Ecological Risk Assessment of Non-native abalone in Oregon: Tiger, Black Lipped, Green Lipped

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Executive Summary

Oregon native abalone has been affected by many variables that have put them in an unpredictable future. The Oregon coastal ecosystem where the abalone resides has suffered from storms, climate change (increased ocean temperatures), and over-harvesting. The storm of 1962, known as the historic Columbus Day storm, has decimated most kelp forest located along the Oregon coast. After the storm, a cascade of events occurred that has made kelp populations and distribution, and as a result abalone, be limited . Additionally, the decrease of sea otters has caused an increased abundance of sea urchins that have over-consumed the remaining kelp forest and algae which is the primary food source for abalone. With increased ocean temperatures in the intertidal zone, bacteria and disease growth have increased , causing a detrimental effect on the native abalone. There are currently efforts in California and Oregon to mitigate the return of native abalone by stopping the harvesting of abalone and reintroducing farmed native species back into areas where the kelp is returning.

While there has been a trending decrease in native abalone along the west coast, an increase in exotic food items, especially in the seafood market, has expanded. This exotic demand in seafood, including abalone, has led to importing non-native species from places like Australia, Africa, New Zealand, and Japan, where they are farmed in great numbers. Some of the aquaculture practices in these locations have used hybrid species, such as the Jade tiger abalone, which is a cross of the black lipped (*Haliotis rubra*) and green lipped (*Haliotis laevigata)* abalone, that exhibit favorable characteristics over the parenting species such as increase growth rates and resistance to pathogens. This assessment found that hybrids tend to have better success in aquacultures and are rarely hybridized in a natural environment. The increase in resistance of farmed hybrids to pathogens can go unnoticed when exported and imported. While this assessment did not find any greater risk to human health compared to other seafood consumed by people in the United States from these pathogens, they do have a considerable risk to the native abalone and the ecosystem they can inhabit.

Oregon does not currently have prohibitions against importing live abalone, whereas California and Washington have stopped all importation of abalone. The greatest risk found in both California and Washington is the herpes-like virus (AbHV) capable of causing mass mortality of abalone, 97% or greater within three days. The new efforts of reintroducing native abalone in reforming kelp beds along the Oregon coast would be at risk by importing non-native abalone, especially hybrids. The possible introduction of an invasive species that has the capability to fill a vacant niche and prevent the native abalone from recovering, would likely be detrimental to not only the marine ecosystem but the local coastal community fisheries.

Introduction

The west coast has seven species of abalone: the red abalone (*Haliotis rufescens*), pink abalone (*Haliot corrugate*), black abalone (*Haliotis cracherodii*), green abalone (*Haliotis fulgens*), white abalone *(Haliotis sorenseni*), pinto abalone, additionally named the threaded abalone (*Haliotis kamtschatkana)*, and the flat abalone (*Haliotis walallensis*) (Anderson, 2018). All seven species listed are native in southern California estuaries. In comparison, three species, the red abalone, flat abalone, and pinto abalone, are located along the Oregon coast, with the occasional black abalone found along the most southern estuaries (Anderson, 2018). The threaded and pinto abalone are considered the same species; however, the threaded is in southern California into Mexico, whereas the pinto abalone is located in northern California into Oregon (Anderson, 2018). Washington has the same three abalone species as Oregon , the red abalone, pinto abalone, and the flat abalone (Anderson, 2018).

Currently, the white abalone is on the Endangered Species Act (ESA), and the black abalone is proposed to be added to the ESA list. Populations of wild abalone located along the west coast have been declining due to decreased abundance of kelp by storms, overharvesting, and disease, more specifically the withering syndrome (Anderson, 2018). The largest species is the red abalone and is considered the best species for aquaculture and collecting on the west coast due to its size and high fecundity.

The hybridization between species in the family Haliotidae is used by the aquaculture industry to get the characteristics in specific targeted markets (Ravi Fotedar, 2011). Many aquaculture farms in other countries export live hybrid abalone that tend to have increased size, disease resistance, and larger offspring numbers (Ravi Fotedar, 2011). The hybrid species, such as the [Jade] tiger abalone is a cross between Australia's green lipped (*H. laevigata)* and black lipped abalone (*H. rubra*), has high hybrid vigor making it a possible threat to native abalone.

The importing of abalone species from farms or wild-harvested specimens from other countries brings health concerns of disease and viruses. Abalone can be a vector for many viruses and diseases (Corbeil, 2010). In 2008 a herpes-like virus was observed in as much as 90% of Australia's farmed and wild-harvested black lipped and jade tiger abalone causing die-offs (Corbeil, 2010). In 1999, a mass amount of abalone mortality was due to a spherical virus found in the infected abalones' liver tissue in China (Hong-Ying Wei, 2018). Abalone shriveling syndrome was noted in China's aquaculture with outbreaks still occuring today (Hong-Ying Wei, 2018).

The increased ocean temperatures have allowed the increment of bacterial pathogens spread to native abalone along the Oregon coast. The decreased kelp forest and increased pathogens has caused a vacant niche that is prime for an invasive species to fill. Prevention of invasive species is the least costly method of control to keep an ecosystem free of invasive species and functioning properly. The intertidal ecosystem has a profound value to the whole marine ecosystem function. Besides the known factors of abalone many studies recognize that there is not enough known about abalone to conclude the full extent of risk (Calisher, 2008).

Characterization of Exposure

Abalone Species Native to Oregon

Black abalone (H. walallensis)

Black abalone are found in the intertidal and shallow subtidal areas of rock reefs, residing in depths of about 20 feet (Yang, 2019). The species has shown sensitivity to water temperatures in which, during cooler years, individuals are smaller and during warmer years their sizes increase. This is likely due to warm waters increasing kelp growth, which the black abalones eat. Conversely, during long warm years, the black abalone is more susceptible to diseases related to bacteria growth (Haas et al., 2019). They spawn between February to August when temperatures reach 62 to 68 degrees Fahrenheit (Nurenskaya Velez-Arellano et. al, 2020). Hybridization is uncommon for the black abalone, even in areas where several species occur together (Yang, 2019).

Red abalone (H.rufescens)

Red abalone are found from Sunset Bay, Oregon to Tortugas, Baja California. North of Point Conception, they are found in the intertidal and subtidal zones to depths of 60 feet (Yang, 2019). These animals can grow to 7.75 inches with a diet consisting of bull kelp, giant kelp, *Laminaria, Egregia, Pterygophora and Ulva* (Haaker et al., 2003). Red abalone spawn throughout the year with peak breeding season being February to August when temperatures reach 62.6 to 68°F (Nurenskaya Velez-Arellano et. al, 2020) (Yang, 2019). Hybridization is common in areas where several species occur together (Yang, 2019). This species may be resilient against ocean acidification, which the coast of Oregon is at an elevated risk of. Increased CO_2 concentration in water does not impact fecundity but does impact lipid metabolism (Swezey, 2020). This may give the red abalone an advantage over other abalone species in the context of ocean acidification which the Oregon coast is prone to.

Pinto abalone (H. kamtschatkana)

Pinto abalone are found from Sitka, Alaska to Monterey, California. They prefer the intertidal and subtidal zones to depths of 70 feet. Some can grow to lengths of 6.49 inches, with average lengths of 4 inches. Alg.ae is their main food source Spawning occurs throughout the summer with peak spawning occurring April to June (Haaker et al., 2003). This species does have the potential to hybridize with other abalone species (Yang, 2019).

Abalone Species Non-Native to Oregon

Green lipped abalone (Haliotis laevigata)

Haliotis laevigata is a large abalone species native to Australian waters, growing to lengths of nine inches They are found in intertidal zones to depths up to 131 feet.. As adults they feed on sea grasses. This species is sensitive to water temperature increases. Green lipped start having significant die off and health issues at 78.8 degrees Fahrenheit, with a higher mortality rate in larger individuals (Shiel et. al, 2020). Ideal growth and breeding temperature for this species is 68 degrees Fahrenheit but can tolerate 60.8- 68 °F (Botwright et al., 2019).

Black lipped abalone (Haliotis rubra)

Haliotis rubra is native to Australia waters and is found in rock crevices and under boulders. The black lipped abalone prefers shallow subtidal systems, normally found in depths less than 32 feet. However, it is possible for them to live as deep as 131 feet. Being a larger abalone species, they weigh over six pounds (Atlas of Australia, 2020). Water temperatures above 73°F will cause significant die off in adults (Jalali, et al, 2010). The juveniles prefer water temperatures around 60.8°F and higher temperatures can cause elevated mortality in the young as well.

*[Jade] Tiger abalone (*Hybrid of *Haliotis rubra* and *Haliotis laevigata*)

The [Jade] tiger abalone is a hybrid of the green and black lipped species. They are produced withinAustralian aquaculture but the two parent species have been known to hybridize in the wild as well. Hybrid vigor has been observed in the [Jade] tiger abalones and can survive in conditions similar to the parent species. Hybrids start having significant die off and health issues at 78.8 degrees (F). With a higher mortality rate in larger individuals (Shiel et. al, 2020).

Breeding Seasons of Native and Non-Native Abalone

Native and non-native species have an overlap of spawning seasons (Table 1). The native black abalone spawns February through August. The native red abalone can spawn through the year with peak spawning occurring February through June. Pinto abalone have a shorter spawning period of April through August, with a peak occurring April through June. Conversely, non-native species breed under similar conditions. The green lipped and black lipped abalone species spawn March through August (Haaker et al., 2003). Although seasonality is interesting to compare, temperature is a better predictor for when non-native abalone will spawn. For further analysis on how well non-natives could propagate off the Oregon coast, average monthly temperatures are considered in the following section.

Table 1. Possible and peak spawning months for Oregon native abalone and non-native abalone. The lighter orange shows possible breeding months and the darker orange shows peak spawning months.

	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Native												
Black abalone (H. walallensis)												
Red abalone (H.rufescens)												
Pinto abalone (H. kamtschatkana)												
Non- native												
Green lipped abalone (Haliotis laevigata)												
Black lipped abalone (Haliotis rubra)												

Oregon Coastal Waters

To assess the risk of non-native species surviving in Oregon coastal waters, the average monthly and bi-monthly temperatures at four coastal locations were compared to the conditions the non-natives thrive in. The locations included Port Orford, Charleston, Newport, and Seaside (Figure 1).

Figure 1. A map of the Oregon coast with the four locations NOAA monitors water temperatures. The monthly and bi-monthly water temperatures for these locations are listed in Table 1.

In the green and black lipped abalones' natural habitat, seasonal water temperatures range from 57.2°F to 71.6 °F (Stone et al., 2014). Aquaculture maintains water temperatures at an ideal temperature range for 60.8- 68 °F. Significant die-off has been shown to occur at 78.8°F (Botwright et al., 2019)(Jalali, et al, 2010). According to the National Oceanic and Atmospheric Administration (NOAA), the 2019- 2020 coastal water temperatures range from 42°F to 68°F (NOAA, 2020). Conditions fluctuate by region and month. Monthly, and bi-monthly, average water temperatures, at the four listed Oregon coast locations (Figure 2). The red line indicates the low end seasonal temperature for the non-native's natural habitat, and is therefore labeled as the temperature threshold. Most regional water temperatures fall below the threshold with the exception of Seaside. From May to September, these areas have water temperatures similar to the low end temperatures found in the native range of non-natives. The [Jade] tiger abalone has shown to have a higher heat tolerance than both parent species but is raised in water temperatures similar to wild conditions (Stone et al., 2014).

Furthermore, it is important to note that much of the coastal waters hover two to three degrees below native conditions for non-native abalone species. The Oregon Department of Fish and Wildlife (ODFW) reflects that Oregon coastal waters have risen by 0.5°F per decade (ODFW, 2020). When considering previous ocean warming trends, future conditions could expand the potential range for non-native abalone species.

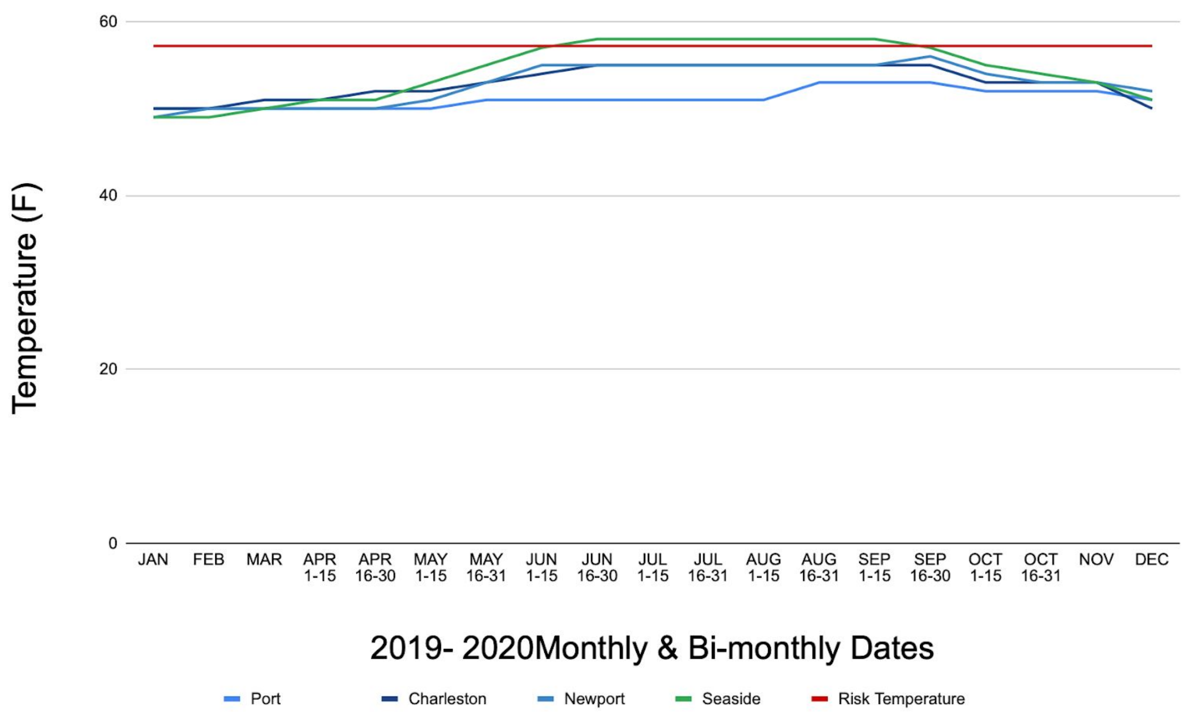

Figure 2. Monthly and bi-monthly water temperatures at all six monitoring sites. The red line indicates the low end seasonal temperature for the non-native's natural habitat and is therefore labeled the risk temperature.

Commercial Propagation

There are two main methods of commercial propagation of green lipped, black lipped and [Jade] tiger abalone. These methods are land based farms and sea ranches. The primary method used in Australia is land-based while sea ranches are less common.

Land based farms are often located on the coast or near large water sources due to their intense water requirements (Figure 3). Within these farms, females produce around one million eggs per spawning. After fertilization, larvae settle onto plates covered in cultured diatoms for up to 12 months. After this time period they are transferred to circular enclosures called grow out tanks. The grow out tanks are covered with mesh and sea water is pumped over them. Most abalone are harvested around their third year when they reach the weight of 1.4 ounces(MESA, 2020).

Figure 3. An aerial view of a land based abalone farm in Australia (MESA, 2020).

Sea ranch aquaculture can include a combination of single-pass, flow through tanks on land, tethered cages or enclosed in the sea (Figure 4). There is little chemical use within abalone farms because antibiotics are essentially ineffective. Within ranches, the abalone are mainly fed harvested algae. Untreated effluent from sea ranches have previously shown to be vectors for disease to wild populations (Seafood Watch, 2017). In 2012, the Department of Fisheries of Western Australia decided that the risk of abalone viral ganglioneuritis (AVG) from farmed abalone was too large of a risk to wild populations (Jones and Fletcher, 2012). Since that time, Australia has started testing the farmed juveniles before being released for sea ranching (FISH, 2012).

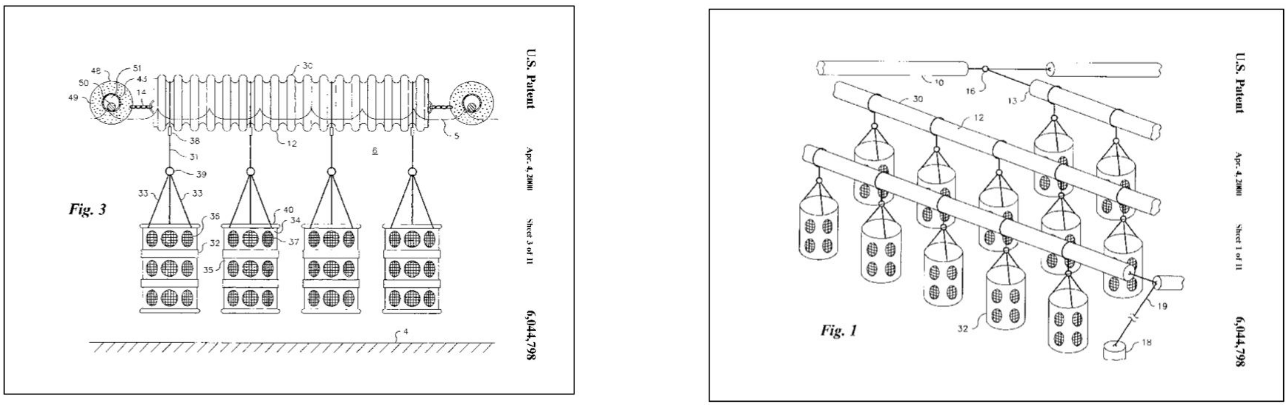

Figure 4. Examples of cages used in sea ranch aquaculture. Abalone are placed within the flow through tanks and the tethered cages are held in place under water (Seafood Watch, 2020).

Import and Export of Australian Abalone

The United States imports most of its abalone from Australia. As of 2015, 34% of imported abalone comes from that single country. As of 2016, the U.S. imported 579538 pounds/262,874 kg of abalone from Australia (Seafood Watch, 2017). These findings suggest a potential for propagule pressure from the live fish market.

Characterization of Ecological Effects

Potential to Prey Upon Native Wildlife

Abalone species tend to be generalists as adults target available macroalgae, while juveniles have the radula/mouth structure, that morphs as it grows, to consume microalgae (Johnston et al, 2005). The individual consumption rate of abalone is slow, therefore, a significant density and competition pressure would be required to limit algae production (Stotz, 2006). Concerns of non-natives preying upon native wildlife would be heightened if distributions were occurring in regions with already limited algae supply, whether that be from other non-native, abiotic influence, or natural causes.

Disease and parasites

A direct risk of disease from imported abalone is withering syndrome and there is little knowledge of where and how the disease originated (M. Neuman). The disease causes reduction in body mass and function of muscular foot as well as increases morality (Braid, et al 2005). Withering syndrome causes abalone to be less resilient to other stressors including limited food supply and increased water temperatures (Braid, et al 2005). Abalone tend to be colonial as they are a slow moving, benthic species that cannot be too distant from each other due to mating requirements (Botwright et al, 2019). Therefore, if a disease were to be introduced to regions, it is likely that whole subpopulations of abalone will contract the withering disease.

A parasite known as a Rickettsiales-like prokaryote (RLP) or *Candidatus Xenohaliotis californienisi*s, is the main contributor to withering disease transmission (Moore et al, 2001). It targets the digestive tract allowing it to easily spread within the abalone and has been observed to unknowingly spread within shared seawater filtrations of controlled experiments (Moore et al, 2001). There is some thought that the infection is spread via consumption, which suggests an alternative method of transmission from vegetation carried on by imported abalone (Braid, et al 2005). The risk of disease and parasites may not only derive from abalone but also from algae and marine vegetation that encursts on live, imported abalone. Spread of disease from marine vegetation of one region to another can decimate the valuable habitat for the abalone and other native wildlife (M. Neuman).

Virial and other disease pathogens are not uncommon within aquaculture, as much of the filtered water is cycled continuously and difficult to isolate. In some cases, such diseases can overcome a pool of organisms within a short time span, giving short notice for diagnosis or treatment. This has been observed with farmed abalone in other regions when they contract an abalone herpes-like virus (AbHV) where it took as short as three days for whole pools to die off with no discrepancy of life stage (Gao et al, 2018).

Competition Characteristics

There are general concerns with competition as native abalone populations have diminished significantly and have a history of drastically reducing in numbers from natural ocean events, such as La Nina. (M. Neuman). Population stocks are fairly low to begin, which causes native abalone to be a weaker competitor for survival resources such as space and food. Their general diet allows them to feed upon most algae present within any environment that non-native abalone species become established in (Stotz, 2006). This poses a threat to the food supply of not only native abalone but other herbivorous species of Oregon’s intertidal ecosystem.

Competition with other intertidal species, such as urchins, can increase especially since the two organisms have similar larval dispersal behavior (Morgan & Shepherd, 2006). Abalone larvae can travel for several kilometers with the aid of ocean currents, however urchins have an extended swimming ability and can disperse a hundred plus kilometers (Morgan & Shepherd, 2006).

Several non-native abalone species have demonstrated being better fit or more competitive compared to native species with stressors or limited resources. Their distribution is not limited as the *H. laevigata* tend to be at deeper depths of 33 to 82 feet while *H. rubra* reside near shore, thus reducing space for other species (Morgan & Shepherd, 2006). The Pacific abalone *Haliotis discus hannai,* have a tolerance to high temperatures, allowing it to sustain warmer sea temperatures from climate change (You et al, 2015). Abalone have a general correlation of high density populations that can result in stunted growth, limiting abalone populations and causing few to reach an appropriate harvesting size (Dixon & Day, 2004).

Human Health Risk and Zoonotic Virus Risk

Abalone are known for being vectors of viruses and bacterial pathogens that can affect other species in the marine ecosystem. The potential risk to humans for these pathogens is comparable to other seafood available for consumption in Oregon. The risk to humans is primarily with bacterial pathogens transmission due to the food preparation process and the consumption of raw shellfish. A possible infection from consuming abalone is a gastroenteritis pathogen, *Vibrio spp.*, which causes food-poisoning symptoms and is not deemed fatal (Lee et al, 2003).

Hybridization Potential

Hybridization among abalone was first experimented in the United States in the early 1980’s (Leighton & Lewis, 1982). While this has led to success in aquaculture rearing of rare abalone species, this biological behavior has yet to be observed or documented naturally within the wild of the United States. Whether this is due to reduced populations, having species distributed sparsely or another aspect is uncertain and is alarming as harvesting for abalone has been discontinued for several decades (M. Neuman).

Abalone aquaculture has been using hybrid abalone for its fast growth rate and resistance to pathogens. Some hybrids' quick growth rates make them more likely to consume resources, limiting them for native abalone. Abalone species are greatly affected by their environment, more specifically, the temperature of water. Studies have found that hybrid abalone are not affected by acute temperature increases with lower oxygen levels while native species are likely affected (Katharina Alter, 2017). The spawn level of abalone is dependent on size, where a smaller abalone may release 10,000 eggs and a larger specimen might release millions of eggs, increasing the risk for hybridization (Katharina Alter, 2017). The aquaculture industry often uses recycled water from marine areas, while the aquaculture uses filters to capture spawn, the likelihood of error is great with millions of spawns.

While hybridization can provide some promise for abalone populations, invasive abalone species have this capability as well. [Jade] Tiger abalone, the hybrid produced offspring of *H. rubra* and *H. laevigata*, have a higher survival rate compared to their parental species, which causes some concern with potentially reducing the genetic diversity of Oregon native abalone species with an increase of the hybrid species. (You et al, 2015).

Economic Cost if not Controlled

Factoring in the potential expense for abalone restoration is important if an invasive species deplete the native populations significantly to where distribution and natural mating is limited. Economic cost for abalone restoration is a multi-million expense, as seen from NOAA with their twelve year practice, which is not nearly as expensive as the efforts towards more popular species of crab and salmon (NOAA, White Abalone) However, potential decimation of vegetation from diseases transmitted from algae and vegetation on imported live abalone, could cause a cascade economic toll (M. Neuman). This cascade could not only directly impact marine vegetation harvest and the struggling kelp forests, but may indirectly impact the stocks of highly harvested marine species which rely on vegetation for survival.

Risk Characterization

Below the twelve criteria for non-controlled classification, from the Oregon Department of Fish & Wildlife is utilized to determine the level of risk (Table 2). Each criteria is given a high, medium, low or unknown rating. A corresponding reason is also provided.

Table 2. Risk characteristics based on criteria (a- j) from Oregon division 56: Noncontrolled Classification of the Oregon Department of Fish & Wildlife. "T" represents the [Jade] tiger abalone, "B" represents the black lipped abalone, and "G" represents the green lipped abalone.

Criteria	High	Medium	Low	Unknown	Reason
Whether Species Habitat is Similar to Oregon's climate & habitat		T, B, G			Oregon is heading to an equivalent climate of non-native habitat
Whether the species has an invasive history			T, B, G		Understanding that some invasions may not be recorded or have yet to be observed
Whether the species can survive in Oregon		T, B, G			May have some limitation from food supply with reduction in algae in tidal habitats
Whether the species has the potential to prey upon native wildlife	T, B, G				Generalist consumers of algae
Whether the species can potentially degrade the habitat of of native wildlife	T	B, G			Tiger abalone have a higher biomass requiring more algae intake/consumption

Whether the species has the potential to pass disease or parasites to native wildlife	T, B, G				Any species can carry the withering syndrome and harbor parasites within the encrusting algae on their shells
What types of disease or parasites could be passed to native wildlife	T, B, G				Any species can carry the withering syndrome and harbor many different parasites within the encrusting algae on their shells
Whether the species has the potential to compete for food, water, shelter, or space with native	T, B, G				Tiger biomass requires significant food for size while green lipped and black lipped have realized niches allowing them to reside in crevices and spaces for native species refuge
Whether the species has the potential to hybridize with native wildlife			T, B, G		Hybridization requires human aid and only seen successful within lab settings
How is this species categorized in “The IUCN Red List of Threatened Species”?				T, B, G	None of these species are considered threaten
Whether the species can be readily distinguished from a native species, or a prohibited or controlled species			T, B, G		Juvenile abalone species may not clearly show characteristics for proper identification
Is the species commercially propagated?	T, B, G				Depending on size and species, abalone spawn thousands to millions of gametes

Summary & Recommendations

With this combination of potential ecological effects that may cause further depletion of not only native abalone species but of other harvested marine species, it would be recommended not to allow the importation of live abalone. An alternative, since the prosperous abalone industry grossed in over $100 million, is to allow the importation of frozen abalone meat and properly cleaned abalone shells. This omits potential risks of invasions from accidental introduction and the spread of marine diseases and parasites.

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