Transmission vectors of Aquatic Invasive species: Causes and Prevention

Bachelor’s Thesis Biology

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Abstract

This paper has endeavored to find out all the main anthropogenic transmission vectors of aquatic species, current laws, legislations and the initiatives surrounding them, as well as providing some examples of what can happen with a lack of regulatory oversight. All information was gathered from literature research. The primary literature sources that this paper is based on are; Minchin et al, 2005, Havel et al, 2015, Patoka et al 2018, Outinen et al, 2024 and Ruiz et al 2015. This paper is divided in seven main sections, where each vector of transmission is covered extensively, exposing both the risks and effects seen within ecosystems post invasion.

In total, seven main transmission vectors have been identified: Hull transport, ballast, Aquarium industry, Aquaculture industry, Fisheries, Leisure activities and Drifting. For every transmission vector, their mechanisms, causes and history have been discussed, in order to paint a clearer picture of their long lasting effects. Current international laws, regulations and initiatives surrounding the seven transmission vectors are also exposed. In short, the anthropogenic transmission vectors can be largely mitigated by increasing public awareness of the consequences of seemingly innocent actions. Developing nations often lag behind the regulatory curve, where their repercussions are felt globally. A unified global effort is the only way we can safeguard our aquatic ecosystems for future generations.

My hope is that this paper can spread awareness on the topic by providing a clear summary of all the anthropogenic vectors that invasive aquatic species utilize.

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Introduction

In recent years humans have become extremely effective in crossing biogeographical barriers and traveling vast distances utilizing many forms of transportation. When doing so they have intentionally and unintentionally brought animals, plants and viruses with them on their travels across the globe (Havel et al,. 2015). The introduction of species into novel environments occurs through many forms of translocation, which are referred to as transmission vectors. Once introduced these species often become invasive. Invasive species are species that have become established, in an environment outside of their native range, where they cause harm to the ecosystem, economy, or human health (Perrings et al 2002).
They are a major driver of global change, displacing native species, acting as ecosystem engineers, and causing local extinctions (e.g., Vitousek et al., 1997; Mooney & Cleland, 2001).

Removal of invasive species is extremely complicated due to facilitation cascades that occur post invasion. Facilitation cascades are the reinforcing effects that occur within the ecosystem, when an invasive species outcompetes local species. This often results in promoting a suppressed species (often a species at a lower trophic level), aiding the success and establishment of the invasive species (Altieri et al 2010). If the "eradication success" is declared prematurely, invasives often bounce back, this is known as the Lazarus effect (Clout and Veitch 2002). The removal of invasives is thus extremely difficult and in some cases impossible (Vander Zanden and Olden 2008, Alteiri et al 2010) often requiring huge cost and effort in the form of long term campaigns. Vectors of transmission are thus of vital importance to identify and manage effectively, to prevent invasives from being introduced in the first place.

Aquatic invasives

Globally, of the 13,867 known established alien species, 26% (or 3605) of them are associated with aquatic habitats (Cuthbert et al, 2021), where 22 of these aquatic species have landed on the list of the"World's Worst Invasive Alien Species" (Wikipedia, 2024).

Recent advancements in shipping and aquaculture are largely to blame (Havel et al, 2015, Kletuo et al, 2016, Minchin et al, 2005, David & Perkovič, 2004, Vander Zanden & Olden, 2008, Outinen et al, 2024). Farmed carp species such as *Hypophthalmichthys nobilis* (Bighead carp) and *Hypophthalmichthys molitrix* (Silver carp) extensively utilized in Asian aquaculture farms, have recently been introduced into US waters (Chapman et al 2016). These fish alone have cost US fisheries billions on an annual basis (Chapman et al 2016). Similar effects can be seen in the mediterranean, where *Caulerpa taxifolia* (Killer algae) and *Pterois volitans* (Common Lionfish) have been introduced by fishermen and the shipping industry (Kletuo et al 2016, Box et al, 2010). Excelling in their new environment without competition, their numbers have exploded. Their presence and unregulated population growth has massively altered ecosystems around the world, decreasing or homogenizing biodiversity (Lu et al,. 2020, Chapman et al 2016, Vitousek et al, 1997, Frazer et al, 2012), increasing predation pressure on native species (Townsend and Crowl, 1991), degrading habitats (Harvey et al., 2011) and transmitting diseases (Minchin et al, 2005).

Within aquatic environments, lakes and streams are particularly vulnerable to invasive species (Ricciardi & Rasmussen, 1999). The presence of invasive species being a leading cause of the global freshwater biodiversity crisis (Reid et al, 2019). The high biodiversity (per surface area) in freshwater habitats plays a critical role in nutrient and water cycling (Wetzel, 2001), which is of great importance to many human societies around the world. Furthermore coastal areas are also vulnerable, out of the world's 15 largest cities, 11 of them are located around coasts or estuaries (Cohen and Small, 2000). Globally many individuals rely on the seas and oceans for both their livelihoods and survival (FAO 2020), and thus it remains forever important to conserve their biodiversity.

In recent years, the rate of transmission of aquatic invasives has only accelerated through rapid advancements in transportation technology (Havel et al,. 2015) as well as globalization (Thomaz et al,. 2015).

The following seven main vectors of transmission in aquatic environments are discussed in further detail below: Hull transport, ballast water, the aquarium industry, aquaculture, fisheries, leisure/recreational activities and drifting.

Shipping

The maritime history of humanity did not begin a few thousands years ago as traditional nautical archeology tends to assume (Sondaar et al,1994) but well over 900,000 years ago, in the early Pleistocene (Bednarik, 2014). Making shipping potentially the oldest ongoing anthropogenic vector of transmission. As the speed and size of ships has rapidly increased, the rate of introductions (of invasives) has also increased over time (Havel et al, 2015).

In recent years, commercial ships have transmitted between 44–78% of all nonindigenous aquatic species to North America of which 52–82% have arrived through ballast water and hull transport (Ruiz et al, 2015), making shipping the largest vector of transmission within aquatic environments (David & Perkovič, 2004, Vander Zanden,& Olden, 2008, Outinen et al, 2024) .

Hull transport/ Hull Biofouling

The underside of a ship (the hull), provides benthic biota such as macroalgae, mussels and barnacles, with a highly beneficial substrate to attach themselves to. The transportation of these organisms on the hull of ships, is referred to as Hull Transport.
Over the last 30 years, 36% of invasive aquatic species have arrived in North America through hull transport (Ruiz et al, 2015). Hull transport is a direct effect of marine fouling/biofouling (attachment of any biological organisms) on ships, which occurs when a ship is not properly treated with antifouling (a type of paint/coating often containing; tin,copper or silicone) (Ismail et al, 2013).

The movement of the ship enhances the water flow over the attached organisms, providing a constant supply of plankton and nutrients which they can filter from the water. The growth of barnacles and their attachment increases linearly with speeds up to 1.5 knots (Smith, 1946).

Biofouling on the hulls of ships increases surface roughness, which in return causes increased ship frictional resistance and thus requires increased powering (Uzun et al, 2020). The ships' operator must then decide whether the ship must travel for longer or increase engine power to arrive on time to its destination (Townsin, 2003). Biofouling is thus of great importance within the shipping industry, impacting the ships performance, fuel consumption, CO_2 emissions and the ecosystems they travel through. This has led to many advances in antifouling technology. However a paradox persists, as traditional antifouling used to contain toxic substances (copper and TBT) often leaching into the environment, but was extremely effective in terms of reducing biofouling (Gonzales et al, 2005). Lately, non-toxic antifouling systems have been developed based on the principle of making the surface "slippery", preventing their adhesion. These Non toxic antifouling systems, mainly based on silicone and ceramic, do not leach into the environment, however require a higher investment and maintenance to maintain their antifouling properties (Gonzales et al, 2005).

Fig 1: barnacles on the hull (Electronic-fouling-control, 2021)

Hull transport policies and regulation

Currently few policies and regulations exist internationally regarding the mitigation of the hull transport. New Zealand and Australia are currently the only countries with enforced biofouling standards.

In 2018, New Zealand made it mandatory for all vessels entering their national waters to meet CRMS-BIOFOUL requirements (Georgiades et al, 2020). The CRMS-BIOFOUL requires all vessel operators to take the following preventive measures; continual maintenance following best practice; or cleaning within 30 days prior to arrival in New Zealand; or a booking with an MPI-approved provider for cleaning or treatment within 24 h of arrival (Georgiades et al, 2020).

Similarly in Australia, vessel operators must adhere to the ABFMR (Australian Biofouling management requirements)(DAFF 2023). Entering vessels must adhere to at least one of the following three management procedures, implementation of an effective biofouling management plan; or cleaning of all biofouling within 30 days prior to arriving in Australian territory; or implementation of an alternative biofouling management method pre-approved by the department (DAFF 2023)

Many mitigation strategies exist but are currently just guidelines and are yet to be legally binding. Recommendations provided by the International Maritime Organisation (IMO), primarily revolve around the correct application and maintenance of antifouling on regions of the ship consistently in contact with water (IMO 2023). Ship operators must consciously choose antifouling depending on the water temperatures they travel in. Often overlooked but not be underestimated niche areas of the ship such as; the anchor (and anchor chain), bow and stern thrusters, propeller (and propershaft), sea inlet pipes and anodes should also be coated with antifouling (IMO 2023). Antifouling inspections should also routinely take place, every 12 - 18 months in order to assess the condition of the antifouling (IMO 2023).

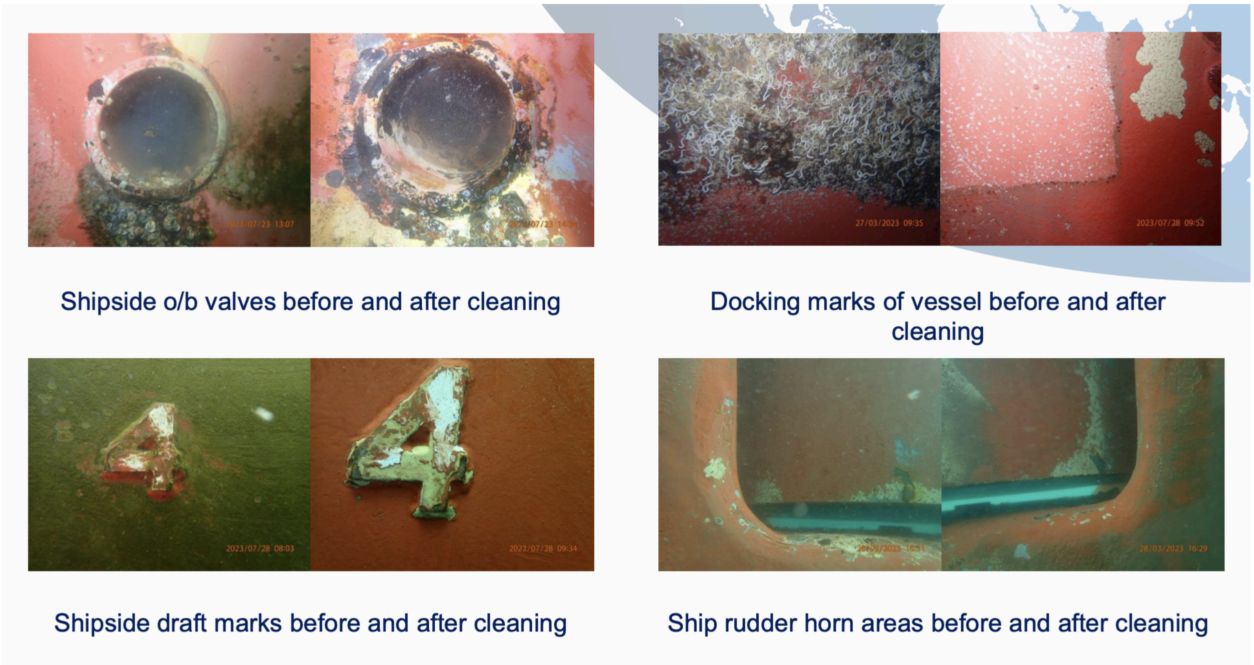

Fig 2 - Niche areas before and after cleaning (Divetech Offshore, 2023)

Ballast - Solid Ballast, Ballast water and ballast sediments.

Solid Ballast

Ballast is the counter weight inside of a ship, which is utilized to stabilize a vessel when it is not carrying its maximum load or if the load is unevenly distributed. Ballast is often taken onboard during the loading or passage phase to set the vessel in its optimum submersed position, increasing fuel economy. Prior to 1870, solid ballast was most commonly utilized, primarily stones, rocks and sand. The on-bringing and removal of this type of ballast was extremely labor intensive and thus ballast water quickly became the new norm.

Fig 3 - solid ballast on medieval ship (Asiansealand, 2021)

Ballast Water

Currently ballast water is the most commonly utilized form of ballast and is held in segregated holdings which can be easily on and off loaded utilizing the ship's ballast water pump system. On average freighter ships can carry anywhere between 1500 - 200,000 tonnes of ballast water. Oil tankers carry the largest amount of ballast water, as when the oil is off loaded water is taken aboard. Large oil tankers are capable of transporting over 200,000 tonnes of ballast water, putting estimates of the global annual ballast water discharged to be over 3.1 billion tonnes (Hernandez et al, 2023). Due to the volume of these ballast water holding tanks, they become vehicles of transportation for species unintentionally captured. The global freighter fleet is estimated to transport as many as 4000 - 5000 taxa per day (Minchin et al, 2005) . Ballast water and the associated sediments within it are known to be the main transmission vector for planktonic life stages of marine organisms (Outinen et al, 2024). These organisms primarily consist of; bacteria, protists, phytoplankton, and zooplankton, numerous fish species, benthic animals, and nearly all pelagic taxa (Lavoie et al, 1999).

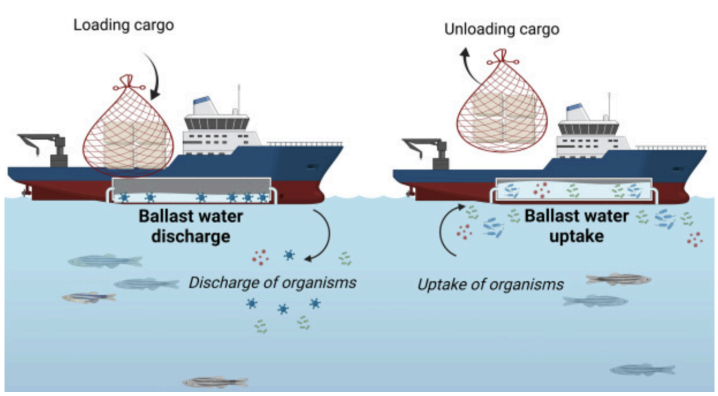

Fig 4 - Ballast water schematic (Naik et al, 2019)

Ballast water legislation

In the 1970’s the IMO, mandated to govern global shipping from a human and environmental perspective. Recognising the environmental impact shipping was having on the global environment they drafted the Marine Pollution regulations (MARPOL), which, amongst all other pollution categories, also deals with transportation of invasive species. The slow adoption process was done in two stages: step 1 promoting mid ocean exchange, and step 2 the installation and mandate of ballast water treatment system (BWTS) ensuring that no living organisms beyond a certain size (50 micrometers) are transported in ballast tanks aboard ships.

From 2005 Mid Ocean exchange became mandatory for ships traveling between ecosystems as an attempt to reduce the spread of invasives. Mid-ocean exchange involves discharging and refilling ballast water out in open sea/ocean (part of the sea/ocean outside of territorial jurisdiction of any country, ~ 12 nautical miles offshore), proven to reduce the survival of coastal plankton (Ruiz et al, 2005). The two methods of mid-ocean exchange are as follows; flow through exchange and fill and empty exchange. Flow through exchange utilizes the overflow of the ballast tanks to flush the coastal water out of the tanks. Fill and empty exchange involves completely emptying the ballast tanks and refilling them.

In 2020 the BWTS regulations were adopted and came into force, internationally traveling vessels carrying ballast water must adhere to the D2 standard (Outinen et al, 2024, IMO 2020), no longer permitting Mid - ocean exchange. The D2 standard is a compliance measure for the density of certain indicator organisms allowed to be present within discharged ballast water. Adherence requires the following densities of indicator microbes to be met;
Organisms larger than 50 micrometers - Fewer than 10 viable organisms per cubic meter.
Organisms between 10 and 50 micrometers - Fewer than 10 viable organisms per milliliter.

Aquarium industry

The global aquarium trade is a multi billion dollar industry, selling and transporting billions of fishes, plants, and invertebrates to millions of enthusiasts every year (Padilla & Williams 2004, Patoka et al 2018). Enthusiasts keep ornamental species in aquariums and ponds, with temperature regulating systems allowing them to survive in regions of the globe where they do not naturally occur in.

Fig 5 - growth of the global aquarium market (Aquarium market share, 2024)

Due to very little regulatory oversight, former pets pose great risk of becoming invasive species when released on purpose or accidentally (Havel et al, 2015). Globally more than 150 aquarium species have become established within novel ecosystems, many of these landing on the “worst invasive species” list (Padilla & Williams, 2004).

Reduction of biotic filters

The increasingly available but limited supply of captive bred species (Pouil et al, 2020) is currently unable to sustain the demand for them. This results in large amounts of pressure on wild fish populations (King, 2019; Rhyne et al, 2012), potentially making them more susceptible to invasion due to reduced numbers of biotic filters (Thomaz et al, 2015). Ornamental keystone species such as redband parrotfish and surgeonfish local to Caribbean reefs, graze primarily on macroalgae. When these species are over exploited, macroalgae often becomes abundant, in turn lowering the growth, fecundity and recruitment of juvenile corals (Burkepile & Hay, 2010), leading to ecosystem destabilization.

Figure 7 - Redband parrotfish (Charpin, 2024) **Figure 8 - Blue Tang, Surgeonfish (Charpin, 2024)**

Despite this, the global trade in marine ornamental fish also offers benefits for conservation, economic development, and financial stability for communities. By creating economic incentives, local communities are financially encouraged to protect these ornamental fish populations and their habitats, to ensure future exploitation (King, 2019).

Policy and legislation of the aquarium trade

Globally regulators and policy makers have initiated numerous regulations on the breeding and export of many previously traded species, in order to reduce the rate of their invasion (Patoka et al, 2018). Three types of government regulatory engagement exist; high engagement, low engagement and no engagement. Countries within the European Union, as well as the U.S.A, Japan and the United Kingdom fall under high engagement. These countries have strict lists and regulations in place which enthusiasts must adhere to, banning the import, export and breeding of many species. For countries within the EU, any species on the IAS list (invasive alien species) may not be kept, bred or transported (Environment Europa, 2024)
Countries such as Brazil fall under low engagement and have few regulations regarding the aquarium trade. Brazil allows the trade of over 2000 species of ornamental fish species (Patoka et al, 2018) including the import of the highly invasive Lionfish. Lastly some countries, such as Chile completely overlook the threat of introduced ornamental/aquarium species and have no regulations regarding the commercial import of non native species even when the species has a history of being extremely invasive elsewhere (Larrain et al 1996, Patoka et al, 2018).

Despite the large amount of pressure put on wild ornamental species, the global trade in marine ornamental fish also offers benefits for conservation, economic development, and financial stability for communities. By creating economic incentives, local communities are financially encouraged to protect these ornamental fish populations and their habitats to ensure future exploitation (King, 2019).

Lionfish Invasion of the western atlantic.

The introduction of the red lionfish *Pteriois Volitans* and the common Lionfish *Pteriois Miles* in the western Atlantic, is one of the most rapid and ecologically damaging marine invasions of all time (Albins & Hixon 2013, Kletou et al 2016). Since the intentional or accidental release of *P.volitans* 1986, they have rapidly spread throughout the East coast of the United States, the Gulf of Mexico and South America.

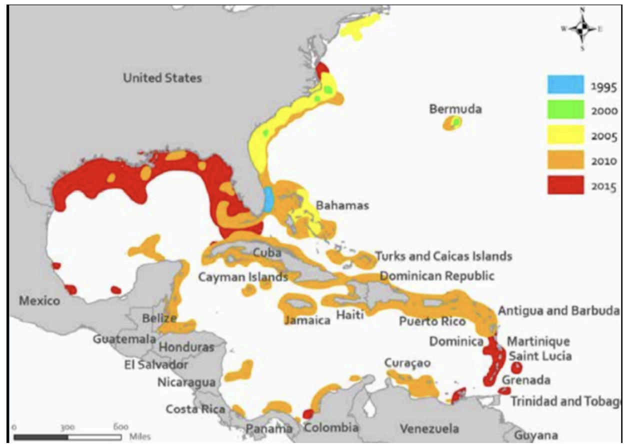

Fig 9 - Red Lionfish (https://www.nationalgeographic.com/animals/fish/facts/red-lionfish)
FIg 10 - Spread of the Lionfish (Scott, 2022)

Its unrivaled defensive, predatory, and reproductive capabilities are key to its invasion success (Kletou et al, 2016). The lionfish is covered on all sides with venomous spines, having 18 in total. These venomous spines deter almost all predators, including sharks, barracudas and large grouper species. *Muraeninae*, moray eels are the only predator known to actively prey on lionfish. Moray eels are sparsely populated on reefs thus are unable to keep up with the reproductive output of the lionfish. Lionfish are able to spawn every 4 days year-round, producing roughly 2 million eggs on an annual basis (Morris et al 2009). Their planktonic eggs are able to travel vast distances with ocean currents aiding their continental invasion (Ahrenholz & Morris 2010). Lionfish are generalist predators feeding on an extremely large variety of fish species and crustaceans. Their invasion in the Western Atlantic has massively impacted native prey species, decreasing their abundance by 65% in just two years (Green et al, 2012).

Currently removal campaigns are largely based around increasing public awareness, relying on the recreational activity from members of the public to combat their spread. The widely successful, Eat ‘em to Beat ‘em (Nuñez, 2021) campaign has effectively marketed lionfish as a delicious delicacy. Heavily relying on divers and fishermen to harvest as many as possible, considering the lack of size and take limits for the lionfish.

Aquaculture industry

Over the last decades the aquaculture industry has seen some of the most growth out of all food production industries (Garlock et al, 2020), annually growing (on average) 6.7% from 1990 - 2020 (FAO 2022). In 2020, aquaculture production reached 178 million tons, yielding over USD 265 billion (FAO 2022). Due to the immense size and nature of the industry, cultivated species are bound to escape and make their way into local bodies of water (Havel 2015). Globally almost all aquaculture takes place in Rivers, Streams, Lakes, Oceans, Seas and Lagoons this is known as water based aquaculture. A small percentage of global aquaculture takes place on land, and this practice is referred to as land based aquaculture.

Water based aquaculture has many potential sources of biological contamination giving livestock many opportunities to escape into local bodies of water. Livestock can either escape directly or indirectly, a direct escape involves the individual itself leaving the aquaculture farm, whereas an indirect escape involves the gametes of an individual leaving the aquaculture farm. Direct escapes often occur due to weaknesses and insecurities in the corral that the livestock being housed in. These may occur overtime due to lack of maintenance, predators attempting to gain access or storms .
Indirect escapes occur when farmed individuals are able to reproduce within their enclosures, as a result of not being sterile or segregated based on sex, allowing for gametes to escape, through bird transmission (Reynold et al 2015), corral insecurities or effluent discharges.

Fig 11 & 12 - water based aquaculture farm (New Roots Institute), **Land based aquaculture farm (Fishfocus)**

Selection for high yield traits

In 2005, 490,000 farm raised salmon escaped during a storm in Norway. Their collective weight, 1300 tonnes exceeded the wild salmon harvest in Norway that year (Hindar et al, 2006)

Cultivated species such as Salmonids have undergone decades of artificial selection and even genetic modification (Smith et al, 2010). The isolation of high yield traits has significantly altered their genomes when compared to their wild counterparts (Hindar et al, 2006). High-invasion scenarios suggest that wild populations are genetically outcompeted and eventually become mixtures of hybrid and farmed descendants (Hindar et al, 2006). This has been a relatively common occurrence in wild Salmonid populations, where the hybridization with farmed individuals leads to a reduction in lifespan, due to the high yield traits (Hindar et al, 2006). With the recovery of wild populations being very unlikely even after decades of little intrusion (Hindar et al, 2006). Due to the ability of farmed individuals to outcompete their wild counterparts the fear of the loss of wild genotypes or genetic pollution is not misplaced.

The economic incentive to cultivate high yield fish species puts the ecosystems they are grown in at high risk of invasion. The industry has a preference for high yield organisms that are able to adapt to varying temperature ranges, salinities and densities (Minchin et al, 2005). Their few requirements make their cultivation accessible to many individuals and businesses. Due to their sought after higher values of competitively advantageous traits and phenotypic plasticity, they can thus quickly become invasive when present in a non-native ecosystem (Matzek 2012). Currently the majority of aquaculture takes place in South and East Asian regions making up 80% of global production (FAO 2022). Regulation in South and East Asian regions is unable to keep up with the growth and demand of the industry thus leading to unregulated development, unsustainable intensification and weak regulatory policies in the region (FAO 2022). The combination of rapid growth and lack of regulation has resulted in many of the most cultivated species becoming invasive. The following species are contribute the largest amount to global aquaculture production; *Oreochromis niloticus 9%* (Nile Tilapia), *Ctenopharyngodon idella* 11.8% *(*Grass carp), *Hypophthalmichthys molitrix* 10% (Silver carp) and *Cyprinus carpio* 8.6% (Common carp), these species are primarily cultivated in South East Asia and all of these species are also on the list of “worst invasive species” (Wiki, 2024).

Figure 13: Silver carp jumping from the water (Asian Carp Canada, 2022)

The policies and regulations surrounding the spread of invasives in aquaculture

Effluent discharge (liquid waste), water access and habitat use

Within the EU and United States standards exist for waste water discharge (much like ballast water discharge), where certain water qualities must be met in order to discharge them. Within the EU standards of the Water Framework Directive (WFD) must be followed. In the United states standards set by the Environmental protection agency must be upheld. Both standards set limits for the concentration of organic pollutants, nutrients, total suspended solids and biochemical oxygen demand.

Aquaculture of non- native species

Countries within the EU must adhere to the Alien species in Aquaculture EC council regulation 708/2007 (European Union (EU), 2007), aiming to “avoid adverse effects to biodiversity” by aquaculture facilities. It states that those transporting alien aquatic species to aquaculture facilities must be permit holders. Allowing for permit holders to be held accountable in event of releases/escapes.

A myriad of policies and regulations exists for the aquaculture industry, many regulations have been initiated in order to limit the spread of invasives. As is often the case, some developing countries lag behind the regulatory curve and are yet to even regulate crucial elements of aquaculture, heavily exposing them to the risk of releasing invasive species.

Grading of aquaculture facilities

Aquaculture facilities around the globe are graded based on certain criteria, currently there is no single standard international grading system in place, and grading is done either through government backed companies or certification programmes such as ASC (Aquaculture stewardship council).

Generally aquaculture facilities are graded on the following criteria.

1. **Environmental Impact**

   Management of waste - How does the facility manage its waste products (effluent discharge)?

   Surrounding water quality - Is the water quality surrounding the facility affected by the aquaculture facility?

   Protection of local biodiversity - does the facility impact local biodiversity?

2. **Animal Welfare**

   What quality of life does the facility offer to its livestock?
   Food quality, management of diseases and stocking density.

3. **Sustainability practices**

   Where does their energy come from, sustainable sources?

   Where do they source their feed?

4. **Regulatory Compliance**

   Does the facility comply with national and international laws and guidelines?

5. **Innovation and technology**

   Are there any implementations of advanced technology?

The combined score of all the criteria is used to give the facility a grade. Five final grades exist; A (excellent), B (good), C (average), D (poor) and F (failing).

Regarding the transmission of Invasive species, only the environmental impact and regulatory compliance grades are of real importance.
Globally only very few facilities have been graded (10 -15 %) and thus the global compliance to international standards and nation laws remains largely unknown.

(Wild) Capture Fishing industry

Fishing activities go back almost as long as mankind itself, being a common practice in all corners of the globe (Sahrhage et al, 2012). Over the thousands of years of practice, fishing has evolved into what it is today. Currently there are approximately 4.1 million fishing vessels around the globe, yielding approximately 90 million tonnes of aquatic biota producing over USD 141 billion in 2020 (FAO 2022). The global fishing fleet primarily utilizes nets to catch fish (Sahrhage et al, 2012), and fishing gear which is insufficiently cleaned allows invaders to hitchhike. These nets when wet can keep small organisms alive for extended periods of time. Small organisms can unintentionally get caught in the nets. Unaware of the organisms still trapped in the nets, fishermen may put them out in new locations where these organisms can potentially establish self-supporting populations (Minchin et al, 2005). *C. taxifolia,* better known as Killer Algae, is believed to have invaded the Mediterranean this way (Minchin et al, 2005), translocating it from the Red sea into the Mediterranean via their nets. Killer algae produces a chemical called caulerpenyne, this chemical is toxic to gastropods, fishes and mammals (Box et al, 2010), which has resulted in rapid unregulated population growth in the mediterranean.

The use of certain bait types have also been shown to be effective vectors of transmission (Fricke et al, 2020). Frozen prawns have spread white-spot syndrome virus (WSSV) through much of Southeast Asia, and are potentially able to infect other prawn species world-wide (Minchin et al, 2005). The use of prawns as bait for the line and trap fishery is common practice around the globe should frozen prawns exposed to the virus be used as bait, the virus could gain access to new regions (Williamson et al, 2002). The use of live bait is common practice in the fishing industry (Minchin et al, 2005). Live bait may be caught and exported around the globe to be used as bait. Worms caught in Korea and the US are globally exported utilizing airfreight to countries within Europe (Minchin et al, 2005), when discarded an obvious vector of transmission exists.

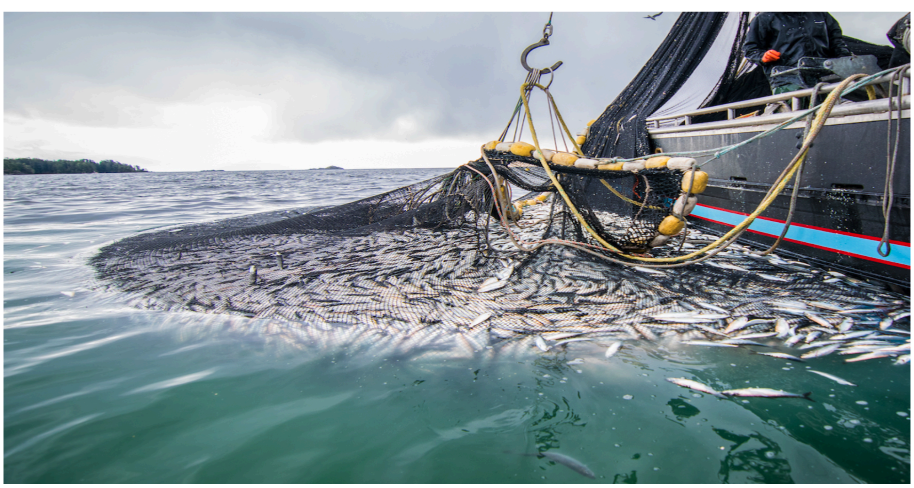

Fig 14 - bottom trawler pulling in its nets (Ho, 2021)

Not isolated to the fishing industry alone, the anchoring of fishing vessels has been shown to pick up and distribute certain forms of biota, and shown to have aided the establishment of the tropical green alga in the Mediterranean Sea (Relini et al, 1998).

Fisheries regulations for mitigating invasives

Ballast water regulations

Much like the shipping industry, fishing vessels often also travel internationally and so must adhere to the D2 ballast water standards (IMO, 2023) reducing the risk of translocation through ballast water.

Bait and tackle restrictions

Many countries and states impose strict restrictions on the use of live bait. Countries like: The Netherlands, Sweden and Norway, all have a zero tolerance policy for the use of live bait, in order to protect their highly sensitive aquatic ecosystems and native species. Many other countries have partial bans restricting the use of live bait in certain areas which have been deemed vulnerable. Restrictions on live bait are

Cleaning/decontamination of equipment and hulls

The IMO's biofoul guidelines advise vessels traveling internationally to clean their hulls and decontaminate their equipment (IMO 2023). The decontamination of fishing equipment/gear has become mandated in almost every nation for vessels traveling internationally. Decontamination is often done utilizing chemical disinfectants like bleach solutions and hot water (above 60C), which are particularly effective in killing mollusc species, like the Zebra Mussel.

Fishing vessels based within the EU, traveling internationally must comply with regulation, No. 1143/2014, requiring them to; inspect, clean and decontaminate all equipment potentially carrying invasive species (nets, ballast tanks, hulls, traps and lines) (EU, 2014).

The fisheries industry is highly scrutinized and regulated internationally. Both Asian and European countries have similar regulations for vessels fishing internationally, where vessels must comply with ballast water standards, decontamination mandates and in some cases bait restrictions. The spread of aquatic invasives through the fishing industry is not underestimated, the great number of regulations are imposed, primarily in order to reduce the spread of aquatic diseases.

Leisure activities

In recent years aquatic environments have gained popularity, becoming host to various forms of leisure activities. Annually in America and Canada alone the recreational fishing industry is estimated to yield tens of billions of dollars (U.S. Department of the Interior 2016; Fisheries and Oceans Canada 2019, Fricke et al, 2020). Millions of recreational anglers (Fricke et al, 2020) and boaters often travel large distances to reach new areas to fish and explore. By doing so they pose the risk of transporting species unintentionally into geographically isolated regions. In North America, a linear relationship between non native species and recreational fishing demand has been demonstrated (Davis and Darling 2017).

Recreational boaters and anglers often use trailers to transport their boats across land into unconnected bodies of water, resulting in the dispersal of many exotic aquatic macrophytes to regions outside of their native range (Johnson et al, 2001, Minchin et al, 2005). The trailers of recreational boaters have been demonstrated to have played a primary role in the translocation of *Dreissena polymorpha the* Zebra Mussel and *Dreissena bugensis* the Quagga Mussel, displacing them well beyond their native range (Johnson and Carlton 1996, Hickey 2010). Fishing using bait is also common practice in the recreational angling scene, using small fish (sometimes alive) or worms to entice a bite from a bigger fish. *Osmerus mordax* or Rainbow smelt, *Micropterus dolomieu* the Smallmouth Bass and *Bythotrephes longimanus* the Spiny Water Flea, have been translocated by recreational anglers, into inland bodies of water (Vander Zanden and Olden 2008, Jackson 2002). These species were most likely introduced via the emptying of live bait holding tanks and bait buckets at the end of fishing sessions (Jackson 2002).

Fig 15 - boat transportation over land (uShip Guides, 2019)

Regulation for aquatic leisure and recreational activities

Use of (live) bait

Recreational fisherman, like the commercial fisherman, must adhere to live bait restrictions in their state or country. As previously stated some countries have zero tolerance policies (Norway and the Netherlands). In Ireland and Canada, the use of non native species as live bait is prohibited, allowing the use of native species. Limiting the effects of the transmission vector, without hindering an angler's method of fishing.

Biofouling regulations

In order to prevent the spread of invasives to isolated regions, countries like New Zealand and Australia require recreational boaters to maintain biofouling standards (CRSM & ABFMR). Some US states like California, Wisconsin, Minnesota and Michigan, require boaters to regularly clean their boats and trailers to prevent the spread of Zebra and Quagga mussels.

Initiatives and campaigns

Few regulations exist for recreational boaters and anglers, some initiatives and campaigns are around and raising awareness of the possible implications of seemingly innocent actions. The check, clean and dry initiative (US Fish and Wildlife Service, 2021) and the stop aquatic hitchhikers campaign (SAH) targets recreational boaters and anglers promoting feelings of responsibility towards limiting their translocation. Some popular boat ramps have implemented cleaning stations, allowing boaters to clean their boats and equipment before entering or leaving the water (Bleitz et al, 2024).

Drifting

Drifting downstream, with currents, or with the wind, is an effective way for aquatic organisms to reach and colonize new regions requiring little effort to travel vast distances (Van Riel et al, 2011). Some organisms utilize (semi) floating objects (often plastics) as vehicles of transportation, giving them access to new regions otherwise inaccessible.

Over the past five or six decades, contamination and pollution of the world's oceans has been ever-increasing, with few signs of slowing down. Marine litter can be made of an infinite number of materials, however plastic marine litter has been found most abundant (Rellán et al, 2023) These floating and semi-submerged plastics also drift with the winds and currents, eventually reaching coastal areas or accumulating in an ocean gyre (Verma et al, 2020). One infamous ocean gyre, which most know as The Great Pacific Garbage Patch (GPDP), reached a size of 1.6 million square kilometers in 2020 (Verma et al, 2020). Four other large oceanic garbage patches exist around the globe, North Atlantic garbage patch, South Atlantic garbage patch, Indian ocean garbage patch and the South Pacific garbage patch.

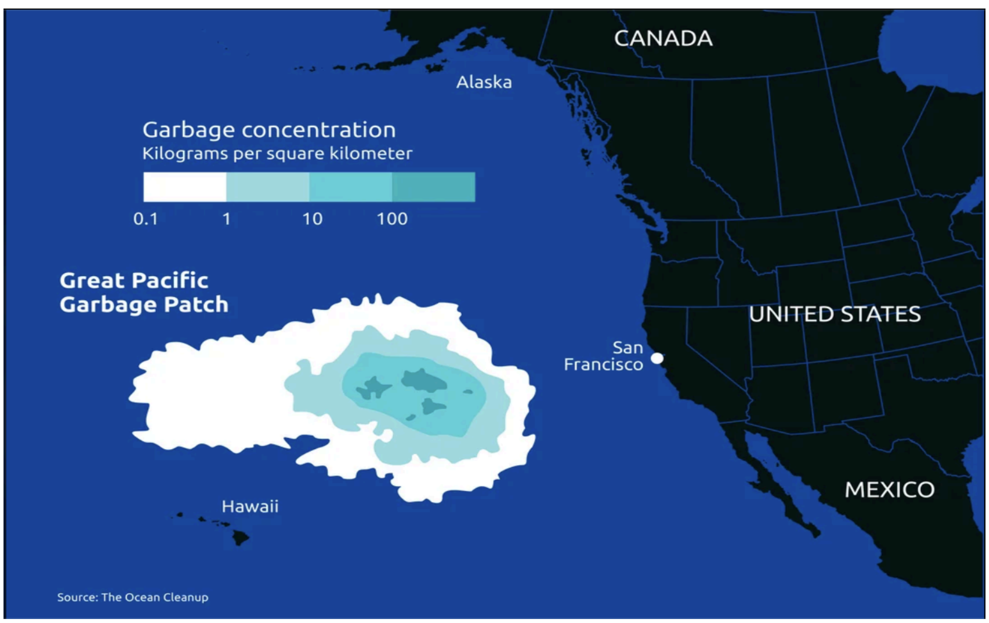

Fig 16 - Size of the great pacific garbage patch (The ocean cleanup)

The use of anthropogenic pollution by invasive species to colonize new regions remains largely theoretical (Minchin et al, 2005) and as of today still largely untested. The lack of research available on the topic, maybe due its complexity.
Organisms using floating objects such as plastics as vehicles, have a high likelihood of accumulating in garbage patches. Even though these organisms may have invaded a

community outside of their native range their effects go unnoticed, shadowed by millions of tonnes of plastics.

International regulations and clean up

UNCLOS - United Nations Convention on the Law of the Sea

Also known as the “constitution of the oceans”, requires member states to “prevent, reduce and control pollution of the marine environment” (United Nations, 1982). With 169 member states UNCLOS has a large international status.

MARPOL 1973/1978 - International convention for the prevention of pollution from ships

The MARPOL is an international convention with 160 member states; these members must adhere to MARPOL 1973/1978. Annex V, specifically deals with the littering of garbage from ships. It prohibits the disposal of plastics and all other forms of potentially harmful waste into the ocean or sea. Vessels in violation of MARPOL regulations can face fines, detention of vessel and or criminal prosecution (IMO 1973/1978)

Ocean cleanup

Founded in 2013, the ocean clean up is a non profit organization developing technologies which are removing vast quantities of plastic pollution from the world's oceans, seas and rivers. The organization aims to clean up the great pacific garbage patch, as well as 90% of floating ocean plastic by 2040. (The Ocean Cleanup, 2024).

The disposal of garbage into the oceans is internationally well regulated, however vast quantities still enter the ocean each year. In 2023, an estimated 11 million metric tonnes of plastics entered oceans around the globe (United Nations Environment Programme, 2021). The majority of plastic enters the oceans through rivers coming out of developing nations discharging into the oceans. Regulations and mandates can be made for internationally traveling vessels but they remain specs in the ocean in comparison to the pollution that is sourced from the land.

Discussion

A general trend that I found when searching for international laws and legislation, was that only first world countries like those in the EU, North America, Oceania and some in Asia have national laws or adhere to international laws, regarding the seven transmission vectors. Developing countries (second or third world nations) often only had few, very generalized laws and in most cases; no laws regarding the transmission vectors. From my research no conclusions could be drawn as to why this is, however the lack of regulation does allow for unhindered rapid development.

I believe that globally, the shipping and aquaculture industries produce the largest quantities of invasive aquatic species and pose the greatest risks to biodiversity.

The immense size of modern freight ships and volumes of ballast water that they carry, pose many challenges. As previously mentioned annual global ballast water discharge is estimated to be around 3.1 billion tonnes (Hernandez et al, 2023), its global effects however are not under estimated. The internationally recognised D2 and BWTS (ballast water treatment systems) have massively hindered the transmission of large organisms (larger than 50 micrometers) through ballast water (considering full compliance internationally). Transmission through hull transport, still remains internationally largely unregulated, and standards like CSRM biofoul (Georgiades et al, 2020) or the guidelines recommended by the IMO (IMO 2023) must be mandated globally if we hope to observe any reduction.

The Irresponsible practice of aquaculture poses arguably the greatest risk of invasion to aquatic ecosystems. This is because the selection of traits improving the individuals yield and adaptability are most sought after. Due to the economic incentives these traits have, the selection for them and the technology used to isolate and view them, will only accelerate with time. Fish are capable of producing enormous quantities of eggs per reproductive cycle, and thus advancements in unintrusive DNA sequencing methods could rapidly increase the efficiency of artificial selection. The lack of international regulation and standards in aquaculture combined with rapid artificial selection of high yield traits, will inevitably lead to the release of hyper competitive artificial species.

Transmission vectors of leisure activities and the aquarium industry are more difficult to mitigate using international policies and legislation, due to individuality of each case. Instead, although highly costly, awareness campaigns like the “stop aquatic hitchhikers” campaign should be initiated world wide. Having obvious major drawbacks: source of funding, backlash, inability to reach target audience or even the creation of further harm. The management of these transmission vectors can only be done through a nation/world wide understanding/realization of the consequences of seemingly innocent actions, like releasing a pet fish into a local body of water.

As for the fishing industry and drifting, their effects are marginal compared to the other five transmission vectors.

The marine fishing industry has seen little if any growth in the gross annual capture over the last 30 years (FOA 2022). Reliance on the industry has also decreased massively due to advancements in aquaculture. Considering current trends between aquaculture fisheries and capture fisheries, once marine aquaculture becomes more widespread, aquaculture is soon to outcompete the capture fishery. The transmission vectors of the wild capture fishing industry are largely identical to those seen in the shipping industry, thus internationally traveling vessels are heavily scrutinized and must adhere to the legislative framework set by the IMO. The heavy regulation of internationally traveling vessels, combined with the fierce competition in the aquaculture industry, is likely to lead to a decrease in the prevalence and utilization of transmission vectors in the wild capture fishing industry.

The invasive capabilities of drifting are not well understood or documented, however they should not be underestimated. Initiatives such as the ocean clean up are having great impacts in terms of capturing floating plastics aiming to clean up “90% of floating ocean plastic by 2040”. They have also effectively raised awareness of ocean plastics, through consistent media coverage of their results. Despite these positive results, if oceanic garbage patches continue to grow, we could see large chunks break off and leave the grasp of the ocean gyres. These large chunks could potentially reach coastal areas, where hitchhikers may be ‘dropped off’ and may invade novel ecosystems. With a projected increase of oceanic plastic in future years (Ostle et al, 2019), the transmission of invasives through drifting is not to be underestimated.

In conclusion, the vectors of transmission used by invasive aquatic species requires a multifaceted, international approach. Stronger enforcement of existing laws, the development of new global standards, and continued public education efforts are vital in mitigating the spread of invasive aquatic species. Only through unified global efforts can we hope to safeguard aquatic ecosystems for future generations.

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