AN ABSTRACT OF THE FINAL REPORT OF

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Title: Ecosystem services provided by Olympia oyster (*Ostrea lurida)* habitat and Pacific oyster (*Crassostrea gigas)* habitat; Dungeness crab (*Metacarcinus magister*) production in Willapa Bay, WA

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Oyster reefs provide an array of ecosystem services. Specifically, they provide structurally complex habitat for fish and invertebrate species such as the commercially important Dungeness crab, *Metacarcinus magister.* This ecosystem service, once provided by the native oyster *Ostrea lurida*, is now provided by the commercially cultured oyster *Crassostrea gigas* in many estuaries on the U.S west coast. An economic investigation was conducted examining the ecosystem services provided by oyster habitat, common economic valuation theories and techniques, and tradeoffs between oyster restoration and aquaculture expansion. A scientific investigation, comprised of three studies, was also conducted to examine Dungeness crab production as an ecosystem service provided by oyster habitat.

Because natural ecosystems, such as oyster reefs, provide beneficial goods and services through time, they should be valued as any other economic asset or capital. Until recently many of these beneficial services have not been accounted for within resource management plans, often resulting in the over-exploitation of those resources. Activities such as coastal development, dredging, aquaculture expansion, or even habitat restoration can affect estuarine ecosystems. While valuing the ecosystems themselves might be difficult, valuation of the services they provide can be a useful tool for identifying and protecting key ecosystem services while implementing plans with minimal negative impact.

The oysters, *O. lurida* and *C. gigas* inhabit different regions of the tidal zone. *O. lurida* is predominantly found in subtidal and low intertidal regions whereas *C. gigas* is predominantly found in intertidal regions. The shift in the dominant species has resulted in a subsequent shift of available recruitment habitat for *M. magister*. We conducted an across-estuary study to examine settlement of *M. magister* in existing *O. lurida*, *C. gigas*, eelgrass, and open mud habitats in Willapa Bay, WA, Netarts Bay, OR, and Coos Bay, OR, to determine tradeoffs in crab production between habitat types. A second study using shell bags as settlement substrate at various tidal elevations was conducted in Yaquina Bay, OR, to obtain density data of *M. magister* by depth. We used these densities, in combination with pre-existing data from Willapa Bay, to compare the production of Dungeness crab as an ecosystem service historically provided by *O. lurida* habitat and production currently provided by *C. gigas* habitat in Willapa Bay, WA. A third study using shell piles was conducted in Yaquina Bay, OR to estimate survival of juvenile *M. magister.* The results of these three studies generally support prior research indicating that densities of juvenile *M. magister* are greater in oyster and eelgrass habitats than in open mud, and are generally greater in oyster habitat than in eelgrass. The Yaquina Bay shell bag study indicated greater densities of juvenile *M. magister* in subtidal regions, while the shell pile study indicated greater densities in higher intertidal regions.

Ecosystem services provided by Olympia oyster (*Ostrea lurida*) habitat and Pacific oyster (*Crassostrea gigas*) habitat; Dungeness crab (*Metacarcinus magister*) production in Willapa Bay, WA.

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Dedication

This is dedicated to my parents, Trini and Dennis Ramsay,

and to my brother, Adam Ramsay

Chapter 1: General Introduction

An estimated 85% of oyster reefs have been lost worldwide (Beck et al., 2009). Along the U.S. west coast, populations of the native Olympia oyster, *Ostrea lurida*, have declined to a fraction of historical (pre-1850's) levels due to extensive harvesting and habitat degradation (Steele, 1957; Ruesink et al., 2005). The Pacific oyster, *Crassostrea gigas*, was subsequently introduced as a cultured substitute and currently dominates west coast oyster aquaculture (Steele, 1957; Dumbauld et al., 2009). The National Shellfish Initiative was created in 2011 with the goal of restoring declining native shellfish populations and expanding shellfish aquaculture (NOAA, 2011a). The Washington State Shellfish Initiative soon followed with similar goals to promote and extend current shellfish aquaculture and to restore native oyster populations (Washington State, 2011). Implementing these initiatives requires defining and understanding the ecosystem services (human-derived benefits) provided by both oyster aquaculture and native oyster populations. A broad array of benefits exists including biofiltration, sediment accumulation and stabilization, nutrient cycling, and the provision of habitat for economically and ecologically important species (Coen et al., 2007; Dumbauld et al., 2009). As such, these ecosystem services should be examined and compared when implementing projects such as restoration, aquaculture expansion, coastal development, or dredging which have the potential to increase or compromise the services provided by oyster reefs and oyster aquaculture.

This paper represents the economic and scientific investigations conducted to examine the ecosystem services provided by oyster habitat in Pacific Northwest estuaries. The native, Olympia oyster, *Ostrea lurida*, and the introduced Pacific oyster, *Crassostrea gigas*, provide a broad array of ecosystem services. In particular, they provide habitat for commercially important juvenile Dungeness crab, *Metacarcinus magister*. This chapter introduces these three species and provides background information relevant to both the economic and scientific investigations that were conducted. Chapter 2 examines, in a broader sense: the multitude of ecosystem services, current economic theories and valuation techniques, and tradeoffs between oyster restoration and aquaculture. Chapter 3 discusses three scientific studies that were conducted to examine Dungeness crab production as one specific ecosystem service provided by native Olympia oyster habitat and commercially cultured Pacific oyster habitat. Chapter 4 concludes the report by discussing management implications of both the economic and scientific investigations.

Olympia Oyster

The Olympia oyster (*Ostrea lurida*) is the only oyster native to the west coast of the U.S and was once abundant in coastal estuaries like Yaquina Bay and Willapa Bay where it inhabited low intertidal to subtidal regions (Baker, 1995; Groth and Rumrill, 2009; White et al., 2009b). The Olympia oyster is relatively small, approximately 3-6 cm and reaches full size in 4 years (Baker, 1995). It is capable of living in full seawater but is more often found in estuaries and bays with minimum salinities of 23 to 24 ppt (Peter-Contesse and Peabody, 2005).

History

Large-scale, commercial harvesting of the Olympia oyster began in 1851 (Trimble et al., 2009), but overharvesting and habitat degradation led to its decline in the late 1800's. In Willapa Bay alone, a minimum of 5 billion individuals were removed between 1851 and 1915, many of which were transported live to distant ports rather than being shucked in place, preventing the replacement of clean shell (cultch) which provide attachment structure for *O. lurida* larval recruits (Ruesink et al., 2009). Small, remnant populations of the Olympia oyster currently exist throughout most of its historic range (Polson and Zacherl, 2009), but these are not comparable to the vast populations that once existed (Dinnel, 2009). Larval attachment requires clean shell in suitable habitats (White et al., 2009b), so in addition to exploitation of spawning stocks, removal of cultch as settlement substrate, may have further hindered population recovery (Ruesink et al., 2009). Trimble et al (2009) showed that abundant broodstock exists, but that appropriate settling substrate for the larvae may be the limiting factor for population recovery. Survival of larvae was shown to be greater at depths below mean lower low water (MLLW) than at elevations above MLLW. White et al. (2009) found a clear trend of higher recruitment at lower tidal height for *O. lurida* recruitment. The lack of appropriate substrate at this lower depth and the abundance of Pacific oysters in the higher intertidal may be resulting in a "recruitment sink" in which the native oyster larvae are recruiting to the Pacific oyster shell and then succumbing to desiccation and temperature extremes (Trimble et al., 2009).

Olympia oysters are noted for their distinct metallic flavor (Gordon et al., 2001) and are fondly referred to as "Olys" by those that appreciate this small oyster (Archer, 2008). Commercial culture of *O. lurida* still exists in Oregon and Washington and until very recently was minimally profitable. However, with the current interest in native oyster restoration and the local food movement it may once again gain in popularity, and some oyster growers are showing interest in developing a boutique market for this oyster (Archer, 2008; Polson and Zacherl, 2009). Recreational harvest is currently allowed in Washington for all oysters greater than 2 ½ in., but prohibited in Oregon (Washington Department of Fish and Wildlife, 2011; Oregon Department of Fish and Wildlife, 2012); however, an increase in population sizes could also lead to increased opportunities for recreational harvesting.

Restoration

In Washington State the Olympia oyster was recognized as a threatened species candidate in 1970 and is currently a species of concern (Cook et al., 1998). Numerous projects have been conducted examining both larval recruitment and best restoration methods using various substrate enhancement materials, including crushed or whole shell in shell bags, loose shell, and cement reef balls (Brumbaugh and Coen, 2009; Dinnel et al., 2009). A plan to rebuild *O. lurida* stocks was developed for Puget Sound and Willapa Bay by the Washington Department of Fish and Wildlife (Cook et al., 2000). According to the Puget Sound Restoration Fund, 155 acres of Olympia oyster currently exist in Puget Sound where 4,000-5,000 acres once existed, and a plan has been implemented for restoring 100 acres of native oyster habitat by 2020 (NOAA, 2011b). Trimble et al. (2009) report the presence of natural recruitment in Willapa Bay, but that naturally occurring settlement substrate is insufficient (occurring too high in the intertidal), and current restoration techniques might lead to fouling of the organisms. Crushed shell is being investigated as a more effective alternative to the use of whole shell (Trimble et al., 2009). In addition to Puget Sound, and Willapa Bay restoration efforts, the Nature Conservancy has an ongoing re-establishment project in Netarts Bay, OR, and restoration is being conducted in the South Slough Reserve, Coos Bay, OR (Brumbaugh and Toropova, 2008; National Estuarine Research Reserve System, undated).

The Pacific Oyster

The Pacific oyster is larger than the Olympia oyster with a mean size of 4-6 in. but can grow larger, and is found in shallow intertidal areas rather than subtidal zones (Trimble et al., 2009). However, some overlap between *C. gigas* and *O. lurida* habitat most likely exists, and both native oysters and current *C. gigas* culture occur at tidal elevation where eelgrass (*Zostera marina*) also occurs (approximately -0.5 to +1.75 m, relative to MLLW, Dumbauld et al., 2011). Market size of *C. gigas* (>75 mm) is reached between 1 and 4 years depending on water temperatures, salinity, food supply, and growing methods.

History

The decline of *O. lurida* in the late 1800's led to the fishery's eventual collapse and abandonment in the early 1900's. The Eastern oyster, *Crassostrea virginica*, a species native to the east coast of the U.S, was introduced and commercially cultivated between 1895 and 1919, but natural spawning events were rare, and mortality was high (Steele, 1957). The Pacific oyster from Japan, *Crassostrea gigas,* was first outplanted in Samish Bay, WA in 1921 (Steele, 1957) and was successfully introduced in Willapa Bay, WA in 1928 (Trimble et al., 2009). It now dominates the U.S. West Coast shellfish aquaculture industry (Dumbauld et al., 2009).

Hundreds of acres of Olympia oyster beds were once found in Willapa Bay, (Steele, 1957) but this estuary is now the largest producer of Pacific oysters on the U.S. West coast. After statehood in 1889, a series of laws and regulations concerning tidelands and harvest restrictions were passed and eventually led to the creation of the Willapa Bay Oyster Reserves, established in 1897 (Trimble et al., 2009). The Oyster Reserves (approximately 4,033 ha; Dumbauld et al., 2011) were intended to protect Olympia oyster stocks, but overharvesting and successful introduction of the Pacific oyster resulted in these areas being utilized largely for commercial production of the Pacific oyster.

Current Aquaculture

Various techniques exist for shellfish aquaculture. This project examines on-bottom aquaculture as opposed to other methods using long lines, trays, floating bags, and rack and bag systems which are often utilized in relatively deep estuaries such as Puget Sound (Dumbauld et al., 2009). Because the oysters are grown out directly on the substrate, on-bottom aquaculture provides crab settlement habitat similar to that of naturally growing oysters. This method is common in Oregon estuaries and comprises one of two common methods (on-bottom and long-line aquaculture) in Willapa Bay (Trimble et al., 2009).

On-bottom aquaculture can be further classified into several categories including “seed beds”, “fattening beds”, “hummocks”, “mixed beds”, or “direct”. Seed beds are comprised of cultch (or clean, shucked shell) which is spread out and used for growing spat, or newly attached young oysters. Fully grown oysters are then moved to fattening beds, closer to the mouth of the bay until ready to be harvested. Fattening beds will have older, larger oysters clustered together and tend to be more densely packed than seed beds. Hummocks are dense reefs of oysters left to grow on their own, and are often found in the southern portion of the bay within the oyster reserves. Trimble et al. (2009) noted that hummocks grow in the same region as the Olympia oyster but in the shallower intertidal region rather than the subtidal region. Hummocks occur where oysters naturally settle. Oyster growers will generally harvest from these beds and transplant oysters to fattening beds for a short period once the oysters are mature, returning shell to the beds for future larval attachment. Mixed beds are a combination of both seed and fattening beds depending on the year, and "direct" are beds in which oysters are grown out and harvested directly from the bed (an approximately three year cycle; B. R. Dumbauld, pers.comm).

Dungeness Crab

Life History

Dungeness crab (*Metacarcinus magister,* formerly *Cancer magister*) are epibenthic marine invertebrates found in estuaries and nearshore environments along the west coast of North America, from Alaska to Baja (Pauley et al., 1989). Estuaries serve as nurseries where crab are provided with warmer temperatures and protection from predation during their first year of life (Stevens and Armstrong, 1984; Gutermuth and Armstrong, 1989). Structurally complex habitats within these estuaries such as oyster reefs, oyster beds, and eelgrass can provide protection and food for juvenile Dungeness crab (Fernandez et al., 1993; Eggleston and Armstrong, 1995; Dumbauld et al., 2000; Feldman et al., 2000).

Dungeness crab hatch in the open ocean in early spring and proceed through five zoeal stages as planktonic larvae. They then metamorphose into megalopae, the last pelagic stage, (see Figure 1) and enter nearshore waters and coastal estuaries from late March – July (McConnaughey et al., 1994; Roegner et al., 2007; Shanks and Roegner, 2007). Actively swimming megalopae then settle onto substrate and metamorphose into the first instar (J1) juvenile stage (Eggleston and Armstrong, 1995). Juvenile crab develop through five instar stages (J1-J5) before moving into open unstructured habitat, which provides foraging areas for larger juveniles (30+ mm) (McMillan et al., 1995; Holsman et al., 2003). Due to variation in temperatures and salinity, juvenile growth varies among estuaries (Pauley et al., 1989). Crab growth is not continuous, but occurs in stages through a series of molts. Each instar stage is characterized by growth in biomass and followed by a molt, or shedding of the external carapace allowing the new carapace to grow in width (Pauley et al., 1989). The crab then swells with water and the newly formed soft carapace hardens over the next few weeks (Losey et al., 2004). Adult crab continue molting once or twice a year (Losey et al., 2004).

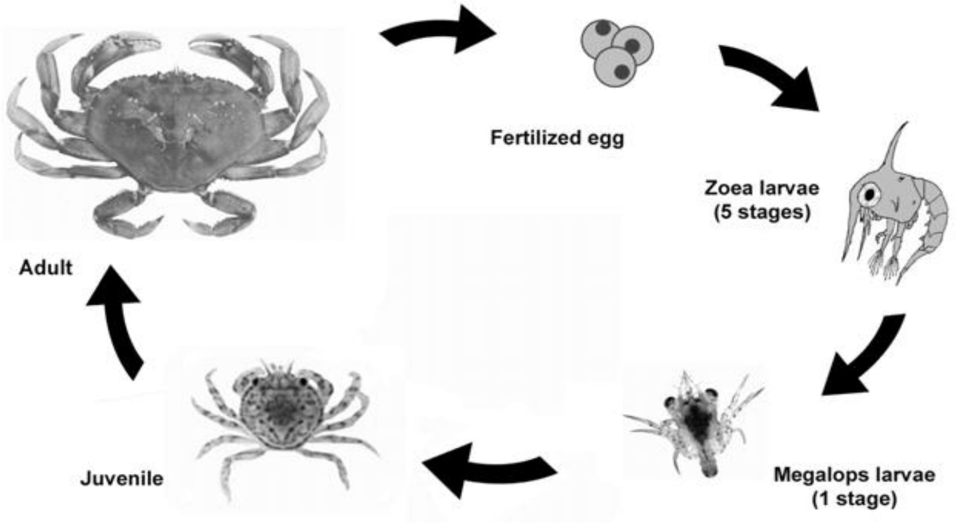


Figure 1. Dungeness crab life cycle.
In Fisher and Velasquez, 2008 and adapted from Pauley et al., 1989.

Recruitment and Survival

Predation on juvenile *M. magister* is highest in open mud and lowest in oyster shell; and densities are generally higher in shell than in eelgrass beds (Fernandez et al., 1993). In lab experiments megalopae and juvenile *M. magister* choose shell substrate over both eelgrass and mud (Fernandez et al., 1993). Doty et al. (1990) reported 4-6 times greater densities of juvenile crab in oyster shell when compared to eelgrass in Willapa Bay, WA. Increased survival rates of juvenile crab in shell have led to the construction of artificial shell plots to mitigate crab loss due to dredging in Grays Harbor, WA (Dumbauld et al., 1993; McGraw et al., 1988). While these structures offer protection from predators such as Staghorn sculpin *(Leptocottus armatus)* and older conspecifics, high densities of *M. magister* within shell habitat may lead to an increase in aggressive behavior and cannibalism among the juveniles (Fernandez et al., 1999). This cannibalistic behavior may be a limiting factor for production in structured habitat (Fernandez et al., 1999).

Shanks and Roegner (2007) suggest that larval transport of *M. magister* is likely due to physical oceanographic processes within the California and Davidson Current Systems in which coastal upwelling brings planktonic larvae inshore. Landings within the Dungeness crab fishery are highly cyclic with peaks approximately every ten years, which may be attributed to larval flux due to the California Current system. This system causes upwelling along the west coast during spring (the spring transition) and results in a shoreward movement of water and planktonic larvae (Shanks and Roegner, 2007). Shanks and Roegner (2007) suggest that if this spring transition occurs early, more larvae return to the coast than if upwelling occurs late, and their research shows a strong correlation between the abundance of megalopae in estuaries and the number of crab landed in the fishery four years later. The timing of the spring transition is therefore believed to be one of the primary factors responsible for these cyclic landings in the fishery.

Dungeness Crab Fishery

The Dungeness crab fishery is a multimillion dollar industry and one of the most important 'single species' fisheries in both Oregon and Washington states. Unlike many other fisheries in which catch is limited by state or federally set quotas, the Dungeness crab fishery is based on states assessments which define rules for "Sex, Size, and Season." Only male crabs larger than 160 mm carapace width (CW) are harvested during a season typically lasting between December and August. However the fishing is intensive and approximately 80% of the catch is obtained within the first two months (Shanks and Roegner, 2007). Afterwards, the closed season protects recently molted, soft-shelled crabs.

Chapter 2: Economic Investigation

Introduction

The biological and physical aspects of ecosystems provide a multitude of marketable goods such as fish and lumber. Over the past decade however, other benefits provided to humans by ecosystems, are beginning to be recognized. These “ecosystem services” are the “benefits human populations derive, directly or indirectly, from ecosystem functions” (Costanza et al., 1997, p.253) and include provisioning services such as food and timber; regulatory services including water filtration, nutrient cycling, climate regulation, and sediment stabilization; and cultural services such as recreation and tourism (Millennium Ecosystem Assessment, 2003). Attempting to apply value to these services can be beneficial for both natural resource managers and industries when determining, if for example, it would be more cost-effective to channelize a degraded stream or to restore vegetation to the riparian area for flood mitigation. Services such as sediment stabilization and storm protection were once taken for granted or overlooked in management plans, but with continued human expansion, assigning value to these services should be examined and compared with the values of activities that could compromise these ecosystems. Ecosystem services, unlike other goods and services, do not pass through the market economy (Costanza et al., 1997) and are often used without notice or recognition. If no payment system exists and these services are inherently free, overuse or exploitation of an ecosystem can result. Assigning some value, monetary or otherwise, may ensure that ecosystem services are not underrepresented in management plans or policy making (Northern Economics, 2009).

Applying a monetary value to or ranking the importance of the components of nature may seem offensive to some, but Wainger and Boyd (2009) suggest that while nature as a whole may be priceless, its components are not, which is evident by the choices we make as a society. That is, we value our way of life (transportation, shelter, types of food) and will “always choose to have fewer trees, dirtier air and water, and compromised habitats because nature’s components are not *all* society cares about,” (Wainger and Boyd, 2009, p. 94). Nature and its components contribute to human well-being since we cannot live without these, and as such, should be valued to prevent the degradation of vital ecosystems (Costanza et al., 1997; Millenium Ecosystem Assessment, 2003; NRC, 2004).

An estimated 85% of oyster reefs have been lost worldwide (Beck et al., 2009) and the ensuing interest in restoration projects and oyster aquaculture for stock enhancement have in part led to the development of a National, and subsequently Washington State, Shellfish Initiatives. These Initiatives seek to promote and expand shellfish aquaculture and restore native oyster populations (NOAA, 2011, Washington State, 2011). Implementing these initiatives requires some understanding of the multitude of ecosystem services provided by oyster habitat.

Aquaculture expansion and native oyster restoration may result in the loss of ecosystem services provided by eelgrass beds or mudflats, and tradeoffs between ecosystem services should be examined so that least-impacting strategies can be developed while retaining key ecosystem services. As marine policy and the reliance on coastal and marine ecosystems becomes more prevalent, valuing these resources and the benefits derived should be of vital importance to minimize loss of ecosystems and ecosystem services. This chapter examines the broad suite of ecosystem services provided by oyster habitat, current economic theories and valuation techniques, and discusses tradeoffs between oyster restoration and aquaculture expansion.

Ecosystem Services

While coral reefs have received much attention for their roles as ecosystem engineers and essential habitat for fish, oyster reefs are just beginning to receive this recognition. Native oyster restoration efforts are beginning to be implemented in bays and estuaries on all U.S coasts in an attempt to restore ecosystem services. In addition to habitat provisioning for Dungeness crab, ecosystem services include biofiltration of sediments and excess nutrients, carbon sequestration, sediment stabilization, coast line protection, and food production (Meyer et al., 1997; Forrest et al., 2009; Tang et al., 2011).

Water filtration can be beneficial in estuaries where anthropogenic input and eutrophication, there is little water flow, and residence time is high (Nixon, 1995). Filtration enhances water clarity allowing sunlight to penetrate to lower depths, thereby stimulating primary production. The amount of sediment, nutrients, and phytoplankton filtered from the water by suspension feeders such as oysters, is dependent on water circulation and residence time within an estuary, as well as phytoplankton population growth (Fulford et al., 2007), all of which can be difficult to monitor in the field (Dumbauld et al., 2009). However, laboratory experiments have shown filtration rates between 1.21 and 5 liters per hour per oyster depending on the size of the oyster (Grizzle, et al., 2008). It is estimated that oysters in the Chesapeake Bay were able to filter the entire volume of water in the bay within a week; however due to overharvesting and degraded water quality, the few populations of oysters that remain would need a full year to accomplish this same task (Newell, 1988). Additionally, the ability to remove nutrients, contaminants, and sediments from the water, which are then stored in tissue, indicate that oysters are ideal to serve as bioindicators for the health of estuaries and bays (Gomez-Batista et al., 2007; Nappier et al., 2008).

Shellfish reefs can help stabilize and protect coastlines by capturing sediment and preventing erosion of tideflats and subtidal areas. They serve as natural buffer zones or breakwaters against wave action and tides, decreasing the impact of boat wakes as well as storm surges. Meyer et al. (1997) noted a significant increase in sediment accumulation behind oyster cultch experimental plats versus regions without cultch, both after a storm and in areas of high boat wake. The minimized water force may also allow for increased growth of eelgrass or marsh in areas behind oyster beds (Meyer et al., 1997).

Both production and restoration of shellfish can stimulate local economies, by providing jobs in the aquaculture industry, increasing recreational fisheries, and increasing eco-tourism with vibrant and diverse ecosystems. As the world's population increases so does the demand for seafood as a source of protein. Global production of aquaculture increased from 1 million tons in the early 1950's to 55.1 million tons in 2009 and is the fastest-growing sector of the animal-food-producing industry, maintaining an annual growth rate of 6.1 percent (FAO, 2011). The U.S was the second largest importer (behind Japan) of fish and fishery products in 2008 (FAO, 2011), and identifying appropriate areas for cultured and restored oyster reefs can decrease our reliance on imports and provide needed jobs.

Economic Theories and Valuation Methods

Economic Review

Ecosystem services are considered “pure public goods” (Costanza et al., 1997) since they are both non-excludable (everyone is free to enjoy the benefits of ecosystem services because exclusion from these is difficult or impossible) and non-rivalry (the benefits can be enjoyed by more than one person) (Northern Economics, 2009). The benefits provided by ecosystem services increase the well-being and utility (or measure of satisfaction) to people. That is, as benefits derived from ecosystem services increase (increased air, water quality, biodiversity, economic value, etc.), then utility and well-being should also increase.

Boyd and Banzhaf (2007) attempt to standardize the term “ecosystem services” by focusing on end products or ecological endpoints, and offer the definition “final ecosystem services are components of nature, directly enjoyed, consumed, or used to yield human well-being” (p. 619). This then suggests that the end product, such as X amount of carbon sequestered by oysters, is the ecosystem service and not the carbon sequestration process, which is a function of oyster cover. They suggest using gross domestic product (GDP) to value a final good or service. For example, a car’s final value is assessed as a whole, and the value of the steel, fabric, plastic, etc. are accounted for within this final value. This does not ignore the benefits or services that are provided but instead their value is embodied within the total value of the end product. If the function or benefit (carbon sequestration) is included within the definition of an ecosystem service, then this would essentially double count (1. carbon sequestration 2. amount of carbon sequestered) the ecosystem service. If the values of the final products are assessed then this can provide standardized accounting units which are more easily used in a conventional market. Wainger and Boyd (2009) refer to these as “socially relevant endpoints” since these endpoints are the benefits that society ultimately cares about.

Economic Theories and Application to Ecosystem Services

Willingness to Pay and Willingness to Accept

Ecosystem services contribute to both marketable and non-marketable values. Marketable values are obtained from commodities which can be bought and sold, such as food or wood, and reflect the consumers’ “willingness-to-pay” for a product (Costanza et al., 1997; Barbier, 2009). Willingness to pay represents the maximum amount a consumer will pay for a product and is often higher than, or at least equal to, the actual cost of the product (NRC, 2004; Barbier, 2009). The cost of a product is often the minimum that a consumer will pay. The difference between the willingness to pay (maximum) for a good and the actual cost (minimum) is the net economic benefit of the item. For example, if a pound of Dungeness crab meat costs $7.50 but a consumer is willing to pay up to $10.00 per pound the net economic benefit realized by that consumer is $2.50. Additionally a consumer’s “willingness to accept” is the amount of compensation that would be accepted for the loss of a good (Barbier, 2009). For example, one landowner may be more willing to accept compensation for the loss of riparian property to be used for restoration purposes than another landowner. The first landowner's willingness to accept compensation would thus be lower than the second landowner. Non-marketable values on the other hand are less easily obtained than marketable values, since these goods or services (clean air, denitrification, etc.) are not traded in markets and therefore lack monetary value.

Natural Capital and Ecosystem Accounting

Because natural ecosystems provide beneficial goods and services through time, they can be valued as any other economic asset or capital (Heal, 2007; Barbier, 2009). This is referred to as natural capital and similar to financial capital, will increase with "investments" such as restoration, and decrease with habitat degradation and pollution (Barbier, 2009). The process of ecosystem accounting attempts to balance these inputs and outputs similar to a financial account and regards natural capital as asset stocks which are represented by benefit flows generated in two ways. The first uses physical units (i.e. number of crab produced, area of oyster bed restored, etc.) and the second is the monetary value represented by the service (Weber, 2011).

Obtaining discrete physical values might be easier than estimating monetary values given the dynamic nature of ecosystems through time. The volume of nutrients and sediment that an oyster can filter in an hour is much easier to quantify than the value the filtered water has in the bay. Previous studies have been conducted examining both monetary and physical valuation and neither method has been shown to be ideal for all situations, and will vary by the situation and the ecosystem services being examined (Northern Economics, 2009; NRC, 2004). Some industries are beginning to examine their use of natural resources and are striving for more sustainable practices. The shoe and clothing company, PUMA, was perhaps the first to publish a fully transparent Environmental Profit and Loss Account which included greenhouse gas emissions, water usage, land use, pollutants, and waste. This report showed that if PUMA treated nature as any other service provider they would have to pay $10 million for core operations including warehouse and office maintenance, and $177 million for supply chain services which include cattle rearing, rubber plantations, and land use conversion among others (PUMA, 2010). This report was an intensive two year process, but indicates that environmental externalities can be evaluated within a company's profit and loss account (PUMA, 2010).

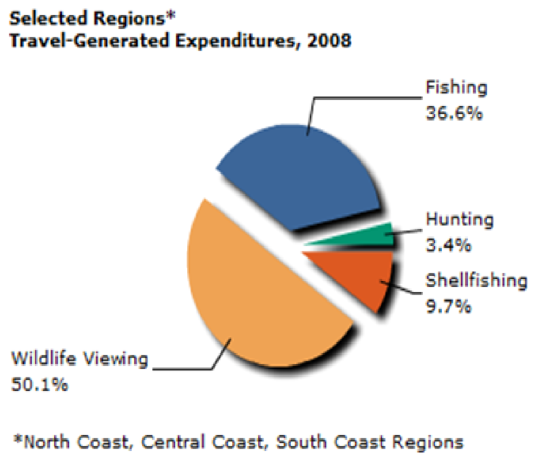
Valuation Methods

Economic Impact

Determining the value of a marketable commodity such as Dungeness crab or oyster as a food item can often be obtained by reviewing various economic impacts of each fishery. Both *C. gigas* and *M. magister* are commercially and recreationally important in the Pacific Northwest and contribute to a thriving shellfish industry providing not only fishing and processing jobs but stimulating local economies through a trickle-down effect.

The U.S. imports 86% of our seafood and produces less than 1% of bivalve shellfish worldwide (FAO, 2011). While this may be a small proportion of global production, local and state economies are greatly affected by these industries. According to the U.S Department of

Agriculture's 2005 Census of Aquaculture (2006), Pacific oyster sales equaled $34 million in Washington and $8 million in Oregon. The Oregon Dungeness crab fishery average fluctuated between $19 million and $54 million in landings revenue and averaged $28 million in annual landings revenue between 2000 and 2009 (NMFS, 2011). The Washington Dungeness crab fishery fluctuated between $29million and $56 million but averaged approximately $43 million in landings revenue between 2000 and 2009.



Selected Regions* Travel-Generated Expenditures, 2008			
Category	**Value**	**% of State Total***	**% of All Travel****
Hunting	$10,923,444	10.50%	0.70%
Fishing	$116,152,539	43.90%	8.00%
Wildlife Viewing	$159,167,850	34.40%	10.90%
Shellfishing	$31,038,716	100.00%	2.10%
Total	$317,282,549	36.80%	21.80%
*North Coast, Central Coast, South Coast Regions **All Oregon Travel expenditures based on Oregon Travel Impacts, 1991-2008p (statewide preliminary estimates).			

Figure 2. Oregon travel-generated expenditures.
Includes all fishing, shellfishing, hunting, and wildlife viewing activities for selected regions in Oregon, 2008. Source: Dean Ryan Associates, 2009.

Recreational shellfishing in Oregon produced $31 million to the state in travel-generated expenses in 2008 (Figure 2). Dungeness crab fishing currently comprises the majority (~55%) of recreational shellfishing activities. Of 2.8 million residents and non-residents who participated in fishing, hunting, shellfishing, and wildlife viewing in Oregon, a total of 175,000 people harvested shellfish. However, recreational harvest of oysters is currently prohibited in Oregon due to the low numbers of native oysters, and the majority of land on which *C. gigas* is grown is privately owned or leased. In Washington state any oyster up to 2 ½ inches on public beaches can be harvested, and in 2006 a total of 652 thousand pounds were harvested from Puget Sound (Table 1). Increasing *O. lurida* populations in Oregon could result in recreational harvesting of native oysters once populations reach sustainable sizes, boosting state and local economies, and perhaps a larger commercial market.

Table 1. Washington recreational shellfish take.
Quantities are in pounds of shellfish, 2006. Source: TCW Economics, 2008.

SPECIES GROUP	NORTH PUGET SOUND	SOUTH PUGET SOUND	STRAIT	COAST	COLUMBIA RIVER	TOTAL
Dungeness Crab	798,104	381,692	39,755	--	--	1,219,551
Shrimp	21,388	82,683	1,850	--	--	105,921
Razor clams	--	--	--	3,601,000	--	3,601,000
Other clams	92,704	252,964	--	--	--	345,668
Oysters	19,106	632,988	--	--	--	652,094

The Production Function

The production function method is often used to examine commercially and recreationally important species and values ecosystem services by the input of these measureable goods (Wainger and Boyd, 2009). We examined the production of Dungeness crab as an ecosystem service provided by two different oyster species. The input was suitable habitat and the output was juvenile Dungeness crab density. Taken further, this could then be used to estimate the eventual economic impact of crab to the fishery or the state. However, our interest was in crab number and not monetary benefit, and more crab from one habitat, given all else is equal, would also result in a greater monetary benefit. Thus this method can be useful for comparing the production of key species between habitats, with or without a marketable value.

Stated and Revealed Preferences

When direct economic evaluation is not possible, the most common methods for monetizing ecosystem services include using stated preferences and revealed preference methods (NRC, 2004; Barbier, 2009). Stated preferences often use surveys to acquire data on consumers' willingness to pay and willingness to accept. Asking fishermen whether they would pay more to fish around oyster reefs with high biodiversity rather than open or unvegetated areas is an example of a stated preference survey. Revealed preferences are demonstrated through actual purchases or choices made by the consumer and include various methods including travel cost, hedonic pricing, and the production function.

The travel cost method is often used to value recreational benefits (Barbier, 2009). Fishing trips and the associated costs (travel, time, fees for access, etc.) to travel to pristine areas with high biodiversity and species richness, may be greater than fishing trips to closer but degraded systems. The preference to fish in an area with cleaner water and more fish, rather than a degraded system even if the pristine area is further and more costly to get to, can then be used as an indicator of the value that recreational fishermen place on “healthy” ecosystems.

Hedonic pricing is another method most often used to value how environmental quality, aesthetics, or amenities affect the housing market (Barbier, 2009). Properties located closer to pristine or scenic environments, or recreational amenities are often more expensive than those that are not. This method was used in a study conducted in Puget Sound, WA which evaluated how commercial aquaculture production in the bay affected the value of neighboring houses (Northern Economics, 2009). According to the respondents surveyed in this study who were homeowners on Puget Sound, the nearby aquaculture farms had no significant impact on the housing market because buyers were still willing to purchase.

Measuring Resilience

Leslie and Kinzig (2009) define resilience as the “extent to which a system can maintain its structure, function, and identity in the face of disturbance” (p. 55). Species diversity and species richness are considered to be vital in determining resiliency and in general, the higher the species diversity, the higher the resiliency of the system (Leslie and Kenzig, 2009). Increasing *O. lurida* populations could potentially increase species diversity in estuaries by providing habitat and foraging grounds for native species. Restoring native species may help to increase biodiversity and in turn increase coastal resiliency to disturbances.

Both pulse disturbances (short discrete events) and press disturbances (longer lasting events) (Glasby and Underwood, 1996), can determine resiliency in a system. These include both anthropogenic and natural disturbances. For example, Dumbauld et al. (2009) indicate that the process of harvesting cultured oysters is a pulse disturbance, occurring periodically. A sudden decrease in temperature can act as a pulse disturbance, freezing and killing oysters that cannot withstand this fluctuation. A system resilient to cold temperatures will rebound while one that is not resilient, may die off, providing resources (food or space) to competitors and possibly resulting in a shift in the ecosystem dynamics. Press disturbances such as competition between species, sea level rise, or sustained effects of cultured or restored shellfish on the surrounding environment can also affect resiliency.

Ecologists stress the importance of resiliency in a system since a more resilient one will withstand, or recover from disturbances (Carpenter and Cottingham, 1997; Leslie and Kinzig, 2009). A less resilient system may be damaged to an extent in which an ecosystem regime shift occurs. For example, a disturbance in a monoculture system may eradicate the one existing species, but a diverse ecosystem would potentially recover since variation among species and individuals increases the likelihood that some of the individuals are resistant to, or are more resilient to the disturbance (Leslie and Kinzig, 2009). The resiliency of a system is thus vital for future ecosystem services, and Heal (2006) associates valuing the resiliency of ecosystems to the response of stock market assets during economic fluctuations. Fluctuations in the economy can result in fluctuations in stock and predicting how the stock may react in response to these disturbances, is similar to predicting how an ecosystem may respond to a disturbance and it is thus valued more if resilient to such disturbances. However, a resilient system is not always the sole desired outcome, as in the case with the Chesapeake Bay system. Due in part to overharvesting of the native Eastern oyster *(Crassostrea virginica)* and other anthropogenic influences, the Chesapeake Bay has experienced eutrophication, excess sediment and nutrient inputs, as well as pollution from pesticides and fertilizers which have resulted in a degraded but resilient, or stable, state (Boesch and Goldman, 2009). This degraded state is then prime for invasive or exotic species, a lack of biodiversity, and decreased ecosystem functioning.

While resiliency may be well understood by restoration scientists, the concept may be less fully grasped by the general public, and valuing resilience may prove to be difficult. However, Scheufele and Bennett (2011) attempt to determine the value society applies to ecosystem resiliency using the rainforests of Border Ranges, Australia as an example. A discrete choice experiment is used to determine the respondents' value of resiliency. A list of choices, representing varying levels of increased resiliency (protection of one type of forest versus protection of various types) with attached monetary values are given to respondents. The results show a significantly positive value for resiliency. This demonstrates that society at least understands that ecosystem resiliency is important and any added level of resiliency would add to the value of the particular ecosystem.

Trade-Offs Between Ecosystem Services

Coastal ecosystems are becoming more heavily used, and allocating resources is becoming more difficult, yet more important. Valuation of ecosystem services is a useful tool for examining tradeoffs between resources and identifying gains from utilizing coastal ecosystems and the resulting losses in ecosystem services (Barbier, 2009). Key ecosystem services can be protected while activities like coastal development can be managed with minimal impact. Tradeoffs between aquaculture expansion and oyster restoration (as well as coastal development, dredging, etc.) should be weighed against the loss of ecosystem services provided by eelgrass and mudflats, and minimizing impact on existing eelgrass beds and open mudflats should be examined when implementing any new management plan.

Oysters versus Eelgrass and Open Mudflats

Oysters may negatively impact eelgrass habitat through competition for space and resources or have a direct impact through the placement of cultch for aquaculture or restoration. Archer (2008) conducted a re-establishment project in Netarts Bay and reported that areas with high density cultch treatments had lower eelgrass percent cover than the lower density cultch treatments. Additionally, activities associated with restoration or aquaculture such as harvesting or transplanting oysters may have a negative impact by removing or smothering clumps of eelgrass (Tallis et al., 2009). Open mudflats may harbor less diversity, but are not desolate areas, instead harboring many burrowing benthic organisms including thalassinid shrimp and polychaetes (Hosack et al., 2006) which in turn contribute to bioturbation, oxygenating the substrate, and serve as prey for many species including Dungeness crab. The ecosystem services provided by eelgrass beds and open mudflats within an estuary therefore contribute to the whole estuarine ecosystem through food web interactions as well as physical and chemical influences, and any impacts to these may affect the estuary as a whole. Valuation of these habitats can then help determine the least-cost, and thus the least-impacting, scenario for aquaculture and restoration activities.

Aquaculture versus Restoration

Areas identified for potential aquaculture and/or restoration should then be evaluated to determine which management strategy, or both, should be implemented. There are several reasons why *C. gigas* currently provides approximately 89% of the region's aquaculture, dominating the industry (Dumbauld et al., 2009). *C. gigas* is a generalist, is fast growing, larger, and has a mellower flavor than that of the more metallic flavored *O. lurida* (Gordon et al., 2001). Establishment of *O. lurida* is limited by its slow growth and sensitivity to temperatures and desiccation. Additionally, at the deeper tidal elevation, *O.lurida* proves a more difficult specimen to harvest than the shallower growing *C. gigas*. If grown in the shallower intertidal, flooded dikes are required so that the water level is controlled and *O. lurida* is protected from temperature fluctuations (Steele, 1957; White et al., 2009b).

It is unknown if the ecosystem services provided by these oysters are comparable. However, many introduced oyster species along the coasts, such as *C. gigas,* tend to have a greater commercial value due to outcompeting native species and dominance in estuaries. If aquaculture is to someday be replaced by native species, the commercial value of *O. lurida* has to be increased to match that of *C. gigas*. Until a larger market for *O. lurida* develops, (if one does develop), *C. gigas* will continue to be the primary oyster for commercial aquaculture.

Even small restoration projects can be expensive, and the associated costs not only include the project cost, but also the environmental and human-health costs (Northern Economics, 2009). As previously mentioned, environmental costs from restoration and aquaculture can negatively impact other species through competition or disturbance due to the associated activities. Additionally, because oysters are vectors for diseases, pathogens, and other “hitchhikers”, the introduction of nonnative oysters has often resulted in the subsequent introduction of additional nonnatives (Ruesink et al., 2005). The Eastern oyster drill (*Urosalpinx cinerea*) and later the Japanese oyster drill, *(Cerastoma inornatum),* were inadvertently introduced with *C. virginica* and *C. gigas* (Carlton, 1979). These predatory gastropods feed on both *C. gigas* and *O. lurida,* and in addition to overharvesting and habitat degradation, may have further contributed to the decline of *O. lurida* (Buhle and Ruesink, 2009). Through their filtering action, oysters also bioaccumulate viruses, bacteria, and toxins (Nappier et al., 2008) which can be used as an indicator for water quality, but also poses a human health threat via shellfish poisoning if these infected oysters are consumed (Friedman, 2005; Meyer et al., 2010). Thus, determining the tradeoffs between costs and benefits derived from a restoration project can provide justification for implementing, altering, or rejecting a project plan.

Conclusion

Ecosystems are not often accounted for in business or resource management plans and this has resulted in the exploitation of fisheries and forests, degraded air and water quality, and loss of biodiversity. By examining ecosystem services as “ecological endpoints” we then have some metric for which to value various components of nature. Valuation of ecosystem services can help identify key services for protection, potential substitutes, and the gains and losses of land use conversion versus protection. Similar to a financial account, the concept of ecosystem accounting attempts to consider these inputs and outputs as a balance in natural capital, a concept which some businesses are beginning to use in an attempt to become more sustainable. As overwhelmingly large a task this may be, there are many valuation methods for ecosystem valuation, the use of which will depend on the situation and ecosystem service or services being valued.

Chapter 3: Scientific Investigation

Introduction

Oyster reefs and eelgrass beds in Pacific Northwest (U.S) estuaries function as important nursery grounds, providing habitat not only for maturing oysters, but also for other ecologically, commercially, and recreationally important fish and invertebrate species such as the Dungeness crab (Armstrong and Gunderson, 1985; Armstrong et al., 2003). In particular, oyster aquaculture, shell habitat, and eelgrass beds provide *Metacarcinus magister* with structurally complex habitat for protection from predators and foraging areas during their juvenile stage (Fernandez et al., 1993; Dumbauld et al., 2000). Habitat was once provided by the native Olympia oyster, *Ostrea lurida,* until its decline in the late 1800's due to overharvesting and habitat degradation. The Pacific oyster, *Crassostrea gigas,* was then introduced as a commercially cultured substitute and now dominates west coast aquaculture (Steele, 1957; Dumbauld et al., 2009). *O. lurida* primarily inhabits subtidal regions whereas *C. gigas* is primarily cultured in shallower intertidal regions. As a consequence, this shift in the dominant oyster species has resulted in a potential spatial shift in available recruitment habitat for *M. magister,* from primarily subtidal habitat to one of intertidal habitat. Native oyster restoration or oyster aquaculture expansion, therefore, have the potential to affect settlement of Dungeness crab. Previous studies indicate the presence of Dungeness crab in intertidal regions (Dumbauld et al., 1993; Eggleston and Armstrong, 1995; Dumbauld and Kauffman, 2001), however there has not yet been a study conducted exclusively comparing differences in abundance of juvenile *M. magister* in subtidal vs. intertidal regions.

The objectives of this scientific investigation were to:
1.) Compare crab densities found in existing *O. lurida, C. gigas*, eelgrass, and open mudflat habitats to better determine tradeoffs in crab production by habitat.
2.) Estimate and compare historical production of juvenile Dungeness crab, as a function of depth, by *O. lurida* habitat and the current production by *C. gigas* habitat in Willapa Bay, WA.
3.) Attempt to track juvenile Dungeness crab survival using a mark-recapture method.

The first objective involved sampling existing *O .lurida*, *C. gigas,* and eelgrass habitats in Willapa Bay, WA, Netarts Bay, OR, and Coos Bay, OR. The second objective was comprised of a study conducted in Yaquina Bay using shell bags as settlement substrate for *M. magister* at various depths and distances from the mouth of the bay. The densities obtained from this experiment were then used in conjunction with proportions obtained from prior literature and historically estimated areas of *O. lurida* and current areas of *C. gigas* in Willapa Bay, WA, to provide a comparison of crab production between the two species of oysters. A third study, also conducted in Yaquina Bay, OR, employed a mark-recapture method to estimate survival of juvenile *M. magister* and also allowed for continued monitoring of crab settlement.

Project Background

Previous Mapping Efforts in Willapa Bay, WA

Dumbauld et al. (2011) conducted an intertidal habitat survey in 2006 and 2007 in Willapa Bay, WA, and mapped the area of Pacific oyster aquaculture. Additionally, an historic map (Collins

1889), which outlined areas of “Natural” and “Cultured” Olympia oysters, was georeferenced and the area within these regions was estimated (Figure 3). These maps provided the basis for our estimates of Dungeness crab production as an ecosystem service provided historically by Olympia oyster habitat versus production by current Pacific oyster aquaculture. Because these two species inhabit two relatively unique tidal zones, we obtained baseline data of crab density by tidal elevation and distance to the mouth of the estuary and applied these to both the historical coverage of Olympia oysters and current coverage by the Pacific oyster. It is unclear if the regions of “Natural” oysters depicted in the Collins (1889) historical surveys also included areas of cultivated oysters, and if the “Cultured” regions were solely created for oyster grow-out and harvest, or contained areas of naturally growing native oysters as well, though there is probably overlap within both.

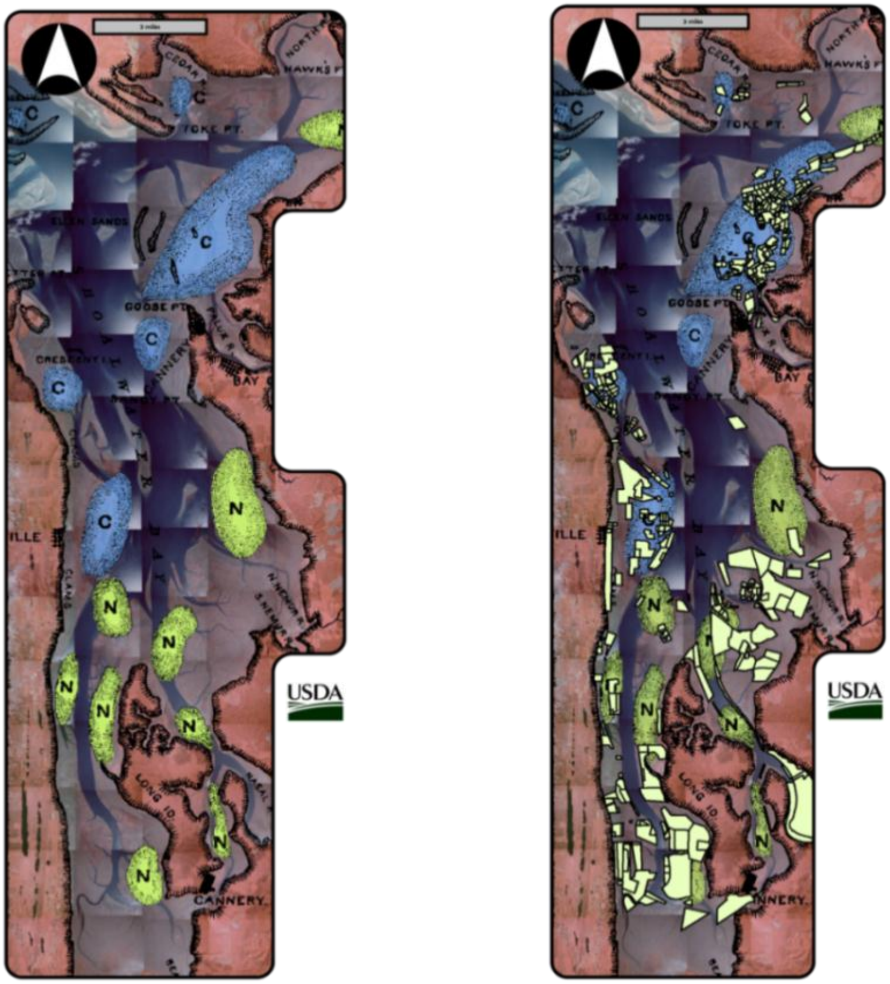


Figure 3. Willapa Bay GIS layers.
Layer on left indicates naturally growing (indicated by “N” in green), and cultivated (indicated by “C” in blue) areas historically covered by *O.lurida*; and with current aquaculture overlay on the right (represented by light green polygons). Source: Dumbauld et al., unpublished data (adapted from Collins, 1892).

Study Sites

Four estuaries in Oregon and Washington were used in this project. The estuaries sampled for the across-estuary study included Willapa Bay, WA, Coos Bay, OR and Netarts Bay, OR (Figure 4). Yaquina Bay was used as the shell bag study site and in the mark-recapture study. Yaquina Bay was chosen due to its proximiity to the Hatfield Science Center in Newport Oregon and because recruitment has been shown to be similar among Pacific Northwest estuaries (Roegner et al., 2003; Shanks and Roegner, 2007).

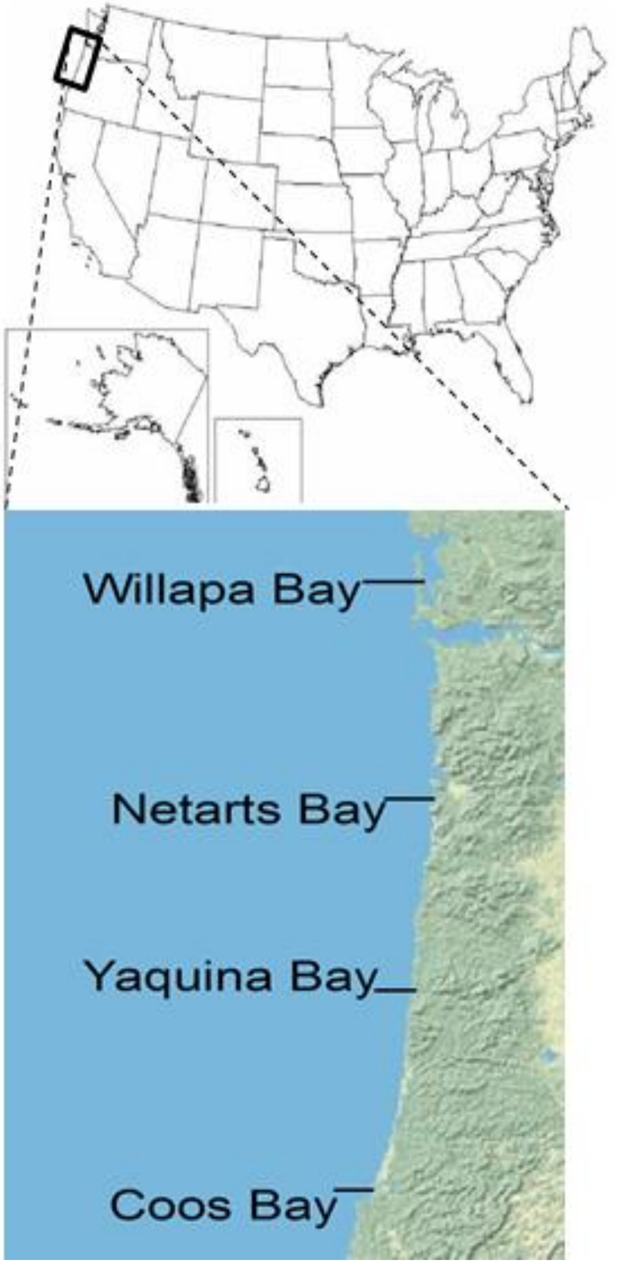


Figure 4. Willapa Bay, WA and Netarts Bay, Yaquina Bay, and Coos Bay, OR, USA.

Willapa Bay, WA

Four estuaries in Oregon and Washington were used in this project. Willapa Bay is a shallow coastal-plain estuary on Washington's southern coast, and is the second largest estuary on the U.S. Pacific coast. It encompasses 31,970 hectares (ha) situated behind a barrier spit and has a watershed basin of about 186,630 ha (Hedgpeth and Obrebski, 1981). The mouth of Willapa Bay opens to the ocean on the northwest side and is approximately 45 km from the mouth of the Columbia River. Willapa Bay has extensive intertidal flats, extending more than 1 km from shore and up to half of the volume of the estuary enters and leaves with every tide (Banas, 2004). The tidal range is 4 to 5 m, and at high tide the volume of water in the bay is approximately 56,585,900 ft^3 and at mean lower low water is 31, 169,000 ft^3 (Hedgpeth and Obrebski, 1981).

Four sites in Willapa Bay were sampled including: Stony Point, Stackpole, Long Island, and Peterson Station (Figure 5). All four sites were within regions containing aquaculture, eelgrass, and mudflats, though the aquaculture beds varied between sites.

Figure 5.Willapa Bay, WA. Sampling sites

Netarts Bay, OR

Netarts Bay is a bar-built estuary in which a sand-spit created over time has resulted in a marine-dominated estuary. Netarts Bay is located along Oregon's northern coast and is approximately 1093 ha in area with a watershed drainage basin of about 157,470 ha (Groth and Rumrill, 2009) and contains extensive eelgrass beds. Salinity is approximately equal to that of the ocean water due to low freshwater inflow and a tidal exchange rate of 75%-88%. The intertidal area is approximately 88%, and the subtidal area is 12% (Kreag, 1979). It is designated as a Conservation Estuary under the Oregon Estuary Classification system (Department of Land Conservation and Development, 1984). A commercial fishery for *O. lurida* began in the 1860's in Netarts Bay, but the oyster is believed to have existed in low numbers in the 1930's (Groth and Rumrill, 2009) and was locally extinct in 1979 (Kraeg, 1979). A re-establishment project carried out by Oregon State University (OSU) and The Nature Conservancy (TNC) began in 2005 to investigate the capacity for self-sustaining populations of *O. lurida* and the effect of cultch on eelgrass populations (Archer, 2008). This restoration effort is currently being conducted in Netarts Bay by TNC and sampling for this study was conducted within this restoration site as well as an adjacent commercial (*C. gigas*) aquaculture site (Figure 6).

Figure 6. Netarts Bay sampling site

Coos Bay, OR

Coos Bay is a drowned river-mouth estuary in which freshwater inflow is high in the winter, but low in the summer and dominated by marine inflow. Coos Bay is located along Oregon's south-central coast and is the largest (5,383 ha) estuary contained within Oregon state lines. Coos Bay is designated as a Deep Draft Development estuary under the Oregon Estuary Classification System because of the jetties projecting from the mouth of the estuary and the routine dredging to deeper than 22 feet of the main channel (Department of Land Conservation and Development, 1984). Living *O. lurida* were not observed in Coos Bay at the time of European settlement in the 1850's but shell can be found along the shoreline and at the bottom of Coos Bay (Groth and Rumrill, 2009). Current populations of *O. lurida* have been found at various sites within Coos Bay including Isthmus Slough and Haynes Inlet which were sites sampled for this study (Groth and Rumrill, 2009) and are believed to have been introduced from Willapa Bay with Pacific oysters (Stick et al., 2009). Haynes Inlet is located in the northern reach of the estuary and Isthmus Slough the south-eastern reach of the estuary (Figure 7).

Figure 7. Coos Bay sampling sites

Yaquina Bay, OR

Yaquina Bay is a drowned river-mouth estuary and classified as a Deep Draft Development estuary (Department of Land Conservation and Development, 1984). Yaquina Bay is located along Oregon's central coast and is approximately 1,700 ha with a watershed drainage basin of 65,526 ha. Extensive beds of *O.lurida* were once found in Yaquina Bay and were commercially harvested (Steele, 1957). Polson and Zacherl (2009) report the current presence of subtidal beds but with an overall low average maximum density of 2.2 (± 0.8) oysters per 0.25 m^2. Since population declines, a variety of habitat enhancement projects restoring shell to the substrate have occurred in Yaquina Bay (Groth and Rumrill, 2009). We chose four sites at various distances from the mouth of the bay for shell bag placement which are shown in Figure 8.

Figure 8. Yaquina Bay study sites

Across-Estuary Study (Targeting Objective 1)

Methods

The objective of this study was to assess and compare crab settlement in different existing habitats within three Pacific Coast estuaries (Willapa Bay, Netarts Bay, Coos Bay). Sampling within each estuary was conducted by visually identifying an appropriate habitat type and then haphazardly tossing a 0.25 m^2 quadrat onto the substrate within each habitat. Percent cover of all shell, eelgrass, algae, and open mud was estimated in 5% intervals for substrate within a 0.25 m^2 quadrat. This was standardized by initially having multiple observers estimate percent cover. All sediment, algae, eelgrass, and shell within a 0.25 m^2 quadrat, to a depth of 2 cm, were removed and placed into a 3 mm mesh box sieve (Figure 9). A dipnet was then used to collect any remaining organisms from water left in the depression. Contents were sieved and all large items such as shell, algae, and eelgrass were inspected for crab and returned to the sediment. All remaining contents and crab were removed from the sieve and placed in plastic bags, labeled, and taken back to the lab for further sorting.

Figure 9. Box sieve and 0.25 m^2 quadrat.

All *M. magister* were measured across the carapace at the base of the posterior spines to the nearest 0.1 mm (Figure 10).

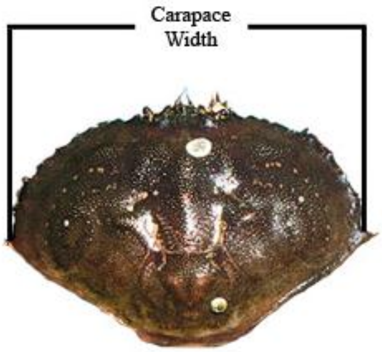


Figure 10. Carapace width measurement.

Sampling protocol had initially been developed so that a minimum of six samples were taken within each habitat type, and each site contained a minimum of three habitat types (shell, eelgrass, and open mud). When time permitted this protocol was followed, however, due to time constraints and tidal fluctuations, the number of habitats sampled was often reduced. In these instances we instead focused on sampling oyster beds and eelgrass beds with a minimum of three samples per habitat. The number of samples taken within each habitat and estuary are given in Table 2.

Willapa Bay

The four sites sampled within Willapa Bay (Stony Point, Long Island, Stackpole, and Peterson Station) represented various distances from the mouth of the estuary and were sampled over a two day period in late June. Sampling protocol was initially developed so that six samples were taken from each of four habitat types (fattening beds, seed beds, eelgrass beds, and open mud habitat, and in the southern portion of the bay hummocks would be substituted for fattening beds). However, due to time constraints and tidal fluctuations, Stony Point was the only site in which four different habitats (fattening, seed, eelgrass, and open mud) were sampled, and unfortunately at two of the sites in Willapa Bay (Long Island and Peterson Station) we were only able to sample one habitat (fattening and hummocks, respectively).

Netarts Bay

The Netarts Bay site was sampled one day in mid-August. *O. lurida*, *C. gigas,* and eelgrass habitats were sampled. This was the only estuary in which both oyster habitats were sampled at one site. The *O. lurida* habitat was located at a lower tidal elevation than the adjacent *C. gigas* plot, but depth here was not measured. Six samples were taken of *O. lurida* and *C. gigas* habitat and eight samples were taken of eelgrass habitat.

Coos Bay

Two sites in Coos Bay (Haynes Inlet and Isthmus Slough) were sampled over a two day period in mid-August. Haynes Inlet contained *C. gigas* aquaculture and eelgrass and the Isthmus Slough site contained *O. lurida* and eelgrass. Seven samples were taken at Haynes Inlet while at Isthmus Slough seven samples were taken of *O. lurida* habitat, and six samples of eelgrass habitat.

Table 2. Number of samples taken by habitat and site.
Total number of samples taken within each habitat and site for Willapa Bay, WA; Coos Bay, OR; and Netarts Bay, OR.

	Ostrea lurida	*Crassostrea gigas*				Eelgrass	Open Mud
		Not Classified	Seed Bed	Hummocks	Fattening Bed		
Willapa Bay							
Stony Point			6		6	6	6
Stackpole					6	3	
Long Island					6		
Peterson Station				3			
Netarts Bay	6	6				8	
Coos Bay							
Haynes Inlet		7				7	
Isthmus Slough	7					6	

Statistical Analysis

All data are maintained in Microsoft Access 2007 and statistical analysis was conducted in 'R' (Version 2.13.1, 2011). For Stony Point, Willapa Bay, WA, an ANOVA was conducted on crab density by habitat type (fattening, seed, eelgrass, and bare). This was followed by Tukey's HSD pairwise comparison to determine differences among habitat pairs. Because of unequal sample sizes and variance at Stackpole, Willapa Bay, WA, a Welch's t-test was used to compare crab densities between two habitat types (fattening and eelgrass). For Netarts Bay and Coos Bay data, ANOVA's were conducted on crab densities by habitat type (*O. lurida*, *C. gigas*, and eelgrass). A second ANOVA for Coos Bay was conducted on crab density by habitat (combined oyster vs. eelgrass habitats) and site (Haynes Inlet and Isthmus Slough).

Results

Willapa Bay

Cultured *C. gigas*, eelgrass, and open mud habitats were sampled at four sites within Willapa Bay, WA. However, Stony Point was the only site in which four habitat types were sampled (fattening, seed, eelgrass, and bare, Table 3). There was a significant difference in crab density between these four habitat types, (ANOVA, $p=0.0016$, Table 4) with fattening beds containing the highest density of *M. magister* (14 crab/m^2, Figure 11) and significantly more crab than the other three habitat types (Tukey HSD post-hoc, $p<0.05$). The only other site in which two habitats were sampled was Stackpole, which had a higher mean density of crab in eelgrass than in the fattening beds but this difference was not significantly different between habitat types (Welch's t-test, $t=0.4472$, $df=3$, $p=0.6846$). *M. magister* densities in all habitats were consistently lower than those found within the fattening beds at Stony Point.

Table 3. Mean density of *M. magister* per m^2 for Willapa Bay sites.
NA indicates habitats that were not sampled.

	Fattening	Hummock	Seed	Eelgrass	Bare
Stony Point	14.00, n=6	NA	2.00, n=6	1.33, n=6	0.67, n=6
Stackpole	0.67, n=6	NA	NA	1.33, n=3	NA
Long Island	2.00, n=6	NA	NA	NA	NA
Peterson Station	NA	2.67, n=3	NA	NA	NA

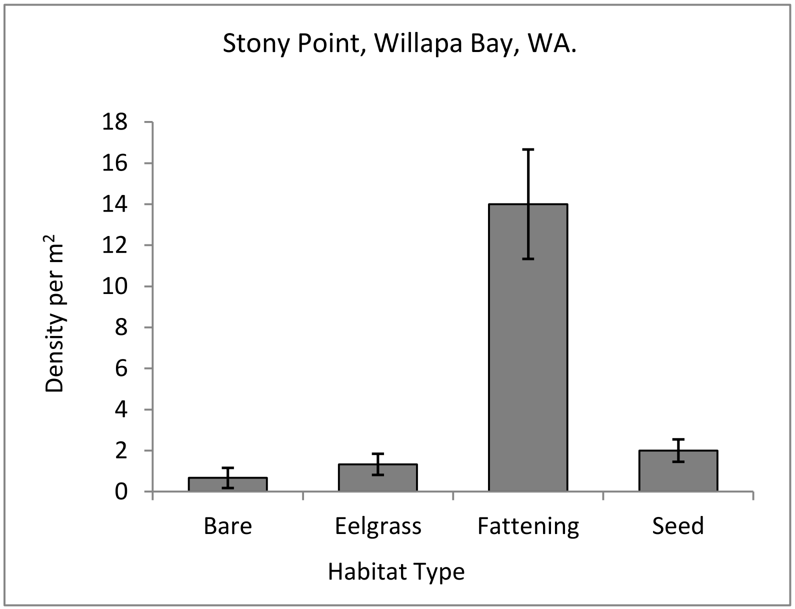


Figure 11. Mean density of *M. magister* per m^2 by habitat type: Stony Point, Willapa Bay, WA.

Table 4. ANOVA table for Stony Point, Willapa Bay, WA.

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Habitat	3	45.458	15.1528	7.3617	0.001637 **
Residuals	20	41.167	2.0583		

Netarts Bay

Netarts Bay was the only site in which *O. lurida*, *C. gigas,* and eelgrass habitats were sampled within close proximity to each other. A higher mean density of *M. magister* was observed (Figure 12) in *O. lurida* habitat (2.7 crab/m^2, n=6) than in both the *C. gigas* habitat (0.7 crab/m^2, n=6) and eelgrass habitat (2 crab/m^2, n=8) but densities were not significantly different among the habitat types (ANOVA, p>0.05, Table 5). Netarts Bay also had the highest mean density of eelgrass percent cover (67%-100%) in all habitat types than in any of the other estuaries (see Figure 13 and Table 6).

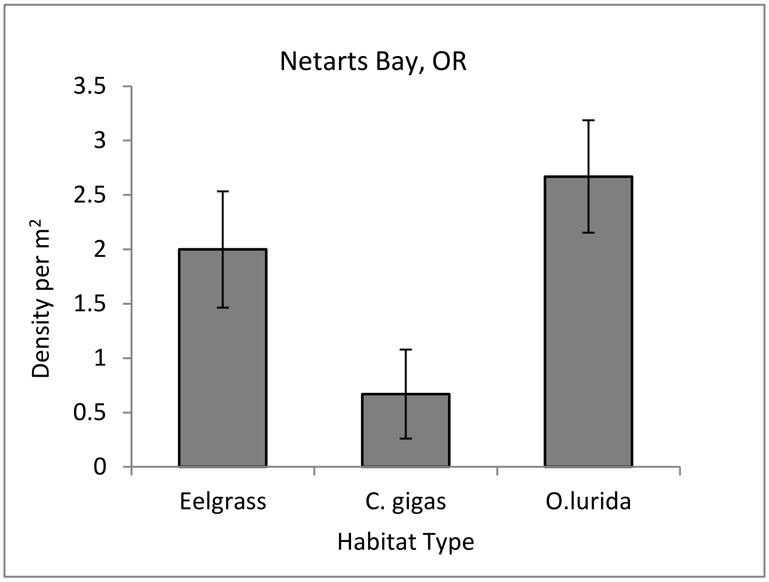


Figure 12. Mean density of *M. magister* per m^2 by habitat: Netarts Bay, OR

Table 5. ANOVA Table for Netarts Bay, OR.
"Habitat Type" represents the three habitats: *O. lurida*, *C. gigas*, and eelgrass.

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Habitat Type	2	0.7833	0.39167	1.598	0.2312
Residuals	17	4.1667	0.24510		

Figure 13. Photo of high eelgrass cover in *O. lurida* habitat, Netarts Bay.
Note that bumps under eelgrass are *O.lurida* oysters, inside a 0.25 m^2 quadrat for reference.

Table 6. Mean percent cover of eelgrass, algae, and shell.
Mean percent cover from each site and habitat type.

	Habitat	Eelgrass %Cover	Algae %Cover	Shell %Cover	Crab/0.25 m^2
WILLAPA BAY					
Stony Point	Seed	5	32	38	0.50
	Eelgrass	100	0	0	0.33
	Bare	0	4	0	0.17
	Fattening	0	63	52	3.50
Stackpole	Eelgrass	90	0	7	0.33
	Fattening	2	33	57	0.17
Long Island	Fattening	3	20	68	0.50
Peterson Station	Hummocks	0	10	80	0.67
COOS BAY					
Isthmus Slough	O.lurida	1	25	77	1.50
	Eelgrass	83	2	3	0.00
Haynes Inlet	C. gigas	1	19	44	2.14
	Eelgrass	71	1	0	0.14
NETARTS BAY					
	O. lurida	100	0	43	0.67
	C. gigas	67	20	56	0.14
	Eelgrass	97	1	0	0.57

Coos Bay

Two habitat types were sampled within each site in Coos Bay. *O. lurida* and eelgrass habitats were sampled within the Isthmus Slough site, and *C. gigas* and eelgrass habitats were sampled within the Haynes Inlet site. A higher mean density of juvenile *M. magister* was observed in *O. lurida* habitat (5 crab/m^2, n=7) than the adjacent eelgrass habitat (0 crab/m^2, n=6) in Isthmus Slough (Figure 14). Crab density in *C .gigas* habitat (8.5 crab/m^2, n=7) was higher than in the adjacent eelgrass habitat (0.57 crab/m^2, n=7) in Haynes Inlet. Site had no main effect (ANOVA, p=0.46788, Table 7) and no interaction effect on habitat type (ANOVA, p=0.61339, Table 7). There was a significant difference between crab densities by shell and eelgrass (ANOVA, p=0.02363, Table 7), but no significant difference in crab densities by *O. lurida*, *C. gigas*, and eelgrass habitats (ANOVA, p=0.05445, Table 8).

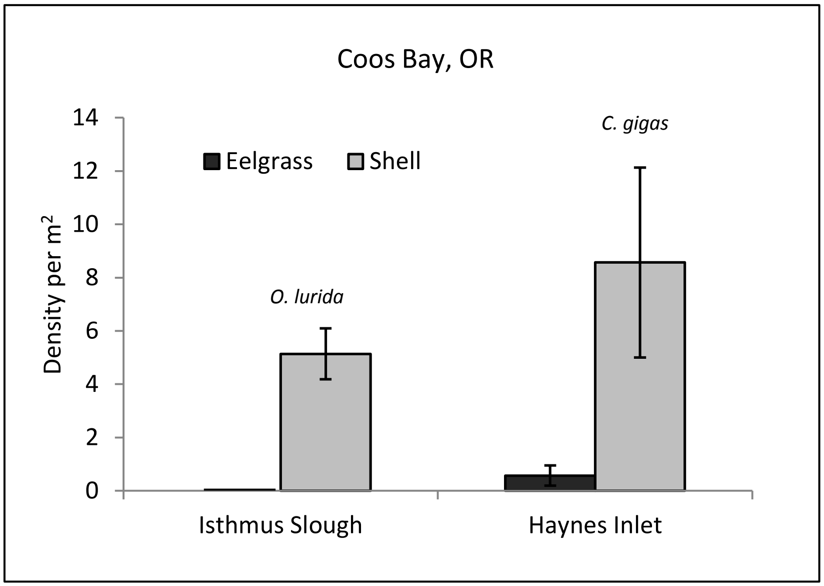


Figure 14. Mean density of *M. magister* per m^2 by site and habitat: Coos Bay, OR.

Table 7. ANOVA Table for Coos Bay, OR: shell and eelgrass.
"Combined Habitat" represents shell (which collectively combines *O. lurida* and *C. gigas)* and eelgrass habitats

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Combined Habitat	1	18.072	18.0716	5.8086	0.02363 *
Site	1	1.780	1.7802	0.5449	0.46788
Combined Habitat*Site	1	0.857	0.8571	0.2624	0.61339
Residuals	25	77.780	3.1112		

Table 8. ANOVA Table for Coos Bay, OR: *O. lurida, C. gigas*, and eelgrass.
"Habitat Type" represents the three habitat types: *O. lurida*, *C. gigas*, and eelgrass habitats.

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Habitat Type	2	20.643	10.3215	3.2937	0.05445
Residuals	24	75.209	3.1337		

Discussion

Previous studies examining juvenile *M. magister* settlement have shown that megalopae actively settle in habitats with shell substrate over mud (Eggleston and Armstrong, 1995; Fernandez et al., 1993), and are found in greater densities in shell versus eelgrass (Doty et al., 1995). Our main objective for this study was to obtain additional density data by habitat type to better determine settlement in existing *O. lurida*, *C. gigas*, and eelgrass habitats.

Willapa Bay

Stony Point was the only site in which four different habitat types were sampled, and exhibited a significantly higher density in the fattening than in the seed, eelgrass, or open mud habitats. Fattening beds tend to be comprised of older, larger oysters clumped together, and generally provide more habitat cover and complexity than seed beds. Doty et al. (1990) reported that more crab were generally found in heavy shell cover than in light shell cover in Willapa Bay, but that more area of the bay is comprised of habitats with light shell cover, such as seed beds, than fattening beds. The hummocks at Peterson Station offer heavy shell cover and exhibited the second highest crab density within the bay, lower than that of the fattening beds at Stony Point. This lower density is presumably due to site location, as Peterson Station is farther from the mouth of the bay than Stony Point. Stackpole was the only site in which crab density was greater in eelgrass than the adjacent fattening bed but the difference was not significant.

In addition to fewer samples, the densities of *M. magister* in Willapa Bay were also relatively low compared to densities acquired from Yaquina Bay. The generally low densities of *M.magister* might be attributed to the timing of the study. Sampling was conducted late June-August, somewhat late in the annual crab recruitment period. Settlement has been reported as late as September but generally occurs between March and July (McConnaughey et al., 1994; Roegner et al., 2007; Shanks and Roegner, 2007). Additionally eelgrass density may have been a contributing factor for variation of crab densities among estuaries and habitats.

Netarts Bay

Netarts Bay was the only site in which both *O. lurida* and *C. gigas* were sampled and can serve as a direct comparison in crab density between the two habitats. *O. lurida* habitat occurred at a subtidal elevation and exhibited a greater crab density than the higher intertidal *C. gigas* habitat. This may indicate that the lower tidal elevation was more conducive for crab settlement. However, densities were generally low and the difference in densities among habitat types was not significant.

Eelgrass habitat was sampled within the site and exhibited the second highest crab density after *O. lurida* habitat. Percent cover of eelgrass was highest in Netarts Bay which had a minimum mean cover of 67% in *C. gigas* aquaculture, 97% for eelgrass habitat, and approximately 100% for *O. lurida* habitat (Table 6). Archer (2008) noted the abundance of eelgrass within the restored site. This heavy eelgrass cover within Netarts Bay, particularly in *O. lurida* habitat might explain the small variation in crab densities between the eelgrass and *O.lurida* habitats. All other sites in Willapa Bay and Coos Bay could be clearly identified as one habitat or another due to the lower percent cover of eelgrass, and with the exception of Stackpole (Willapa Bay, WA.), mean densities of *M. magister* occurred in significantly higher densities in shell than in eelgrass, where both habitats were sampled.

Coos Bay

Within Haynes Inlet, crab density was greater in *C. gigas* habitat than in eelgrass. Similarly, in Isthmus Slough, crab density was higher in *O. lurida* habitat than in eelgrass. Higher crab densities were observed in both habitats within Haynes Inlet than in the habitats within Isthmus Slough. The higher densities within both habitats in Haynes Inlet might be attributed to its proximity to the mouth of the estuary (refer to Figure 7) and thus proximity to the source of recruitment. Isthmus Slough however is located up a narrow channel farther from the mouth of the bay and hence farther from the source of recruitment.

Yaquina Bay Shell Bag Study (Targeting Objective 2)

Methods

Our main objective for this study, was to estimate and compare crab production (as a function of depth) historically provided by *O. lurida* habitat and currently provided by *C. gigas* habitat. In order to develop the estimate of crab production, we needed to develop a metric that represented crab production at various tidal levels. We accomplished this by developing a study in Yaquina Bay that involved using shell bags as a settlement substrate at various tidal elevations. We also examined variability in settlement at various distances from the mouth of the bay and employed an existing habitat "control" at each tidal elevation as a comparison for settlement in thick shell vs. existing habitat. Therefore, in this study we examined three factors potentially influencing settlement:

1. tidal elevation (above and below MLLW),
2. site (4 distances from the mouth of the bay),
3. and habitat (shell bag vs. existing habitat).

Fifty shell bags were constructed using 2cm mesh material, cut to approximately 2 ft in length. A square piece of plastic was placed inside each bag to allow the shell to rest on top of the substrate with minimal sinking. Equal quantities of clean *C. gigas* shell, were then placed on top of the plastic in each mesh bag. These bags were deployed in June 2011 at four sites in Yaquina Bay, OR: NOAA Dock, Idaho Point, Raccoon Flats, and Poole Slough, (refer to Figure 4). Three bags were placed at each of four tidal elevations, two above mean lower low water (MLLW) and two below MLLW (approximately -1, 0,+1,+2, relative to MLLW) at each of the four sites, so that a total of 12 shell bags were deployed at each site. Two additional shell bags were also placed at a fifth tidal elevation at the NOAA Dock site. All bags were placed approximately 10 ft apart, and secured into the sediment using metal stakes. An additional sample was taken from existing habitat at each tidal depth, approximately 10 ft from the shell bags (Figure 15) to serve as a control. Tidal elevations were approximate and estimated in the field using sites prerecorded into a handheld Trimble GPS unit (Trimble, Sunnyvale, CA) from U.S Department of Agriculture bathymetry data (see Appendix 1 for bathymetry map of Yaquina Bay).

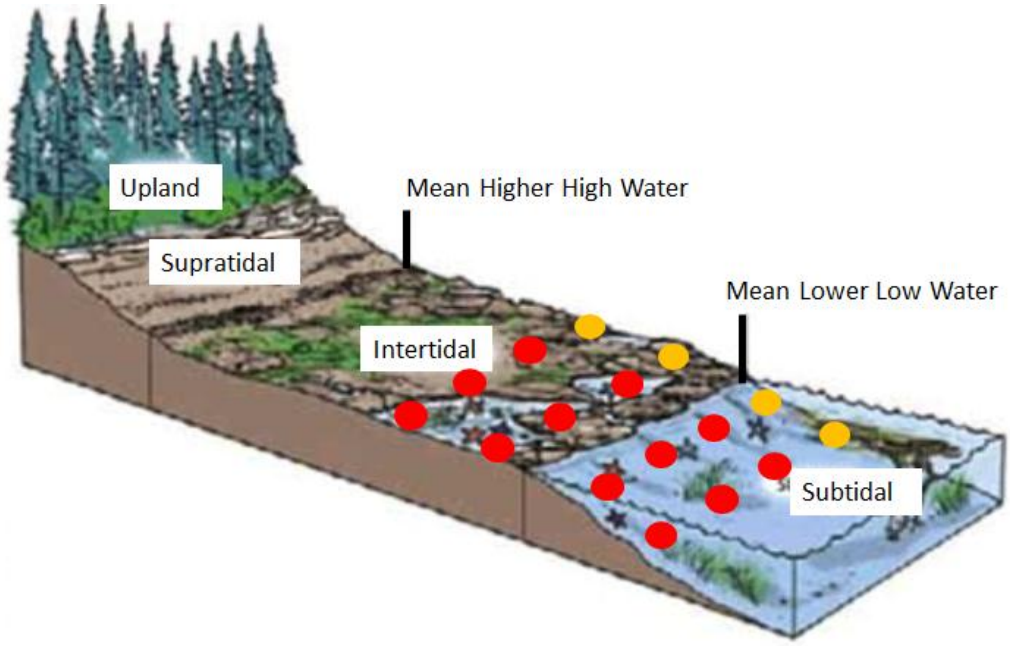


Figure 15. Schematic of shell bag placement.
Red dots represent shell bags and yellow dots represent "existing habitat". Diagram adapted from http://www.seattle.gov/transportation/images/glossaryimages/intertidal_zone_1.jpg.

Retrieval of shell bags (Figure 16) was conducted at low tide in early July 2011, one month after deployment. A 0.25 m^2 quadrat was placed around each shell bag and percent cover of algae, eelgrass, and open mud within the quadrat was visually estimated and recorded. The shell bag and surrounding substrate within the 0.25 m^2 quadrat, were sieved using the same technique employed in the across-estuary study, and all *M. magister* were measured. This same methodology was followed to sample existing habitat at each tidal elevation. Each tidal elevation was then flagged and subsequently recorded into a mapping-grade GPS system (Trimble, Sunnyvale, CA) at a later date. After acquiring tidal elevations it was recognized that shell bags had not been placed below MLLW at the Idaho Point site. All other sites had bags at two tidal elevations above and below MLLW.

Figure 16. Shell bags at time of retrieval inside 0.25 m^2 quadrats.
Bags set in June 2011, photos taken in July 2011.

Willapa Bay Comparison

Densities acquired from the shell bags were used to estimate and compare historical crab production in *O. lurida* habitat and current production in *C. gigas* habitat in Willapa Bay, WA. Previously mapped areas of the intertidal region created by the U.S Department of Agriculture, which include the estimated area of native oyster coverage and the present Pacific oyster aquaculture coverage, were used for this comparison. The Collins 1889 historical map initially divided *O. lurida* habitat into “Native” and “Cultivated” regions. Both regions probably contained beds where oyster growers moved oysters for grow out and harvesting. It is unclear, however if the “Cultivated” regions encompassed both naturally occurring beds and beds of oysters that were moved for harvest, or were simply regions created for commercial harvesting. This comparison is therefore broken into two scenarios:

- Scenario 1 (Cultivated and Native): This assumes that historically, both the “Native” and “Cultivated” beds were naturally occurring, with some (minimal) movement of oysters into the “Cultivated” regions for harvesting. This scenario best represents post-1850’s commercial harvesting (Brady Blake, pers. comm.).
- Scenario 2 (Native only): This further assumes that only the “Native” beds were naturally occurring and all “Cultivated” beds were created by humans, and are thus removed from the comparison. This scenario best represents pre-1850’s naturally occurring populations.

Because there were no bags placed below MLLW at Idaho Point, data from this site was not used for the Willapa Bay comparison. For the other three sites, crab densities per shell bag were extrapolated to crab per m^2 for above MLLW and below MLLW. This was done by taking the mean of all shell bags for above MLLW and below MLLW, and assuming that the shell bags represented an area equivalent to a 0.25 m^2, multiplying by 4. These two extrapolated densities could then be used in combination with the proportions obtained from prior literature (Doty et al., 1990; Dumbauld and Kauffman, 2001), along with a set of assumptions (Table 9) for recruitment to different aquaculture bed types and areas of the bay.

Table 9. List of Assumptions
*proportion from Doty et al., 1990
**proportion from Dumbauld and Kauffman, 2001

Assumptions made:
• Bay was spilt into two regions: "close to the mouth" and "far from the mouth", which assumes that less crab will recruit far from the mouth of the bay ○ North of Long Island represented "close" ○ South of this represented "far" (refer to Fig. 2 or 4) • Shell bag treatments are equivalent to Fattening beds and Hummocks, which provide more 3-dimensional cover and therefore more habitat • Seed beds provide less 3-dimensional cover and therefore less habitat • Mixed beds and Direct beds are some mixture of Seed beds and Fattening beds Proportions from Literature: • 100% of crab recruit to Natives and Cultured close to the mouth of the bay, • 16% recruit to Natives and Cultured far from the mouth of the bay** • 100% of crab recruit to Fattening beds and Hummocks close to the mouth of the bay • 16% of crab recruit to Fattening beds and Hummocks far from the mouth of the bay** • 60% of crab recruit to Seed beds close to the mouth of the bay* • 16% of those recruit to Seed beds far from the mouth of the bay** • Mixed beds (combination of seed and fattening beds) = $\frac{seed\ bed + fattening\ bed}{2}$ • Direct beds (1 year in seed, 1 year in mixed, 1 year in fattening) = $\frac{seed\ bed + mixed\ bed + fattening\ bed}{3}$ = Mixed bed • Densities obtained from the Yaquina Bay experiment will represent some proportion of crab recruitment to "above MLLW" and "below MLLW" in all bed types.

This assumes that, for example, if 100 crab recruit to fattening beds close to the mouth of the bay, then 16 crab would recruit to fattening beds far from the mouth of the bay, and some proportion would then also recruit to areas above MLLW and below MLLW. These proportions could be applied to fattening beds, seed beds, mixed beds, direct, as well as above and below MLLW, and close and far from the mouth of the bay.

Statistical Analysis

Age classes (instar stages) were separated using modal progression analysis (MPA) in the Bhattacharya's method for normal distribution of means in the FiSAT II software program (FAO-CLARM Fish Stock Assessment Tool, Version 1.2.2). After separation, all instar stages J4-J5 were removed from the data since these juveniles may have been large enough to move between the shell bags. All crab from the existing habitat samples were removed so that comparisons between crab densities in the shell bags could be made. A scatterplot of all shell bags was produced (Microsoft Excel 2007) and fitted with a trend line. A Welch's t-test ('R', Version 2.13.1, 2011) was used to compare crab densities by tidal elevation (below MLLW and above MLLW).

Results

A total of 703 crab from shell bags (mean=14 crab/shell bag, n= 50) and 48 crab from existing habitat (mean=3 crab/0.25 m^2, n= 16) were counted and measured. The width-frequency distribution of crab measurements from both the shell bags and existing habitat is shown in Figure 17 with the results of the Bhattacharya's method for age class (J1-J5) separation. The highest mean density of juveniles occurred in the J3 instar stage.

Instar	Mean	Std.Dev.	Population	CW Range
1	6.1	0.56	83	<7.3
2	9.2	0.98	166	7.4-11.1
3	12.7	1.17	397	11.2-14.2
4	17.2	1.62	111	14.2-20.2
5	24.2	0.05	7	>20.2

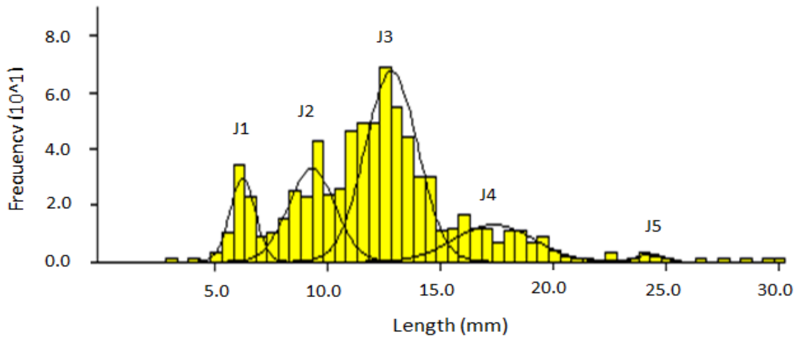


Figure 17. Width-frequencies of *M. magister* with age class separation.
Output is from Bhattachaya's method in the FiSAT II program. Age classes are identified as J1-J5.

At the NOAA Dock, Raccoon Flats, and Poole Slough sites, crab density decreased as tidal elevation increased. At Idaho Point, crab density increased as tidal elevation increased. In general, however, there was a decreasing trend in crab density with increasing tidal elevation (Figure 18). NOAA Dock had the highest densities at four of the five tidal elevations, with the highest density per tidal elevation (109 crab/bag) occurring at a subtidal depth of -0.74 ft., relative to MLLW. The lowest density by tidal elevation was found at Idaho Point (7 crab/bag) at an intertidal elevation of +0.26 ft., relative to MLLW. A Welch's t-test indicated that there was no significant difference between densities due to tidal elevation (above and below MLLW), (t=1.56, p=0.132, df=22). Densities from shell bags were extrapolated to m^2, resulting in a mean density of 66 crab/m^2 below MLLW and a mean density of 37 crab/m^2 above MLLW (Figure 19 and Table10).

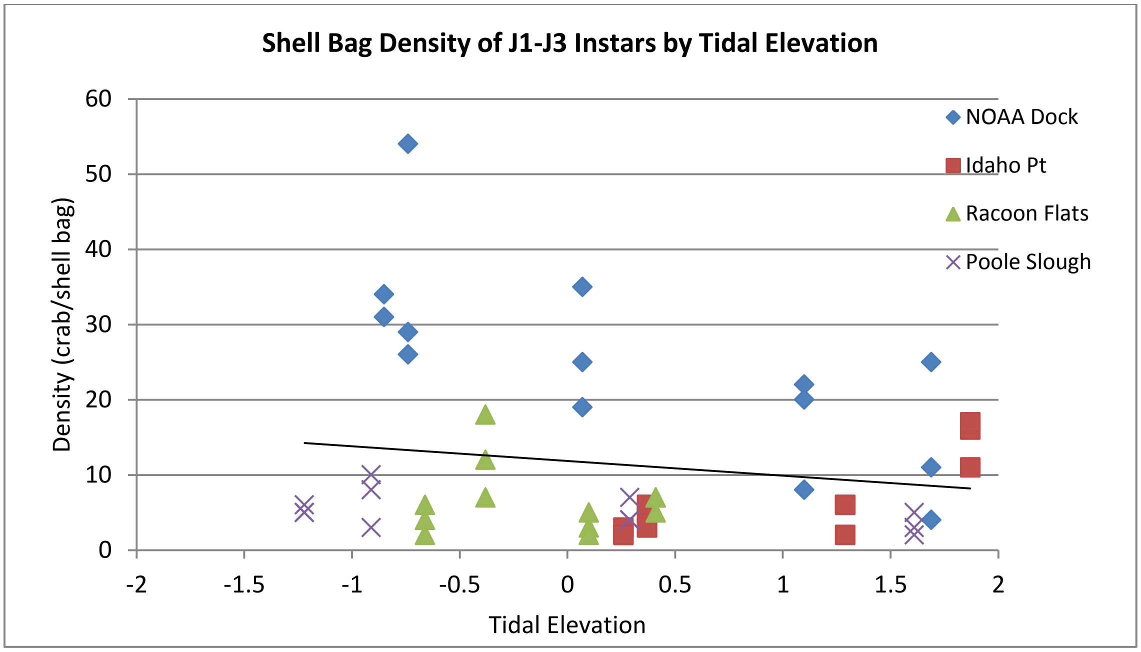


Figure 18. Density of J1-J3 instars within each shell bag by tide height.
Mean density of *M. magister* (J1-J3 instars) per shell bag (or 0.25 m^2) by tide height at each site.

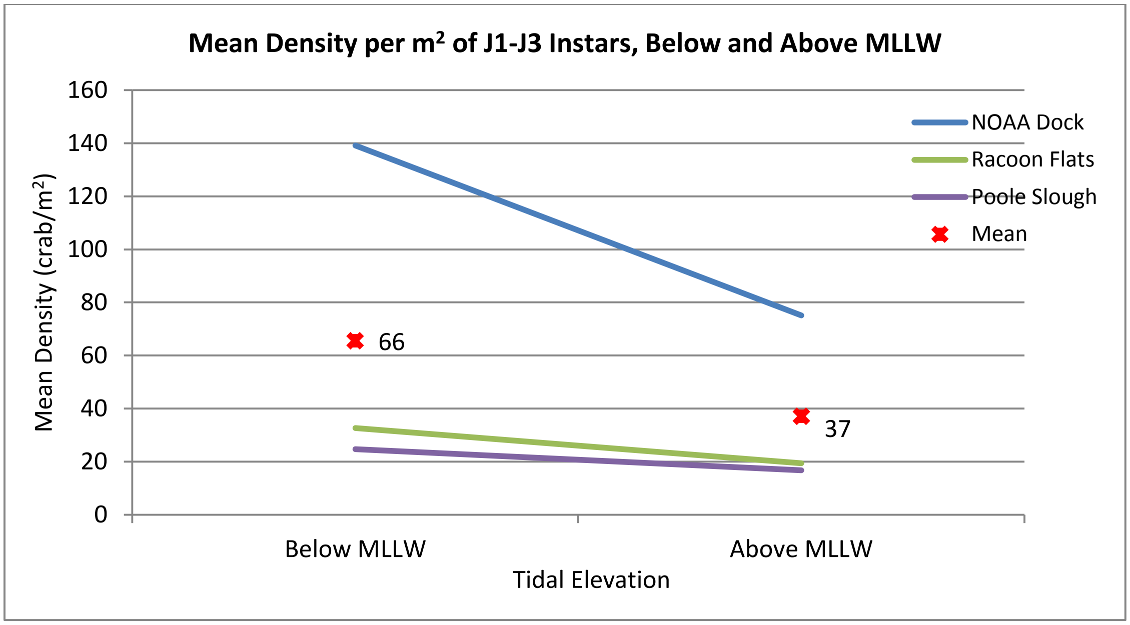


Figure 19. Mean density below and above MLLW.
Mean density of *M. magister* (J1-J3 instars) per m^2 below MLLW and above MLLW. Note that Idaho Point has been removed due to absence of shell bags below MLLW.

Table 10. Densities of *M. magister* from Yaquina Bay shell bags.
Total densities from shell bags by each tidal elevation, n=3 (except NOAA Dock tidal elevation, -0.85; n=2).
*Does not contain Idaho Point data

	Tidal Elevation (ft)	Total Crab	Mean Crab	Std. Dev.
NOAA Dock	-0.85	65	33	2.12
	-0.74	109	36	15.37
	0.07	79	26	8.08
	1.1	50	17	7.57
	1.69	40	13	10.69
Idaho Pt.	0.26	7	2	0.58
	0.37	14	5	1.52
	1.29	14	5	2.31
	1.87	44	15	3.21
Raccoon Flats	-0.66	12	4	2.12
	-0.38	37	12	5.51
	0.1	10	3	1.53
	0.41	19	6	1.15
Poole Slough	-1.22	16	5	0.58
	-0.91	21	7	3.61
	0.29	15	5	1.73
	1.61	10	3	1.53
Mean Density Below MLLW/Shell Bag (0.25 m^2)*		16		
Mean Density Above MLLW/Shell Bag (0.25 m^2)*		9		
Mean Density Below MLLW (m^2)*		66		
Mean Density Above MLLW (m^2)*		37		

The two mean densities for below MLLW (66 crab/m^2) and above MLLW (37 crab/m^2) were used in combination with the proportions obtained from prior literature and the historically estimated area of *O. lurida* and previously mapped areas of *C. gigas* habitat. Extrapolating crab densities by area of habitat, we obtained the following crab densities produced historically by *O. lurida* habitat and produced currently by *C. gigas* aquaculture (Table 11):

- Scenario 1 (native and cultivated beds): Approximately 2.9 billion *M. magister* were produced historically from all *O. lurida* habitat
- Scenario 2 (native beds only): Approximately 1.4 billion *M. magister* were produced from native beds of *O. lurida* habitat
- Current *C. gigas* aquaculture: Approximately 0.9 billion *M. magister* are currently produced

Table 11. Crab produced in Willapa Bay, WA
Habitat areas obtained from B. R. Dumbauld, USDA-ARS, unpublished data.

		AREA (m^2)			CRAB/m^2		TOTAL CRAB PRODUCED	
		Total Area	Below MLLW	Above MLLW	Below MLLW	Above MLLW	Below MLLW	Above MLLW
HISTORIC		62,191,800	32,183,100	30,008,700				
NATIVES		31,384,800	20,067,300	11,317,500				
	Close to Mouth	24,063,300	16,288,200	7,775,100	66	37	1075021200	287678700
	Far from Mouth	7,321,500	3,779,100	3,542,400	11	7	41570100	24796800
CULTURED		30,807,000	12,115,800	18,691,200				
	Close to Mouth	30,807,000	12,115,800	18,691,200	66	37	799642800	691574400
	Far from Mouth	0	0	0	11	7	0	0
AQUACULTURE		38,059,200	11,210,400	26,848,800				
MIXED		2,160,000	1,112,400	1,047,600				
	Close to Mouth	2,160,000	1,112,400	1,047,600	53	30	58734720	31008960
	Far from Mouth	0	0	0	8	5	0	0
SEED		25,536,600	6,089,400	19,447,200				
	Close to Mouth	14,328,900	3,048,300	11,280,600	40	22	120712680	2570429320
	Far from Mouth	11,207,700	3,041,100	8,166,600	6	4	19268410	29007763
FATTENING		5,116,500	2,745,000	2,371,500				
	Close to Mouth	5,116,500	2,745,000	2,371,500	66	37	181170000	87745500
	Far from Mouth	0	0	0	11	7	0	0
DIRECT		910,800	448,200	462,600				
	Close to Mouth	910,800	448,200	462,600	53	30	23664960	13692960
	Far from Mouth	0	0	0	8	5	0	0
HUMMOCKS		430,200	54,000	376,200				
	Close to Mouth	321,300	0	321,300	66	37	0	11888100
	Far from Mouth	108,900	54,000	54,900	11	7	594000	384300
UNKNOWN		3,905,100	761,400	3,143,700				
	Close to Mouth	1,837,800	242,100	1,595,700	66	37	15978600	59040900
	Far from Mouth	2,067,300	519,300	1,548,000	11	7	5712300	10836000

TOTAL CRAB	**Below MLLW**	**Above MLLW**	**Total Crab Produced**
HISTORIC NATIVES & CULTURED	1916234100	1004049900	**2920282000**
HISTORIC NATIVES ONLY	116591300	312475500	**1429066800**
AQUACULTURE	425835670	494033803	**919869473**

Discussion

The decline in *O. lurida* and the subsequent cultivation of *C. gigas* has led to a regime shift in the available settlement habitat for *M. magister,* from that of primarily subtidal habitat (below MLLW) to one of primarily intertidal habitat (above MLLW). Our main objective for this study was to obtain density data by depth to estimate and compare crab production provided historically in *O. lurida* habitat and currently in *C. gigas* habitat in Willapa Bay, WA. Site and habitat type were also examined as factors influencing crab density.

Shell Bags, Site, and Tidal Elevation

In general, higher crab densities were observed in the shell bags, closer to the mouth of the bay, and below MLLW. Shell bags represent habitats with thick shell cover, such as fattening beds or hummocks. As such, they provide more cover and greater habitat complexity than the existing habitat and exhibited greater crab density.

Shell bags at the NOAA Dock site exhibited the highest densities at four of five tidal elevations, presumably since this site was closest to the mouth of the bay and thus closer to the source of larval recruitment. The decreasing trend in crab density by tidal elevation, as illustrated in Figure 18, might primarily be driven by the high densities found within the NOAA Dock site. However, three of the four sites did exhibit greater crab densities below MLLW, and at the fourth site, Idaho Point, we failed to place any bags below MLLW for comparison. Higher densities below MLLW indicate that *O. lurida* might provide habitat more conducive for crab settlement within these subtidal regions. Further, extrapolating crab densities by area, suggests that a higher total density of *M. magister* was produced historically in native *O. lurida* habitat, than is currently produced in cultured *C. gigas* habitat in Willapa Bay, WA.

Habitat existing in the subtidal region could minimize the effects of temperature extremes on juvenile crab. Kondzela and Shirley (1993) reported that water temperature affected the period between molts and survival rates in juvenile *M. magister*, and varied between no molting with a 79% survival rate at 0°C, to short intermolt periods with a steep decline in survival (30% survival rate) at 20°C. Generally metabolism increases with temperature, and at 20°C survival rates during the various life stages of *M. magister,* have been shown to decrease presumably due to metabolic stress (Brown and Terwilliger, 1999; Kondzela and Shirley, 1993). Additionally, an experiment conducted by Brown and Terwilliger (1999) in which crab were subjected to temperatures experienced during an average 8-hr tidal cycle (10°C-20°C) in Coos Bay, OR, indicated that megalopae and first instar juveniles are more temperature sensitive than fifth instar juveniles. Temperature sensitivity in young crab might be attributed to their transition from relatively stable oceanic conditions to estuarine areas with fluctuating temperatures and salinity, while survival at all stages decreases at temperatures of approximately 20°C (Brown and Terwilliger, 1999).

Distance from Main Channel

The variation in densities we observed among tidal elevations might also be attributed to distance from the channel. The NOAA Dock site, Raccoon Flats, and Poole Slough all showed the greater densities at the second lowest tidal elevation. Since these depths varied somewhat, this could suggest that instead of depth being an influencing factor, distance to the main channel might be important. Idaho Point, as its name implies, forms a point or small sand bar situated between a large intertidal area and a small stream, and is across from another large intertidal area (see Appendix 1). Idaho Point is much closer to the main channel and the surrounding landscape may also have some effect on recruitment to the site. Because distance from the main channel also represents distance from the source of recruitment, it seems likely that a higher presence of crab, due to passive settlement, would be found closer to the channel. This may also be beneficial to the life history strategy of subadult and adult crab. Little is known about subadult movement once crab are of sufficient size and the nursery habitat is abandoned. Some evidence from tagging studies and video surveys suggest that subadult and adult Dungeness crab move into open intertidal habitat from the subtidal to forage due to lack of prey in the subtidal region, (Holsman et al., 2003; Holsman et al., 2006). If subadult or adult crab move into these deeper subtidal channels once the nursery habitat is abandoned, then proximity to the main channel or side channels could be beneficial. Shell bag placement to include a wider spread of depths, for example-2 to +2 (MLLW), as well as slope intensity (distance from the channel) may produce more definitive results.

Willapa Bay Comparison Caveats

This comparison includes caveats that should be considered including differences in geomorphology between Willapa Bay and Yaquina Bay, accuracy of the historical 1889 Collins map, and the broad assumptions made among habitat types.

Existing historical data for Willapa Bay and the importance of this estuary as a prime producer of cultured *C.gigas* made this estuary the location of choice for a comparison of historic and current crab production. Using Yaquina Bay as the experimental site, though not ideal, was a necessary logistical choice due to bay access and the proximity to the Marine Hatfield Science Center in Newport, OR. However, there are striking dissimilarities in geomorphology between these two estuaries. While Dungeness megalopae are active swimmers, tides and currents influenced by the geomorphology of the estuaries may affect settlement. Willapa Bay is much larger and wider than Yaquina Bay and is situated parallel to the coastline whereas Yaquina Bay is smaller, narrower, and more perpendicular to the coastline. Prevailing winds (as well as freshwater inflow, temperature, etc.) may affect currents, tides, and eddies which could subsequently affect settlement of *M.magister*. Conducting this settlement experiment in Willapa Bay would then provide a more direct comparison for crab production between *C. gigas* and *O. lurida*.

Additionally, the historical 1889 map that Collins created, which was used to estimate *O. lurida* habitat, may not be as accurate as the recently mapped area of *C. gigas* aquaculture. This may have resulted in an over- or underestimate of crab density within the various habitat types.

Lastly, many assumptions were made regarding settlement to the various habitat types. To the best of our knowledge this is the first study conducted, examining crab density within *O. lurida* habitat and at subtidal depths. Little is known about the bed morphology of *O. lurida* prior to exploitation and few remnant populations currently exist in which to compare. We assume when extrapolating densities, that historical *O. lurida* beds were comprised of thick shell and equivalent to that of *C. gigas* fattening beds and hummocks. This assumption, if inaccurate, could further result in an overestimate in crab produced by *O. lurida* habitat.

Yaquina Bay Shell Pile Study (Targeting Objective 3)

Methods

Sampling was continued at the NOAA Dock site in Yaquina Bay to track survival and to continue monitoring crab settlement. Shell from the initial study was returned to the substrate to form three shell piles at a “High” intertidal depth and at a “Low” subtidal depth. These were then sampled for crab every two weeks for eight weeks using the same quadrat and sieving techniques as previously mentioned, but percent cover was not visually estimated. A thick algal mat was removed prior to sampling to locate the shell piles within the subtidal region. To estimate survival, a mark-recapture method was implemented and all crab were “marked” by the removal of the left, rear walking leg on the first sampling date. The molting rate and potential effect on leg regrowth was uncertain so twelve crab were brought back to the lab to monitor molting and leg regrowth. These were kept in pvc containers with mesh-lined bottoms in a tank circulating seawater from the bay and fed frozen mud shrimp, *Upogebia pugettensis,* (as much as would eat) for six weeks and then returned to the bay. Carapace measurements were recorded weekly. All data are maintained in Microsoft Access 2007, and graphs were produced using Microsoft Excel 2007 and ‘R’. A Welch’s t-test was used to compare crab densities between the “High” and “Low” tidal elevations.

Results

Results from this study indicate a higher total mean density (14.75 crab per pile) within the “High” elevation treatment piles and a lower total mean density (6.83 crab per pile) at the “Low” elevation treatment piles. The first sampling date resulted in identical crab densities at each of the three piles for both tidal elevations (6 crab per pile). However, all subsequent sampling dates resulted in higher mean densities at the “High” elevation piles, but densities at both elevations decreased over time after the second sampling date (Figure 20). A Welch’s t-test on crab densities indicated that there was no significant difference due to tidal elevation (t= 1.83, p = 0.16, df = 3).

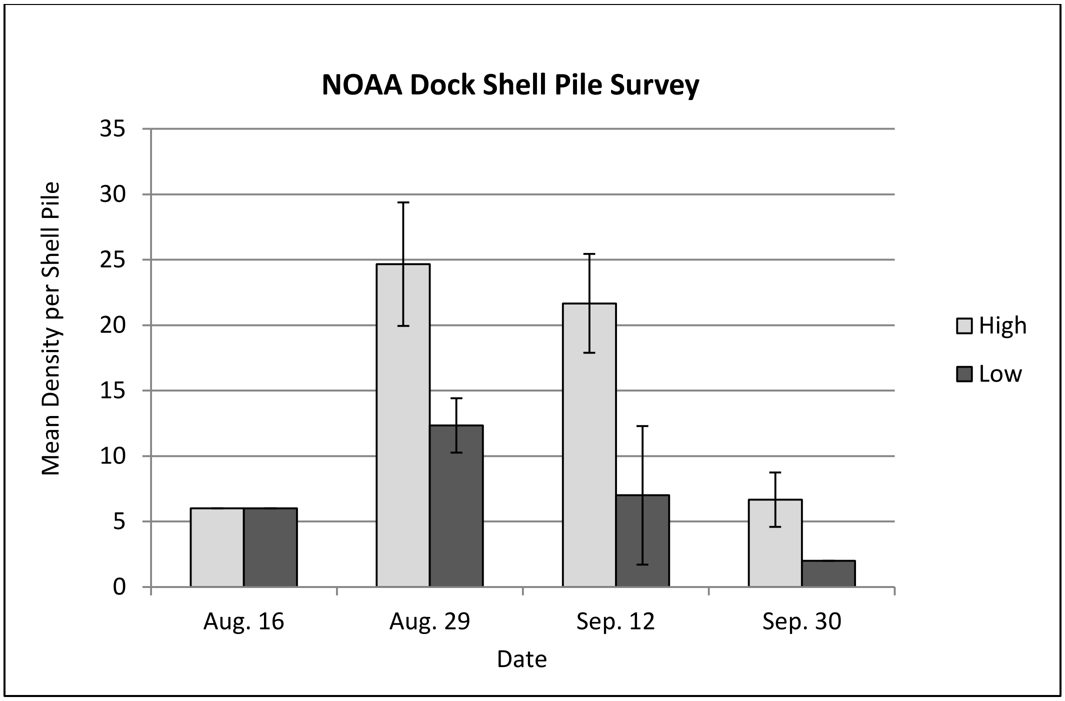


Figure 20. NOAA Dock shell pile survey.
Mean density (n=3, error bars=std.dev) of *M. magister* from the “High” and “Low” shell pile treatments at NOAA Dock, Yaquina Bay, OR.

Unfortunately, no “marked” individuals were recaptured during any of the subsequent trips to the NOAA Dock shell piles. Two crab from each of the 6 piles were brought back to the lab on the first sampling day, but molting ceased in all individuals after two days in the lab and no leg regrowth occurred. Width-frequencies of all crab from this survey are shown in Figure 21. Though survival could not be estimated, the presence of ~5 mm crab demonstrated that settlement was still occuring as late as the end of September.

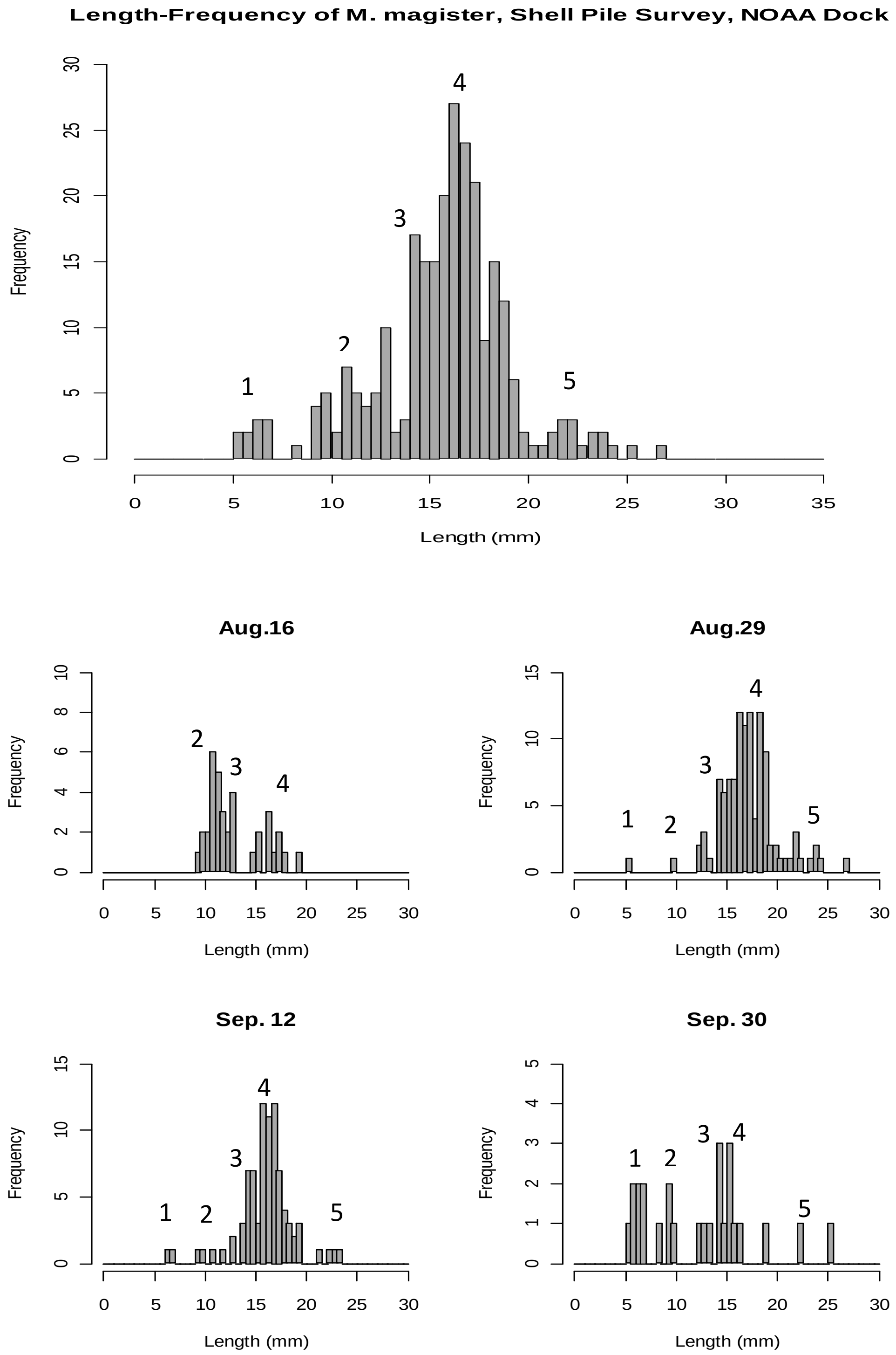


Figure 21.Width-frequencies of crab from NOAA Dock shell pile survey.
Top diagram includes all crab, and the bottom four are separated by date. Note the presence of ~5mm crab in late September. Numbers indicate juvenile instar stages J1-J5.

Discussion

Our main objective for this study was to track crab survival through time using a mark-recapture method, while continuing to monitor settlement by depth in Yaquina Bay, OR.

Mark-Recapture and Survival

We had hoped that marking individual crab would enable us to track survival and movement over time. Unfortunately we were unable to definitively track survival due to lack of "marked" individuals in the field as well as the lack of growth in the laboratory crab. The absence of "marked" individuals may be due to rapid molting and leg regrowth, emigration from the shell piles, or mortality. It was assumed that leg regrowth would be slow enough over a two week time period to be observed during subsequent sampling dates if these crab were indeed recaptured. However, the removal of this rear walking leg may have significantly affected their ability to escape predation or cannibalism by conspecifics, or to forage for food.

It is unknown if the lack of growth and molting in the laboratory crab, may be due in part to diet, stress, or both. Sheen (2000) reported that the mud crab, *Scylla serrate,* required 0.2% to 0.8% of dietary cholesterol in combination with lipids for weight gain and molting, but that excessive cholesterol had a negative impact on both. Feeding a more varied diet than just mud shrimp, might meet the dietary requirements needed by the juvenile crab.

Survival

Though we could not definitively track survival from the shell pile survey, the decreasing trend in abundance over the last three sampling periods might be representative of the survival rate. As the season progresses and recruitment to the shell piles decreases, emigration would continue and the total abundance would decrease. The abundance of J1 increased slightly over the 8-week period, from zero to seven crab, and the presence of ~5 mm juveniles indicated that recruitment was still occurring as late as the end of September. The abundance of J3-J5 instars decreased dramatically towards the end of September (Figure 21) and might be attributed to both predation by larger conspecifics migrating from the subtidal zone, and emigration.

Tidal Elevation

This study indicated higher densities in the "High" elevation piles and lower densities in the "Low" elevation piles. However, during all four sampling dates, a thick algal layer was observed which covered most of the lower tidal region. Sections of the algal mat had to first be removed before the shell piles could be located. This thick algal cover was not encountered during the shell bag study which occurred earlier in the summer. This algal cover could potentially smother organisms and lead to anoxic conditions in this lower region of the tideflat and may explain why crab density here was lower than in the "High" treatment shell piles. Total settlement densities observed during the shell pile survey were also lower than densities during the shell bag study which could indicate that recruitment into the area was waning or that predation was greater due to the absence of the mesh bag which may have offered some protection to the juvenile crab. Predation of the "marked" individuals by larger crab migrating from deeper subtidal regions, might also explain the lower densities observed within the "Low" elevation shell piles.

Conclusion

The results from these three studies generally support those from previous studies demonstrating that crab densities are higher in structured substrate than open mud habitat, and are generally higher in habitat with shell substrate than in eelgrass in Pacific Northwest estuaries. The shell bag study also provided initial baseline data on crab settlement at various tidal elevations, representing *O. lurida* and *C. gigas* habitats. Results indicate that lower tidal elevations inhabited by *O. lurida* inhabits might be more conducive for crab settlement, and thus produces more Dungeness crab than *C. gigas*.

Settlement does occur within higher intertidal regions, as seen in all portions of this study. While depth potentially affects settlement; distance to the channel and shell cover are also important. Further research, conducting more extensive sampling between existing *O. lurida, C. gigas*, and eelgrass habitats may lead to more definitive results. A similar study to the one conducted in Yaquina Bay, will be conducted in Willapa Bay in the summer of 2012 to provide a more applicable comparison of Dungeness crab production.

Chapter 4: Management Implications

This project was conducted to broadly examine ecosystem services provided by oyster habitat as well as to more specifically examine the production of Dungeness crab as an ecosystem service provided by oyster habitats. Dungeness crab are an economically important resource for Pacific Northwest states, and it is important to define the habitat in which they are associated so that impacts to the species can be minimized. Further, defining general ecosystem services can serve as tools for improving estuarine water quality or for preventing further degradation (NRC, 2010). Services such as water filtration, carbon sequestration, nutrient assimilation, and habitat provision all have the potential to be accounted for through the development of markets and credit systems.

Mitigating for Crab Loss due to Dredging

Defining habitat used by Dungeness crab, is vital in minimizing or mitigating for impacts during activities such as dredging which have the potential to result in high mortality (Armstrong, 1989). Much research has come from examining the impact of dredging on Dungeness crab due to the U.S Army Corps of Engineers Navigation Improvement Project in Grays Harbor, WA, which was completed in 1990 (Dumbauld et al., 1993; Armstrong et al., 1991; Armstrong et al., 1989). Intertidal shell plots were constructed to enhance settlement substrate to mitigate for the loss of older crab in the subtidal due to dredging in Grays Harbor (Dumbauld et al., 1993). However, if a large proportion of settlement occurs subtidally as well, dredging may further impact crab populations by not only removing adult crab but also juvenile crab. While intertidal plots may serve as a mitigation tool, the construction of subtidal plots, might better serve this purpose. Beyond constructing just shell plots, native oyster restoration might be a useful tool for mitigating crab loss due to dredging. This would entail taking a more integrated approach and identifying sites not affected by dredging, which could serve as crab habitat, while implementing regular monitoring for the presence of oyster larvae and juvenile crab.

Mitigation for Degraded Water Quality

Developing markets for ecosystem services such as the buying and selling of credit for carbon sequestration, denitrification, and water filtration can lead to better resource use and valuation techniques (Beck et al., 2011). This could be applied to both aquaculture and restoration practices. Tang et al. (2011) found that bivalve aquaculture in China serves as a significant sink for carbon and that between the years of 1999 and 2008, shells sequestered 0.67 million tons of carbon annually, and 0.20 million tons were absorbed by shellfish tissue annually. Harvesting shellfish additionally serves as a long term sink in many areas where shucked shells are discarded on land or buried, resulting in the net long-term removal of carbon (NRC 2010, Tang et al., 2011). Credits for water quality improvement and carbon sequestration would generally benefit the aquaculture industry and oyster restoration while applying costs to those that contribute to estuarine degradation (NRC, 2010).

Conclusion

Mitigating for crab loss and degraded water quality through the use of oyster restoration and aquaculture expansion, represent only a fraction of potential possibilities that might arise from quantifying ecosystem services. Because of the dynamic nature of the environment these are often difficult to value, and until recently many of these services have been undervalued, ignored, or exploited. To prevent the loss of biodiversity, degraded ecosystems, and the loss of benefits that we derive from healthy ecosystems, these should be valued an accounted for in management plans, coastal development, and by the various user-groups utilizing these resources.

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Appendices

Appendix 1. Bathymetry map of Yaquina Bay.
Source: Lee McCoy, USDA-ARS