Framework for the Ecological Risk Assessment of Green Crab *Carcinus maenas* in Oregon

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Executive Summary

Assessing the risk of invasive species when introduced to a novel environment is imperative for natural resource managers in determining the ecological and economic impacts to the region. Green crabs (*Carcinus maenas*) are native to the northeast Atlantic coastline and have invaded every continent except Antarctica. *C. maenas* was reported in Oregon in the late 1990s, with populations remaining low until 2015 after an El Niño and marine heatwave. *C. maenas* inhabits a variety of coastal habitats and has a broad tolerance for water salinity and temperature, making it a successful invader to new environments. *C. maenas* is a generalist and actively competes with other marine species for both habitat and food.

This paper provides a framework for an ecological risk assessment for several native marine species potentially at risk from *C. maenas* invasion in Oregon. Due to both technical limitations and time constraints, this assessment is not comprehensive but can be used as a foundation for future *C. maenas* risk assessments in Oregon. This risk assessment provides a detailed description of marine species that are potentially at risk from *C. maenas* invasion in Oregon Bays. Our research considers the impacts of *C. maenas* within five bays along the Oregon coastline: Tillamook Bay, Netarts Bay, Yaquina Bay, Alsea Bay, and Coos Bay. The focal native species include Olympia oysters (*Ostrea lurida*); Pacific oysters (*Crassostrea gigas, syn. Magallana gigas)*; razor clams (*Silqua patula*) and bay clams, which comprise of cockles (*Clinocardium nuttallii*), butter clams (*Saxidomus gigantea*), gaper clams (*Tresus capax*), and littleneck clams (*Leukoma staminea*); Dungeness crab (Metacarcinus magister); red rock crab (*Cancer productus)*; yellow shore crab (*Hemigrapsus oregonensis)*; and eelgrass (*Zostera marina)*. There is general concern over both the ecological and economic impacts *C. maenas* have on commercial and recreational fisheries, especially to Dungeness crabs and native bivalves.

The results of this risk assessment consider relative abundance of focal species, *C. maenas* Catch per unit effort (CPUE), and overall risk level in Tillamook Bay, Netarts Bay, Yaquina Bay, Coos Bay, and Alsea Bay. Species relative abundance was derived from the Shellfish and Estuarine Assessment of Coastal Oregon (SEACOR) data and the Office of Coastal Management (2022) Olympia and Pacific Oyster Data. Olympic oysters (O. *lurida*) are considered high risk in Tillamook Bay, Yaquina Bay, and Coos Bay, and moderate risk in Netarts Bay. Pacific oysters (*C. gigas*) were assessed by culture methods: ground cultured were high risk in all bays with *C. gigas*, raised cultured were low risk in all bays with *C. gigas*, and suspended cultured only occurred in Yaquina Bay where it was moderate risk. Native clams are at high risk in Alesa Bay and moderate risk in Tillamook Bay, Netarts Bay, Yaquina Bay, and Coos Bay. Dungeness crab (*M. magister*) is considered moderate in Yaquina Bay and Coos Bay, and high risk in Tillamook Bay, Netarts Bay, and Alesa Bay. Red rock crab (*C. productus)* is considered low risk in Tillamook Bay, Netarts Bay, Yaquina Bay, and Coos Bay. Yellow shore crab (*H. oregonensis)* is at high risk in all the Oregon bays, except in Tillamook Bay where populations are absent. Finally, eelgrass (*Z. marina)* is at high risk from *C. maenas* in all the bays.

Introduction

Green crab (*Carcinus maenas*) is native to the northeast Atlantic coast, from northern Africa to Norway, including the British Isles, and Iceland (Crothers, 1968; Roman & Palumbi, 2004). As a successful invader, *C. maenas* has expanded its range to every continent except Antarctica (Klassen & Locke, 2007). Global dispersal of *C. maenas* is most likely linked to the transoceanic movements of fouled and bored ships throughout the 19th century (Cohen et al., 1995). *C. maenas* was first introduced to the eastern coastline of the United States in the early 19th century, where it was initially found between New Jersey and Massachusetts and has now spread from Newfoundland to Virginia (Grosholz & Ruiz, 1996; Klassen & Locke, 2007). Between 1989 and 1990*, C. maenas* was confirmed in San Francisco Bay, California (Cohen et al., 1995). By 1994, Cohen et al. (1995) had surveyed multiple locations throughout San Francisco Bay and found both mature males and gravid females, confirming that the population was established in the area. In 1998, thousands of *C. maenas* were found in Coos Bay, Oregon by a shellfish grower (Yamada, Peterson, & Kosro, 2015). Since then, *C. maenas* populations have remained relatively low in Oregon attributed to poor recruitment until 2015 when populations dramatically increased due an extended marine heatwave and El Niño event (Behrens Yamada et al., 2021). More recently, *C. maenas* has expanded its east Pacific range into Alaska (de Rivera, per. com., 2022). In July, 2022, during a survey of the Annette Islands Reserve, the Metlakatla Indian Community discovered *C. maenas* shells, and by August caught several live adults confirming established populations in Alaska (NOAA Fisheries, 2022)..

C. maenas is an ideal invader because of its phenotypic plasticity, allowing it to easily adapt facets of its biology to a specific environment (Young & Elliot, 2020). Tepolt and Somero (2014) attribute its invasion success to its acclimatory plasticity, allowing it to adjust its thermal limits across different regions. *C. maenas* can tolerate water temperatures as low as 0°C and as high as 35°C (Cohen & Carlton, 1995; Tepolt & Somero, 2014). As an eurytherm, they have been found to have a significant tolerance to heat compared to other temperate crab species that share a similar environment (Tepolt & Somero, 2014).

Furthermore, *C. maenas* typically live four to six years in the Pacific Northwest (PNW), but they reach maturity faster and grow larger in the PNW when compared to populations in their native range (Yamada et at., 2005; Kelley et al., 2015). Crabs have a rigid skeleton and can only grow through molting (Crothers, 1967). Yamada et al. (2005) found that *C. maenas* in Oregon molted at least once a year, while in Portugal, *C. maenas* molted less frequently even though the growing season is usually longer. In addition, regional differences have been found in *C. maenas* populations (Howard et al., 2018). For example, *C. maenas* demonstrated higher attack rates in British Columbia than in Northern Ireland (Howard et al., 2018). Also, handling times were significantly lower with maximum feeding rates higher for *C. maenas* in North America than South Africa and Northern Ireland (Howard et al., 2018).

C. maenas live in a variety of habitats within the coastal environment; there are no records of *C. maenas* floating at sea (Cohen et al., 1995). *C. maenas* can tolerate water salinities from 4-52 parts per thousand (Cohen & Carlton, 1995). In its native range, *C. maenas* can be found in both hard and soft substrates, from secluded bays to exposed rocky shorelines on the outer coast (Grosholz & Ruiz, 1996). If exposed, *C. maenas* will seek refuge by shuffling into the sand or mud when limited coverage is available (Crothers, 1968). It is worth noting, they are not continuously active during a 24-hour period, but instead are found to be most active at high tide and at night (Crothers, 1968).

In Newfoundland, Best et al. (2017) found that *C. maenas* males reach sexual maturity when the carapace reaches 32mm and females reach sexual maturity when the carapace reaches 37mm. *C. maenas* generally reproduce at temperatures between 18 and 26 degrees Celsius (Cohen & Carlton, 1995). Males typically select a mate a few days before the female is expected to molt and carry the female under his body until she molts, at which point copulation occurs (Crothers, 1967). After copulation, the female will lay up to 185,000 eggs, which she carries for several months until the eggs hatch (Crothers, 1967). During development, *C. maenas* has six instars, which occur in three major stages: the eggs hatch to free swimming protozoea, then zoea, and last megalopae, when they form functional appendages and begin to look more like a crab (Crothers, 1967).

As with other invaders, *C. maenas* establishment is limited by abiotic factors. For instance, coastal water temperatures affect both the rate of larval development and survivability. The normal development of *C. maenas* larvae occurs between 10 degrees Celsius and 18 degrees Celsius (Crothers, 1967; de Rivera et al., 2007). In addition, de Rivera et al. (2007) found that in a lab setting the average larval development took 59 days at a temperature of 12.5 degrees Celsius. In Yaquina Bay, the fastest predicted larvae development ranged from 22 to 86 days (de Rivera et al., 2007). However, prolonged water temperatures under 12.5 degrees Celsius decreases the larval development rate, potentially exposing them to other threats (i.e., predation or other environmental conditions) and decreases the chances of survival (de Rivera et al., 2007).

Water circulation is also important in larval development and successful recruitment of young crabs (Yamada et al., 2015). During the zoea stage, the larvae travel to the surface to ride the tides from the estuary to the shore so that they can feed and develop into megalopae larvae (Queiroga et al., 2006; Yamada et al., 2015). In Oregon, the winter ocean conditions and timing of the spring transition are essential factors to consider in determining the larval survival rate from southern sources (Behrens Yamada et al., 2021).

C. maenas is a generalist and has been found to feed on a variety of both living and dead animal matter (Crothers, 1968; Cohen & Carlton, 1995; Grosholz & Ruiz, 1996). Grosholz and Ruiz (1996) found in Western North American, *C. maenas* diet consists largely of mollusks, mainly bivalves, other crustaceans, and a modest number of polychaetas and green algae. In this risk assessment, we further analyze the risk of competition and predation to the common native species found in Oregon's estuaries: Olympia oysters (*Ostrea lurida*); Pacific oysters (*Crassostrea gigas, syn. Magallana gigas)*; razor clams (*Silqua patula*) and bay clams, including cockles (*Clinocardium nuttallii*), butter clams (*Saxidomus gigantea*), gaper clams (*Tresus* *capax*), and littleneck clams (*Leukoma staminea*); Dungeness crab (*Metacarcinus magister*); red rock crab (*Cancer productus)*; yellow shore crab (*Hemigrapsus oregonensis)*; and eelgrass (*Zostera marina)*.

Focus Sites

This assessment focuses on six main sites along the Oregon coast: Tillamook Bay, Netarts Bay, Yaquina Bay, Alsea Bay and Coos Bay. The Salmon River Estuary is also described here, but was not part of the full risk assessment due to limitations in data, time and research. An overview of the perceived risk to Salmon River Estuary can be found in the discussion portion of the assessment (see page 26).

Tillamook Bay at Tillamook and Garibaldi, Oregon, is the largest bay in Tillamook County at approximately 9,216 acres and is considered a development bay (*Tillamook*, 2022; *Tillamook,* 2018). It is fed by the Wilson, Trask, Miami, Tillamook, and Kilchis Rivers, and is a drowned river mouth estuary (*Tillamook*, 2022; *Estuaries*, n.d.). It is approximately 6.2 miles long and 2.1 miles wide, with an average depth of 6.6 feet (*Tillamook,* 2018). At low tide 50% of the bay is exposed as intertidal mudflats (*Tillamook,* 2018). It's known for its strong oyster industry, salmon fishing and commercial crabbing, with Dungeness being a prominent portion of both the recreational and commercial crabbing (*Tillamook*, 2022; Rumrill unpublished data). It is also home to numerous other species of fish, shellfish, crabs, birds, seals and seagrasses (*Tillamook,* 2018).

Netarts Bay is a conservation bay in Netarts. It is approximately 2,325 acres and is considered a marine dominated, bar-built estuary (Hamilton, 1972; *Estuaries*, n.d.). 812 acres of the bay are permanently submerged and 1,513 are intertidal land, mainly mudflats (Hamilton, 1972). The bay waters drain and refill twice a day on average, where upwards of 40-90% of the water is flushed out and back in (Glanzman, 1971). It is an excellent habitat for many shellfish species, with recreational clamming and crabbing being a main attraction (ODFW, 2014-a; *Where,* n.d.-c). Cockles and oysters are commercially harvested in this bay (ODFW, 2014-a).

Yaquina Bay located in Newport is approximately 4,329 acres and is considered to be a marine dominated development bay (*Estuaries,* n.d.; *Where*, n.d.-e). It is freely connected to the ocean, fed by the Yaquina River, and is considered a drowned river mouth system consisting of salt marshes, sloughs, and mudflats (ODFW, 2014-b). It is an excellent habitat for shellfish and crabs, and has ample opportunities for recreational clamming and crabbing (*Where*, n.d.-e; ODFW, 2014-b).

Alsea Bay is a drowned river mouth conservation estuary fed by the Alsea River located in Waldport and is approximately 2,516 acres (*Estuaries,* n.d; *Where,* n.d.-a). It has a long history of recreational fishing, clamming, and crabbing habitats (*Where,* n.d.-a). It is a fairly shallow bay, with the upper bay dominated by mudflats, and eelgrass beds are sparse and patchy

(*Where,* n.d.-a). The mouth of the river lacks jetties, causing a strong tide pull out to the ocean (Axt, 2020-a).

Coos Bay is the largest bay in Oregon, at approximately 13,348 acres and is a development bay (*Estuaries,* n.d; Axt, 2020-b). Fishing and shellfish production are foundations of Coos County (*Estuaries,* n.d). The lower bay is marine dominated and offers highly productive shellfishing opportunities, being the main crabbing and clamming area (*Crabbing,* n.d.;, Axt, 2020-b). Crabbing opportunities in this bay are accessible year round (*Crabbing,* n.d).

The Salmon River estuary, a natural bay, is located near Otis and is 438 acres (*Estuaries,* n.d). It is one of the smaller estuaries in Oregon (Axt, 2020-c). It is ocean fed by only a small river mouth, so the salinity can vary highly depending on rainfall and tides. Typically it is freshwater dominated (Axt, 2020-c). It is mainly popular with anglers, offering a high number of Chinook salmon returning to the estuary (Axt, 2020-c). Crabbing and clamming are possible here, but are not nearly as popular as the other bays in our assessment (Axt, 2020-c).

Summary of Native Species Possibly at Risk

Olympia Oysters (*Ostrea lurida*)

Olympic oysters (*O. lurida*) are bivalves with thin valves that are typically irregular in shape and can range in color from gray to purple-black (Carpenter, 1964, as cited in Fitch, 1952). *O. lurida* was once a prevalent native species throughout the Pacific Northwest, where they were found in beds on mudflats or gravel bars in the intertidal and subtidal regions of estuaries; however, due to overharvest there was a collapse in many of the estuaries by the early 20th century (Carpenter, 1964, as cited in Fitch, 1952; Groth and Rumrill, 2009). As the only native oyster species found along the west coast of North America, *O. lurida* was an important food source to indigenous people (Baker, 1995; McGraw, 2009). As bivalves, *O. lurida* provide many ecosystem services to the marine environment: they create valuable habitat by forming reefs, promote biodiversity, improve water quality through filter feeding, and reduce shoreline erosion (Pritchard et al., 2015).

According to ODFW (*Oysters*, n.d.), recreational harvest of *O. lurida* is prohibited in Oregon to promote the recovery of the species. Historically, it has been reported in Netarts Bay and was most likely introduced to Yaquina Bay and Coos Bay (Baker, 1995; Groth & Rumrill, 2009). Evidence shows that isolated populations have become established in Coos Bay, but there are several limiting factors potentially affecting widespread recovery of the species including: “(a) suboptimal biotic and physical conditions that may hamper feeding, survivorship growth, and reproduction; (b) inadequate production, and larval retention; (c) decreased availability of adequate shell substratum for settlement; (d) poor survival of post settled juveniles; and (e) predation, competition, and other ecological interactions with other established Olympia as well as nonnative species” (Groth and Rumrill, 2009).

Pacific Oysters (*Crassostrea gigas*)

Pacific oysters (*C. gigas*) are bivalve mollusks known for their rapid growth rate and prolific reproduction; females can produce between 50 and 200 million eggs each (NOAA Fisheries Pacific Oysters, n.d.). *C. gigas* is highly variable in shape, which depends on the type of substrate it grows on and the level of crowding (Nehring, 2006). *C. gigas* was introduced from Japan to the Pacific Northwest after the population collapse of *O. lurida* during the early 20th century (Chew, 1987). In its native range, *C. gigas* will adhere to any hard surface, usually rocks, but it can also be found in muddy or sandy areas (Nehring, 2006).

They are grown in several Oregon estuaries including Coos Bay, Yaquina Bay, Tillamook Bay, and Netarts Bay (ODFW *Oysters*, n.d.). *C. gigas* is typically grown in tidal areas directly on the substrate, in mesh bags, on trays, or even in cages that are secured in the water column or drifted on rafts (NOAA Fisheries *Pacific Oyster*, n.d.). In Oregon, the most common method for growing *C. gigas* is directly on the substrate, often referred to as "ground cultured" (ODFW *Oysters*, n.d.). The oysters are usually harvested in intervals of two to four years (ODFW *Oysters*, n.d.).

Native Clams

As bivalves, clams are filter feeders that live a mostly sedentary life within sand, mud, wood, or rocks, except when they are free swimming larvae (Fitch, 1953). There are many species of clams found along the Oregon coast so for the purposes of this risk assessment, this analysis will focus on the key species that are a target of both recreational and commercial fisheries. It is important to mention that *C. maenas* has strong impacts on other clam species that are not typically harvested by people, and clams are also a major food source for other crabs and shorebirds (Grosholz et al., 2000). The native clam species that are the most popular to harvest in Oregon are razor clams (*Silqua patula*) and bay clams, which includes cockles (*Clinocardium nuttallii*), butter clams (S*axidomus gigantea*), gaper clams (*Tresus capax*), and littleneck clams (*Leukoma staminea*) (Ainsworth et al., 2014). From 2008 to 2012, Tillamook Bay recreational bay clam harvesting was surveyed between April and August and the species that were targeted included *L. staminea*, *C. nuttallii*, *T. capax*, and *S. gigantea* (Ainsworth et al. 2014).

S. patula are mostly found along the open coast, with some populations found near Coos Bay and Tillamook Bay (Clams ODFW, n.d.). *S. patula* have "elongate shells, thin, flat and smooth; covered with a heavy, glossy, yellowish periostracum," which is the outer shell layer that protects it from damage (Dixon, 1788, as cited in Fitch, 1953). As the name implies, bay clams are found throughout the bays in Oregon and in a variety of habitats. *T. capax* are large clams and are typically known by the gape at the posterior end (or terminal part of the clam containing the siphon) and their large ligament pit (Marriage, 1954). *T. capax* are typically found in muddy and sandy areas of high salinity, 12 to 32 inches from the surface (*Clams ODFW,* n.d.). *C. nuttallii* can be identified by their equally spaced ridges or ribs on their exterior shell; the color of their shell is affected by their habitat type (light-brown shell color in sandy sediment and dirty-gray shell color in muddy sediment) (Marriage, 1954). *C. nuttallii* prefers high salinity, sandy tide flats and can be found close to the surface with typically at least a portion of their shell exposed (*Clams ODFW* n.d.; Fitch, 1953). *S. gigantea* are identified by their large, external ligament and ovate shell with fine concentric lines (Marriage 1954). *S. gigantea* typically prefers beaches made of sand, shell or gravel and lives 6-12 inches from the surface (*Clams ODFW,* n.d.). *L. staminea* looks like *C. nuttallii*, often cream to gray in color, but lacks the deeply scalloped edge that *C. nuttallii* has (Marriage, 1954). Interestingly, *L. staminea* can move horizontally by extending their foot ahead and moving the rest of the body after, but it rarely moves more than four feet along the sand or mud (Fitch, 1953). *L. staminea* can be found in areas of sand, mud, gravel, or rock within six inches of the top substrate (*Clams ODFW,* n.d.). The locations of each clam species, derived from ODFW *Where to Dig Bay Clams* (n.d.), can be found in **Table 3**.

Recreational Harvest

Recreational clam diggers typically aim for *L. staminea*, *C. nuttallii*, *T. capax*, and *S. gigantea.* Oregon Department of Fish and Wildlife (ODFW) allows a daily harvest of up to 20 clams per person, 12 of which can be *T. capax* (Ainsworth et al. 2014). Clam diggers are allowed to keep the first 12 *T. capax* they catch with no regulation on size or condition since they are more susceptible to predation, mostly by crabs, if dug up and discarded on the mudflat (Ainsworth et al. 2014). For Tillamook Bay an estimated average of 149,000 clams were harvested, with *C. nuttallii* being the most common species harvested (Ainsworth et al. 2014). Recreational bay clam harvesting was surveyed in Netarts Bay between spring and summer from 2008 to 2012 and identified an average of 232,000 clams were collected annually, and the most common species harvested being *C. nuttallii* (Ainsworth et al. 2014). In Yaquina Bay, the survey season from 2008 to 2012 for recreational bay clams was longer each year than the other bays surveyed. For some years, the sampling season started in January and ended in August, with an average of 120,000 clams collected annually, and the most common species harvested being *C. nuttallii* and *T. capax* (Ainsworth et al. 2014). Finally, in Coos Bay was surveyed during the spring and summer from 2008 to 2012, with an average of 200,000 clams collected annually; *S. gigantea* comprised of 40% of the catch and gaper clams comprised of 43% of the catch (Ainsworth et al., 2014).

Commercial Harvest

Since at least 1891, commercial fisheries have been harvesting bay clams, including *C. nuttallii*, *S. gigantea*, *T. capax*, and *L. staminea*, across Oregon estuaries (Ainsworth et al., 2014). In Oregon, there are two types of bay clam fisheries, commercial dive clam and intertidal fishery, each requiring different permits (Rumrill et al., n.d.). As the second largest estuary in Oregon, Tillamook Bay supports over 70% of the commercial bay clam fishery in the state where most of the clams harvested consisted of *C. nuttallii* (Ainsworth et al., 2014). Most of the intertidal commercial harvest occurs in Tillamook, with the *C. nuttallii* being the primary species of bay clams collected, and mostly all the dive bay clam fishery permits are active in Tillamook Bay (Rumrill et al., n.d.). From 2008 to 2020, 88.5 percent of the total commercial bay clam harvest in Oregon occurred in Tillamook Bay and 5-25 percent of the biomass of bay clams were harvested from Netarts, Coos, and Yaquina (Rumrill et al., n.d.). In Tillamook Bay, subtidal dive fishery is limited to an annual quota of 185,000 pounds of *C. nuttallii*, which is usually met in the first 3-4 months of the year; *S. gigantea* have an annual quota of 225,000 pounds, and *T. capax* has an annual quota of 235,000 pounds, which are both used for bait in the commercial Dungeness crab fishery (Rumrill et al., n.d.).

Dungeness Crab (*Metacarcinus magister*)

Dungeness crabs (*M. magister*) range geographically from Alaska to Santa Barbara, California and typically can be found from intertidal zones to a depth of 230m; however, they are most commonly observed in sand or muddy intertidal zones and eelgrass beds (Maxwell, 2002). They are considered the largest edible crab species on the west coast of the United States and therefore are held in high importance for fisheries commercially, economically, and recreationally (Maxwell, 2002). In 2021, a total of 24,246,441 were caught commercially in Oregon alone, bringing a value of over $119 million dollars to commercial fisheries (ODFW, 2022-b). They also offer a great recreational activity for locals and tourists looking for a crabbing experience. They typically have a red-brown to purple carapace with ten spines on either side of their eyes (Maxwell, 2002). They are sometimes confused with red rock crabs, but can easily be differentiated by recognizing their white tipped claws (*Dungeness,* 2022). Adult crab diet consists of a number of fish and invertebrate species (*Dungeness,* 2022). In bays, *M. magister* typically prefers to congregate in the higher salinity areas, moving further away from the inland areas during heavy rains (*Dungeness,* 2022). Only the males are legal for fishing, leaving the females, who can live up to at least 6 years old and lay upwards of 2.5 million eggs, to maintain population growth (Maxwell, 2002; *Dungeness,* 2022). Seasonally, *M. magister* populations fluctuate based on temperature and salinity (Mcmillan et al., 1995). One study found abrupt population increase in summer followed by a rapid decline in density through winter and spring (Mcmillan et al., 1995). Seasonally, the population densities were also varied based on habitats, with higher densities in mixed sand and gravel, intermediate densities in eelgrass habitats and the lowest densities in sand (Mcmillan et al., 1995).

Red Rock Crab (*Cancer productu*s)

Red rock crab (*C. productus*) is a large, predatory crab native to the eastern Pacific. Their range extends from Alaska to Baja, California (Behrens Yamada & Groth, 2016). In Oregon, *C. productus* is common in large, high saline estuaries, such as Coos, Yaquina and Tillamook Bay (ODFW). They are typically found in the cooler, more salinated lower estuary, and prefer habitats with hard substrates such as rock, gravel, shells, hard-packed sand or cobble (Behrens Yamada & Groth, 2016). Juvenile crabs are often found buried in coarse substrate in intertidal nursery habitat. Adult crabs are highly mobile and are known to leave the subtidal zone to forage in the intertidal during high tide (Behrens Yamada & Boulding, 1996; Behrens Yamada & Groth, 2016).

C.productus is an important predator in marine benthic communities (Rilov, 2009; Behrens Yamada & Groth, 2016). They are one of Oregon's larger native crabs, with adult crabs achieving carapace widths over 160mm (Hunt & Behrens Yamada, 2003). They are distinguished from other native and invasive crabs of similar size (*M.magister, C.maenas*) by their powerful monomorphic claws which are specialized for crushing shells. *C. productus* are considered specialists of hard-shelled prey, particularly bivalves such as mussels, clams, and oysters (Behrens Yamada and Boulding, 1998) as well as barnacles, snails and smaller decapods, including juvenile *C.maenas* (Knudson, 1964; O'Claire & O'Claire, 1998; Hunt & Behrens Yamada, 2003).

C.productus is caught recreationally year-round, although it is often overlooked in favor of the popular Dungeness crab (*M. magister*). Historically, there were no limits to *C.productus* harvest as they were seen to be in competition with the shellfish industry (Behrens Yamada & Groth, 2016). Current daily harvest limits in Oregon are set at 24, of any size or sex (ODFW, Shellfish regulations).

Yellow Shore Crab (*Hemigrapsus oregonensis)*

The yellow shore crab (*H.oregonensis*) is a small intertidal shore crab common in many bays and estuaries along the Oregon coast. *H.oregonensis* is tolerant of a wide range of abiotic conditions and occurs throughout estuarine environments from Alaska to Baja, California. They are commonly found in open mud flats, mats of green algae (*Enteromorpha*), eelgrass (*Zostera*) beds, and along rocky shores. Primarily herbivores, they feed on diatoms and *Enteromorpha,* but will occasionally scavenge meat. (Oliver & Schmelter, 2018).

H.oregonensis is one of two *Hemigrapsus* species native to Oregon, the other being *H.nudus*. Both are common in the intertidal zone, and are often found together, although one species is typically dominant. *H. oregonensis* is generally dominant in habitat with fine-grained, silty or muddy sediment (Low, 1967). They utilize shelter in the intertidal zone as protection from predation and can form high-density assemblages, with densities as high as 624 crabs^{-2} documented in Bodega Harbor, CA (Jenson, 2002). *H.oregonensis* competes with other native crabs, including juvenile *C. magister* for intertidal cover from predation (Visser et al., 2004). Predators of *H.oregonensis* include shorebirds, fish, various mammals and other decapods, including *C.maenas (*Grosholz et al., 2000*)*.

Eelgrass (*Zostera marina*)

Along the Oregon coast, eelgrass (*Z. marina*) is present in 24 of the 110 estuaries and is considered the most widely established species of *Zostera*, alongside small beds of *Z. japonica* (Sherman et al., 2018; de Rivera per. com., 2022). *Z. marina* is found in the low intertidal and shallow subtidal zones and is considered a "foundation" species that contributes to the solidification of community structures for many types of organisms (Sherman et al., 2018; Neckles, 2015). The dense meadows offer habitat for many different species and have been known to exhibit both high species diversity and abundance, especially for fish. A study that looked at Coos Bay, Netarts Bay and Yaquina Bay found 14, 12, and 13 species of fish respectively within the present eelgrass habitats (Sherman et al., 2018). In Tillamook Bay, Chinook salmon, a species protected by the Endangered Species Act, have been frequently observed in *Z. marina* meadows (Sherman et al., 2018; Fisheries, 2022). Other Pacific salmon species and Pacific herring species rely heavily on eelgrass ecosystems for both survival and reproduction (Howard et al., 2019). *Z. marina* offers a wide range of supporting services including: primary production of energy; habitat provision and food web support; carbon export to adjacent services and other nutrient cycling; primary and secondary level food source; nursery and refuge habitat for spawning fish and shellfish; and substrate for reproduction (Sherman et al., 2018). On top of offering all these supporting services, *Z. marina* also provides many regulating services such as shoreline protection, sediment stability, carbon sequestration, and water quality improvement by trapping and storing particles and nutrients (Sherman et al., 2018). One study that underwent hugely successful restoration of *Z. marina* meadows showed a net gain of coastal ecosystem services (Orth et al., 2020). This species can be found in all of the bays in our assessment, with varying densities (Rumrill, unpublished data).

Results

Risk to Focus Species

Dungeness Crabs (*M.magister*)

Over the years of *C. maenas* invasion, a great deal of research has looked at how *M. magister* populations will be impacted. *M. magister* hold great importance in estuarine and bay habitats, so any risk to their populations should be taken with great concern. One major concern has been regarding *C. maenas'* ability to out compete *M. magister* in habitats where they both reside (Mcdonald et al., 2001). *M. magister* have been found to emigrate from their habitats based primarily on space competition, regardless of food availability or increase of predation (Oscar et al.,1994). Food consumption levels in such habitats has been found to be significantly lower when crab density is higher, showing that when *M. magister* are out competed for space, they will feed less aggressively (Oscar et al., 1994). *M. magister* and *C. maenas* have a significant dietary overlap, and *C. maenas* have been found to behave aggressively towards *M. magister* when competing for habitats and food, even at times dominating on this aspect (Mcdonald et al., 2001).

In oyster shell habitats, *C. maenas* have shown to cause emigration of early benthic phase *M. magister* as a result of competition and predation, causing these young *M. magister* to need to retreat from the safety of the shell habitat which heightens their risk of predation by other fish, shellfish, and birds (Mcdonald et al., 2001). Additionally, adult *C. maenas* predation on young *M. magister* within these shell habitats has been found as a significant source of *M. magister* mortality (Mcdonald et al., 2001). This leaves young *M. magister* at high risk, especially given that their first habitat preference is these shell habitats, with eelgrass as a second choice, and mud as the last, where a majority of the young of the year are consumed by predators (Fernandez et al., 1993).

In addition to this aggressively competitive behavior, *C. maenas* claw morphology, in comparison to *M. magister,* has shown to be aiding *C. maenas* in out competing (Yamada et al., 2010). *C. maenas* have a significantly larger and stronger crusher claw, which is therefore more powerful than the two monomorphic claws of *M. magister* (Yamada et al., 2010). In some lab studies, C. maenas have been found to consume significantly more mussels and oysters per day when compared to *M. Magister* feeding rates, which is likely due to the stronger claws (Yamada et al., 2010). These stronger claws also put young *M. magister* at higher risk of predation from *C. maenas,* especially because the juveniles are smaller in size in comparison. These studies show a clear **high risk** situation for *M. magister* if *C. maenas* were to populate their habitats.

Bivalves

As a primary food source for crabs, bivalves may be at increased risk of *C. meanas* invasions when compared to other marine species. As discussed earlier, when compared to *M. Magister* feeding rates, *C. maenas* consume more mussels and oysters, which can possibly disrupt the greater food web (Yamada et al. 2010). During a long-term sampling study in Bodega Harbor, California, Grosholz and Ruiz (1996) found a decline in populations of bivalves (*Transennella* spp.) since the influx of *C. maenas* populations. Grosholz and Ruiz (1996) predict bivalve mollusks are at high ecological risk from *C. Maenas* invasion in western North American.

With many clam species harvested recreationally and commercially, the invasive spread of *C. Maenas* may create additional pressure on native clam populations and possibly impact commercial fisheries in the future. It is important to note that although *T. capax* are typically found 12-32 inches below the substrate, based on recreational harvest activities and populations present in four of the Oregon bays being evaluated, *T. capax* may be at increased risk of being affected by *C. maenas* invasions. Based on the former research on predation by *C. maenas* and the overlapping habitat*, S. patuala* and all the bay clam species are at the **high risk** level if *C. maenas* populations increase in Oregon.

Furthermore, *C. maenas* appear to have a strong impact on *O. lurida*, increasing the threat to the recovering species. For example, *C. maenas*, can disrupt "trait- and density-mediated trophic cascades usually occupied by native crabs" leading to increased *O. lurida* mortality (Prichard et al., 2015). In a lab setting, Yamada et al. (2010) found *C. maenas* can eat 0-1.2 *O. lurida* per crab per day. Also, if *C. maenas* was only presented with oysters it ate significantly more than *C. Magister* (Yamada et al. 2010). In feeding experiments done in Tomales Bay, California, Snyder (2004) compared feeding rates of *C. maenas* on *O. lurida* and found that smaller *C. maenas* (30-39mm) consume the most *O. lurida* overall and 58 percent of the small *O. lurida* available. When comparing *C. maenas* predation to the native crab species, it is important to note the increased threat to *O. lurida* populations, if *C. maenas* continues expanding its range and population (Snyder, 2004). Populations of *O. lurida* are found to be very low in all the Oregon bays where they are present (Rumrill, per. com., 2022). Based on primary habitat and the very low abundance, *O. lurida* are at the **high risk** level as *C. maenas* populations continue to increase in Oregon.

According to the 2018 USDA Census of Aquaculture, Oregon reported $19.6 million in annual sales from oysters (USDA, 2019). Therefore, the commercial sale of *C. gigas* may be under threat from increased *C. maenas* invasion in Oregon bays. Since the majority of *C. gigas* is ground cultured in Oregon, this leaves the species vulnerable to predation. Each of the Oregon bays is assessed in **Table 1** depending on the method in which *C. gigas* is grown. Based on personal communication with Steve Rumrill; ground cultured occurs in Tillamook Bay, Netarts Bay, Yaquina Bay, and Coos Bay; raised cultured occurs in Tillamook Bay, Netarts Bay, and Coos Bay; and, suspended cultured occurs only in Yaquina Bay. Since *C. gigas* is a commercially significant species to the Oregon economy, this puts populations at the **high risk** level as *C. maenas* populations become invasive in Oregon bays. However, based on the different culture methods, the ground cultured industry is at **high risk**, the raised cultured industry is at **low risk**, and the suspended cultured industry is at **moderate risk** (Rumrill, per. com., 2022).

Red Rock Crab (*Cancer Productus*)

Native predators can limit the establishment and spread of introduced species, providing partial or total biotic resistance to invasion. In eastern North America, the blue crab (*Callinectes sapidus*), a large native predatory crab, was found to limit the geographic range expansion of *C. maenas* (de Rivera et al., 2005). In Oregon, *C. productus* presence in lower estuary and subtidal habitat appears to provide a similar resistance to the expansion of *C. maenas* distribution in estuarine habitat (Hunt & Behrens Yamada, 2003; Hunt, 2001).

Past studies along the Oregon coast (Hunt & Behrens Yamada, 2003; Hunt, 2001; Behrens Yamada, Schooler et al., 2021) have found little overlap in the distribution of *C. productus* and *C. maenas* . In these studies, *C. productus* was found to be dominant in the low estuary, which is characterized by cool temperatures and high salinity. In bays and estuaries with *C. productus* populations, *C. maenas* was restricted to the upper and middle estuary, characterized by warmer water and lower salinity (Hunt & Yamada, 2003). This partitioning of estuarine habitats is in part due to the low physiological tolerance of *C.productus* to low salinities and warm water temperatures (deFur & McMahon, 1984). In contrast, *C. maenas* tolerates a wider range of abiotic conditions and was found to survive in lower estuarine habitats when caged to exclude predation (Hunt, 2001). The exclusion of *C. maenas* from lower estuaries inhabited by *C. productus* suggests *C. productus* may provide Oregon bays and estuaries with a degree of biotic resistance (Hunt & Behrens Yamada, 2001; Ens et al., 2021). In laboratory experiments, *C. productus* was found to depredate smaller *C. maenas* crabs, indicating that predation may be the mechanism of biotic resistance (Hunt & Yamada, 2003). A study in California found similar patterns of *C. maenas* habitat restriction based on the presence of large native predators (*C. productus*, *C. antennarius*), and observed *C. productus* capturing and killing *C. maenas* in their tethering experiments (Jenson, 2007).

C. maenas sampling efforts in four of our study estuaries (Tillamook, Netarts, Yaquina and Coos Bay) in 2020 and 2021 found that *C. maenas* remained absent (or rare) from lower estuaries (Yamada et al., 2022). Trapping data from Coos Bay sampled from May-August of 2021 found that CPUE for *C. maenas* was highest in the middle to upper estuary where adult *C. productus* and *M. magister* were absent. *C. productus* was trapped exclusively in the lower estuary, and adult *M. magister* was most abundant in the lower to middle estuary (Schooler et al., 2021). This data suggests that *C. productus* is still dominant in the lower estuary and adult native crabs are continuing to prevent *C. maenas* habitat expansion. Given their role as a predator of *C.*

maenas and the biotic exclusion of *C. maenas* from *C. productus* habitat, *C. maenas* currently poses **low risk** to *C. productus* populations in Oregon.

With changing abiotic conditions along the Oregon coast comes the potential for changes in the ecological relationship between *C. productus* and *C. maenas*. The two species share a prey resource (bivalves) so if the current partitioning of estuarine habitat were to fail, competition between the species would likely increase. In addition, the impacts of *C. maenas* on juvenile *C. productus* is unclear. Juvenile *C. productus* are more commonly found in the intertidal zone (Behrens Yamada & Boulding, 1996) where they may compete with juvenile *C. maenas* for shelter and food. Adult *C. maenas* also have the potential to be predators of juvenile *C. productus*. More research is needed to determine the relationship between *C.maenas* and juvenile *C. productus*, which adds a degree of uncertainty to the current *C. productus* risk assessment.

Yellow Shore Crab (*Hemigrapsus oregonensis)*

There is considerable overlap in the distribution of *H. oregonensis* and *C. maenas* in estuarine environments (Theil & Dernedde, 1994; Oliver & Schmelter, 2018). *C. maenas* has the potential to impact *H. oregonensis* populations through competition and predation. Juvenile *C. maenas* compete with *H. oregonensis* for both food and shelter in the intertidal zone. Shelter, in the form of rocks, vegetation and marine debris, is particularly important for species inhabiting the intertidal zone, providing refuge from predators, desiccation, and abiotic stress. Jenson et al. (2002) found that *H. oregonensis* remained dominant in intertidal shelter despite *C. maenas* presence, but was outcompeted for food (bivalves) in lab settings. Increases in *C. maenas* populations may alter outcomes in habitat competition. More research is needed to determine how abundance impacts competition between *C. maenas* and *H. oregonensis*.

Several studies conducted in Bodega Harbor, CA (Grosholz et al., 2000; de Rivera et al., 2007; de Rivera et al., 2011) found that *C. maenas* is a predator of *H. oregonensis*, with the potential to have significant impacts on their population. Grosholz et al (2000) found that the mean abundance of *H. oregonensis* populations declined by 10x following the introduction of *C. maenas*. Long term analysis of *C. maenas* impacts on *H. oregonensis* populations in Bodega Harbor found *H. oregonensis* abundance declined precipitously following increases in *C. maenas* abundance, and then rebounded in 2001 following a decline in *C. maenas* abundance. In addition, *C. maenas* predation pressure was found to affect *H. oregonensis* body size and intertidal habitat distribution. Mean body size of *H. oregonensis* decreased by over 2/3rd between 1993 and 2004, only increasing in the last two years of the study (de Rivera et al., 2011). Reduction in mean body size over time has the potential to impact the reproduction potential of crab populations (Prager et al., 1990; Hines, 1991; Berkeley et al., 2004 as cited in de Rivera et al., 2011). *H. oregonensis* distribution in intertidal habitat also shifted over the course of the study, with a greater proportion of individuals moving into the high intertidal zone. Occupance of the high intertidal is thought to decrease crab foraging time, as they are at greater risk for predation and desiccation (de Rivera et al., 2011). The changes in abundance, body size and intertidal distribution documented in these studies demonstrate the **high risk** *C. maenas* poses to *H. oregonensis* populations in Oregon bays and estuaries.

Eelgrass (*Zostera marina*)

Z. marina is of high importance within estuarine habitats, links of impact from *C. maenas* on it certainly are cause for concern. One study in Newfoundland found upwards of 50 - 80% decline in *Z. marina* bed size from 1988 to 2012 in bays where *C. maenas* were found populated, which coincided with a significant reduction in fish biomass and abundance within these bays (Matheson et al., 2016). In four of their sites, *Z. marina* coverage even disappeared completely and one other declined 90%, all five of which were linked to *C. maenas* (Matheson et al., 2016). Another study in Casco Bay, Maine was able to link *C. maenas* to a huge decline in *Z. marina* beds, which was considered to be a "near-complete disappearance" and coincided directly with a population explosion of *C. maenas* (Neckles, 2015).

These losses of *Z. marina* beds are attributed to a few foraging techniques done by *C. maenas*. The first one being bioturbation, in which *C. maenas* have been known to completely dislodge whole plants while foraging for prey (Howard et al., 2019; Brown, 2021). The intensity of this damage from bioturbation is found to be directly proportional with *C. maenas* population density (Davis et al., 1998). Compounding with bioturbation, *C. maenas* have also been observed consuming *Z. marina* rhizomes, benthic fauna, and detritus by a process known as "blade-shredding" (Howard et al., 2019; Brown, 2021). The consumption and subsequent destruction of the upper blades of the plants prevents successful reproduction, leading to bed collapse (Howard et al., 2019; Brown, 2021). Post larvae and juvenile *C. maenas* have also been known to use *Z. marina* beds as shelter from predation and have shown lower mortality and higher population density within eelgrass habitats compared to sand habitats (Moksnes et al., 1998). All of this clear evidence of negative impacts from *C. meanas* to *Z. marina* puts it on a **high risk** level if crab populations were to overtake any areas of the Oregon coastline with high amounts of eelgrass habitats.

Risk to Focus Sites

Risk to focus sites was evaluated based on native species presence and abundance, *C.maenas* abundance, and assessed level of risk to native species (**Table 1**). Native species population data, with the exception of *O. lurida*, was provided by Steve Rumrill based on extensive intertidal surveys conducted by Oregon Department of Fish and Wildlife (ODFW). *O. lurida* population size was estimated based on NOAA Olympia & Pacific Oyster Data Portal (Kornbluth et al., 2021). *O. lurida* populations were low in all surveyed estuaries and absent from Alsea Bay. Population abundance data was not available for the non-native *C. gigas,* so mariculture presence/absence data was used. Mariculture operations are present in all of the sites, with the exception of Alsea Bay. *M. magister* abundance varied across sites, with the highest population documented in Coos Bay and lowest in Alsea Bay. *C. productus* populations were very low across sites, likely because sampling was restricted to the intertidal zone and *C. productus* is most common in the subtidal zone. *C. productus* was not documented in Alsea Bay. *H. oregonensis* population varied across sites, and were notably absent from Tillamook Bay, although this observation is likely due to error in data collection (de Rivera per com., 2022).

Native clam populations were high across sites, with the exception of Alsea Bay. **Table 3** provides a more detailed breakdown of native clam species populations at the focus sites.

C. maenas population levels at the focus sites, with the exception of Alsea Bay, were evaluated based on CPUE from 2021 sampling efforts (Behrens Yamada et al., 2021). *C. maenas* abundance was generally consistent across sites, with the exception of Coos Bay, which had approximately 2x the CPUE. CPUE data for Alsea Bay was based on ODFW sampling efforts in 2022 (Vance, per com., 2022). Reported CPUE varies depending on a number of factors including: type of trap used, time of year, length of soak, distribution of traps, and number of traps deployed. Due to temporal and technical variations in sampling techniques, comparison between the CPUE in Alsea and the other focus sites is limited.

Populations were assessed for risk based on their abundance within the bay (**Table 5**), natural distribution within the estuary, and impact from *C.maenas. O.lurida* was assessed for risk based on *C.maenas* abundance in the bay, and was considered high risk at low population sizes due to their rarity and overlapping estuarine distribution with *C.maenas*. *C. gigas* mariculture operations in each bay were assessed for risk based on the type of culturing operation: ground, raised or suspended. Ground cultured was considered high risk, suspended cultured was considered moderate risk, and raised cultured was considered low risk. Native clams were considered at high risk at low abundance, and moderate risk at high abundance. Risk to native clams likely varies by species, given that *C.maenas* has exhibited differential prey preference amongst clam species (Rumrill per. com., 2022). *M. magister* and *H.oregonensis* were considered high risk at low and moderate abundance, and moderate risk at high abundance. Due to considerable overlap in habitat use by *H. oregonensis*, juvenile *M. magister* and *C.maenas*, potential for competition and predation between these species and *C.maenas* is considered high when populations are at low to moderate densities. *C.productus* at low abundance was considered to be low risk, since intertidal habitat is not this species primary habitat. *Z. marina* was considered high risk regardless of abundance based on recent research which indicates that *C.maenas* impacts *Z. marina* across densities (Brown, 2021). Further consideration of risk may be given to several species with commercial and recreational value, such as *C.gigas*, *M. magister* and native clam species.

Table 1: Population level of focus species in focus bays with assessment of level of risk from *C. maenas* to focus species in said bays. Size of bay is noted in approximate acreage (*Estuaries,* n.d.). Catch per unit effort (CPUE) of *C.maenas* is noted in each of the bays based on previous studies. Abundance for focus species is assessed in a metric of very low (<100), low (100-500), moderate (501-1,000), high (1,001-2,000) or very high (>2,000). Data was provided by ODFW and values can be found in appendix h: table 5 and figure 2. These populations are then color coded based on the level of risk, see table (2). White cells have an absent population, and therefore no risk assessment. Pacific Oyster Mariculture (a) are ground cultured, (b) are raised cultured, and (c) are suspended cultured (Rumrill, per.com., 2022).

	Tillamook (9216 acres)	**Netarts** (2743 acres)	**Yaquina** (4329 acres)	**Alsea** (2516 acres)	**Coos** (13348 acres)
Green Crab	0.93	0.72	0.88	1.3	1.96

CPUE	(Behrens Yamada et al., 2021)	(Behrens Yamada et al., 2021)	(Behrens Yamada et al., 2021)	(Vance, per. com., 2022)	(Behrens Yamada et al., 2021)
Olympia Oysters	Very Low	Very Low	Very Low	Absent	Very Low
Pacific Oyster Mariculture (a)	Present	Present	Present	Absent	Present
Pacific Oyster Mariculture (b)	Present	Present	Absent	Absent	Present
Pacific Oyster Mariculture (c)	Absent	Absent	Present	Absent	Absent
Dungeness Crab	Moderate	Moderate	High	Low	Very High
Red Rock Crab	Very Low	Very Low	Very Low	Absent	Very Low
Yellow shore crab	Absent	Low	Moderate	Low	Moderate
Native clams	High	High	High	Low	High
Eelgrass	Low	Moderate	Low	Low	Low
Gini-Simpson's Diversity Index	0.47	0.69	0.65	0.43	0.78

Table 2: Risk assessment color coordination key.

No Known Risk
Low Risk
Moderate Risk
Very High Risk

Table 3: Locations of Native Clam Species within Oregon Bays

Clam Species	**Common Names**	**Tillamook Bay**	**Netarts Bay**	**Yaquina Bay**	**Alesa Bay**	**Coos Bay**
S. patula	Razor	Present	Absent	Absent	Absent	Present
C. nuttallii	Cockles	Present	Present	Present	Present	Present

S. gigantea	Butter	Present	Present	Present	Absent	Present
L. staminea	Littleneck	Present	Present	Present	Absent	Present
T. capax	Gaper	Present	Present	Present	Absent	Present

Overall Risk in Oregon

Questions at the end of the Oregon Administrative Rule in Division 56 were assessed to provide justification and data regarding the overall risk in Oregon (**Table 4**). These questions offer a wide array of angles for assessing the impact of a NNS.

First in the assessment (a) was regarding their native habitat vs. Oregon habitats. As previously stated, *C. maenas* native range covers from Mauritania in North Western Africa, through Atlantic Europe to Northern Norway and Iceland (*European,* 1970; Yamada et al., 2008). This is already a very wide range, and certainly within this wide range there are habitats that are very similar to the Oregon coastline. Typically *C. maenas* prefer mudflats and rocky protected bays and estuaries, which coincides directly with habitats within Oregon bays (*European,* 1970). Since they are found in temperature ranging from 0^{o}C to 30^{o}C and salinities from 1.4 and 54 ppt, this again enforces that their natural range is similar enough to that of the Oregon coastline (Lovell et al., 2007). This assessment was labeled as high.

Assessment (b) looks at whether or not the species has an invasive history. *C. maenas* is widely cited as having an immense and long lived invasion history (European NSW; Holmes, 2001; Yamada et al., 2008; Lovell et al., 2007; Cohen et al., 1994; Ens et al., 2022). They have been invading foreign waters since the late 19th century, and were even found all the way in Australia around 1900 (Holmes, 2001). They are known to be established in South Africa, Eastern Australia, Tasmania, the Patagonian coast of South America, the Atlantic Coast of North America and the Pacific Coast of North America (Yamada et al., 2008). This assessment was labeled as high.

The next assessment (c) is concerned on whether or not the species can survive in Oregon. Yamada et al. (2008) found that after introduction into Oregon, *C. maenas* were able to persist past the 6-year lifespan of the colonists that originally arrived as larvae in 1997/1998. This was at first found with a downward population trend, that later reversed to an upward trend in 2005 (Yamada et al., 2008). Researchers estimate that *C. maenas* will be able to survive along the Pacific coastline from Baja California, Mexico, to just north of the Aleutian Peninsula in Alaska (Lovell et al., 2007; Cohen et al., 1994). Additionally, the Salish Sea in Washington and other bordering bays and estuaries in Washington, have been considered prime habitat for *C. maenas*, all of which are similar to the Oregon coastline habitats (Ens et al., 2022). Given all this information, this assessment was labeled as high.

Assessment (d) gave light to whether or not the species has potential to prey on native wildlife. This is widely known to be a huge concern with *C. maenas* invasion due to their generalist diet (Crothers, 1968; Cohen & Carlton, 1995; Grosholz & Ruiz, 1996). They are known as a "voracious predator" and feed on many types of organisms that are present in our native habitats (*European*, 1970). Data shows they have an impact on softshell clam, mussels, scallops, hard shell clams, oysters, snails, other crabs, polychaetes, isopods, barnacles and algae (Holmes et al., 2001; Grosholz et al., 2011). This assessment was labeled as high.

The next assessment (e) looked at whether or not they are a threat to the habitat of native wildlife. Lots of literature has shown that *C. maenas* are responsible for degradation of eelgrass habitats (Howard et al., 2019; Matheson et al., 2016; Davis et al., 1998; Necklaces, 2015). Other literature shows direct evidence of habitat degradation from their bioturbation actions (Holmes et al., 2001). They have also been known to negatively impact habitat suitability which in turn affects biodiversity and ecosystem functionality, mainly from their over exploitation of native wildlife from predation and competition (Lovell et al., 2007). This assessment was labeled as moderate/high. The medium was marked on the assessment due to a need for more literature regarding direct habitat degradation solely in Oregon.

Assessment (f) and (g) were grouped together in **Table 4**, (f) being the potential to spread diseases or parasites to native wildlife, and (g) assessing what types of diseases or parasites could be passed. One study found *C. maenas* to be an interim host for *Profilicolis botulus,* which is an endoparasite of shorebirds and can be passed to shorebirds after consumption of *C. maenas* and was considered to be a serious threat (Holmes, 2001). Another known parasite that can be carried and passed by *C. maenas* is *Sacculina carcini,* a castrating parasite which has been found to infect some native estuarine species in Oregon (Kiris et al., 2007; Goddard et al., 2005). Another study in Argentina found that pathology data showed *C. maenas* and native species were sharing parasites (Frissera et al., 2021). These findings are assessed as a moderate threat. More studies and research need to be done to fully understand this threat.

The next assessment (h) looked at *C. maenas* ability to out compete native wildlife in their habitats. *C. maenas* is widely known to be highly competitive for food, water, shelter and space in most all invaded habitats, especially when in high populations (Holmes, 2001; Yamada et al., 2008; Lovell et al., 2007; Cohen et al., 1994; Grosholz et al., 2011; Ens et al., 2022). This assessment is labeled as high with complete certainty.

Assessment (i) regards hybridization with native wildlife. Some researchers have found that *C. maenas* will hybridize with other *Carcinus* species, specifically this has been seen in the mediterranean and North Atlantic regions (Jeffery et al., 2017; Darling, 2011). However, this assessment lacked in research so it was labeled as low, mainly due to the lack of any other *Carcinus* breeds on the Oregon coast with which to hybridize with.

The last assessment (j) on the table discusses identification and whether *C. maenas* could be readily distinguished from other species. Currently, outreach and public awareness is relatively low in Oregon, especially among recreational crabbers. When identification skills are present, *C. maenas* are easily identified, but when these skills are not present, they are commonly mistaken for other native crab species (*European,* n.d.). WDFW has suggested the public not kill suspected *C. maenas* due to fear of mistaken identity (*European,* n.d.). This assessment is therefore labeled as moderate/low risk. Public awareness needs to be funded and pursued in order to reduce this risk. Once the public is more readily aware of identification techniques, the risk of misidentification will be lower.

The last two questions on the division 56 assessment are not cited on the table, but still need to be mentioned. The first being on whether or not the species is categorized in "The IUCN Red List of Threatened Species" of which *C. maenas* are not listed (*The IUCN,* n.d.). The species itself is not threatened by extinction, and this will likely be the case for many years to come. Lastly, the assessment asks whether or not the species is commercially propagated. *C. maenas* is rarely propagated commercially. Currently in Oregon, commercial propagation is prohibited (*European,* 2022). This overall assessment puts *C. maenas* as a **high risk** species within Oregon's coastline, and should be taken as a serious threat to our native species and habitats.

Table 4: Assessment of Oregon Division 56 Noncontrolled Classification Questions for deciding on how to label a NNS. Classifications are labeled a-j where **(a)** Whether the species' natural range and habitat is similar to Oregon's climate and habitat; **(b)** Whether the species has an invasive history; **(c)** Whether the species can survive in Oregon; **(d)** Whether the species has the potential to prey upon native wildlife; **(e)** Whether the species can potentially degrade the habitat of native wildlife; **(f)** Whether the species has the potential to pass disease or parasites to native wildlife; **(g)** What types of diseases or parasites could be passed on to native wildlife; **(h)** Whether the species has the potential to compete for food, water, shelter, or space with native wildlife; **(i)** Whether the species has the potential to hybridize with native wildlife; and **(j)** Whether the species can be readily distinguished from a native species, or a prohibited or controlled species. Classifications with more than 1 risk labeled are considered to be both. Risk columns are also color coded, with high risk being red, moderate being orange, low being green.

Div 56 Classification	LOW RISK	MOD RISK	HIGH RISK
(a) Habitat Similarity			X
(b) Invasive History			X
(c) Survivability			X
(d) Predation			X
(e) Habitat Degradation		X	X
(f/g) Diseases & Parasites		X	
(h) Resource Competition			X
(i) Hybridization	X		
(j) Ease of Identification	X	X	
Total	2	3	6

Discussion

Risk in Oregon

Risk of Dispersal and Spread

The original source of *C.maenas* populations along the Oregon coast has been attributed to larvae transported via oceanic currents from California. Larvae is transported northward in the Davidson Current during the winter months; transport is particularly successful in El Nino years when strong northward ocean currents and warmer ocean temperatures increase success of *C.maenas* recruitment (Behrens Yamada, Fisher & Kosro, 2021). Populations along the Oregon and Washington coasts have increased since 2015, when El Niño conditions and the 2014-2016 marine heatwave improved conditions for *C.maenas* recruitment. Recent studies indicate that local recruitment is now occurring along the Oregon coast (Behrens Yamada, Fisher & Kosro, 2021; Yamada et al., 2022). Locally produced larvae were collected as early as 2010 in Coos Bay (Shanks et al., 2011, as cited in Behrens Yamada, Fisher & Kosro, 2021). However, size frequency distributions remained relatively consistent until 2016, indicating that California remained the main source of recruitment prior to 2016. Recruitment from California is characterized by large crabs (30-60 mm carapace width) which settled the previous winter and early spring. Observations of small crabs (< 30 mm carapace width) and small molts in Oregon and Washington estuaries between 2016-2020 suggests local larval production, with juvenile crabs likely settling in late spring and summer (Behrens Yamada, Fisher & Kosro, 2021). In addition, genetic evidence analyzed by Caroline Tepolt shows that *C.maenas* populations on Vancouver Island, WA are seeding Oregon populations in Tillamook Bay and Netarts Bay (Yamada et al., 2022).

These studies, coupled with increased *C.maenas* abundance over the past 6 years suggest that the *C.maenas* populations in Oregon estuaries are potentially self-sustaining. However, the extent that local recruitment and larval transport from northern populations contributes to populations in Oregon estuaries is currently unknown (Yamada et al., 2022). Continued seeding from California, along with these additional sources of *C.maenas* in Oregon, indicate that risk for dispersal and spread to uninvaded bays and estuaries is high.

Anthropogenic vectors are another potential source of *C.maenas*. Shipping, aquaculture practices, recreational and commercial boating, live bait and trade, and unintentional release from researchers and educators are all potential human-mediated sources of *C. maenas* (Drinkwin et al., 2018; Davidson et al., 2009). While natural vectors are thought to be the main source of *C.maenas* in Oregon (Behrens Yamada & Hunt, 2000), increases in *C.maenas* populations may increase the risk of local transport via anthropogenic vectors. Further research into the potential contribution of anthropogenic vectors in Oregon is needed to understand future risk of human-mediated transport of *C.maenas*.

Risk of Establishment

C.maenas is an aggressive invader, aided by its tolerance of a wide range of temperature and salinity conditions (Cohen et al., 1995). They are currently established in estuaries and bays along the western coast of North America, including in Oregon. Recruitment strength in Oregon remains associated with ocean conditions, particularly sea surface temperature (Behrens Yamada & Kosro, 2010). Previous research indicated that cool ocean temperatures along the Oregon coast may have limited *C.maenas* recruitment (de Rivera et al., 2007), but warmer ocean temperatures associated with recent El Niño events and the 2014-16 marine heatwave facilitated strong recruitment in Oregon since 2015 (Behrens Yamada, Fisher & Kosro, 2021). Predicted increases in ocean temperatures related to climate change has the potential to further expand *C.maenas* range and increase recruitment success in Oregon (de Rivera et al., 2007).

Biotic resistance is the ability of a community to partially or completely resist the establishment, population growth, or spread of an invasive species. Increased biodiversity has been shown to increase biotic resistance to invasion, often due to higher levels of competition and reduced resource availability (Beaury et al., 2020). The presence of abundant native predators or strong competitors has also been shown to provide communities with biotic resistance, independent of community diversity. On the east coast of North America, blue crabs (*Callinectes sapidus*) were found to limit the southern geographic range expansion of *C.maenas*, likely due to increased predation pressure (de Rivera et al., 2005). Similarly, in Oregon, native crab predators (*C. productus, M. magister*) appear to limit the distribution of *C.maenas* within estuaries to upper and middle estuary habitat (Hunt & Behrens Yamada, 2003; Hunt, 2001; Yamada et al., 2021). Biotic resistance may reduce risk of *C.maenas* establishment in the subtidal zone and lower estuary, however rising ocean temperatures associated with climate change has the potential to alter this dynamic. In a lab setting, *C.productus* preyed less on *C.maenas* than *C.sapidus* did and only at colder temperatures. This suggests that *C. productus* may provide Oregon with weaker biotic resistance to *C.maenas* then what is seen along the east coast and that their ability to exclude *C.maenas* from lower estuarine habitat may degrade as ocean temperatures warm (Connolly-Randazzo, 2022). Ongoing trapping throughout estuaries in Oregon is necessary to monitor for changes in *C.maenas* range and habitat use.

Climate Change

Climate change has the potential to impact native and nonnative marine species along Oregon's coastline. Changing abiotic conditions associated with climate change, such as temperature, salinity, ocean acidification, and hypoxia, impact the internal physiology and behavior of marine organisms (Pörtner, 2010; Somero, 2010). Species such as *C.maenas*, that exhibit phenotypic plasticity, coupled with a broad abiotic tolerance, may be more successful acclimating to changes in abiotic conditions (Tepolt & Somero, 2014; Somero, 2010).

As previously discussed, ocean temperature is a key factor determining *C.maenas* range and distribution (Compton et al., 2010). Adult *C.maenas* are highly eurythermal, and demonstrate thermal acclimatory plasticity in their native North American range, as well as parts of their invasive range (Tepolt & Somero, 2014). *C.maenas* larvae have a narrower thermal tolerance-successful development is limited to temperatures between 10-22.5°C (de Rivera et al., 2007). Larval temperature requirements may limit *C.maenas* dispersal, particularly while larvae still occur within the estuary, as during the first zoeal stage and megalopal stage (de Rivera & Heath, 2022, unpublished). *C.maenas* fecundity has also been found to be affected by temperature, in addition to other environmental variables (e.g. salinity, hydrodynamics). Fecundity is low at higher temperatures (Montiero et al., 2022), suggesting that *C.maenas* population growth may be limited under warming conditions. However, the rate of larval development is expected to increase with increasing ocean temperatures until 25°C, suggesting 2°C warming may facilitate range expansion (de Rivera et al., 2007). Given the varying effects temperature has on *C.maenas* dispersal, survival, and reproduction, more research is needed to determine how warming will affect *C.maenas* population growth and range expansion along the Oregon coast.

Warming temperatures may also impact *C.maenas* behavior and alter current ecological relationships. Impacts of *C.maenas* predation have the potential to increase with warming, due to expanding foraging range (Zarrella-Smith et al., 2022) and changes in phenology that favor *C. maenas* (Strasser and Günther, 2001). Ocean warming may differentially affect *C.maenas* and their native competitors, leading to changes in competition and community structure. Several studies have found *C.maenas* to be more efficient at foraging at warmer temperatures than native crabs (Matheson and Gagnon, 2012; Howard et al., 2022- as cited in de Rivera & Heath, 2022, unpublished). In Oregon, predation pressure on *C.maenas* by *C.productus* may be reduced, due to decreased predation by *C. productus* and increased mortality of *C.productus* at warmer temperatures (Connolly-Randazzo, 2022). In turn, this may weaken the biotic resistance provided by *C. productus*, allowing *C.maenas* to expand into the lower estuary and subtidal zone.

Other changes in ocean geochemistry related to climate change, including changes in salinity and acidification, may impact *C.maenas* physiology and behavior. Current research indicates that *C.maenas* may be more resilient to ocean acidification than other marine organisms (Fehsenfeld et al., 2011; de Rivera & Heath, 2022, unpublished). *C. maenas* is tolerant of a wide range of salinities (4-52 ppt; Broekhuysen, 1936; Ameyaw-Akumfi and Naylor, 1987; McGaw and Naylor, 1992; Klassen and Locke, 2007- as cited in de Rivera & Heath, 2022, unpublished) and therefore may be well adapted to dealing with potential changes in salinity associated with climate change. However, salinity has been shown to impact *C. maenas* larval development and fecundity (Cieluch et al., 2004; Monteiro et al., 2022). Given the complexity of interactions between abiotic stressors, and the variation in impact of these stressors on different life stages of *C. maenas*, it is difficult to accurately predict the effects of climate change on this species.

Risk to Study Sites

Study sites were evaluated for risk based on *C.maenas* abundance, and abundance and risk of estuarine focus species: *O.lurida*, *C.gigas,* native clams (*S.patula*, *C.nuttallii*, *S.gigantea*, *T.capax*, *L.staminea*), *M.magister*, *C.productus, H.oregonensis* and *Z.marina.* Diversity at each focus site, calculated using the Gini-Simpson's Diversity Index, was also considered. Risk to study sites is discussed below, in order of highest to lowest risk.

Coos Bay

C.maenas risk was highest in Coos Bay due to high *C.maenas* abundance at this site, as well as high abundance and diversity of native estuarine organisms. Calculated diversity in Coos Bay was considerably higher (0.78) than at other focus sites. *C.maenas* abundance in Coos Bay has been increasing since 2016, and has been consistently high since then. In 2021, monitoring efforts in Coos Bay reported CPUE as high as 6.32 when using Fukui traps (Yamada et al., 2022).

All native focus species assessed for risk were present in Coos Bay. Of particular concern are *O.lurida* and *Z.marina* which are present at low densities in the bay and are of high risk for impact by *C.maenas*. Of additional concern are the *M. magister* and native clam populations in the bay. Both are currently high in abundance but have high commercial and recreational value at this site. *C.gigas* mariculture operations consist of ground and raised cultured, which are at high and low risk, respectively. The presence of *C. productus* in this bay likely plays a role in the exclusion of *C.maenas* from the lower estuary, which was confirmed by sampling efforts in 2021 (Yamada et al., 2022).

Yaquina Bay

Risk in Yaquina Bay was similarly high, although current *C.maenas* CPUE data suggests that *C.maenas* populations in Yaquina Bay are less than half that of Coos Bay. However, documented annual fluctuations in *C.maenas* recruitment and abundance between bays suggests that this data may change (Yamada et al., 2022). In addition, Yaquina Bay is considerably smaller than Coos Bay, suggesting that the density of *C.maenas* may be higher in this bay.

All native focus species are present in Yaquina Bay. This bay was among the most diverse (0.65) of the focus sites, although diversity was lower than that of Coos Bay (0.78) and Netarts Bay (0.69). *O.lurida* abundance is very low, and is considered high risk at this site. *C.gigas* mariculture operations consist of ground and suspended cultured, which are at high and moderate risk, respectively. A transition to raised bed culture of *C.gigas* would lower the risk to these operations. *M. magister* populations are high in the surveyed intertidal area, putting them at moderate risk for competition and predation from *C.maenas*. Native clam abundance is also high, and considered at moderate risk. Native clams and *M.magister* are both valued commercial and recreational resources in this bay, which may increase concern over the risk to these species. *H.oregonensis* abundance is moderate, putting them at high risk. *Z.marina* is present at low density, putting it at high risk for degradation by *C.maenas*.

Tillamook Bay

Tillamook bay was ranked as the third highest at risk. This bay is the second largest bay in this assessment, and is of high commercial and recreational value. Yamada et al. (2022) found that *C. maenas* abundance had increased from 2016 to 2019, but has decreased through 2020 and 2021, showing that the assessment of this bay could fluctuate over time. The CPUE data suggests that *C. maenas* population was very similar to that in Yaquina Bay, but with Yaquina Bay being nearly half the size of Tillamook Bay, this could mean a lower overall *C. maenas* abundance in comparison to bay size.

Regarding *C. gigas* mariculture, the lack of suspended cultured but presence of raised cultured puts *C. gigas* at a lower risk overall, due to *C. maenas* preference to predation on the suspended beds compared to the raised beds. With *M. magister* abundance at moderate in such a large bay, this is further cause for high risk. The noted absence of *H. oregonensis* in Tillamook Bay is very unlikely to be true, and that gap in our data analysis does alter the state of the assessment. It's highly likely that *H. oregonensis* is present in low populations, in which case they would be put at a high risk in the assessment, which would increase the risk in Tillamook Bay overall. In future assessment, the presence of *H. oregonensis* needs to be backed with data to give a more accurate view of the risk in Tillamook Bay. The presence of low percent cover of *Z. marina* puts this species at high risk, again especially considering how large this bay is. If *C. maenas* were to overtake the *Z. marina* beds, they could wipe them out.

Netarts Bay

Similar to Tillamook Bay, *C. maenas* abundance in Netarts Bay saw a rise from 2016 to 2019, and a fall through 2020 and 2021 (Yamada et al., 2022). That being said, the risk in Netarts Bay is slightly lower than in Tillamook Bay, mainly due to the markedly lower CPUE. This mainly affected the risk assessment for *O. lurida,* which made it the only bay where this species is marked as at moderate risk. *C. maenas* population threshold for impact is under researched, especially when considering each species specifically, so this moderate risk decision can be considered an assumption. Further research is certainly needed to grasp a full understanding of how *C. maenas* abundance will change the risk to the species at hand.

All the other risk rankings were the same in Netarts Bay as they were in Tillamook Bay, aside from a high risk ranking to *H. oregonensis*, of which our data showed a low population present. These comparisons make Netarts Bay and Tillamook Bay hard to rank with one another, but given that Netarts Bay has a slightly lower commercial and recreational value, it can be considered at slightly less risk than Tillamook Bay. The size of Netarts Bay is also cause for concern, and given that it is the second smallest bay in the assessment, it could be easily overtaken by a *C. maenas* population.

Alsea Bay

Alsea Bay is considered to be at the lowest risk when compared to the other bays assessed, although it is still at a moderate risk overall. The main reasoning for this conclusion was due to the absence of *O. lurida*, *C. gigas* and *C. productus.* Despite the lack of those species, the low abundance of *M. magister*, *H. oregonensis,* native clams and *Z. marina* are all put at a high risk. Alsea Bay is not a commercially valuable clamming bay, but is an important recreational area for clammers and crabbers alike. *C. maenas* CPUE for Alsea Bay was under-studied for this assessment, and there was a lack of information regarding their population gradient over the years. Further monitoring and research at Alsea Bay should be considered for a more accurate assessment.

Salmon River Estuary

Salmon River Estuary was initially one of the proposed study sites for this risk assessment, however due to a current lack of data on *C. maenas* and native estuarine species abundance, we were unable to perform a complete assessment of ecological risk for this site. *C. maenas* has been documented at this site as recently as August, 2022 during research trips conducted by Dr. Cat de Rivera. There are also known present populations of *M. magister*, *H. oregonensis, Z. marina,* and various native clam species (de Rivera, per com., 2022), which are likely to be at risk. At 438 acres, Salmon River Estuary is considerably smaller than the formally assessed estuaries (*Estuaries*, n.d.). A current proposal for *C. maenas* eradication efforts at this site may provide valuable insight into the feasibility and efficacy of eradication. The abundance and distribution of native marine species, as well as *C. maenas*, in Salmon River Estuary is necessary for an accurate assessment of ecological risk at this site.

Monitoring and Observations

Annual sampling of Oregon bays and estuaries known to have *C.maenas* populations have been conducted with the primary purpose of tracking *C.maenas* abundance and annual recruitment strength. Recruitment strength has been found to be synchronous between estuaries, and has been strong in Oregon since 2015 (Yamada et al., 2022). A strong year class was documented following 1998 El Niño conditions, however in following years *C.maenas* abundance decreased and remained low in Oregon until 2015. The highest documented recruitment event in Oregon was in 2017 in Coos Bay. Abundance has consistently been highest in Coos Bay and Yaquina Bay since 2016, and has steadily increased in Netarts Bay and Tillamook Bay since 2015 (Yamada et al., 2019). Prior to 2017, researchers were able to use data from a mark-recapture study and shifts in size-frequency distribution tables to estimate the age structure of *C.maenas* in estuaries. Due to strong recruitment over the past 6 years, researchers have been unable to accurately distinguish year class (Yamada et al., 2022).

Sampling of Oregon bays and estuaries was reduced in 2020 and 2021 during the COVID pandemic (Shooler et al., 2021). Sampling between 2020-2021 was conducted in four Oregon estuaries (Tillamook, Netarts, Yaquina and Coos), as well as Willapa Bay in Washington. The focus of this effort was to determine the abundance and source of young-of-the-year crabs. Strong year classes were documented both years, despite cool winter sea surface temperatures. Higher than predicted young-of-the-year catches during 2020 and 2021 support the possibility of local larvae production and additional northern sources of larvae (Yamada et al., 2022).

Until recently, *C.maenas* has only been documented in estuaries and bays in Oregon. In October of 2022, several gravid *C.maenas* were discovered on the outer coast at Cape Kiwanda by a private citizen (Rumrill, email correspondence). The discovery of *C.maenas* along the outer coast necessitates adaptation of current monitoring methods and habitat risk characterization in Oregon.

Control Actions

Vector Management

Assessment and management of transport pathways can be the first step in preventing and managing the spread of an invader (Kern et al., 2002). Understanding invasive species transport pathways can aid in predicting regions at risk for invasion which may inform monitoring decisions for early detection (de Rivera, 2007). In many cases, there is potential for transport via anthropogenic vectors, and the management of these sources is critical for preventing the initial stages of *C.maenas* invasions. An Early Detection Rapid Response (EDRR) plan developed for *C.maenas* management in Alaska prioritized management of vector and population sources in an effort to reduce propagule pressure (Davidson et al., 2009). Similarly, the Salish Sea transboundary action plan developed several strategies for reducing anthropogenic transport including preventing *C.maenas* introduction from aquaculture operations, ballast water, biofouling, live trade, bait trade, recreational boating, research and education (Drinkwin et al., 2018). In Oregon, more research is needed to understand the relative role of anthropogenic transport in *C.maenas* spread, particularly as local populations have increased.

Natural vectors are considered to be the source for the majority of *C.maenas* populations in Oregon (Behrens Yamada & Hunt, 2000). As natural vectors are difficult if not impossible to manage, efforts should be made to reduce source populations, thereby reducing potential for propagule dispersal (Davidson et al., 2009). Efforts to reduce *C.maenas* populations in California have the potential to benefit Oregon *C.maenas* control efforts by reducing propagule pressure. Additionally, reduction of *C.maenas* population density in Oregon and Washington estuaries may help to reduce propagule pressure if these populations continue to be self-sustaining.

Early Detection and Rapid Response

Early detection of *C. maenas* has been a critical component of management plans to control and reduce spread in other states (Grayson et al., 2018t; Davidson et al., 2009). Early detection of invaders provides an opportunity for eradication while populations are still small. Eradication efforts are generally most successful, and cost effective, when invader populations are small (Hobbs and Humphries 1995; Crooks and Soulé 1999 as cited in de Rivera et al., 2007). Monitoring of invaded and uninvaded areas is necessary to detect any potential range expansions and forecast significant increases in abundance (Kern et al., 2002). In Washington, a volunteer-based early detection program was established in 2012 and was quickly followed by an EPA funded Crab Team in 2014. The Crab Team program used satellite imagery of Washington's inland marine shorelines to determine suitable *C. maenas* habitat to inform a targeted monitoring approach. Sites were selected based on habitat characteristics that are favorable to *C. maenas* establishment including isolated pool or lagoon presence, braided/meandering tidal channels, impoundment, marsh vegetation, low wave energy and moderate to low freshwater input. Selected sites were monitored monthly from April to September, with 3 main survey components: trapping, molt surveys and habitat surveys. In the instance that *C. maenas* or signs of *C. maenas* were discovered, a rapid assessment of the site was initiated. Rapid assessments involved rigorous trapping of the site and nearby suitable habitat to determine *C. maenas* presence and proper control response (Grayson et al., 2018).

With effective early detection monitoring in place there is a greater chance for successful rapid response and localized extirpation of *C. maenas* (Kern et al., 2002). Rapid response plans should be coordinated efforts between state and local agencies, researchers, nonprofits, mariculture industry, native peoples and the public. Rapid response efforts begin with confirmation of *C. maenas* detection, followed by an assessment of the magnitude and extent of the invasion. Interagency communication is critical for efficient and effective response to *C. maenas* detections. After determining the magnitude and extent of the invasion, managers should determine appropriate management strategies in collaboration with involved agencies and communities. Typically rapid response plans involve coordinated removal efforts; physical removal is currently the preferred and the primary method of *C. maenas* removal (Davidson et al., 2009).

Physical Removal

Physical removal is one of the primary methods used in controlling *C. maenas* populations. There are several methods for physical removal, including baited traps, habitat traps, pitfall traps, beach seines, trawls, snorkel transects (Davidson et al., 2009), however the use of baited traps is currently considered the most effective method with minimal impact on native ecosystems (Ens et al., 2022). Physical removal using baited traps was shown in Bodega Harbor, CA to be highly effective at reducing *C. maenas* populations (Larson et al., unpublished data; Davidson et al., 2009). Baited Fukui and minnow traps are recommended when trapping for *C. maenas*, and should be deployed simultaneously. Fukui traps are most effective at catching larger adult crabs, and minnow traps are more effective at catching young-of-the-year crabs and small adult crabs (30-55mm carapace width) (Larson & de Rivera, unpublished data; Davidson et al., 2009).

Recreational harvest can contribute to *C. maenas* removal efforts, however they are unlikely to significantly reduce *C. maenas* populations in Oregon estuaries (OFWC, 2022-a). Previous harvest limits in Oregon of 10 crabs per person have recently been increased in response to public requests. With consideration to growing *C. maenas* populations, Oregon Department of Fish and Wildlife (ODFW) increased *C. maenas* recreational catch limit to 35 crabs per person per day. *C. maenas* is considered a controlled species, meaning once harvested it is unlawful to return the crab to state waters, regardless of size or sex (ODFW, 2022-a).

Public Outreach

Education and public outreach is an important step in invasive species management. An educated and vigilant public can serve as a first line of defense against *C. maenas*, assisting with monitoring and early detection (Davidson et al., 2009). Recent *C. maenas* management plans in both Washington and Alaska included public outreach as one of their priorities (Davidson et al., 2009; Drinkwin et al., 2018). Public presentations, online resources, citizen science, printed resources, and signage are examples of public outreach methods used to inform and mobilize the public (Davidson et al., 2009). In the case of *C. maenas*, proper identification of the species is critical. Educational material and signage communicating key identifying characteristics and differentiating *C. maenas* from Oregon's native crab species is particularly important to public outreach efforts. Current public outreach in Oregon is limited to online content provided by ODFW, which does provide information to aid in *C. maenas* identification. Additional public outreach efforts will likely be incorporated into Oregon's *C. maenas* management plan.

To aid in further public outreach concerning this invasion, we created an infographic to display the results of our risk assessment in a way that would appeal to the general public and environmental professionals alike (see Appendix G). The infographic highlights that proper identification of *C. maenas* is one of the most important aspects of public outreach, with particular attention to the 3-5 diagnostic features: *C. maenas* has 3 lobes between its eyes and 5 spines on the outside side of each eye. ODFW's recent increase of daily harvest to 35 crabs per day and other messaging efforts around these diagnostic features will hopefully help to prevent misidentification.

Mitigation

In cases where *C. maenas* populations are well established, total eradication or population control may not be immediately feasible (Ens et al., 2021). In these instances, efforts should be made to mitigate the impact that *C. maenas* has on native organisms, habitat, and marine resources. Managers may choose to strive for functional eradication of *C. maenas*, which involves lowering population density below established thresholds to minimize the impact on the native ecosystem (Ens et al., 2021). Other methods of mitigation may be targeted towards vulnerable species or habitat, or marine resources such as shellfish beds. Several techniques have been used to successfully reduce *C. maenas* impacts on cultured bivalve mollusc beds, including "covering plots with predator netting, changing the timing of planting seed, increasing seed size and density, modifying the substrate, and placing the seed in bags, cages, or on racks"(Kern et al., 2002). Further research on mitigation methods is necessary to elucidate best practices for mitigating the impacts of *C. maenas* on Oregon's native species and marine habitat.

Further Research And Actions

In addition to the mitigation and eradication efforts mentioned above, ongoing research is needed to better understand *C. maenas* impacts and to determine best management options. Potential areas of future research in Oregon include: the impacts of *C. maenas* on Oregon's native estuarine species and effective mitigation methods; determine the sources and relative contribution of *C. maenas* recruitment; determine functional eradication thresholds; assess *C. maenas* movement and interactions with high risk species throughout estuaries; evaluate potential changes in *C. maenas* range and habitat use; determine risk level for anthropogenic vectors and effective vector management options; evaluate social and economic costs of *C. maenas* in Oregon; and evaluate impact to indigenous cultural resources.

At the time of writing, several actions important to *C. maenas* research and management are taking place. Firstly, steps are being taken to standardize catch-per-limit-effort protocols, which will greatly improve assessments of *C. maenas* abundance and comparability across sites. Secondly, recent research in the Gulf of Maine aimed at tracking *C. maenas* daily and seasonal movement found that daily *C. maenas* movement was minimal and restricted to the lower estuary and subtidal zone. Seasonally, they reported *C. maenas* movement downstream, associated with decreasing water temperatures (Zarrella-Smith et al., 2022). Understanding *C. maenas* movement throughout estuarine environments is important for planning removal and mitigation efforts. However, given the differences between the abiotic and biotic characteristics of the Oregon Coast and the Gulf of Maine, more research is needed to determine *C. maenas* movement in this environment. Lastly, current proposed eradication efforts in Salmon River Estuary, if implemented, will allow researchers to evaluate the efficacy of eradication in controlling *C. maenas* and will help to inform future management plans in Oregon.

The writing of this risk assessment was limited by time constraints and technical limitations and therefore should not be considered comprehensive. We recommend that additional work be done to determine native species population density within each bay, as well as distribution of native species and *C. maenas* throughout the bay. The presence of *C. maenas* along the outer coast, and in ecologically important habitat such as Salmon River Estuary, suggest that further sampling in understudied habitats will be necessary for a complete assessment of risk to Oregon's native marine species.

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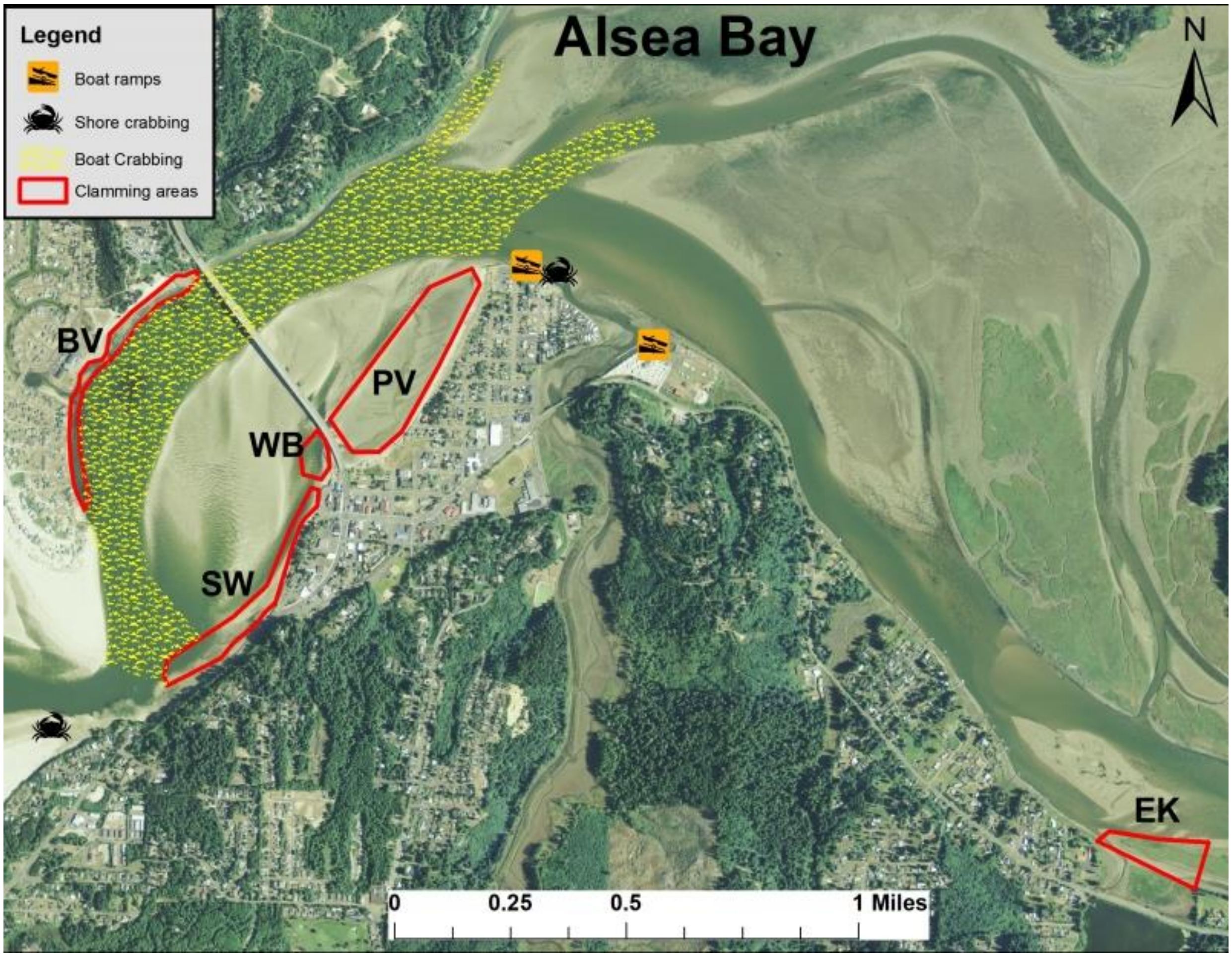
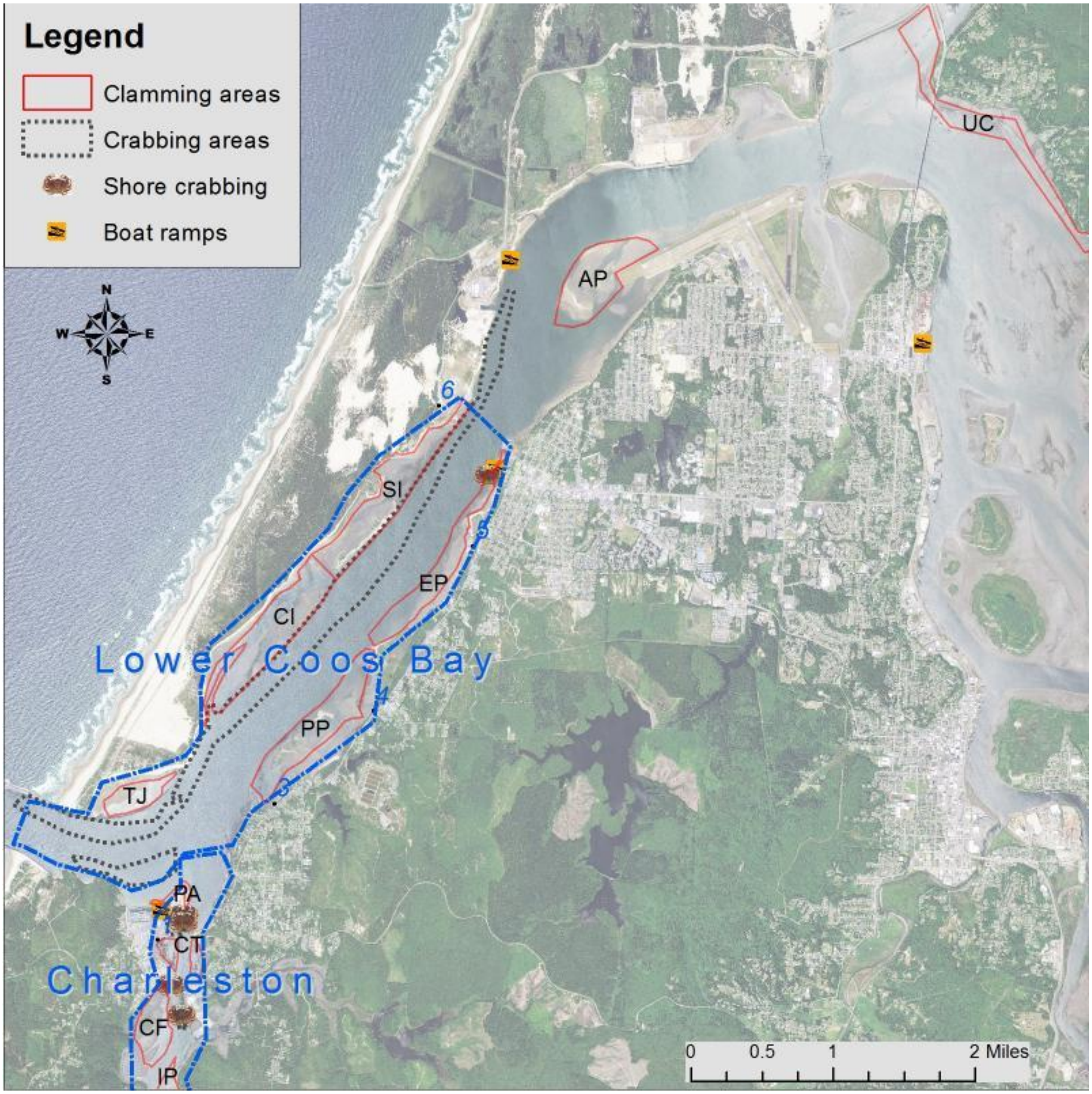
Appendix A: Alsea Bay



Appendix B: Coos Bay

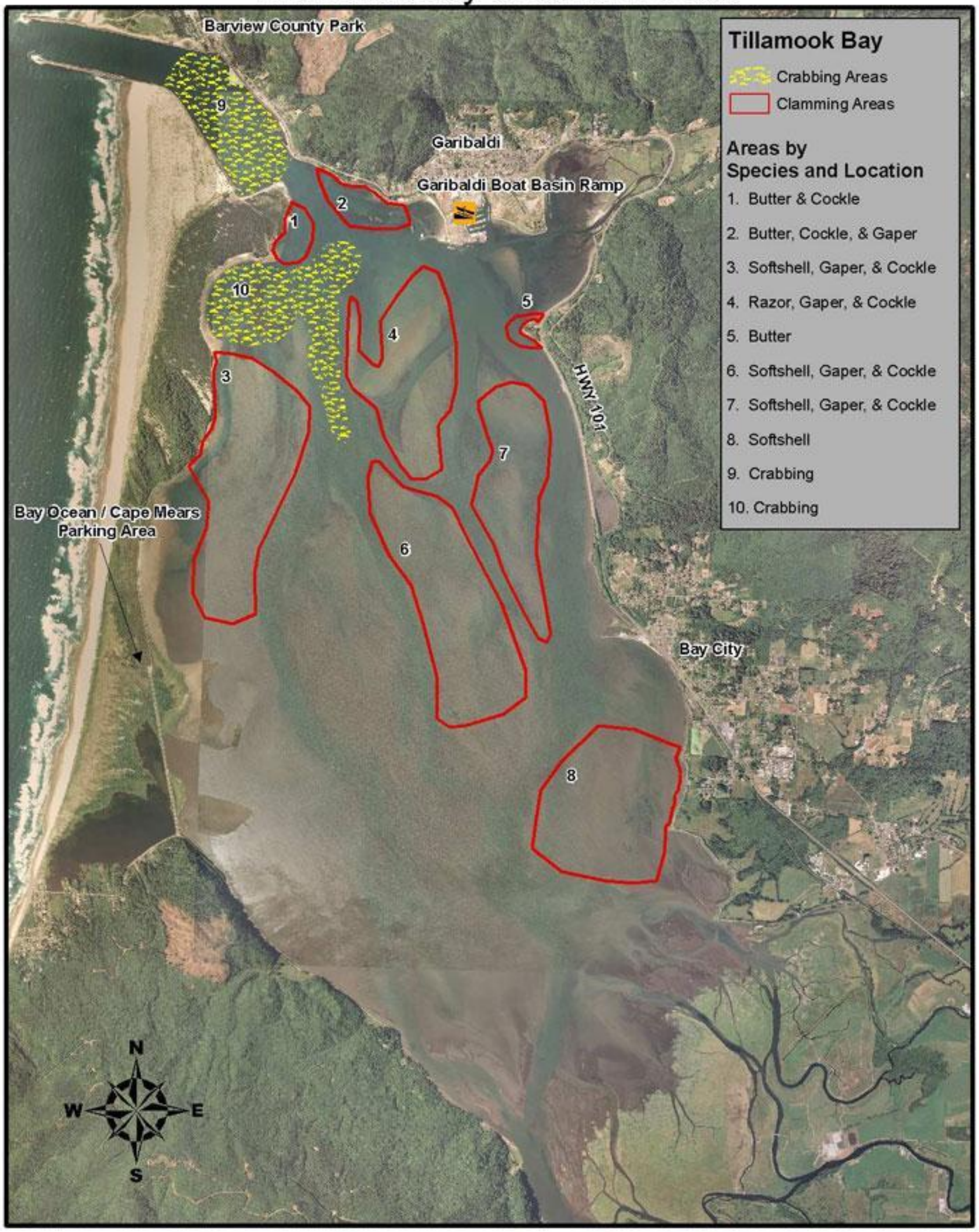


Appendix C: Netarts Bay

Netarts Bay Shellfish Areas

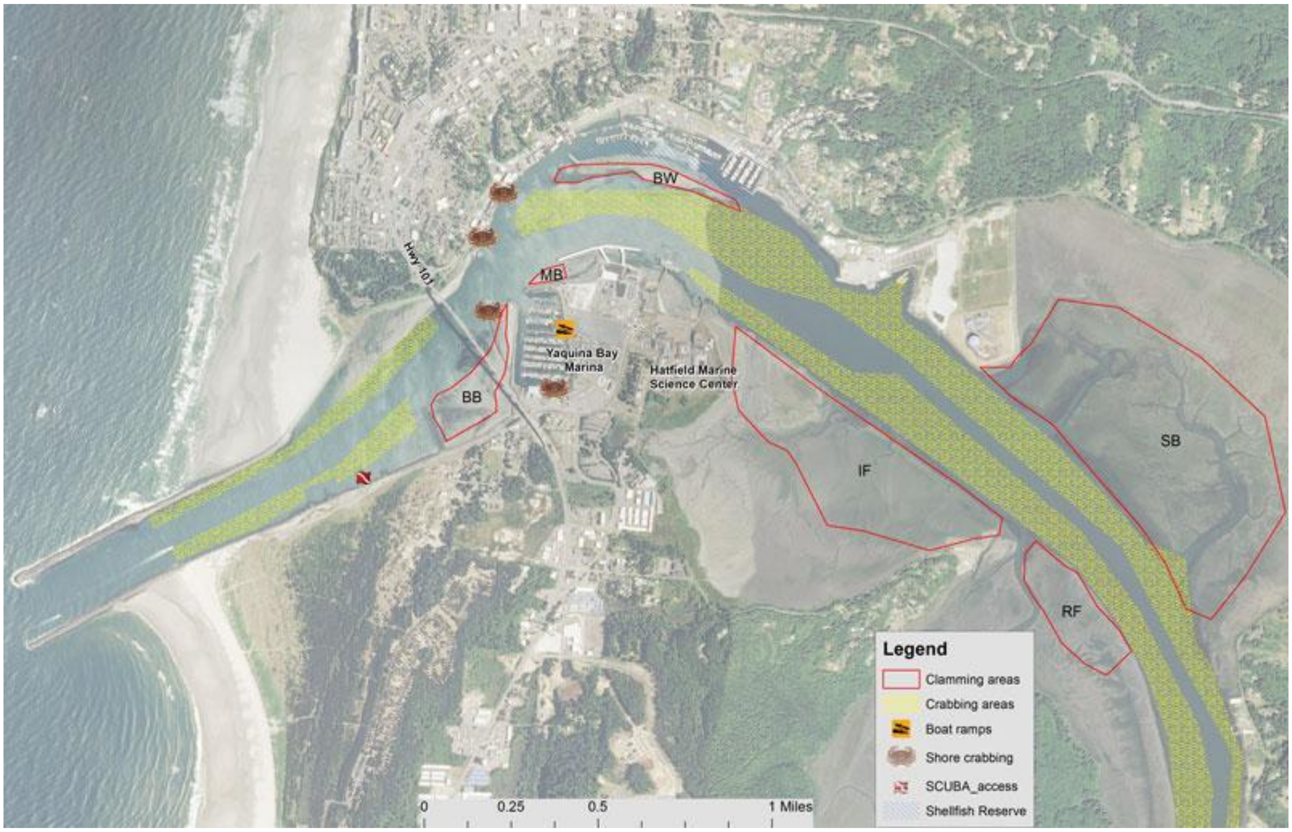
Appendix D: Tillamook Bay

Tillamook Bay Shellfish Areas



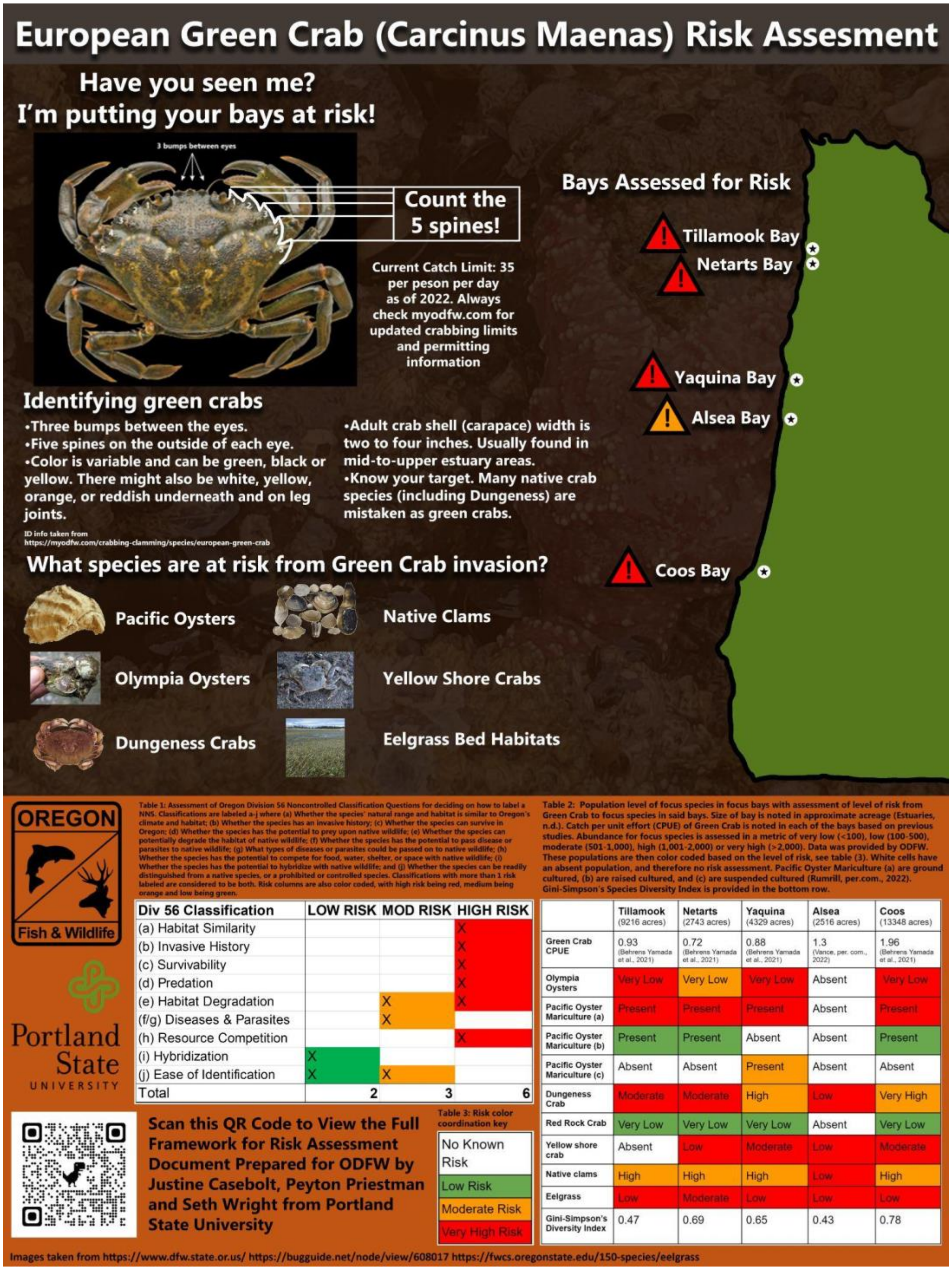
Appendix E: Salmon River Estuary

Appendix F: Yaquina Bay



Appendix G: Infographic

Image 1: Infographic of risk assessment results for public outreach and quick communication. Included is identification information, display of bays at risk, display of species at risk, inlay with the tables we created in our assessment (table 1, 2 and 4) and a direct link to the full risk assessment document.



Div 56 Classification	LOW RISK	MOD RISK	HIGH RISK
(a) Habitat Similarity			X
(b) Invasive History			X
(c) Survivability			X
(d) Predation			X
(e) Habitat Degradation		X	X
(f/g) Diseases & Parasites		X	
(h) Resource Competition			X
(i) Hybridization	X		
(j) Ease of Identification	X	X	
Total	2	3	6

	Tillamook (9216 acres)	Netarts (2743 acres)	Yaquina (4329 acres)	Alsea (2516 acres)	Coos (13348 acres)
Green Crab CPUE	0.93 (Behrens Yamada et al., 2021)	0.72 (Behrens Yamada et al., 2021)	0.88 (Behrens Yamada et al., 2021)	1.3 (Vance, per. com., 2022)	1.96 (Behrens Yamada et al., 2021)
Olympia Oysters	Very Low	Very Low	Very Low	Absent	Very Low
Pacific Oyster Mariculture (a)	Present	Present	Present	Absent	Present
Pacific Oyster Mariculture (b)	Present	Present	Absent	Absent	Present
Pacific Oyster Mariculture (c)	Absent	Absent	Present	Absent	Absent
Dungeness Crab	Moderate	Moderate	High	Low	Very High
Red Rock Crab	Very Low	Very Low	Very Low	Absent	Very Low
Yellow shore crab	Absent	Low	Moderate	Low	Moderate
Native clams	High	High	High	Low	High
Eelgrass	Low	Moderate	Low	Low	Low
Gini-Simpson's Diversity Index	0.47	0.69	0.65	0.43	0.78

Appendix H: Data Tables and Graphs

Table 5: Species population data across the 5 bays as provided by ODFW. Data was collected in quadrats mainly in the intertidal zones of the bays. Number of quadrats was not supplied.

Estuary	Shorthand	Species	Abundance
Alsea	*Sax*	Butter (Saxidomus giganteus)	0
Alsea	Cockle	Cockle (Clinocardium nuttallii)	90
Alsea	Dunge	Dungeness crab (Metacarcinus magister)	74
Alsea	*Mya*	Eastern softshell (Mya arenaria)	83
Alsea	Gaper	Gaper (Tresus capax)	67
Alsea	MLN	Manila littleneck (Ruditapes philippinarum)	0
Alsea	NLN	Native littleneck (Protothaca staminea)	0
Alsea	PVC	Purple varnish clam (Nuttallia obscurata)	3277
Alsea	*Neo*	Bay ghost shrimp (Neotrypaea californica)	9372
Alsea	*nasuta*	Bent-nose macoma (Macoma nasuta)	262
Alsea	*Upo*	Blue mud shrimp (Upogebia pugettensis)	50
Alsea	*Crypto*	California softshell (Cryptomya californica)	35888
Alsea	*Crangon*	Crangon shrimp (Lissocrangon stylirostris)	64
Alsea	*Pea*	Pea Crab (Pinnixa faba)	193
Alsea	*inquinata*	Pointed macoma (Macoma inquinata)	93
Alsea	*RRC*	Red rock crab (Cancer productus)	0
Alsea	*Hemi*	Shore crab (Hemigrapsus nudus + H. oregonensis)	163
Coos	*Sax*	Butter (Saxidomus giganteus)	1703
Coos	Cockle	Cockle (Clinocardium nuttallii)	724
Coos	Dunge	Dungeness crab (Metacarcinus magister)	6904
Coos	*Mya*	Eastern softshell (Mya arenaria)	453
Coos	Gaper	Gaper (Tresus capax)	537
Coos	MLN	Manila littleneck (Ruditapes philippinarum)	0
Coos	NLN	Native littleneck (Protothaca staminea)	152
Coos	PVC	Purple varnish clam (Nuttallia obscurata)	828
Coos	*Neo*	Bay ghost shrimp (Neotrypaea californica)	15524
Coos	*nasuta*	Bent-nose macoma (Macoma nasuta)	20614
Coos	*Upo*	Blue mud shrimp (Upogebia pugettensis)	2191
Coos	*Crypto*	California softshell (Cryptomya californica)	28250
Coos	*Crangon*	Crangon shrimp (Lissocrangon stylirostris)	24
Coos	*Pea*	Pea Crab (Pinnixa faba)	10
Coos	*inquinata*	Pointed macoma (Macoma inquinata)	5903
Coos	*RRC*	Red rock crab (Cancer productus)	35
Coos	*Hemi*	Shore crab (Hemigrapsus nudus + H. oregonensis)	774
Netarts	*Sax*	Butter (Saxidomus giganteus)	2025
Netarts	Cockle	Cockle (Clinocardium nuttallii)	527

Netarts	Dunge	Dungeness crab (Metacarcinus magister)	715
Netarts	*Mya*	Eastern softshell (Mya arenaria)	774
Netarts	Gaper	Gaper (Tresus capax)	792
Netarts	MLN	Manila littleneck (Ruditapes philippinarum)	208
Netarts	NLN	Native littleneck (Protothaca staminea)	885
Netarts	PVC	Purple varnish clam (Nuttallia obscurata)	1358
Netarts	*Neo*	Bay ghost shrimp (Neotrypaea californica)	6152
Netarts	*nasuta*	Bent-nose macoma (Macoma nasuta)	18079
Netarts	*Upo*	Blue mud shrimp (Upogebia pugettensis)	18688
Netarts	*Crypto*	California softshell (Cryptomya californica)	49270
Netarts	*Crangon*	Crangon shrimp (Lissocrangon stylirostris)	116
Netarts	*Pea*	Pea Crab (Pinnixa faba)	413
Netarts	*inquinata*	Pointed macoma (Macoma inquinata)	1376
Netarts	*RRC*	Red rock crab (Cancer productus)	30
Netarts	*Hemi*	Shore crab (Hemigrapsus nudus + H. oregonensis)	256
Tillamook	*Sax*	Butter (Saxidomus giganteus)	2496
Tillamook	Cockle	Cockle (Clinocardium nuttallii)	2559
Tillamook	Dunge	Dungeness crab (Metacarcinus magister)	865
Tillamook	*Mya*	Eastern softshell (Mya arenaria)	238
Tillamook	Gaper	Gaper (Tresus capax)	2826
Tillamook	MLN	Manila littleneck (Ruditapes philippinarum)	0
Tillamook	NLN	Native littleneck (Protothaca staminea)	152
Tillamook	PVC	Purple varnish clam (Nuttallia obscurata)	14
Tillamook	*Neo*	Bay ghost shrimp (Neotrypaea californica)	7688
Tillamook	*nasuta*	Bent-nose macoma (Macoma nasuta)	13019
Tillamook	*Upo*	Blue mud shrimp (Upogebia pugettensis)	6522
Tillamook	*Crypto*	California softshell (Cryptomya californica)	107177
Tillamook	*Crangon*	Crangon shrimp (Lissocrangon stylirostris)	124
Tillamook	*Pea*	Pea Crab (Pinnixa faba)	380
Tillamook	*inquinata*	Pointed macoma (Macoma inquinata)	5116
Tillamook	*RRC*	Red rock crab (Cancer productus)	46
Tillamook	*Hemi*	Shore crab (Hemigrapsus nudus + H. oregonensis)	0
Yaquina	*Sax*	Butter (Saxidomus giganteus)	52
Yaquina	Cockle	Cockle (Clinocardium nuttallii)	293
Yaquina	Dunge	Dungeness crab (Metacarcinus magister)	1342
Yaquina	*Mya*	Eastern softshell (Mya arenaria)	317
Yaquina	Gaper	Gaper (Tresus capax)	696
Yaquina	MLN	Manila littleneck (Ruditapes philippinarum)	1
Yaquina	NLN	Native littleneck (Protothaca staminea)	72

Yaquina	PVC	Purple varnish clam (Nuttallia obscurata)	6
Yaquina	*Neo*	Bay ghost shrimp (Neotrypaea californica)	2841
Yaquina	*nasuta*	Bent-nose macoma (Macoma nasuta)	16482
Yaquina	*Upo*	Blue mud shrimp (Upogebia pugettensis)	24402
Yaquina	*Crypto*	California softshell (Cryptomya californica)	53916
Yaquina	*Crangon*	Crangon shrimp (Lissocrangon stylirostris)	142
Yaquina	*Pea*	Pea Crab (Pinnixa faba)	326
Yaquina	*inquinata*	Pointed macoma (Macoma inquinata)	2930
Yaquina	*RRC*	Red rock crab (Cancer productus)	58
Yaquina	*Hemi*	Shore crab (Hemigrapsus nudus + H. oregonensis)	362

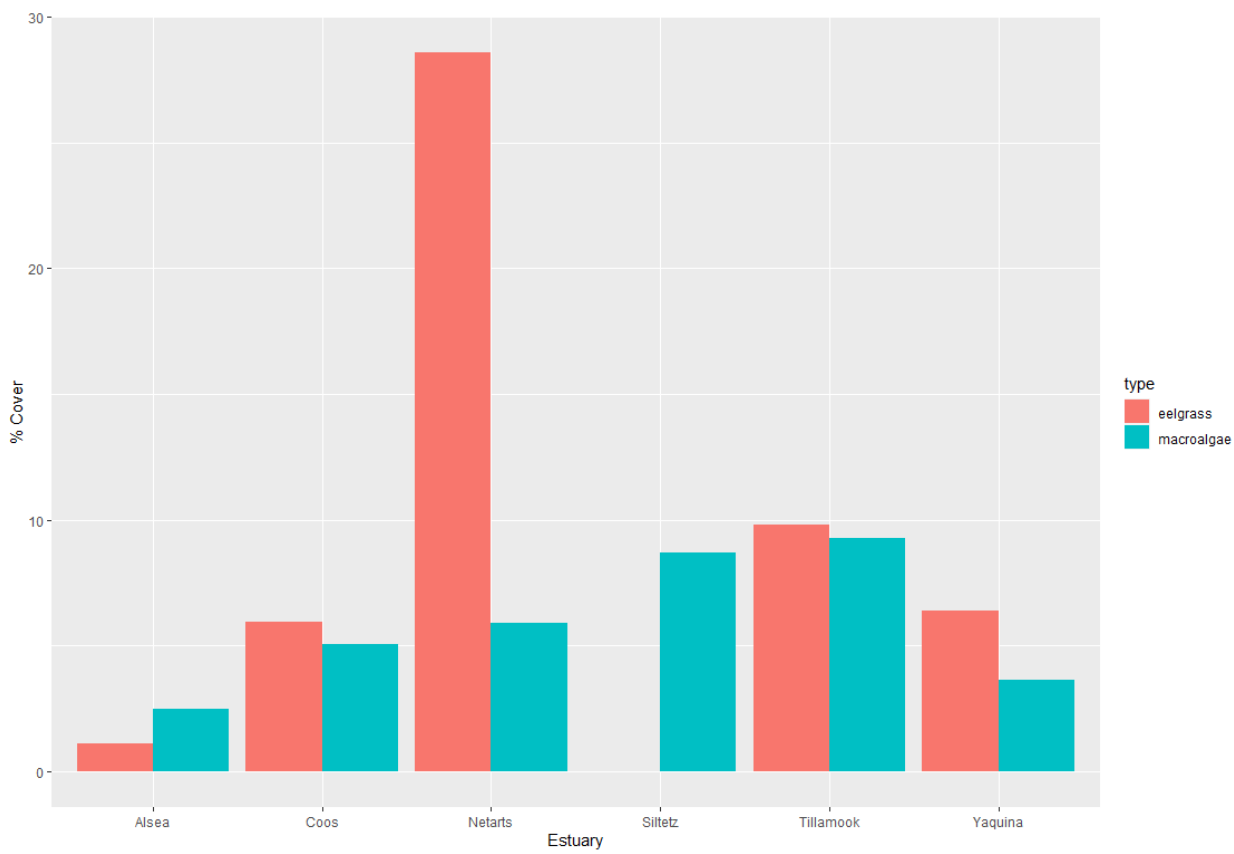


Figure 2: Eelgrass bed percent cover data provided by PSU.