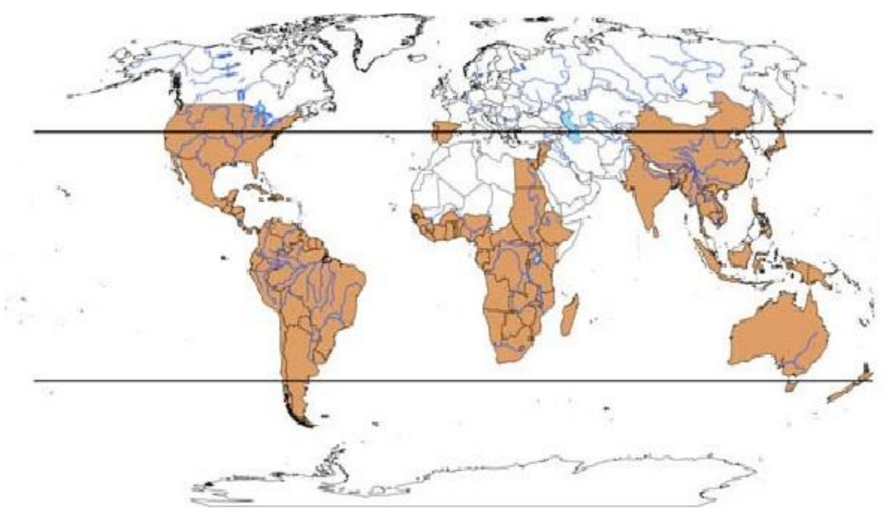


Figure 2. A map depicting where the common water hyacinth can be found. https://wiki.nus.edu.sg/display/TAX/Eichhornia+crassipes+-+Water+hyacinth

Vectors

The common water hyacinth was brought over from South America to the US in 1880's as an ornamental plant because the flowers are quite pretty. This species was also introduced to Egypt in 1879, to Asia in 1888, and to Australia around 1890 (Danoff-Burg JA, 2002).

Impacts

Environmental

The common water hyacinth clogs up the surface of the water. This blocks the sun, causing other water plants to die due to the lack of sunlight which is vital to photosynthesis. The hyacinth can also block the air-water interface, this in turn causes a lack of oxygen in the water, commonly known as hypoxic and anoxic zone causing the deaths of aquatic animals and fish. (Aquatic Weeds, 2019) The lack of fish in the water also causes a lack of food for land predators who eat fish. The plant also provides a breeding ground for mosquitoes which leads to the spread of diseases.

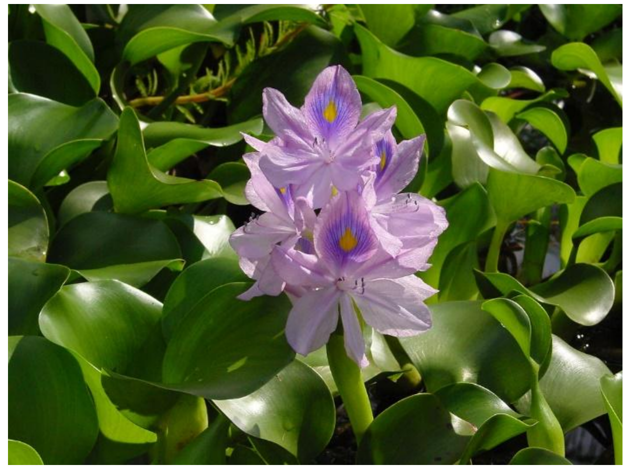


Figure 3. Photo depicting the pretty flowers on the common water hyacinth
https://en.wikipedia.org/wiki/Eichhornia_crassipes

Human Health

One of the impacts that the common water hyacinth has on human health is that the increased population of mosquitoes has a higher likelihood that disease would be spread from mosquitoes to humans; diseases like malaria and west nile virus. Another health impact would be the lack of fish, people who go fishing to eat may not get a fish to eat.

Economic

Due to the fact that the common water hyacinth clogs up waterways, it becomes really hard to do any kind of water activities, such as boating, fishing, or swimming. This negatively impacts any kind of revenue brought in by tourism to a lake. It also impacts the money made off of boat, kayak, and canoe rentals a lake might do.

Success of the Species

The common water hyacinth is one of the world's fastest growing plant species. (Shuyan 2014) This is a great reason it is successful, if a species can reproduce fast, it spreads fast, this also makes a species very hard to get rid of. The species spreads mainly through vegetative reproduction; this is accomplished by stolons (a type of runner), that grow from the base of the plant, which grow into more plants. Another way it spreads is through fragmentation; fragmentation is when a plant can spread and grow from a small fragment of the original plant. “A single plant under ideal conditions can produce 3,000 others in 50 days and cover an area of 600 sq meters in a year” (Danoff-Burg, 2002). This coupled with the fact that they have no natural predator makes them incredibly successful.

Another reason they are so successful is because they can withstand many types of conditions. They primarily grow in temperate and tropical climates; their growth increases in the summer. The plant cannot grow in temperature below 54 degrees Fahrenheit but will regrow when the temperature increases. The common water hyacinth can also handle extremes in nutrient supply and pH levels. This allows them to handle multiple conditions even further, for example runoff from farms which contain nitrates. This species has also been shown to grow in toxic water, water that has been tainted with pollution, this opens many possibilities in places with high levels of pollution. Due to the fact that it spreads incredibly fast and can handle extreme conditions this plant is a highly successful invader.

Mitigation Strategies

Unfortunately, this plant is very hard to control, mitigation and eradication has been attempted in the past with very little success. In the past the US tried to use arsenic to poison the plants, this however only partially got rid of them, on top of that arsenic also poisoned the rest of the ecosystem. After that explosives and fire was used in an attempt to control the plants, this also did not work because the plants reproduce from small fragments (Danoff-Burg, 2002).

One strategy for controlling common water hyacinth now is manually going and cutting them and removing them from the bodies of water they inhabit. This is an expensive method because it is slow and laborious. (Shuyan 2014) This method is also not extremely effective because the plants grow so fast, they regrow almost as soon as they get removed. One method that was used that had a significant effect was draining the water where it is growing to prevent it from getting the nutrients and water it needs. This method also impacts the environment negatively as well as prevents the use of the water bodies.

Pesticides are also used on the common water hyacinth but are not used often, at least in the US, because there are only 6 pesticides that are ok to use for water (Shuyan 2014). There are only 6 pesticides used for water because testing new pesticides is expensive. Another reason they are not used often is because of the plants fast growth rate, pesticides do not work instantaneously, and this fact needs to be considered against the growth rate. (Shuyan 2014)

The most effective method of control found is the use of predators from the common water hyacinths natural environment. This method is based on the logic that the species does so well because it does not have a natural predator where it invades. This is a careful process as the species introduced for control should not cause more harm. There have been 4 species introduced to control the common water hyacinth, 2 species of weevil and 2 species of moth. The two weevil species are *Neochetina eichhorniae* and *Neochetina bruchi,* and the two species of moths introduced are *Niphograpta albiguttalis* and *Xubida infusella*. (Shuyan 2014) These specific species are host specific to the hyacinth and should not cause further harm to their non-native environments. This control method is a self-sustaining one. (Shuyan 2014)

Conclusion

There are many important things that can be taken from this case study; Ones that should be considered is how quickly the common water hyacinth grows, how it can withstand many environments, how it can grow in toxic environments, and how hard it is to control. I think further research should be done in mitigation strategies. Climate change impacts should also be researched as increase in temperature will continue to cause the plant to spread

References:

Common Water Weeds - Water Hyacinth. Aquatic Weeds. 2019 Jun 17 [accessed 2021 Mar 20]. http://www.aquaticweeds.com/2019/06/common-water-weeds-water-hyacinth/

Danoff-Burg DJA. Invasion Biology Introduced Species Summary Project - Columbia University. [accessed 2021 Mar 20]. http://www.columbia.edu/itc/cerc/danoff-burg/invasion_bio/inv_spp_summ/water%252520hyacinth.html

NOAA Great Lakes Environmental Research Laboratory. NOAA National Center for Research on Aquatic Invasive Species (NCRAIS). Nonindigenous Aquatic Species. [accessed 2021 Mar 20]. https://nas.er.usgs.gov/queries/greatlakes/FactSheet.aspx?SpeciesID=11&Potential=Y&Type=2&HUCNumber

Shuyan L. Wiki.nus. 2014 [accessed 2021 Mar 21]. https://wiki.nus.edu.sg/display/TAX/Eichhornia+crassipes+-+Water+hyacinth

Water Hyacinth. Western New York PRISM. 2019 Dec 9 [accessed 2021 Mar 21]. https://www.wnyprism.org/invasive_species/water-hyacinth/#:~:text=Water%20hyacinth%20infestations%20can%20be,also%20used%20as%20bio%2Dcontrols.&text=Water%20hyacinth%20was%20introduced%20as,aquarium%20and%20water%20garden%20release.

Invasion of two species of green algae (genus *Caulerpa*) in the Mediterranean Sea

Author: Conor Wiley

Editor: Abbigail Felix

Introduction:

Marine macroalgae make up 20% of all invasive species in the ocean (Glasby, 2012). And when it comes to macroalgae, the Mediterranean Sea is the most heavily invaded marine region in the world (Vázquez-Luis *et al.*, 2012), as around 100 species of invasive macroalgae have been introduced there (Klein & Verlaque, 2008). Therefore, analyzing a case study involving invasive macroalgae in the Mediterranean Sea seems the best way to istroduce the unique characteristics of marine macroalgae. Of all the invasive species established in the Mediterranean, none are as infamous as the green algae species *Caulerpa taxifolia* and *Caulerpa racemosa*. Belonging to the Caulerpaceae family of the phylum Chlorophyta, both *C. taxifolia* and *C. racemosa* are green algae that are commonly found in tropical and sub-tropical waters (Yeh & Chen, 2004). Both species are native to a number of locations, such as much of the Indian and Pacific Oceans, Australia, the Caribbean Sea and more (Hoddle, 2019). The invasive strain of *C. taxifolia* is frequently called the "aquarium strain" in the literature because of its origin and for its numerous differences from the native strain. Molecular study has confirmed that the two strains are identical (Glasby *et al.*, 2005).

Figure SEQ Figure * ARABIC 1: *Caulerpa taxifolia* (left) and *Caulerpa racemosa* (right)

https://cisr.ucr.edu/invasive-species/caulerpa-taxifolia-or-killer-alga
https://www.monaconatureencyclopedia.com/caulerpa-racemosa/?lang=en

Impacts:

Both species of *Caulerpa* cause serious ecological and economic harm to the Mediterranean Sea and beyond. *C. taxifolia*'s impacts have been more widely studied than *C. racemosa*'s, however since the two species are very similar in most aspects it can be assumed that their impacts are similar as well. Both species create dense mats that smother other algae, marine plants, sessile organisms, and the sediment itself (Hoddle, 2019). *C. taxifolia* invades both open and sheltered areas and spreads very rapidly (Glasby, 2012). It has been shown to positively impact recruitment of clams but negatively impact the growth and survival of those clams. *C. taxifolia* and *C. racemosa* outcompete native algal species due to their ability to tolerate environmental stress (Klein & Verlaque, 2008). *C. racemosa* affects the feeding habits of herbivorous amphipods by pushing out their preferred algae to feed upon (Vázquez-Luis *et al.*, 2012). Both species have been shown to reduce benthic fish abundance in invaded areas (Glasby, 2012). A particularly interesting aspect of *Caulerpa*'s biology is the presence of a toxin called caulerpenyne, a major metabolite within the algae (Marić *et al.*, 2017). This toxin has been shown to inhibit biological properties of zebrafish, and buildup of this toxin within the bodies of fish can make them inedible for humans (Hoddle, 2019).

One of the most impacted areas are seagrass beds. While there is little evidence of negative impacts on seagrass beds by *C. taxifolia* (Glasby, 2012), the impacts of *C. racemosa* have been studied. The number of flowering seagrass shoots decreases in the presence of *C. racemosa* (Ceccherelli *et al.*, 2014). This is potentially due to the way seagrasses get their nutrients: primarily from the sediment through their roots. Conversely, *C. racemosa* gets nutrients from both the water column and the sediment. Despite this, there is a question as to whether or not *C. racemosa* drives the loss of seagrasses or if it is merely a passenger benefitting from a problem caused by humans. Seagrass beds are disturbed through human activity by dredging and trawling, and *C. racemosa* can be found along the edges of disturbed beds. Additionally, areas with stronger seagrass presence contain less *C. racemosa*.

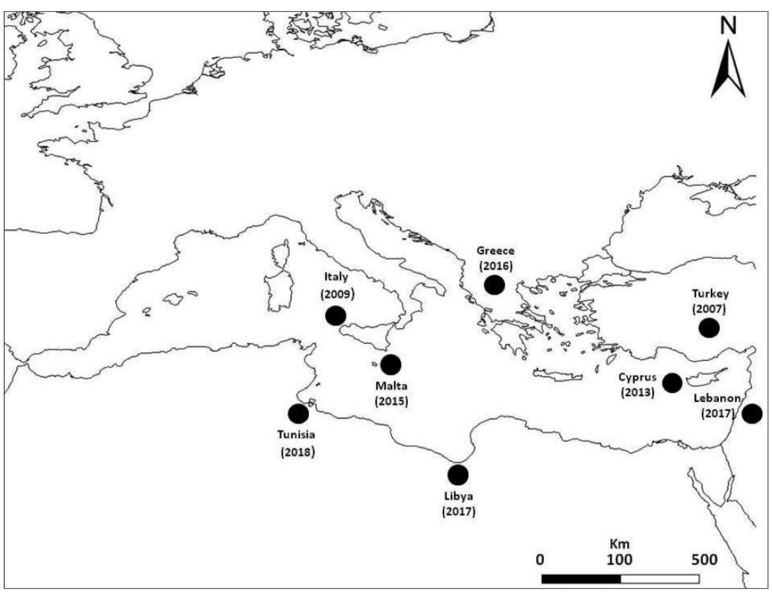


Figure 2: Map showing the countries in which Caulerpa taxifolia has been observed since its establishment from Mannino et al., 2019.

Despite all these negative impacts, there are still some ways *Caulerpa* positively impacts the areas which it inhabits. In 2012, Gribben *et al.* found that *C. taxifolia* presence positively affected the survival of the gastropod *B. australis*. They concluded that while the invasive species may have negative impacts for infauna such as bivalves it also has positive impacts for epifauna, and these impacts need to be weighted when discussing *C. taxifolia* overall.

Vectors:

Both species of *Caulerpa* entered the Mediterranean through the aquarium trade, one of the primary vectors of this algae. Released specimens can establish new invasions if not controlled. The primary vector for *Caulerpa* is shipping; fragments of the algae are transported both through fouling on the hulls of ships and through ballast water (Hoddle, 2019). Fragments can also be transported through currents.

The aquarium strain of *C. taxifolia* was selected by aquarium managers of the Wilhelm Zoo in Stuttgart, Germany for its tolerance towards cold water in 1980, and by 1984 a wild colony of this strain has been observed in the Mediterranean for the first time (Hoddle, 2019). Since its establishment, the aquarium strain has been observed within the borders of eight countries in the Mediterranean as well as several locations in south Australia and California (Wright, 2005).

C. racemosa came from Australia to the Mediterranean in 1990, being observed for the first time in Libya (Klein & Verlaque, 2008). How this species was initially introduced is still unclear. Since its establishment, it has been observed in twelve countries and all of the Mediterranean islands.

Why are they successful:

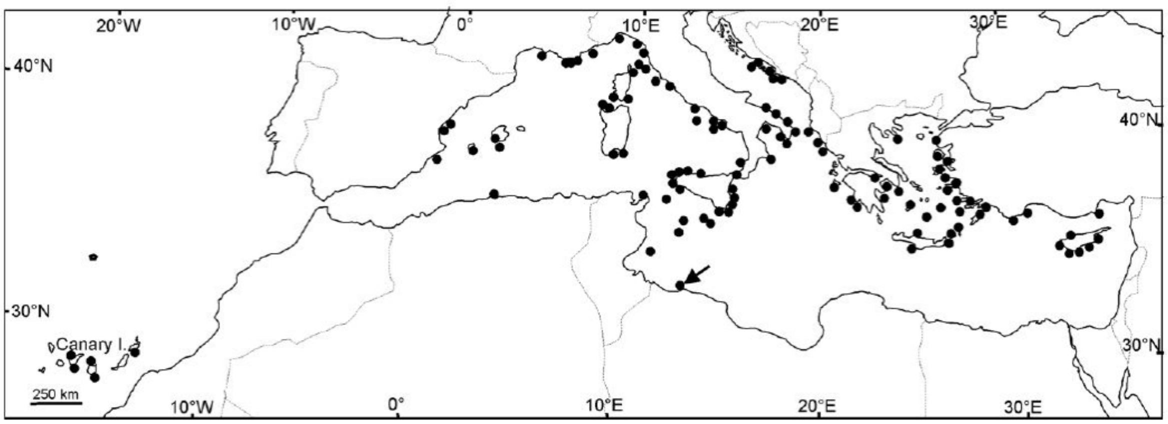


Figure 3: Map showing observed colonies of *Caulerpa racemosa* in the Mediterranean Sea and the Canary Islands from Klein & Verlaque, 2008. The arrowhead represents the location it was first observed at in Libya.

There are multiple factors belonging to *C. taxifolia* and *C. racemosa* which make them successful as invaders. The aquarium strain of *C. taxifolia* was specifically selected for its cold-water tolerance, so it and *C. racemosa* are more resistant to temperature fluctuations than native species (Hoddle, 2019). Additionally, *C. taxifolia* has high levels of asexual reproduction via fragmentation, and fragments as short as one centimeter can establish a successful individual (Wright, 2005). Additionally, both species of *Caulerpa* create dense mats which suffocate native species and outcompete them for resources.

Detection:

Early detection of *C. taxifolia* and *C. racemosa* in new areas is critical to the management of both invasive species. When the aquarium strain of *C. taxifolia* appeared in California, the Southern California Caulerpa Action Team (SCCAT) was formed to respond to the threat (Fisheries, 2019). State and local governments along with private organizations came together in this committee to monitor and eradicate any new incidents of *C. taxifolia* or other *Caulerpa* infestation in California waters. The committee took legal and educational action to use preventative measures against future *Caulerpa* invasions. Legally, the Assembly Bill 1334 makes owning, selling, or moving *C. taxifolia* in California illegal, and San Diego passed a city ordinance restricting the possession of the entire *Caulerpa* genus. NOAA has provided online educational materials describing *Caulerpa* and urging mariners to check their boats for infestations, as well as providing information on how to handle *Caulerpa* if it is found. Eradication of *C. taxifolia* in California involved covering the infested areas with tarpaulins and filling the tarpaulins with chlorine, which killed the algae trapped under the tarpaulins (Hoddle, 2019). Unfortunately, the chlorine also eradicated all other marine organisms trapped under the tarpaulins. The managers concluded that the loss of these organisms was a necessary loss to prevent *Caulerpa* from spreading. This project took six years and $7 million to undertake but managed to successfully eradicate *C. taxifolia* in California. The state's battle with *C. taxifolia* highlights the importance of preventative measures and early detection in handling *Caulerpa* as the use of chlorine as an eradication method would prove too economically and ecologically costly to use in areas where *Caulerpa* has spread too much.

Climate Change:

Climate change will increase the number of areas *Caulerpa* could successfully invade. Rising water temperatures will make waters that were once too cold for *Caulerpa* warm enough for the algae to survive. Sea ice melt in the Arctic Ocean will open new shipping routes and increase the risk of invasive species spread to the United States (Nong *et al.*, 2019). These impending changes make monitoring and managing *Caulerpa* and other invasive species more important than ever.

Conclusion:

When it comes to invasive species, *Caulerpa* provides a great example of the invasive algal species which will continue to cause problems in the world's oceans, but it does not cover all of the potential impacts invasive algae can have. Other invasive algae can cause wildly different impacts based on their species, such as algae that form harmful algal blooms. Understanding *Caulerpa* does not mean understanding all marine invasive algae. Additionally, marine algae tend to be species that are poorly understood by the public due to their uncharismatic nature, and this will result in poorer public influence on governments to act against invasive algae. This examination of *Caulerpa* is just one case study which needs to be done in order to solve the larger problem of marine invasive algae in the world.

References:

Ceccherelli G, Pinna S, Cusseddu V, Bulleri F. The role of disturbance in promoting the spread of the invasive seaweed *Caulerpa racemosa* in seagrass meadows. Biological Invasions. 2014;16(12):2737–2745. doi:10.1007/s10530-014-0700-7

Cevik C, Yokes MB, Cavas L, Erkol LI, Derici OB, Verlaque M. First report of *Caulerpa taxifolia* (Bryopsidales, Chlorophyta) on the Levantine coast (Turkey, Eastern Mediterranean). Estuarine, Coastal and Shelf Science. 2007;74(3):549–556. doi:10.1016/j.ecss.2007.05.031

Fisheries NOAA. Aquatic Invasive Species on the West Coast: *Caulerpa taxifolia*. NOAA. 2019 Sep 30 [accessed 2021 Mar 21]. https://www.fisheries.noaa.gov/west-coast/habitat-conservation/aquatic-invasive-species-west-coast-caulerpa-taxifolia

Glasby TM, Creese RG, Gibson PT. Experimental use of salt to control the invasive marine alga Caulerpa taxifolia in New South Wales, Australia. Biological Conservation. 2005;122(4):573–580. doi:10.1016/j.biocon.2004.09.012

Glasby TM. Caulerpa taxifolia in seagrass meadows: killer or opportunistic weed? Biological Invasions. 2012;15(5):1017–1035. doi:10.1007/s10530-012-0347-1

Gribben PE, Byers JE, Wright JT, Glasby TM. Positive versus negative effects of an invasive ecosystem engineer on different components of a marine ecosystem. Oikos. 2012;122(6):816–824. doi:10.1111/j.1600-0706.2012.20868.x

Hoddle M. Caulerpa Taxifolia or Killer Alga. Center for Invasive Species Research. 2019 Dec 26 [accessed 2021 Mar 7]. https://cisr.ucr.edu/invasive-species/caulerpa-taxifolia-or-killer-alga

Infantes E, Terrados J, Orfila A. Assessment of substratum effect on the distribution of two invasive Caulerpa (Chlorophyta) species. Estuarine, Coastal and Shelf Science. 2011;91(3):434–441. doi:10.1016/j.ecss.2010.11.005

Klein J, Verlaque M. The Caulerpa racemosa invasion: A critical review. Marine Pollution Bulletin. 2008;56(2):205–225. doi:10.1016/j.marpolbul.2007.09.043

Mannino AM, Cicero F, Toccaceli M, Pinna M, Balistreri P. Distribution of Caulerpa taxifolia var. distichophylla (Sonder) Verlaque, Huisman & Procaccini in the Mediterranean Sea. Nature Conservation. 2019;37:17–29. doi:10.3897/natureconservation.37.33079

Marić P, Ahel M, Senta I, Terzić S, Mikac I, Žuljević A, Smital T. Effect-directed analysis reveals inhibition of zebrafish uptake transporter Oatp1d1 by caulerpenyne, a major secondary metabolite from the invasive marine alga Caulerpa taxifolia. Chemosphere. 2017;174:643–654. doi:10.1016/j.chemosphere.2017.02.007

Nong D, Warziniack T, Countryman AM, Grey EK. Melting Arctic sea ice: Implications for nonindigenous species (NIS) spread in the United States. Environmental Science & Policy. 2019;91:81–91. doi:10.1016/j.envsci.2018.10.013

Ruitton S, Javel F, Culioli J-M, Meinesz A, Pergent G, Verlaque M. First assessment of the Caulerpa racemosa (Caulerpales, Chlorophyta) invasion along the French Mediterranean coast. Marine Pollution Bulletin. 2005;50(10):1061–1068. doi:10.1016/j.marpolbul.2005.04.009

Vázquez-Luis M, Sanchez-Jerez P, Bayle-Sempere JT. Does the invasion of *Caulerpa racemosa var. cylindracea* affect the feeding habits of amphipods (Crustacea: Amphipoda)? Journal of the Marine Biological Association of the United Kingdom. 2012;93(1):87–94. doi:10.1017/s0025315412000288

Wright JT. Differences between native and invasive *Caulerpa taxifolia*: a link between asexual fragmentation and abundance in invasive populations. Marine Biology. 2005;147(2):559–569. doi:10.1007/s00227-005-1561-5

Yeh W-J, Chen G-Y. Nuclear rDNA and internal transcribed spacer sequences clarify *Caulerpa racemosa* vars. from other *Caulerpa* species. Aquatic Botany. 2004;80(3):193–207. doi:10.1016/j.aquabot.2004.07.008

Tunicate invasion of aquaculture resources and human activities

Authors: Emily Lewis, Bradley Spear

Biology:

Tunicates are distributed in ocean waters from the polar regions to the tropics. Free-swimming tunicates are found throughout the oceans as plankton, while sessile forms grow mainly on solid surfaces. The tunicates reproduction and vectors allow them to travel around the world and have a good chance of survival. The question is then raised, what happens when they invade a new environment? In order to grasp the complexity of invasive tunicate invasions we must begin with basic taxonomy and anatomy. This background will provide necessary information in order to understand the organism and how it interfaces with its surrounding environment.

Tunicates belong to the phylum Chordata which is characterized by having a “notochord, a dorsal hollow nerve cord, pharyngeal slits, and a post-anal tail" (McNeil, 1981). More specifically, tunicates are part of the class Ascidian, along with sea squirts, which are characterized by being marine invertebrate filter feeders, having a sac-like outer “tunic” made of a polysaccharide. There are three types of tunicates: solitary tunicates, colonial tunicates, and drifting tunicates. Solitary tunicates are tunicates that settle and grow alone, while colonial tunicates settle in batches and live alongside one another. Drifting tunicates do not settle on any substrate and use their siphons to move (Tunicates). Colonial ascidians are the only known chordates capable of regenerating all body tissues. The process was documented by Brown, in a study describing “whole body regeneration (WBR), as the ability to form an entirely new individual from the peripheral vasculature” (Brown, 2009). This is of special interest for researchers because they are phylogenetically close to humans and can have outside applications for medical advancements. The multiple ways tunicates can disperse and their regenerative capabilities makes them a resilient organism. This resilience proves to be a problem in the context of invasive species, especially impacting aquaculture.

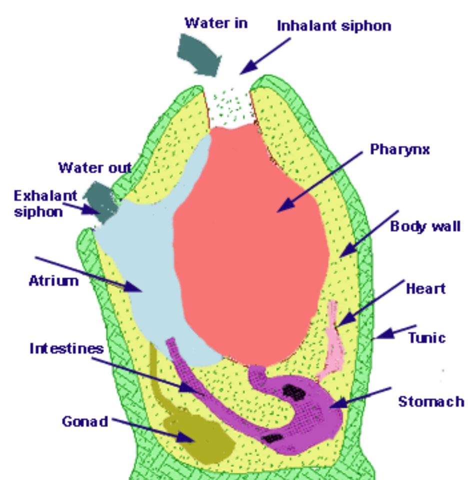


Figure 1: The anatomy of a tunicate. You can visibly see the inhalant and exhalant siphons that were previously mentioned as well as the digestive system of the tunicate. http://www.mesa.edu.au/tunicates/

To begin with anatomy, the big question is how does the organism gain its nutrients. Tunicates have an inhalant siphon where water is facilitated and sucked into the pharynx with the help of cilia. Inside the pharynx is where the separation of nutrients and water occurs. Cilia and mucus filter and capture plankton and other suspended organic matter, which is then transported to the digestive system. The exhalant siphon allows the tunicate to discard any water that was filtered through.

Distribution:

In this study, the focus was primarily on the invasive tunicate *Botrylloides violaceus*, commonly known as the orange sheath tunicate. It is native to the Pacific Northwest and is now located in temporal regions across the globe (see Figure 2).

Figure 2: Distribution of *Botrylloides violaceus* throughout the world. It is extremely prevalent in the Pacific northwest as well as along the North Atlantic coastline of North America going up into Canada. It is located in several other regions around the world but not as common (Deibel et al., 2014). https://www.researchgate.net/figure/Global-occurrence-of-Botrylloides-violaceus-as-reflected-by-information-from-several_fig2_262865034

The dispersal history of *B. violaceus* has been difficult to trace due to its similar looks to other *Botrylloides* species, making it hard to identify what species it is. However, *B. violaceus* is completely dominant over commercial species, and can block settlement of native species and smother organisms by growing on cultured stock. It is the most dominant species of ascidian on anthropogenic structures, between native or non-native species. This tunicate doesn't discriminate against hard substrates and will commonly be found on marina floats, pilings, and aquaculture installations. This will in turn, not only impact the surrounding environment and biodiversity, but more specifically the culture of other species and anthropogenic activities.

B. violaceus is introduced into new environments in a few ways. Firstly, they are introduced via the dispersal of asexual buds. This process is also known as fragmentation, and the pelagic buds can float along and last for up to 35 days. Another introduction pathway is the utilization of short-term locomotion with swimming, during the larval stage. This larval stage has certain negative and positive trade-offs. It focuses more of their energy budget into locomotion instead of survival for an extended period of time, like the asexual buds. Allowing them to have the ability to, somewhat chose the direction they can travel, in an attempt to find a suitable habitat but only for about two days. The asexual buds choose to focus on survival and be at the grace of the currents to find a suitable habitat.

Other than reproduction they are also introduced to new areas by ship fouling, which is when they settle and grow on the submerged portion of a ship. In this case they can outcompete other organisms even through adverse conditions such as pollution. A study by Agell (2003) analyzed the effects of pollution in the, closely related to tunicates, colonial ascidian *Pseudodistoma crucigaster*. Their goal was to find early biomarkers to detect some effect of pollution before changes in community structure or species composition occur. They did this by examining the effect of Cu on growth rates and presence of resistance forms. A transplant experiment occurred where they studied a Cu polluted harbor and recorded growth rates. They concluded that "HSP's can be used in this ascidian as an early warning system for sublethal pollution" (Agell 2003). This study could have outside applications by using tunicate species for pollution indication but more research must be done. Introduction also naturally occurs when they are on floating debris or organic material allowing them to travel and colonize in new areas.

Invasive capabilities and impacts:

These tunicates are extremely successful invaders for many reasons. Firstly, they grow very quickly and therefore can reproduce quickly due to this short maturation time. *B. violaceus* also has very few predators that very rarely prey on this species. These include flatworms and gastropods, which are both benthic species. They may not prey on *B. violaceus* very often possibly due to unpalatable chemical defenses that the tunicate would use to deter predators. Another reason is because of where the tunicate tends to invade. *B. violaceus* tends to invade aquaculture installations that float at the surface. Since the predators of this tunicate are benthic species, they are not able to reach a free floating device, which allows the tunicate to grow, reproduce, and spread with very little time as free swimming larvae (Simkanin, 2013). These organisms also have a high phenotypic plasticity. Their phenotypic plasticity, can be described by, the ability to adjust their growth and reproductive strategy in response to variable environmental conditions, making them remarkably resilient. According to a study by Millar "tunicates can survive stressful environmental conditions by discontinuing sexual reproduction and reducing the rate of budding" Millar (1971).

Figure 3: A visual on how tunicates can disperse and colonize through the reproductive method of budding displayed by the smaller orange buds extending out from the larger buds. Also shows, in the top right what appears to be a white nudibranch feeding or traveling over the tunicate. https://racerocks.ca/category/species/subphylum-urochordata

Budding is a form of growth and colonization, shown in figure 3 below, by the smaller orange spots spreading out from the main zooids. If all zooids are lost and only the vascular ampullae in the matrix survive, then vascular budding can generate a new colony when conditions improve. The vascular ampullae is like the colonial blood vessel for the organism carrying, blood and nutrients. Habitat destruction also allows these organisms to take over a whole area because it clears the surfaces for them to settle. Climate change is also a major factor which will be talked about a little later.

B. violaceus can have positive and negative impacts on the environment they have invaded. One positive effect is that they do improve the water quality by removing suspended particulate matter. That is where the positive effects end and the negative impacts begin. They cause the spread of pathogens that affect certain shellfish, including *Vibrio*. This is a huge problem for aquaculture, due to their ability to grow on the aquaculture installations, which often hold shellfish primarily for human consumption.

A study by Costello investigated the effect of invasive tunicates on the success of pathogens that affect commercial bivalves. The commercial bivalve species included the cultured species *Ostrea edulis* (European flat oyster), *Crassostrea gigas* (Pacific oyster), and the fished species *Cerastoderma edule* (Common cockle). Just for a reference an investigation by NOAA Fisheries Aquaculture labeled the United States as producing up to "$180 million per year in the oyster industry" (NOAA, 2017). That number alone makes the tunicate investigations worth it. One of the focal pathogens in the study was *Vibrio aestuarianus* along with others. The range of pathogens in their molluscan hosts was determined and the tunicate *Botrylloides violaceus* was then then screened for the same pathogen, field samples from oyster culture sites. "Sanger sequencing and histology confirmed the presence of *V. aestuarianus* in the tunicates, suggesting that the tunicate can facilitate replication of this species" (Costello, 2021). The virus is hypothesized to enter the filtering system of the tunicate and can be expelled at a later date or assimilated into the organism that eats the tunicate. This finding has great implications to the understanding of human health as it pertains to virus transfer through food chains.

Typically finfish and shellfish are cultured within net pen cages. These cages can potentially become infested with a mat of colonial tunicates, that will inherently reduce or eliminate the flow of oxygen and particulate matter through that mesh. Thus, resulting in suffocation or starvation of the species inside. They may also overgrow seed collectors in aquaculture, smothering juvenile organisms that are being cultured or excluding settlement of the desired species in that location. The competition for space with these tunicates will also greatly affect the community diversity in a negative way. *B. violaceus* are also a nuisance fouling organism, growing on the hulls of ships, docks, and buoys, allowing for further spread of the species if not removed from these areas as often as possible.

Mitigation:

In general, the three principles of eradicate, contain and mitigate is the strategy for controlling the spread of an invasive species. Eradication is usually the first option because it is most successful in the early stage of an introduction. Eradication becomes very difficult with tunicate species due to the geographic dispersal. Containment utilizes the concept of restriction. Restriction by some means of the space occupied by the invasive species. This is particularly difficult in the case of colonial tunicates that have the ability to spread asexually by means of budding, fragmentation or larval dispersal. The final option is mitigation. Mitigation involves the development of management strategies to reduce the impact of the invasive species. Because the introduction of tunicates can't be quickly eradicated, this is often the only remaining option.

The best strategy to control tunicate populations would be a natural one, usually by Predation. Predation has been shown to be a successful control of the population on these tunicates. One study was done on these organisms revealing that predation can also create zonation due to predators only eating what is closest to them. Another way to control the population is routine removal of these tunicates from aquaculture equipment before they are big enough to reproduce, which prevents the spread of these species. Some suggest that equipment should be treated with freshwater or vinegar when overgrowth occurs. However, some scientists such as Coutts and Sinner actually "caution against de-fouling operations because fragmentation of these tunicates would exaggerate the problem further" (Coutts, 2004).

Climate change works in the favor of these tunicates, as a warming climate gives them a further range where they can handle the temperature allowing them to expand their populations beyond their typical borders. In a study by Brunetti (1980), he grew *Botrylloide* tunicates at nine different combinations of temperatures between 13 and 25 degrees Celsius and with a salinity range of 25ppt to 40ppt. He detected no effects on the tunicates until the fifth generation, but high temperatures and intermediate salinity stimulated gonad maturation at this point. In general, the adult colonies tolerated a wider range of temperature and salinity conditions than the younger colonies.

Conclusion:

Botrylloides violaceus is extremely important in terms of invasive species in the present and in the future as we turn towards aquaculture. They cover surfaces blocking macroalgae and other native species from settling in these areas. They cause diseases within cultured shellfish, which can result in humans becoming sick, and with aquaculture becoming a prominent producer of shellfish this can cause problems with the global food supply. More information is required to accurately assess the impact of these species on the growth and survival of cultured shellfish, which is critical to devising control measures to reduce the risk of further dispersion. They do not have many predators in their invaded environments, so their populations can grow very large very quickly. Tunicate species exhibit different life history traits depending on food resources and temperature conditions highlighting the urgent need for studies documenting the growth, generation time and longevity as it pertains to local populations, like the Gulf of Maine and globally as a successful invasive species.

References:

Agell, G, X. Turon, S. De Caralt, S. López-Legentil, M.J. Uriz, Molecular and organism biomarkers of copper pollution in the ascidian *Pseudodistoma crucigaster*, Marine Pollution Bulletin, Volume 48, Issues 7–8, 2004, https://doi.org/10.1016/j.marpolbul.2003.11.001.

Brunetti R., L. Beghi, M. Bressan and M.G. Marin. 1980. Combined effects of temperature and salinity on colonies of *Botryllus schlosseri* and *Botrylloides leachi* (Ascideacea) from the Venetian Lagoon. Mar. Ecol. Prog. Ser. 2: 303-314.

Costello KE, Lynch SA, McAllen R, O'Riordan RM, Culloty SC. The role of invasive tunicates as reservoirs of molluscan pathogens. Biological Invasions. 2020;23(2):641–655. doi:10.1007/s10530-020-02392-5

Coutts, A.D.M. and J. Sinner. 2004. An updated benefit-cost analysis of management options for *Didemnum vexillum* in Queen Charlotte Sound. Cawthron Report No. 925 prepared for the Marlborough District Council. 14 p.

Deibel, D., McKenzie, C.H., Rise, M.L., Thompson, R.J., Lowen, J.B., Ma, K.C.K., Applin, G., O'Donnell, R., Wells, T., Hall, J.R., Sargent, P., and Pilgrim, B.B. 2014. Recommendations for eradication and control of non-indigenous, colonial ascidian tunicates in Newfoundland harbours. Can. Manuscr. Rep. Fish. Aquat. Sci. 3039

Federico D. Brown Elena L. Keeling Anna D. Le Billie J. Swalla. Whole body regeneration in a colonial ascidian, *Botrylloides violaceus* 08 July 2009 https://doi.org/10.1002/jez.b.21303

https://www.researchgate.net/profile/Claire-Carver/publication/239864955_Biological_Synopsis_of_the_colonial_tunicates_Botryllus_schlosseri_and_Botrylloides_violaceus/links/00463534ff9dd225d9000000/Biological-Synopsis-of-the-colonial-tunicates-Botryllus-schlosseri-and-Botrylloides-violaceus.pdf

Millar, R.H. 1971. The biology of ascidians. Adv. Mar. Biol. 9: 1-100.

NOAA, https://www.fisheries.noaa.gov/topic/aquaculture

R. McNeil Alexander. The chordates. CUP Archive 1981. 0521236584,9780521236584

Simkanin C, Dower JF, Filip N, Jamieson G, Therriault TW. Biotic resistance to the infiltration of natural benthic habitats: Examining the role of predation in the distribution of the invasive ascidian *Botrylloides violaceus*. Journal of Experimental Marine Biology and Ecology. 2013;439:76–83. doi:10.1016/j.jembe.2012.10.004

Tunicates. coraldigest. [accessed 2021 Mar 21]. https://www.coraldigest.org/index.php/Tunicates

Mammals: Invasion of Pablo Escobar’s Hippos (*Hippopotamus amphibius)*

Authors: Abbigail Felix & Doyle Proto

<u>History of Pablo Escobar’s Hippopotamuses (*Hippopotamus amphibius)*</u>

Pablo Escobar was a notorious drug lord located in Columbia who assembled the Medellín Cartel. Surprisingly, Escobar was also a lifelong animal lover and ran on a political platform that advocated to plant trees and rescue endangered animals in Columbia’s jungles. When he rose to power, he created a private zoo on his estate, Hacienda Nápoles, that contained flamingos, giraffes, and rhinos among other exotic wildlife. One of his more impressive additions were 4 adult hippopotamuses (3 female, 1 male) from New Orleans. After his death in 1993, anti-narcotics agents worked to move most of the animals to zoos across South America. However, the rhinos and hippos were too large and aggressive to safely transport so they remained at Hacienda Nápoles (Subalusky *et al.*, 2021).

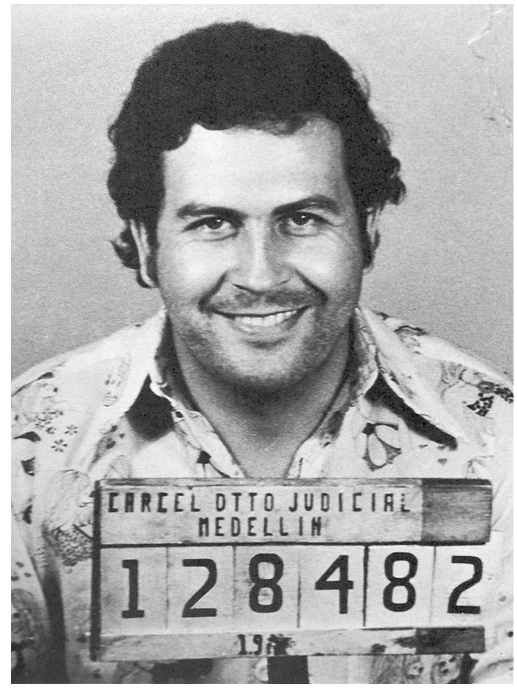


Figure 10. The infamous 1976 mugshot of Columbian drug lord and politician, Pablo Escobar, who brought hippos into Columbia (Colombian National Police, 1981).

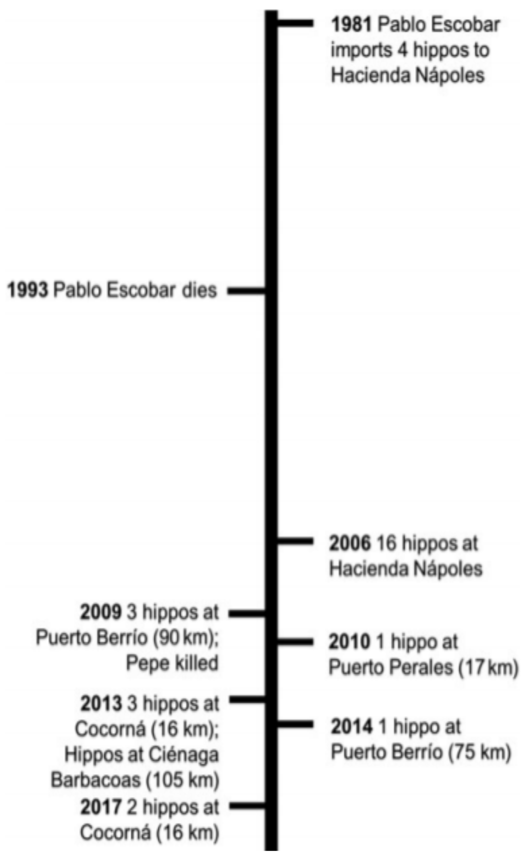


Figure 2. The hippos that have escaped from Pablo Escobar's estate have dispersed across time and settled in different parts of the basin. Distance travelled by the hippos was measured as a straight line from said estate (Subalusky *et al.,* 2021).

The estate and remaining animals were left neglected for over a decade. By the time the Columbian government gained ownership of the property once more in 2006, the rhinos had completely died out while the hippos flourished, and the population grew to 16 individuals. Three years later, 3 hippos were sighted more than 90km away in the Magdalena River Basin (Subalusky *et al.,* 2021). Since then, around 8 more hippos have been recorded along the river, but researchers estimate there could be as many as 100 individuals within the basin. Projections show the hippos could reach a population of over 5,000 individuals by 2050 at a growth rate of 11%. If management occurs and/or resources the population depend on become scarce, the projections show only a 5% growth rate lowering the number of hippos to about 400-800 by 2050 (Castelblanco-Martínez *et al.,* 2021). In order to understand how these hippos became the world's sole species of invasive megafauna, we need to understand aquatic mammals and how they have evolved.

<u>Aquatic Mammals and Hippos</u>

Many aquatic mammals such as cetaceans rely on expansive migratory ranges to breed, rear young, and forage. Various aquatic mammals are endangered in their defined home ranges due to overhunting and warming waters. The hippopotamus's native range is sub-Saharan Africa and the Nile River. Archaeological and paleontological evidence indicate a pre-historical range that once spanned across all corners of Africa even in the Sahara Deseret which at the time was savannah in a time period known as the African humid period during the Pleistocene and Holocene geological epoch (Eltringham, S. K *et al.,* 1999). Historically their ranges began to shrink as humans hunted them into their present habitat. Hunting of hippos likely developed for a variety of reasons such as threat prevention and as a food resource which drastically changed the surrounding ecosystems.

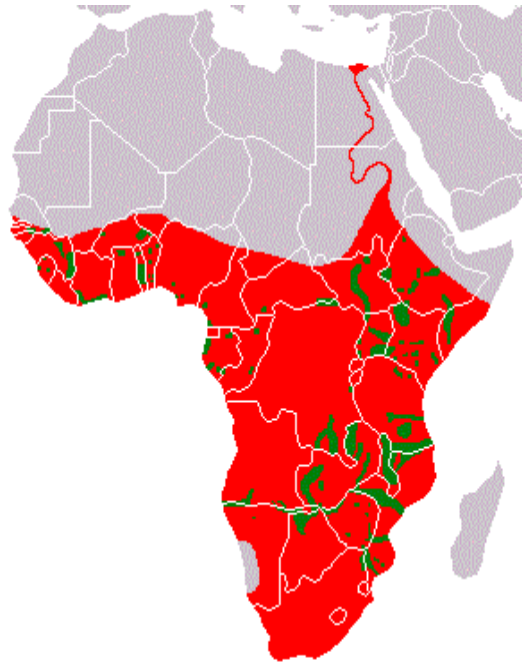


Figure 3. Red is the historical range of the hippopotamus. Green is the current range Africa. Hippos are currently vulnerable in their home range (Lewiston, 2017)

Aquatic mammals fill specific niches within their environment which may not be available everywhere and therefore reduces their success as invasive species. Many aquatic mammals such as beavers, sea otters, and seals represent keystone species. Keystone species are species of animals that help to maintain the wider ecosystem. Typically, a species is designated as a keystone species if the ecosystem would drastically change without them. While some keystone species such as wolves are top predators and fill niches high on the trophic level, others such as hippos and beavers are ecosystem engineers.

Hippos have massive impacts on the environment and drastically change the very structure of their habitat primarily the flow of nutrients. While this allows them to change an ecosystem to better fit their needs it can lead to several negative impacts for other species including humans. Hippos produce large amounts of waste which can lead to harmful algal blooms and contaminate water supplies. Hippos also function as bioturbators and stir up sediment by walking on the bottom of the river. In the Magdalena river basin, sediment disruption may affect benthic organisms (Subalusky *et al.,* 2021).

While the negative impacts of large mammals on novel ecosystems are an obvious problem, the majority have low reproductive rates compared to other invasive species. The internal gestation of young is one of the defining traits of placental mammals. This method of reproduction heavily favors high parental investment and long rearing times. Mammals do come in a range of different r/K selection, but when compared to the whole canon of life, mammals generally share a K-type architype. Hippos, or *Hippopotamus amphibius*, are a strong K-type with the time between calves for a hippo cow being two to three years. Hippo cows, or female hippos, become sexually mature at the age of 8 and live for about 40 to 50 years. This gives cows a time span of 32-42 years to breed and give birth to calves who will stay with their mothers for 6 to 8 years. They will be nursed by their mothers for roughly eight months before being weaned and eating a combination of fresh and pre-chewed grass. A hippo cow will have more than one calf in her care at a time, however as discussed, they are usually separated by two or three years. Calves are significantly smaller than the adults and this sometimes ends in death or injury when caught between fighting adults. Therefore, hippo cows will raise calves for their first weeks away from the bloat, name for a group of hippos, and when in captivity calves are partially raised by zookeepers.

Hippos are endangered in their native habitat which has led to conservation efforts and captive breeding programs to preserve this beloved species. Currently, there are about 476 hippos in captivity around the world (Snyder, 2015). Having such a close relationship with mankind adds to the presumed charisma of the species. While there is no way to quantify how humans will feel about a specific animal there is a common way to interpret it. Generally, the closer an organism is to human beings the more compassion they will show towards it. This does not only refer to phylogenetic terms it also implies like attributes. This mainly relates to traits they possess which can be easily anthropomorphized such as intelligence and empathy.

In this case, hippos have charisma to spare. Hippos are one animal that is commonly taught about early on in education. They are popular in story books, cartoons, movies, zoos, and advertisements. Their personalities can be aggressive and terrifying but also possess a kind of relatable sloth, sunbathing in the water all day to come out and apply their own natural sunscreen. Hippos, in addition to all this, capture the African megafauna mystique. The vast continent of Africa has turned out some of the most powerful forms of animal life known to exist and hippos can count themselves among the lion, the elephant, and the giraffe. This is not even counting those hippos who have gained fame in human society. Fionna the hippo is a 6 month prematurely born hippo at the Cincinnati Zoo, who has captured international attention since her birth. Not only are baby hippos endearing (See Figure 4) but the fact that she was prematurely born kept her in the headlines with updates on her condition. This sentiment of popularity is not only shared within the international community but especially with the people of Colombia's Magdalena River basin. Pablo Escobar's hippos are heralded as local icons just like Fiona is to the city of Cincinnati.

Figure 4. Fionna the Hippo in the Cincinnati Zoo. Her dangerous birth led people around the world to follow her story (NPR, 2017).

Mitigation

Mitigation of Pablo Escobar's hippos will not only be costly to the Columbian government, but extremely political, therefore no real plan is set in place. Presently, the small population of hippos within the Magdalena River basin are slowly expanding through its tributaries and waterways. Magdalena River basin is bounded on the east, south, and west by the northern tip of the Andes mountain range. Current evaluations of the geographic range suggest that they will not be able to move past the mountains and get into the Amazon basin which is one of the primary concerns of them as an invasive species. If this were to occur intense mitigation efforts such as extermination would need to be put in place which as of now is extremely unpopular.

Exterminating the population goes against the wishes of many locals. In 2009, a hippo bull named Pepe was shot by the Colombian military. The killing of Pepe had been motivated by property damage he and family had committed. Pepe had been the mate to a hippo cow named Matilda and had a calf named Hip. The nuclear family had knocked down several fences, ruined local crops, killed several cattle calves, and was becoming a general nuisance in the area. The whole family had been pegged to be killed if not for a large public outcry over the killing of Pepe which halted further action. As stated in earlier sections the hippos had become local icons bringing in tourists and money into the area. This seemingly has been enough to ingratiate the hippos with the local population so that locals and the hippos do not seem to mind occasional interactions.

However, veterinarians across Columbia have suggested spaying and neutering a percentage of the population yearly to control their spread. The cost to spay a female dog can be upwards of 500 dollars (Lynch *et al.*, 2021). In order to perform a similar procedure on a female hippo the anesthesia alone cost 3,000 dollars. Neutering a male dog can cost upwards of 250 dollars and take close to 20 minutes (Lynch *et al.,* 2021). Neutering a male hippo costs 50,000 dollars and the operation can last 12 hours due to their highly mobile testicles (Parker, 2014). Hypothetically, neutering all the male hippos in population, not counting calves, would be effective. The gender ratio in the common hippo works out to roughly 53.9% male and 46.1% female (Pluháček *et al.*, 2015). This would mean that there are about 54 males in the current population which would total around 2.7 million dollars. This is not even accounting for the tracking, the transporting, the maintenance of the facilities and vehicles used, or paying personnel involved.

In order to better illustrate these costs, we will go into the exact compounds that are used to sedate these animals. The compound used to sedate hippos for castration is a mixture of medetomidine, a synthetic drug that can be used as both surgical anesthetic and an analgesic, and ketamine, commonly call horse tranquilizer. For this to be effective on a hippo the mixture must be made to the following specifications: 60 to 80 mg/kg medetomidine and ketamine 1 mg/kg (mg per kg of weight). This mixture will buy the user roughly 27 minutes plus or minus 11.8 minutes of complete immobilization (Stalder *et al.*, 2012). These might not sound like much but keep in mind this is an organism that can weigh upwards of 4500 kg and this dosage level needs to be maintained for 12 hours straight. Management of the Columbian hippo population seems to be a fight that the government is losing, but some positives may come from their introduction.

<u>Broader Influences</u>

During the end of the Pleistocene, the world experienced an extinction event that caused the loss of many large mammals. South America was heavily impacted by the extinction and lost around 80% of the native megafauna (Figueroa *et al.*, 2016). Megafauna are defined as any terrestrial mammal species weighing more than 44 kg and separated into four categories: megaherbivores (>1000 kg), large herbivores (45-999 kg), megacarnivores (>100 kg), and large carnivores (21.5-99 kg) (Mantecón, 2020). Megaherbivores were critical to nutrient cycling and dispersal which affected primary production and vegetation structure (Lundgren *et al.*, 2020). South America was home to giant sloths (>3000 kg), macrauchenias (>1000 kg), and glyptodons

(>2000 kg) whose populations suffered not only due to intense climate change, but also migrating groups of early humans that hunted the already declining populations. The loss of many grazing megafauna also led to the loss of large predators such as the *Canis dirus* better known today as the dire wolf (60-68 kg) and the *Homotherium venezuelensis*, typically known as scimitar-toothed cats (189 kg). The size difference between megaherbivores and megacarnivores led to carnivores needing to hunt in packs to bring down adult animals or targeting young herbivores. Today jaguars (60.5-119 kg), *Panthera onca,* are the largest predators in all of South America while the largest native herbivore is the Southern tapir (150 to 320 kg), *Tapirus terrestris.* The jaguars and tapirs ranges overlap often. However, the jaguars tend to avoid the large tapir and prey on small and medium-sized mammals such as peccaries and capybara. The jaguars are no match for Pablo Escobar's hippos who weigh in at about 1500-4000 kg which has allowed the population to thrive unimpeded.

The case of Pablo Escobar's hippos is a great example of an invasive species possibly filling an empty environmental niche. As previously discussed, hippos, like many megafaunas, are considered ecosystem engineers and change the very composition of the environment. The question at hand is what ecosystem do humans care about? Ecosystems are constantly changing due to range shifts, natural disasters, and human interactions including physical alterations and climate change. Range shifts happen naturally as populations need access to resources as they grow. For example, some aquatic mammals such as whales have migration routes that are changing due to warming water and destruction of critical habitat. When the ecological impacts of invasive species are discussed, should researchers worry about the structure of the ecosystem as it is today or historical iterations such as during the last ice age?

On what timescale should invasive species be judged? There are two possible options. The first is an ecological time scale. Ecosystems are constantly changing due to several natural and

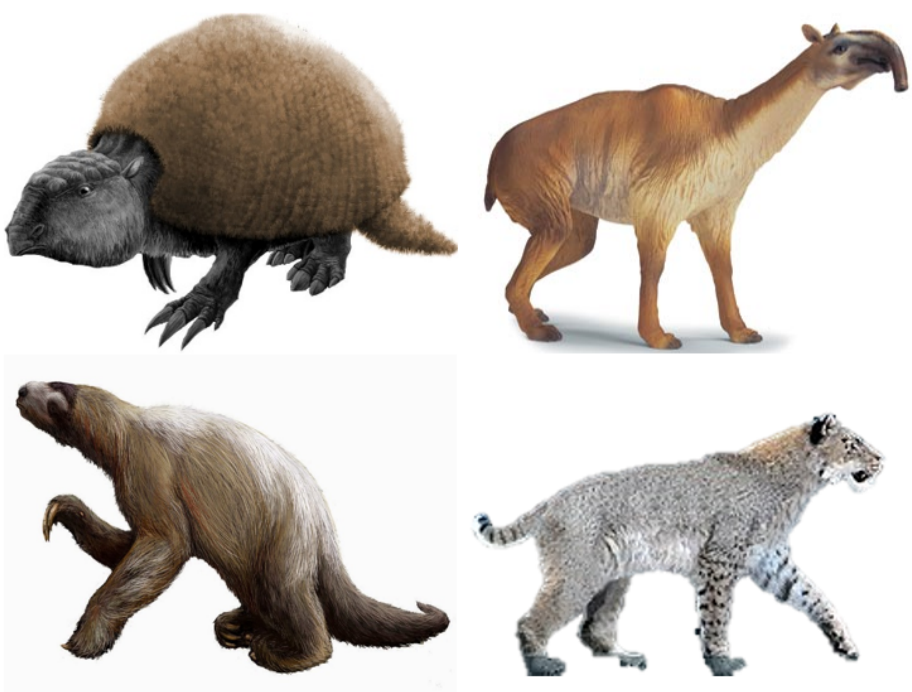


Figure 5. Examples of common megafauna of the Pleistocene who's extinction have left ecological niches open. Starting at the top left we have the glyptodon and to the right the Macrauchenia. On the bottom row is the giant sloth and the Homotherium venezuelensis. https://www.thoughtco.com/glyptodon-carved-tooth-1093213

anthropogenic causes as previously mentioned. Ecological time scales revolve around the physical and biological processes of a specific ecosystem spanning anywhere from a few seconds to decades (Carroll *et al.*, 2007). This time scale would encourage researchers to use current data as well as recent historical records to determine impact of invasive species. The focus on recent events would disregard any vacant ecological niches left over from prehistoric extinctions.

The second proposal then is the evolutionary timescale. Evolution occurs over many generations and can lead to interesting interactions between organisms such as the coevolution of the monarch butterfly and milkweed. The monarch caterpillars have developed both physiological and behavioral adaptations that allow it to thrive on milkweeds while most other insects are unable to ingest it due to the plant's toxins called glycosides and latex sap. As adults, the caterpillars repurpose the milkweed toxin as an antipredator defense by sequestering it in their blood and wings. Invasive species lack this kind of coevolution with natives which allows populations to grow unrestricted. If a native organism can feast on an invasive species, we tend to see a lower carrying capacity, less interaction diversity, and less species diversity as many invasive species compete over similar niches as natives. An evolutionary time scale would help us to consider naturalization for animals such as the South American hippos that would not have these negative impacts on biodiversity as they are filling an empty niche (Lundgren *et al.*, 2020).

Conclusion

It can be assumed that Pablo Escobar never intended to introduce one of the most controversial invasive species known today. The expansion of the hippos is a rare example of an aquatic mammal becoming an invasive species with major impacts on the ecosystem, economy, and human safety. However, Pablo Escobar's hippos open a debate on the naturalization of invasives, especially those who fill the niches of extinct prehistoric species. This is less of a question of could the Columbian government intervene, but should they? Is this simply a range expansion of the hippopotamus as they are vulnerable in their native habitat? To determine these questions and many others, long term studies of the hippos' impacts must be conducted to fully understand their unique position.

References

Carroll, SP., Hendry, AP., Reznick, DN., Fox, CW. 2007. Evolution on ecological timescales. Functional Ecology. 21(3):387–393.

Castelblanco-Martínez, D.N., Moreno-Arias, R.A., Velasco, J.A., Moreno-Bernal, J.W., Restrepo, S., Noguera-Urbano, E.A., Baptiste, M.P., García-Loaiza, L.M., Jiménez, G. 2021. A hippo in the room: Predicting the persistence and dispersion of an invasive mega-vertebrate in Colombia, South America. Biological Conservation. 253:108923.

Colombian National Police. 1981. A mug shot taken by the regional Colombia control agency in Medellín in 1976. Colombia National Registry; Colombian National Police.

Dembitzer, J. 2017. The Case for Hippos in Colombia. Israel Journal of Ecology and Evolution. 63(3–4):5–8.

Eltringham, SK. 1999. *The Hippos: Natural History and Conservation*. Academic Press.

Figueroa, V. & Andrea N. 2016. Late Quaternary Megafaunal Extinctions in South America: Chronology, environmental changes and human impacts at regional scales. UC Berkeley.

Hernández, CA., Ruiz, IC., Villegas, JP., Duque, DL. 2015. Ovariectomy in a common hippopotamus (Hippopotamus amphibius). J Zoo Wilds Med. 46(2):374–377.

Lewison, R., Pluháček, J. 2017. "Hippopotamus amphibius". *IUCN Red List of Threatened Species*. **2017**: e.T10103A18567364. Accessed 19 Mar 2021.

Lundgren, EJ., Ramp, D., Rowan, J., Middleton, O., Schowanek, SD., Sanisidro, O., Carroll, SP., Davis, M., Sandom, CJ., Svenning, J-C., *et al.* 2020. Introduced herbivores restore Late Pleistocene ecological functions. Proc Natl Acad Sci USA. 117(14):7871–7878.

Lynch, E. "Ask a Vet: All You Need to Know About Spay/Neuter Surgery • MSPCA-Angell." MSPCA-Angell, https://www.mspca.org/pet_resources/ask-a-vet-all-you-need-to-know-about-spayneuter-surgery/. Accessed 8 Apr 2021.

Mantecón, LG. What is megafauna? True Nature Foundation. https://truenaturefoundation.org/what-is-megafauna/. Accessed 19 Mar 2021.

NPR. 2021. Colombia Has A Hippo Problem, Thanks To Pablo Escobar – ProQuest.

Parker, M. 2014. The "Highly Mobile" Testicles Frustrate Effort to Calm Hippos in Captivity. Scientific American. https://www.scientificamerican.com/article/highly-mobile-testicles-frustrate-effort-to-calm-hippos-in-captivity/. Accessed 8 Apr 2021.

Pluháček, J., & Steck, BL. 2015. "Different Sex Allocations in Two Related Species: The Case of the Extant Hippopotamus." *Ethology*, vol. 121, no. 5, pp. 462–71.

Shurin, JB., Aranguren-Riaño, N., Negro, DD., Lopez, DE., Jones, NT., Laverde-R, O., Neu, A., Ramos, AP. 2020. Ecosystem effects of the world's largest invasive animal. Ecology. 101(5):e02991.

Snyder, KD. 2015. The Common Hippopotamus in the Wild and in Captivity: Conservation for Less Charismatic Species. Journal of International Wildlife Law & Policy. 18(4):337–354.

Stalder, GL., Thierry, P., Horowitz, I., Hermes, R., Saragusty, J., Knauer, F., Walzer, C. 2012. "Use of a Medetomidine-Ketamine Combination for Anesthesia in Captive Common Hippopotami (Hippopotamus Amphibius)." *Journal of the American Veterinary Medical Association*, vol. 241, no. 1, July 2012, pp. 110–16.

Subalusky, AL., Anderson, EP., Jiménez, G., Post, DM., Lopez, DE., García-R, S., Nova León, LJ., Reátiga Parrish, JF., Rojas, A., Solari, S., *et al.* 2021. Potential ecological and socio-economic effects of a novel megaherbivore introduction: the hippopotamus in Colombia. :105–113.

Tidmarsh, K. 2017. While fighting the odds, fiona the hippo became a social media star. NPR.org. https://www.npr.org/2017/07/24/538874374/while-fighting-the-odds-fiona-the-hippo-became-a-social-media-star. Accessed 8 Apr 2021.

European Green Crab, *Carcinus maenas*

Author: Edwin Gao

Introduction

In the vast ocean, there are many animals that call it their home. Species of animals range widely, from tunicates to mammals, all living together. However, even among all the diverse wildlife, there are species that invade other environments. These species are called invasive species, given the fact that they invade new environments and take over as the dominant species.

The European green crab, *Carcinus maenas*, is a common littoral crab that is native to the northeast Atlantic and Baltic sea and is invasive to almost all other bodies of water (Dubinsky 2021). It is so abundant and widespread that it has been on the list for the world's 100 worst alien invasive species, even being in the top 5. Although it is called the green crab, it can also come in a few different colors ranging from green to brown, even red or grey in color.

Impacts

When it comes to impacts, the green crab has had a negative effect on the environment. The biggest effect that the green crab has on the environment is their ability to outcompete native species and reducing the biodiversity of an ecosystem. An ecosystem is in harmony when there is a balance between the predators, prey, and primary energy producers. When an invasive species invades an ecosystem, they disrupt this balance.

When it comes to green crab invasions, this balance is greatly altered. When introduced, the crabs will outcompete other native crabs in the area, taking over as the top predator (McDonald 2001). This is bad for all the other organisms living in the area, especially the prey organisms. Since the green crab is a new predator, there are no defenses in place to protect themselves (McDonald 2001). As a result, the shellfish populations in these areas have decreased greatly, resulting in a loss in biodiversity.

Besides the decline in shellfish and native crab populations, green crabs also physically alter the environment. The green crabs hunt and make their burrows in seagrass beds, which is detrimental to the health of the ecosystem (Malyshev *et al*. 2011). The green crabs would rip and tear the seagrass beds, hunting for shellfish and other small organisms to feed on. They also dig into the substrate under the seagrass to make their burrows. The green crabs essentially destroy entire seagrass bed populations in their pursuit for prey and housing (Malyshev *et al*. 2011). With the destruction of the seagrass beds, there will be nothing there to keep the substrate in place, resulting in the complete loss of biodiversity and a buffer against erosion (Malyshev *et al*. 2011). The seagrass beds are also a nursery for juvenile fish and other organisms, and so the loss of these beds will result in a decrease in the population of all the organisms that use the beds as a nursery.

The green crabs also negatively impact the economy. Since the crabs prey on shellfish and other crabs, there has been a decline in the shellfish market and industry.

Success

Green crabs can give their extraordinary success to a few factors. One such factor is their amazing anatomy and physiology. They can tolerate a larger range of temperatures and salinities than their native competitors, meaning they can survive in a larger area than the native crab populations. Besides being able to survive a wider temperature and salinity range, green crabs also have one of the greatest body designs for a predator. With a hard exoskeleton for protection and two powerful claws for grabbing and tearing prey, green crabs are like tanks, unstoppable in their pursuit of prey.

Another factor that makes green crabs so successful is their behavior. Green crabs are typically faster and more aggressive than the native crabs, which gives the green crab an advantage when it comes to hunting for prey. Speaking of prey, green crabs have a diverse diet that typically includes clams, scallops, and any other bivalve. The claws on a green crab are very effective in opening bivalves, making them easy prey for the crabs.

Reproductively speaking, the green crabs are r-strategists, meaning they produce a lot of offspring at once. This is an effective way for organisms like crabs to reproduce, since it involves making many offspring and hoping some survive. This method is even more effective for the green crabs in their invaded territories, spreading their offspring since there is no competition.

With the ultimate body design for a predator, their ability to tolerate large temperature and salinity ranges, as well as the lack of competition and predators, green crabs are very effective in invading a new environment and taking it over.

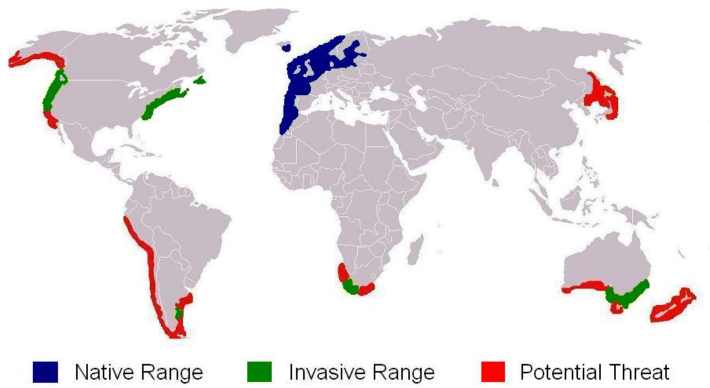


Figure 1. Green crabs are found natively in the northeast Atlantic. From there, they have invaded or potentially will invade the Americas, South Africa, Australia, and Japan

Vectors

Like other invasive species, the main way that the green crab has spread was through ballast water. Ballast water is water that a ship takes in to balance themselves while traveling. The thing about ballast water is that it is not sterile, so whatever is living in the water when it is taken up will be transported to a new location when the ship dumps the water.

Besides the ballast water, wave action also helps the spread of the green crab. Once invaded, the waves can help spread the offspring of the crabs, spreading them along the coast. After hatching from their eggs, the larvae are small so then the waves will be able to move them more easily.

Since the green crab mainly feed on bivalves, they are often found around areas with high concentrations of bivalves. One such place are aquaculture farms that grow bivalves. When the bivalves are harvested and shipped out or are moved, there may be green crab larvae in the water along with the bivalves. This ends with the green crab moving to a new location and spreading even more.

Detection

Finding and identifying green crabs is a relatively simple task. Even though they are called the green crab, they are not always green. As mentioned before, the green crab can range in color from green to brown, even red or grey in some cases. The green crab is a shore crab, meaning it can be found along the shore, usually hiding in the intertidal or anywhere where it can fit

("Identifying European Green Crab."). They are also found in muddy environments and inlets, posing a problem to the native wildlife there.

The carapace on an adult green crab can be up to 60 mm long and 90 mm wide, making it a relatively large crab. Along the front of the carapace, to either side of the eyes, there should be 5 spines ("Identifying European Green Crab."). This is unique to green crabs and is often the easiest way to tell if a crab is a green crab or not.

Figure 2. A green crab as seen from above. It has a mottled carapace, but the main identifying feature are the 5 spines that are sticking out from either side of the eyes

Mitigation

When it comes to dealing with green crabs, almost everyone has the same thought: get rid of them. Green crabs are seen as a pest and there have been many attempts at removing them. One of the first things fishers tried was trapping the crabs. In theory this is a good way to remove critters that should not be there. However, with the green crabs, this method is not effective in controlling population sizes. Rather, it is a good way to keep the average size of individuals in a population down (Barry *et al*. 2020). Along with the trapping, there are also events where people can go and hunt green crabs. Typically, these are held in an effort to kill green crab populations with fishers going out and killing as many crabs as they can (Barry *et al*. 2020). Although this is good for getting rid of some crabs, it has some negative effects. Bivalves can detect when there are green crabs around and will withdraw if they sense some nearby. By killing the green crabs and letting their bodily fluids into the water, this puts the bivalves into high alert and will not come out until all the green crab fluids have disappeared.

Besides actively removing the green crabs, there has also been a lot of research into the crabs. People research the lifecycle of the crabs and try to figure out a way to stop the invasion of the crabs. In a different pathway, research into edible recipes for the crabs is also underway. To increase public interest and knowledge, recipes on how to cook and eat green crabs are in development. The crabs themselves are edible, but not many people find the thought of eating green crabs appealing.

Mitigation efforts have been in effect for a long time now, all in an effort to stop the spread of the green crab and the destruction they leave behind in their invasion. Between the physical removal of the crabs and the research going into them, hopefully there will be a way to remove these crabs and return the environment back to normal.

Climate Change

Climate change is a real threat to the world, not only does it change the environment, but it also has major impacts on all the organisms living on Earth. For the most part, organisms living in their environment are adapted to that environment and cannot adapt to quick changes quick enough to survive. This is a different story for green crabs and other invasive species. Since the green crab can survive in a larger temperature range than native species, the increase in ocean temperature will only help the green crab (Parks 2020). Since the native species cannot keep up with the temperature change, there will be a loss of competition for the green crabs, allowing them to take over and become the dominant species in the environment.

References

Barry, Patty; Browning, Melissa; Bryson,, Alexis; Fuchs, Harrison; and Maipi, Etilet, "European Green Crab Mitigation in Whatcom County" (2020). *WWU Honors Program Senior Projects*. 355. https://cedar.wwu.edu/wwu_honors/355

Dubinsky J., The Green Crab: Marine Science. *Maria Mitchell Association*, www.mariamitchell.org/the-green-crab#:~:text=These%20invaders%20are%20extremely%20efficient,declines%20in%20native%20crab%20species.

"Identifying European Green Crab." *Washington Sea Grant*, wsg.washington.edu/crabteam/greencrab/id/.

Malyshev A., Quijón P, Disruption of essential habitat by a coastal invader: new evidence of the effects of green crabs on eelgrass beds, *ICES Journal of Marine Science*, Volume 68, Issue 9, September 2011, Pages 1852–1856, https://doi.org/10.1093/icesjms/fsr126

McDonald S., Jensen G., Armstrong D., The competitive and predatory impacts of the nonindigenous crab (L.) on early benthic phase Dungeness crab *Cancer magister* Dana, Journal of Experimental Marine Biology and Ecology, Volume 258, Issue 1, 2001, Pages 39-54

Parks M. Green Crabs and Climate Change. GREENCRAB.ORG, 27 Sept. 2020,www.greencrab.org/blog/2020/9/26/green-crabs-amp-climate-change#:~:text=Green%20crabs%20also%20lack%20natural,the%20grips%20of%20climate%20change.

Pacific Oyster, *Crassostrea gigas*: An economically important invasive bivalve

Authors: Kristen Wurth, Sierra Brown;

Edited by: Alexandra Michaud

Introduction

There are numerous types of animals that call the ocean their home. The invertebrate organisms make up a majority of the different groups. One of those invertebrate groups are called molluscs. The species within this group can range from the incredibly smart octopuses all the way to small periwinkles. Somewhere in the middle are marine bivalves. Marine bivalves are organisms that have two hard outer shells called valves, that are connected to each other and open and close using a hinge. In between the shells is where the soft, squishy part of the invertebrate body resides. Organisms within the bivalve group include clams, mussels, scallops, and oysters. A majority of the bivalve species are considered delicacies in many human cultures and are widely farmed. Typically, native species are farmed in their natural habitat though it is not unusual for a nonnative species to be brought. This will happen if farming the native species is no longer possible, an ecological niche needs to be filled, or to increase the stocks to fulfill a growing demand. The case of the Pacific Oyster (*Crassostrea gigas*) is unique in that it has history in being a farmed species and also an invasive species.

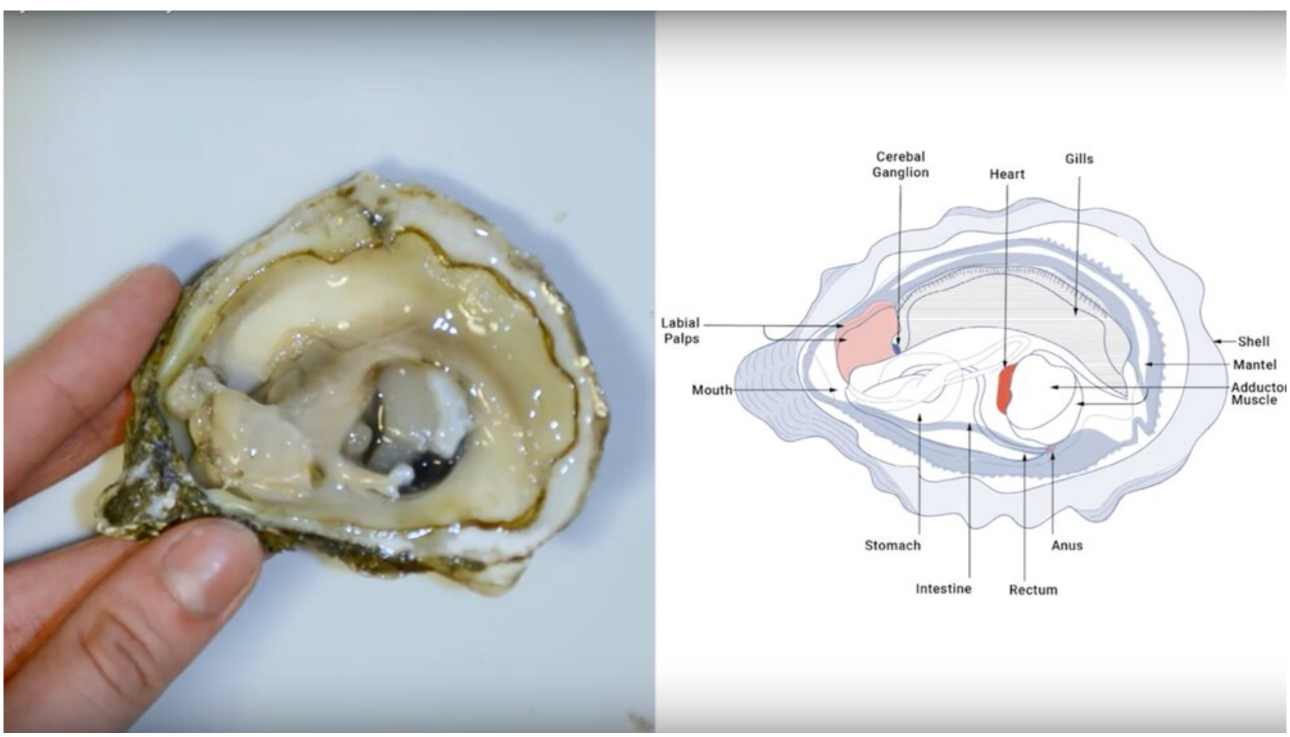


Figure 1. Side by side view of a real oyster with an anatomical diagram of an oyster.
Available: https://www.billionoysterproject.org/remote-learnin

Like many other marine bivalves, the Pacific Oyster is a sessile organism. They will attach to any rocky or hard surface and can grow to be about 15-20 cm long (GISD 2021). They are also filter feeders and primarily feed on bacteria, protozoa, diatoms, and detritus (GISD, 2021). Originally this species is from Japan but it spread quickly to other parts of Asia and is now generally considered an Asian species. This species is known to be very fertile with females releasing 50-100 million eggs per spawning event (GISD, 2021). This species goes through several life stages starting with being a fertilized egg, then a trochophore (larval stage). Next, the oyster trochophore goes into its veliger stages where it starts to look more like an actual oyster. After the veliger stages, the juvenile oyster goes into its spat stages where it settles down and becomes an adult oyster. The trochophore and veliger stages occur over a period of about 3 weeks and once settled the young oyster will grow 2.5 cm each year (GISD, 2021).

Figure 2. Illustration of the pacific oyster (*Crassotrea gigas*) Available: https://thisfish.info/fishery/species/pacific-oyster/

The invasive success of this species is highly due to its reproduction. Not only do they produce a huge amount of offspring at one time, but the resulting larvae can travel kilometers away from their parents before settling down (GISD, 2021). They will also attach to any hard surface or substrate, often even attaching to other Pacific Oysters, making themselves a versatile species (GISD, 2021). Even though only a small percentage of the larvae make it to this stage, it is still considerably more than other oyster species. In many of the areas that the pacific oyster is now found, they have very few predators which is another indicator of a successful invader (Troost, 2010). Pacific oysters are also really good at changing the habitat when colonizing new areas. Due to their reproductive biology, they can very easily create new reefs just by settling on top of each other (Troost, 2010).

Vectors

The Pacific Oyster was both intentionally and unintentionally introduced. It was intentionally introduced through aquaculture in the Southern North Sea, Netherlands 1965 (Reise, 1998). The Pacific oysters were imported and grown on oyster trestles in the North Sea (Reise, 1998). Since oysters are broadcast spawners, meaning they release their eggs or sperm directly into the water column, their ability to establish themselves in a new area is dependent on the direction of currents and temperature of the water (GISD, 2021). Spat fall refers to a successful landing and establishment of oyster larvae (US department of commerce, 2021). In 1975, the first recorded spat fall of pacific oyster larvae was recorded outside of aquaculture (Reise, 1998). The spread continued to the East Frisian Wadden Sea near Germany (Reise, 1998). The Wadden Sea ecosystem has very low biodiversity and consists mostly of mudflats and intertidal sand, meaning it has many open ecological niches (Reise, 1998). When an area has open ecological niches this means that it can easily be invaded. The Pacific oyster took advantage of this and prospered in the Wadden Sea, eventually establishing a set population (Reise, 1998). This population in the Wadden Sea caused an increase in biodiversity through the construction of reefs by the oysters as a habitat and filtering the surrounding water (Reise, 1998). Although an increase in biodiversity is traditionally viewed as a positive, it is still a change to the original Wadden Sea ecosystem. The introduction of the pacific oyster to the Wadden Sea also served as a secondary vector for other invasive species to be present in the ecosystem (Reise, 1998). Two nonnative species of algae *Ascophyllum nodosum* and *Sargassum muticum* were both found in the Wadden sea due to the oyster industry transplanting the Pacific oyster and was found on oyster trestles (Reise, 1998).

As for other areas in the world, pacific oysters were unintentionally being transported to France and Britain through ballast water and on ship hulls (Reise, 1998). The Pacific Oyster continued to prosper and spread throughout Africa, Australia and the Americas (Figure 1.) The Pacific oyster still continues to be spread and is establishing populations all over the world mostly through the vectors of ballast water and aquaculture (Molnar *et al.,* 2008).

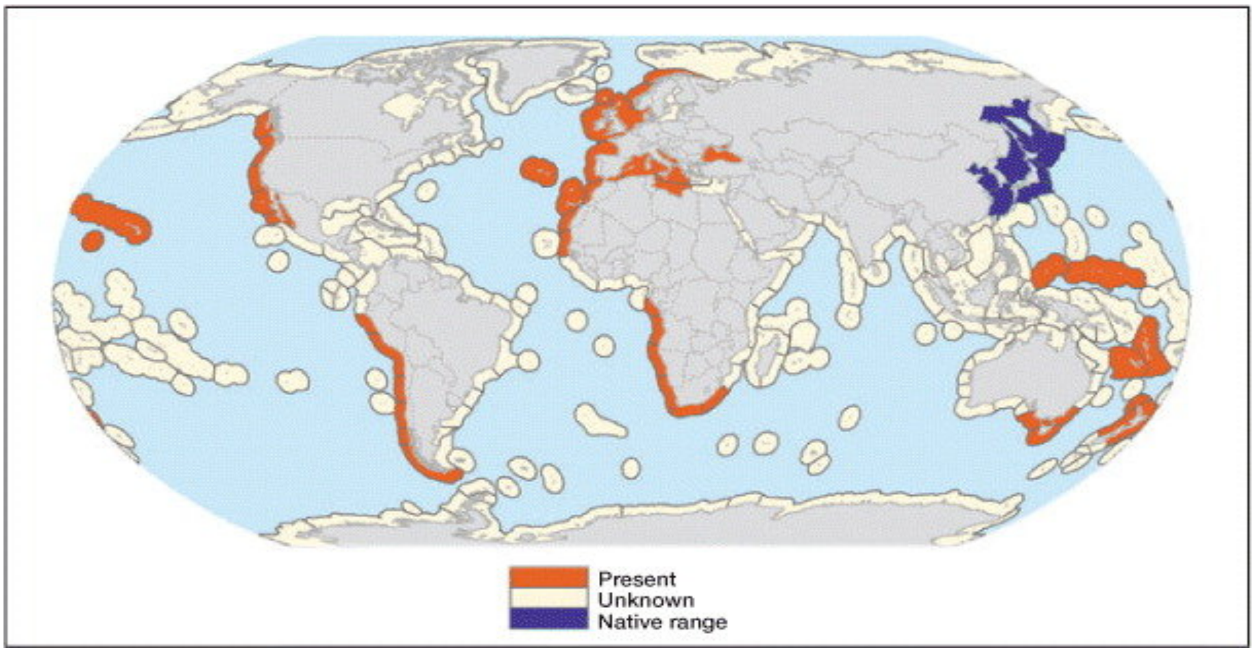


Figure 3. Map of present, unknown and native range of the Pacific Oyster (*Crassotrea gigas*) (from Molnar *et al.* 2008)

Detection

Not many detection efforts have been put into place for the Pacific oyster due to the fact that in many places it was intentionally introduced for aquaculture (Reise, 1998). One of the main vectors of unintentional introduction is through ballast water (Reise, 1998). There have been some efforts to detect oyster larvae in ballast water. Morphological detection is a time-consuming process and pacific oyster larvae is unable to be morphologically identified from other invertebrate larvae (Patil, 2004.) This is why the use of nested polymerase chain reaction (nPCR) has been the method of choice for oyster larvae detection in ballast waters (Patil, 2004). A specific primer was created to identify the presence or absence of pacific oysters (Patil, 2004). In nPCR the specific primer will bind to the pacific oyster DNA if it is present (Patil, 2004). nPCR is used in this case because it is more accurate than traditional PCR (Patil, 2004). This is because nPCR has both inner and outer primers that allow for the final target DNA to be more precise (Patil, 2004). This method has not only been useful in preventing the unintentional introduction of the pacific oyster through ballast waters but also helps from an aquaculture and fisheries perspective (Patil, 2004). Since the Pacific oyster is very economically important it's essential for fisheries and aquaculture companies to keep track of their oyster populations (Reise, 1998; Goedknegt, 2017; Troost, 2010). By using the specific primer created, fisheries are able to predict the distribution of the oysters and settlement rates (Patil, 2004). By understanding distribution and settlement rates, fisheries are able to assess the health and revenue of the oyster farms.

Economic Impacts

As mentioned earlier, the Pacific Oyster was often introduced to new areas for the purpose of aquaculture. The majority (84%) of pacific oyster cultivation occurs in China with the next top producers being Japan (262,000 tons), the Republic of Korea (238,000 tons), and France (115,000 tons) (FAO, 2021). The United States of America and Taiwan are also big producers of the pacific oyster producing 43,000 tons and 23,000 tons, respectively (FAO, 2021). In 2003 the global production of the pacific oyster was estimated to be about $3.9 billion USD (FAO, 2021). Most of the production is for domestic use but France does export to other European countries such as Ireland and the UK (FAO, 2021). Since this species is so easy to maintain, it can be pretty profitable. However, they have the potential to get out of control fairly quickly if not maintained properly. The best way to combat this is to keep production within small family-owned businesses (FAO, 2021) where the species can be easily monitored so they don't get out of control.

Ecological Impacts

Like other bivalves the pacific oyster inhabits mudflats and rocky or sandy intertidal habitats (GISD, 2021). This means that the pacific oyster has the ability to alter the structure of these intertidal habitats. Pacific oysters have the ability to outcompete other bivalve species, destroy existing habitats, alter food webs, increase biodiversity and mitigate eutrophication events that affect water quality (GISD, 2021; Troost, 2010). The mitigation of eutrophication events and alteration of food webs is due to the Pacific oysters filter feeding (Troost, 2010). Pacific oysters have an effect on the types and number of phytoplankton and zooplankton that are present in an area (Troost, 2010). By feeding on phytoplankton this can decrease the intensity of various algal blooms (Troost, 2010). Pacific oysters exert a top down control on phytoplankton thus affecting organisms like (fish, seals, sharks etc.) at a higher trophic level (Troost, 2010).

Since the pacific oyster can settle in dense aggregations this causes them to exclude other species from the intertidal space. These dense aggregations also cause pacific oysters to alter the substrate type by creating hard substrate oyster reefs that don't naturally occur in mudflats (Troost, 2010). These reefs are also a hot spot for an increase in biodiversity (Troost 2010; Reise, 1998). Biodiversity is usually viewed as a positive concept in biology and usually is supported, this is not the case with the Pacific oyster. The Pacific oysters' role in increasing biodiversity in areas that have low biodiversity is very controversial between researchers (Troost 2010; Reise, 1998). Some researchers believe that areas like the Wadden sea that have a low biodiversity to begin with should stay the way it is instead of promoting increased biodiversity (Troost 2010, Reise, 1998). This is contradicted by the rationale that since anthropogenic activities and climate change has caused an overall decrease in biodiversity, having oysters invade various areas and increase biodiversity will compensate for the damage done by humans (Troost, 2010).

The blue mussel (*Mytilus edulis*) and European oyster (*Ostrea edulis*) have been impacted by pacific oyster invasions (Goedknegt, 2016). Since the blue mussel, European oyster and pacific oyster inhibit the same intertidal habitat they end up having many interactions (Goedknegt, 2016; Troost, 2010). Pacific oysters will grow in between the cracks of blue mussel beds and also grow directly on blue mussels, overtaking mussel beds and creating a hybrid oyster reef and mussel bed (Goedknegt, 2016).

Figure 4. Pacific oyster and blue mussel growing and living in syncrasy Available: https://qsr-waddensea-worldheritage-org.cdn.gofasterstripes.download/sites/default/files/styles/inline_image_half_width/public/qsr2016-beds%20of%20mussels-figure%201.3-picture.PNG?itok=xoaTxWvG

Since these three bivalves are filter feeders this causes a possibility for competition for food and resources (Troost, 2010). Originally it was thought that the pacific oyster and blue mussel competed for similar food sources but later studies with the use of stable isotope signatures showed that they in fact eat different species (Troost, 2010). Although this is true for the blue mussel, the European mussel still occasionally competes with the pacific oyster when it comes to food (Zwerschke *et al.,* 2018). Abiotic stressors play a role in the severity of the competition and niche overlap. When there is little to no abiotic stressors, the competition and niche overlap remains low but when abiotic stressors are increased competition and niche overlap increases. An increase in these stressors actually causes the European oyster to have a smoother shell structure which then causes the pacific oyster to have a reduced ability to retain water and stabilize temperatures (Zwerschke *et al.,* 2018). This showcases the complexity of intraspecies competition coupled with abiotic stressors.

Introduced pacific oysters also are a new prey item for many seabirds (Troost, 2010). Although the pacific oyster is not preyed upon by as many seabirds as other bivalves specifically in the Wadden sea ecosystem, they have become an important food source for some seabirds (Troost, 2010). Herring gulls (*Larus argentatus*) and oyster-catchers (*Haematopus ostralegus*) are two birds that feed on the pacific oyster by dropping them on rocks from the air (Troost, 2010). Since there are only two recorded bird species that feed on the pacific oyster it's part of the reason pacific oysters are able to continue to compete and become established in various ecosystems (Troost, 2010).

Mitigation

The Pacific oyster has the ability to be a host of various parasitic copepods (Goedknegt, 2016). In the Wadden sea ecosystem research has been done on the introduction and effects of these native and invasive parasitic copepods (Goedknegt, 2016). The pacific oyster carries the invasive parasitic copepod, *M. Orientalis* (Goedknegt, 2016). While the native bivalve species, blue mussel (*Mytilus edulis*), common cockle (*Cerastoderma edule*) and baltic tellins (*Macoma balthica*) have the existent parasitic copepod, *M. intestinalis.* These parasitic copepods have been known to affect filtration ability of bivalves, cause mass mortalities and oxygen consumption (Goedknegt, 2016). There has been reported spillover (invasive copepod species infecting native hosts) but no spillback reported (native copepod species infecting invasive hosts) (Goedknegt 2016). This means that the invasive pacific oyster is not only taking over other bivalves' physical habitats but also affecting the health of other native species (Goedknegt, 2016).

As previously mentioned there are parasitic copepods that negatively impact pacific oyster, however certain copepods are not the only organisms that are parasitic to pacific oysters. The *Pseudostylochus* spp. are marine flatworms that are known to be associated with high mortality rates in pacific oysters (GISD, 2021). Both the mudworm *Polydora* spp. and the sponge *Cliona* spp. Are also known to cause shell damage to the pacific oyster (GISD, 2021). Also, the trematode worm *Renicola roscovita* is known to infest pacific oysters but not as intensely as the other previously mentioned species (GISD, 2021). All of these species have the potential to be a biological mitigation factor to help control the pacific oyster in areas where they are not wanted but more research needs to be done in order to fully understand exactly how they can be used against pacific oysters.

Conclusion

In general, pacific oysters are pretty hardy organisms, but as the ocean temperatures rise some populations may be subjected to changes in their reproductive history. When this species spawns is determined by the temperature of the water. Spawning usually occurs at 20℃ (Quayle, 1969) with the cue being an increase in the water temperature as summer grows near (Grangeré *et al*., 2009). An overall increase in water temperatures could disrupt the spawning practice and lead to an unfavorable environment for the offspring of pacific oysters. As climate change continues to progress, ocean heat content and ocean acidification continues to worsen (Hall-Spencer *et al.,* 2015.) Ocean acidification causes sea water to be much more acidic and have a lower pH (Hall-Spencer *et al.,* 2015.) This specifically affects the pacific oysters' growth, size and survival rate when the pH is below 7.8 (Hall-Spencer *et al.,* 2015.) Although the pacific oyster is negatively affected by ocean acidification, it is actually less vulnerable than other native species like the blue mussel (*Mytilus edulis*) and European oyster (*Ostrea edulis*) (Hall-Spencer *et al.,* 2015.) This gives insight into the future invasion success and locations of the pacific oyster. Since the pacific oyster stimulates many different economies and is a beloved cuisine, it makes characterizing regulations on pacific oyster as an invasive species very difficult. The negative impacts of the pacific oyster have to be weighed against the positive impacts. These impacts will also be forever changing with the continuation of climate change so it is imperative for all aspects of the pacific oysters' effects as an invasive species are discussed. Should invasive species that have positive economic impacts have different treatments than those that do not? If an invasive species was originally intentionally introduced, should they not be considered invasive? These are questions that still need to be answered or at least discussed by researchers, aquaculturists and invasive species managers to insure a broad perspective and understanding of unique invasive species like the pacific oyster.

References

Global Invasive Species Database (2021) Species profile: *Crassostrea gigas*. Downloaded from http://www.iucngisd.org/gisd/speciesname/Crassostrea+gigas on 24-03-2021.

Molnar JL, Gamboa RL, Revenga C, Spalding MD. Assessing the global threat of invasive species to marine biodiversity. Frontiers in Ecology and the Environment. 2008;6(9):485–492.

US Department of Commerce NOAA. What is spat? NOAA's National Ocean Service. 2008 Oct 27 [accessed 2021 Mar 9]. https://oceanservice.noaa.gov/facts/spat.html

Reise K. Pacific oysters invade mussel beds in the European Wadden Sea. Senckenbergiana maritima. 1998;28(4-6):167–175.

Goedknegt MA, Schuster A-K, Buschbaum C, Gergs R, Jung AS, Luttikhuizen PC, van der Meer

J, Troost K, Wegner KM, Thieltges DW. Spillover but no spillback of two invasive parasitic copepods from invasive Pacific oysters (*Crassostrea gigas*) to native bivalve hosts. Biological Invasions. 2016;19(1):365–379.

Quayle DB. In: Pacific oyster culture in British Columbia. 1st ed. Ottawa: Fisheries Research Board of Canada; 1969. p. 23.

Patil JG, Gunasekera RM, Deagle BE, Bax NJ. Specific Detection of Pacific Oyster (*Crassostrea gigas)* Larvae in Plankton Samples Using Nested Polymerase Chain Reaction. Marine Biotechnology. 2005;7(1):11–20.

Cultured Aquatic Species Information Programme. *Crassostrea gigas*. Cultured Aquatic Species Information Programme. Text by Helm, M.M. In: *FAO Fisheries Division* [online]. Rome. Updated . [Cited 24 March 2021].

Troost K. Causes and effects of a highly successful marine invasion: Case-study of the introduced Pacific oyster *Crassostrea gigas* in continental NW European estuaries. Journal of Sea Research. 2010;64(3):145–165.

Hall-Spencer J, Allen R. The impact of CO_2 emissions on 'nuisance' marine species. *Research and Reports in Biodiversity Studies*. 2015;4:33-46

Grangeré K, Ménesguen A, Lefebvre S, Bacher C, Pouvreau S. Modelling the influence of environmental factors on the physiological status of the Pacific oyster *Crassostrea gigas* in an estuarine embayment; The Baie des Veys (France). Journal of Sea Research. 2009;62(2-3):147–158.