An Analysis of the Commercial Pacific Oyster (*Crassostrea gigas*) Industry in Willapa Bay, WA: Environmental History, Threatened Species, Pesticide Use, and Economics.

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A Thesis Submitted in partial fulfillment
of the requirements for the degree
Master of Environmental Studies
The Evergreen State College
April 2012

This Thesis for the Master of Environmental Study Degree

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ABSTRACT

An Analysis of the Commercial Pacific Oyster (*Crassostrea gigas*) Industry in Willapa Bay, WA: Environmental History, Threatened Species, Pesticide Use and Economics.

The environmental history of Willapa Bay, specifically the decline of finfish predators, the installation of hundreds of dams on the Columbia River and its tributaries, the loss of native oyster reefs and logging practices all contribute significantly to modern pest management issues between oyster growers, citizens, and burrowing ghost shrimp. By examining the effects of pesticide control on commercially valuable species (Dungeness crab) and non-commercially important, but Endangered Species Act (ESA) listed species Green Sturgeon; the complexities of history and modern natural resource management are explored. By combining interviews with local citizens, growers and researchers with an extensive literature review and field visits, these issues are explored holistically. In conclusion, there is little evidence to suggest that the chemical control of burrowing ghost shrimp has driven the decline of the Green Sturgeon; nor evidence which shows that the Dungeness crab harvest is compromised as a result. However, the history of anthropogenic disturbances and industries within this watershed likely drove an increase in the population of burrowing ghost shrimp in the mid 1900's which contributes to the pest control issues. The oyster growing industry has changed significantly over the last 150 years from harvest of a native species of oyster, which grew naturally in reefs, to a largely commercial industry, which relies on cultivation of a single non-native species via hatchery production and mechanized harvest methods. Recommendations for future research include assessing the feasibility for Green Sturgeon enhancement and exploration of a sustainable seafood label, which could potentially recover some of the increased cost associated with alternative growing practices that would not rely on chemical control of the burrowing ghost shrimp.

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Acknowledgements

Thanks are due to many for their support, love, and patience with me while I worked on this project: To my husband Dave and son Jonah, thank you! Ralph, I would not have completed this project without your support, advice, and encouragement.

Introduction

The second largest estuary on the Pacific Coast is in the southwest corner of Washington State. Willapa Bay harbors a profitable oyster industry and several commercial fisheries: Dungeness crab (*Cancer magister*), English sole (*Parophrys Vetulus*), as well as a variety of salmon species. The bay also provides habitat for migrating shorebirds, waterfowl, and many non-commercially important fish (Feldman et al., 2000). Until about 150 years ago, like much of the Pacific Northwest, the land surrounding the Bay was home to ancient stands of hemlock, spruce, fir and cedar trees. Much of the native forest has been cut and processed for lumber and other products, with the majority of commercial timberlands replanted. This change within the landscape, as well as several others detailed below, gave way to a pest management issue between burrowing ghost shrimp and oyster growers that has persisted for decades.

Modern oyster harvest is primarily comprised of the Pacific oyster species (*Crassostrea gigas*). Pacific oysters were introduced to the Willapa region from Japan in the late 1800s-1920s. The native Olympia oyster (*Ostrea lurida*) still occurs in some areas, and was once the basis of the industry, but is no longer commercially significant having been depleted in the late 1800's and replaced by the Pacific species (Feldman, K. et al, 2000). This Bay is the center of what Kim Patten, a WSU researcher in the region calls: "…one of the most difficult pest management projects in agriculture" (Wagner, 2010). Two species of native burrowing ghost shrimp affect the survival of oysters by burrowing under and destabilizing the sediment that the oysters are grown on. This leads to the oysters sinking below the sediment and suffocating and also makes it difficult for farmers to move around on the beds.

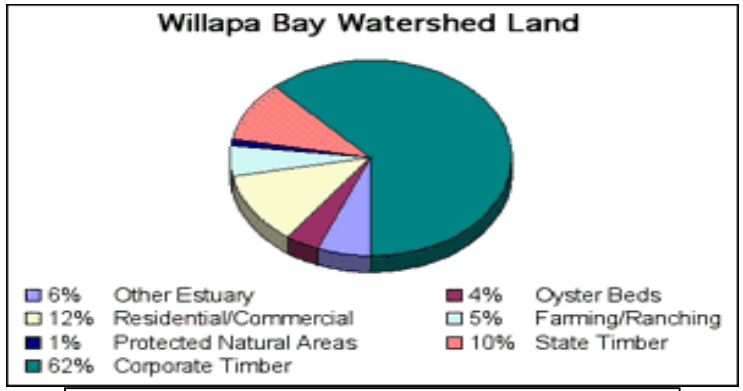
Since the early 1960's the pesticide carbaryl, (trade name Sevin, which is a naphthyl methylcarbamate pesticide), has been applied by many oyster growers to areas of the farmed tidelands as a method to control the shrimp. Sevin is one of the most commonly applied insecticides for terrestrial uses in the United States (U.S.), but it is also used only for aquatic/marine uses in Washington State. It is widely used across the US for fruit tree pest, forage, cotton and other crops as well as on poultry, livestock and pets (NPIC, 2003). Many other countries have banned the use of carbaryl including: the United Kingdom, Germany, Denmark, Sweden, Austria, and Algona. Carbaryl is classified by the Environmental Protection Agency to be a "likely human carcinogen" based animal testing (NPIC, 2003). In Willapa Bay, this chemical treatment is performed mid-summer by spraying a powder (generally by helicopter) over the tidelands or sometimes applied by hand (Feldman, 2000) to control burrowing ghost shrimp. Treatments are timed so as not to interfere with salmon and steelhead migrations and regulated as to the wind speed and tides as well. Willapa Bay and one other smaller estuarine bay to the north, Gray's Harbor, are the only two areas in the country where aquatic application of carbaryl is allowed. Oregon and California banned this practice in 1984 (Feldman et al, 2000).

The Pacific County Economic Development Council reported in their 2009 Economic Snapshot that oyster farming in Willapa Bay produces over 23%

of the nation's oysters and two thirds of Washington State's oysters on an annual basis. Annually fishing and shellfishing (aquaculture) is a 31.5 million dollar industry, which provides this rural community with over 2,000 jobs (PCEDC, 2009). Annual landings are 24 million pounds of fish (primarily salmon species) and 5.5 million pounds of shellfish (PCEDC, Undated).

The economic contributions of the oyster industry deepen this conflict. Some residents and oyster growers, as well as many crabbers, oppose the application of pesticide into the bay while other oyster growers insist that the carbaryl treatments are necessary for a viable industry. This controversy has persisted for many years and resulted in a lawsuit in the late 1990's, which, was ultimately settled out of court. The agreement has phased out the use of carbaryl over a ten-year period and implemented a ban prohibiting this control method beginning in 2012. While very effective at killing the target native shrimp, carbaryl is also toxic to many other species including Dungeness crab, which, use the oyster shells in the bay as habitat while they are young. Dungeness crab, like oysters, are also economically significant to the region. The Green Sturgeon, while not considered commercially important due to its taste, is listed as both threatened and a species of concern under the Endangered Species Act (per different population segments). The Green Sturgeon is a predator of the native burrowing ghost shrimp. Many residents around the bay are concerned about drift, transport and residence time of carbaryl when it is applied for personal and environmental health reasons.

Figure 1. Willapa Watershed Land Use



Land use percentages within the watershed
http://willapaharbor.org/natural_resources.php

Willapa Bay has a long history of natural resource based industries. Figure one details the current land use within the watershed. Cranberry and dairy farming in addition to logging and fisheries/aquaculture have supported these communities for many generations. Of the 150,000 acres of privately owned tidelands in Willapa Bay between 10,000 and 15,000 are currently used for oyster cultivation (BSCC, 1992). Most oyster cultivation, regardless of the growing method, occurs from -0.5 to -1.1 Mean Lower Low Water (MLLW)[1] on varying combinations of mud, sand, and gravel. While many factors are important to oyster production the type of bottom substrate, exposure, temperature and salinity are particularly important (Simenstad and Fresh, 1995). These factors combine in Willapa Bay for some of the most productive aquaculture beds in the entire country.

The ecology of the Bay, the biology and species of oysters cultivated, the Dungeness crab industry, and Green Sturgeon survival are linked and dependent upon the land use and environmental history of the Bay. There is a significant correlation to the current day pest management issues including shrimp population growth and the history of anthropogenic developments over the last 150 years. Understanding these factors in the context of market demands (both

[1] Mean Low Low Water (MLLW): The average of the lower low water height of each tidal day observed over the National Tidal Datum Epoch. http://tidesandcurrents.noaa.gov/mllw.html

oyster and crab) and, non-market based responsibilities of natural resources management (ESA listing of the Green Sturgeon) puts into perspective the application of a pesticide to control a native species while enabling the culture of a non-native oyster species that provides jobs for many. It is the intention of this study to inform future management decisions as pest management strategies and alternatives are being identified after 2012 when carbaryl will be banned per legal settlement.

Utilizing a variety of methods detailed below, this project explores the demographics and ecological characteristics of the communities of Willapa Bay to set a framework for exploring whether the application of carbaryl impacts the harvest of Dungeness crab or the survival of Green Sturgeon. There is an analysis of four major anthropogenically driven watershed scale changes: timber harvest, hydropower, commercial fisheries off the mouth of the Columbia River, and the loss of native oyster reefs. These changes are strongly linked to the current pest management issues at hand, which, are explored at length in the context of biology, ecology, and economy. Finally, the impacts of the oyster industry and the associated shrimp control methods are explored in relation to Dungeness crab commercial harvest and Green Sturgeon population dyamics. The economics of the oyster industry and recommendations for future research follow in conclusion.

These issues are emblematic of conflicts faced by natural resource agencies and industry in many places where historical land use has driven long-standing changes within our environment. The ethics and responsibilities of ecosystem management balanced with rural jobs and a healthy economy is, while not easy, familiar for this region given the history of natural resource extraction. The issues at hand are in part a product of the past and understanding this will better inform future management decisions.

Statement of Methods

Several methods including a literature review, interviews, and economic analysis were used to gather data for this project to answer two research questions: 1) has the Pacific Oyster (*Crassostrea gigas*) industry's use of carbaryl impacted the harvest of Dungeness crab (*Metacarcinus magister*); 2) have populations of Green Sturgeon (*Acipenser medirostris*) been affected by the carbaryl applications either directly or by reducing populations of their food source?

Interviews were conducted over a two-month period in the winter of 2011. Participants were chosen to represent sectors of interest and included three oyster farmers, three researchers, and two citizens. The oyster farmers were chosen to represent different scales of operation from small hobby farms to large commercial scale operations. The interviewed researchers had all spent good portions of their careers working in this region on this and other pest management issues. The citizens were chosen for their willingness to be interviewed and involvement in the pest management issues. Interviews were conducted both over the phone and in person.

Data was also collected on two field trips to the region and included visits to the local library in Ocean Park and historical society in South Bend. Economic costs and benefits for the oyster industry in Willapa Bay region are based on data from the Pacific County Economic Development Council and from the Washington State Office of Financial Management as well as the Integrated Pest Management Plan written by Steve Booth for the Oyster Growers Association. The timing of this project is particularly significant, as a legal settlement requires that all carbaryl applications cease in the Bay after 2012 (Dewey et al, 2003). Research is underway to evaluate alternative control methods (chemical and cultural) once carbaryl is banned. Thus growers, residents, and researchers find themselves in the midst of a dilemma: as many growers feel that the use of carbaryl is necessary to sustain the industry at its current valuable scale and the most effective (and toxic) treatment identified to date will soon no longer be available.

Figure 2: Willapa Bay

The approximate location of oyster beds within Willapa Bay.

Source: http://www.goosepoint.com/willapabay.html

There are tangible economic benefits of growing oysters in this region and in terms of ecosystem services provided. There are also externalities that result from the scale of the industry and the chemical shrimp control. For perspective on the scale of the industry in the Bay please refer to Figure 2 above. Regional natural resource agencies are charged with managing both the health of the estuary and providing for several economically substantial fisheries stocks. It is challenging to quantify the exact relationship between shrimp density and oyster loss given variable conditions over the large geographic area of the bay, differences in substrates and growing practices, and shrimp biology (they are difficult to count based on number of burrows present alone and they live within the sediment). Chemical treatment, whether carbaryl is used or a proposed alternative is applied, requires balancing the economy with this region's ecology.

Geography and Ecological Characteristics

Willapa Bay is located between the Columbia River and Grays Harbor Bay in the southwest corner of Washington State. The Columbia River empties more than 160 million-acre feet of water into the Pacific Ocean each year, which is more than any other waterway in the Western Hemisphere (Lloyd and LaRue, 1980). Willapa Bay encompasses 260 square miles of water and tidelands of which between 10,000 and 15,000 acres are used for oyster cultivation (Feldman et al, 2000). The adjacent coastal waters are a primary source of nutrients and phytoplankton. The estuary is 25 miles long and approximately 8 miles wide. It is orientated north/ south and is bordered by the Pacific Ocean to the west (Feldman et al, 2000). Several major rivers including the: North, Willapa, Bone, Niawiakum, Palix , Naselle, and Bear in addition to several smaller drainages empty the surrounding watershed. The watershed is relatively undeveloped and rural. The Bay and associated drainages support fall Chinook, Coho, fall Chum Salmon and winter Steelhead Trout. The Willapa Bay watershed is estimated to be over 600,000 acres and includes over 100 miles of shoreline (Willapa Harbor Chamber, Undated)

The estuary is shallow with only an estimated 15% of the Bay deeper than 7 meters. Over half of the surface of the bay is exposed at low tide. Sediments range from mud to mixed mud and sand. The sandy sediment is more prevalent near center and the mouth of the estuary while mud sand composite is more dominant near the river mouths. Salinity ranges from 7% to 30% depending on location and season. The lower salinity levels are generally found near river mouths from October to March. Water temperature range with location and season from 3-21°C (Feldman et al, 2000). Each day approximately two thirds of the water in the Bay is exchanged with incoming ocean water (Lloyd and LaRue, 1980).

Eelgrass *(Zostera marina)* is common on the intertidal and sub-tidal mudflats. This marine grass provides refuge and foraging opportunities for various fishes, waterfowl, and benthic invertebrates. It is an important component of detritus based marine food webs. Oyster shell is also a recognized structural component with habitat value in this estuary. It has been found to support high densities of Dungeness crab (*Cancer magister*, shore crab *Hemigrapsus* *oregonensis*)[2], gunnels (*Pholis ornate*), copepod species, and amphipod species. (Doty, et al, 1990). Ghost and Mud shrimp are native to the bay and their population fluctuates. They are a dominant feature of the mud flats with burrow densities approaching 600 holes in m-2 in some areas (Feldman et al, 2000). One shellfish grower noted that shrimp populations are highest near river mouths (Oyster Grower 2, 2011).

Eradication of Spartina, which is a non-native cord grass that spread extensively over 12,000 acres of Willapa Bay, has been largely successful due to applications of the herbicide "Habitat." The plant threatened the integrity of intertidal and near shore areas by forming dense stands and colonizing previously open mud flats. The affected areas became channelized marsh flats, which changed the habitat for wildlife, fisheries and shellfish growing areas. At one point Spartina was estimated to be covering more than 20,000 acres of the Bay. State law mandates the removal and control of Spartina (WSU, 2006). When the Pacific oyster species was first introduced from Japan they are anecdotally known to have been packed in Spartina grass; thus introducing this invasive species to the Willapa ecosystem.

A thorough background on the geography and ecological characteristics of this region underpins an understanding of the demographics, industries, and current pest management issues. The habitat complexities and the fauna

[2] Note that impacts to Dungeness crab were evaluated in this thesis as a representative commercially important species. Population impacts to non-commercially important crab and other species were not evaluated within this scope.

supported as well as a species' native origin is important to keep in mind as ecosystem services and industry contributions are explored.

Demographics

Willapa was once called "Shoalwater Bay" which means slight in depth or shallow. This was changed in 1893 when the county seat was moved to Southbend from Oysterville (Lloyd and LaRue, 1980). Current day demographics for Pacific County rank the aquaculture and fishing industry sector fifth by number of employees. This number has changed throughout time in response to modernized technology for harvest. The forest resources sector has also changed tremendously in the last 150 years, and this has impacted not only the landscape and people but also Willapa Bay.

Pacific County was founded in 1851. The largest city in the county is Raymond, which was settled in the early 1900's as a lumber town. (Pacific County, Undated). It was located in the midst of thick stands of cedar, fir, hemlock, and spruce trees. The swampy tidelands dominated the area along the Willapa River and delayed development of the settlement. The business and residential portions of Raymond were initially built on stilts above the marshy tidelands. Today, the community is protected from high waters by dikes. During the peak of Raymond's economic boom from 1912 to 1932, at least twenty sawmills and factories operated along the city's waterfront. A large sawmill operated by Weyerhaeuser still dominates the waterfront. Economic growth has slowed in the region from these boom times but logging remains central to

Raymond's history and contemporary economy, which is emblematic of many of the communities within Pacific County (NOAA Community Profile, Undated).

As of 2009, there was an estimated 21,800 residents in Pacific County (OFM Databook, 2009). The racial makeup of county residents is as follows: Caucasian 90.54%, .2% African American, 2.44% Native American, 2.08% Asian, .09% Pacific Islander, 4% from two or more races and, 5% of the population is Hispanic or Latino. The median income for households in the county was $31,209, and the median family income was $39,302 in 2009 (Pacific County EDC). About 14% of the population lives below the poverty line. There are ten recognized communities (Bay Center, Chinook, Ilwaco, Lebam, Long Beach, Naselle, Ocean Park, Raymond, South Bend, Tokeland) via the US Census and about as many unincorporated areas (Wikipedia, Pacific County). The county is home to four port jurisdictions and many parks as well as a national wildlife refuge.

Figure three below details the employees and average annual wages in Pacific county by sector; however this is only for jobs and wages within Pacific County. The actual impact of the oyster industry in particular spreads beyond the boundaries of the county however. Taylor Shellfish, one of the largest growers, transports daily their harvested shellfish to neighboring Mason County for processing. The wages and jobs affiliated are thus are not fully captured by the table in Figure 3 (PCEDC, Personal Communication). The Washington Office of Financial Management groups the sectors differently than shown below by combining Agriculture, Forestry, Fishing and Hunting into one sector. The relative contribution of these combined sectors is just over 8% of the total. The largest employment sector is Government at 43%, followed by manufacturing at 13% and wholesale/Retail Trade at 7%. It is not possible to determine if the manufacturing and wholesale sectors are accounting for the appropriate processing components any of the aquaculture industry or if they are lumped into the combined sector.

Figure 3: Pacific County Employment Sectors

Sectors	2008 Employees	Average Annual Wages
Overall	**6,309**	**$28,289**
Agriculture (Animal & other)	185	$18,985
Aquaculture/Fishing	255	$29,647
Forest Resources	115	$38,562
Government	1,878	$40,849
Healthcare/ Retirement Services	469	$24,012
Manufacturing	792	$29,282
Hospitality/Tourism	1,237	$16,250
Technology	81	$26,733

The average wages and employment numbers by sector in Pacific County from 2008, Pacific County Economic Development Council: http://www.pacificedc.org/demographics2.htm

One of the common arguments for maintaining the oyster industry at the current commercial scale (thereby justifying the use of carbaryl or other chemical control to maintain it) is the economic contribution of the industry to the community. While perhaps not fully represented within this data (given that some of the economic benefit spreads beyond the borders of Pacific county) the relative contribution of the industry is less then 10%. This percentage is undoubtedly important to those families and people whom are represented by the numbers and as well is culturally significant to the area, but, it is also less then I had expected.

Historically, this region was the territory of the Lower Chinook Indians, a Salishan Tribe. They travelled the inland waterways in cedar canoes, and their villages were always located near the water's edge. Fishing, hunting, processing salmon, elk, berries, and wapato (a potato like tuber) were the most important occupations of the villagers. When the salmon were not running in the streams there were abundant native Olympia oysters, clams, crab, and mussels to harvest from the beaches. The abundant natural resources of this region provided not only sustenance but also items for trade including: dried salmon, sturgeon, smelt, seal meat, dried shellfish, furs and dried meat. The tribal population, which numbered several thousand, was greatly reduced by the smallpox and malaria epidemics, which arrived with European settlers (Chinook Nation, Undated). Many Chinooks and white settlers intermarried. It is important to acknowledge and honor the people for whom a wind pattern, language, and a salmon species are named for today. The history of this region would not be complete without an understanding of the native history.

The Shoalwater Bay Tribe was created by executive presidential order on September 22nd, 1866. A 355-acre parcel was set-aside in the order for "Miscellaneous Indian Purposes." This reservation became home for the last remaining Willapa Chinook, Lower Chehalis and Willapa Hills People. The 355-acre parcel was intended to provide lands for fishing, shellfish harvesting and potato farming. Today the descendants of these people make up the approximately 300 enrolled members of the Shoalwater Bay Indian Tribe. Currently about 100 enrolled members live on the reservation (Shoalwater Bay Tribe, Undated)

Active forest management dominates the landscape still with 78% of the land in timber production, 12% estuary lands, 6% in agriculture and 4% zoned residential development (Pacific Conservation District, 2007). The majority of the slopes surrounding the Bay are dominated by the Douglas Fir/Western Hemlock forest type and are managed under either the Washington Department of Natural Resources Habitat Conservation Plan or the Washington Forest and Fish Agreement. Some of the largest trees ever encountered in the Pacific Northwest were once present in these hills. Elevations within the watershed range from ten feet mean sea level (MSL) near the city of Raymond to approximately 3,000 ft MSL in the Willapa Hills. The eelgrass and marshlands provide habitat for 70+ species of migratory birds. Farms, mainly cranberries, make up another 7% with 1400 acres of bogs that produce virtually the entire state of Washington's cranberry harvest (1.5 million lbs per year). Other traditional farms raise beef and dairy cattle with the associated production of hay, silage and calves.

Oysters are farmed on 10,000-15,000 acres of tidelands within Willapa Bay. Pacific Salmon returning to spawn in Willapa streams are caught by fisherman in the open waters of the Bay. Commercial fishing has always been an integral part of the community and local economy. Salmon accounts for roughly 90% of the finfish caught in Willapa Bay. The commercial and sport Dungeness crab fishery also thrives in Pacific County with an annual catch between 2 and 10 million crabs per year. Oysters have been farmed in Willapa Bay for 100+ years. Willapa Bay produces about 23% of the national oyster crop, most of it shipped as shucked meat. Suitable grounds for growing oysters are found in low intertidal and shallow sub tidal areas. Historically, the native Olympia oysters grew on more than 20,000 acres as reef, now that reef has been largely dismantled and replaced with a single non-native species produced at a commercial scale. The local industry is now concentrated on about 10,000 acres and grows Pacific oysters. Oyster harvests average three to four million pounds per year (Willapa Harbor Chamber, Undated).

Regional demographics, including the makeup of the modern day communities and employment sectors, land use patterns, cultural and natural history are important to understanding the geography of this region. Understanding how the community has developed over time in relationship to the natural resources and fisheries-based economy illustrates where some of the tension in the current pest management issues is rooted. It also sets the stage for understanding the scale of ecological changes that have taken place in the watershed over the last 150 years.

Watershed Scale Anthropogenic Changes

Timber

An interviewee shared that logging practices may have altered the makeup of the substrate of the Bay- perhaps even raising its elevation (Oyster Grower 1, 2011 personal communication). Many residents and oyster growers suggested anecdotally that shrimp populations climbed during the 1950s and 1960s. This was further substantiated within the literature. This was likely due, at least in part, by timber harvest practices detailed below.

Hunt and Kaylor in their 1917 book Washington- West of the Cascades, reveal that it was likely in 1884 at the hands of successful timber baron Andrew Polsen that the first splash damn was established in the Willapa watershed on the Hoquiam River (Hunt and Kaylor, 1917). Splash damming and log driving were among the earliest reported management disturbances in rivers of the Pacific Northwest (Miller, undated). A project which reconstructed the location and frequency of splash dams in western Oregon streams reveals that this practice was quite common from the 1880s through the 1950s as a way to transport timber to downstream mills before extensive logging roads were constructed (Miller, undated). There is also historical evidence that this practice extended to Washington on the other side of the Columbia River. The Pacific County Historical Society's Sou'Wester publication's profile of the logging industry in the Willapa region reveals that:

> All logging at this time was water orientated. The Naselle River had a large holding boom where all the logs from upriver were caught and held until they could be sorted and rafted according to brands.

> The upper river used splash dams to get their logs down. The rafting ground could close the river with a gap stick when a log drive was on.
>
> (Pacific County Historical Society, 2000)

A splash dam was constructed to span the width of a river. This created an upstream reservoir in which water and logs were stored until the spillway was opened to release a large flood, thus easily transporting the timber downstream. Splash dams were common in the Pacific Northwest before the significant infrastructure of logging roads and mechanized transportation was available. This practice left affected rivers with a signature legacy of exposed bedrock, fewer deep pools, and fewer pieces of key large wood than un-splashed reaches. These changes all have lingering consequences for salmon to this day (Miller, Undated).

Logging in the watershed increased turbidity by increasing sediment flows and freshwater discharges to Willapa Bay. Loss of turbidity can affect the ability of eelgrass to successfully photosynthesize. As noted earlier, eelgrass is an important component of the marine food web as well as important habitat that many species depend upon. To consider the effects of early logging practices and upland developments separate from the nearshore estuary systems is ecologically naïve. It is apparent that this practice impacted Willapa Bay and the drainages that feed the Bay given the scope and scale.

While I found no evidence directly linking splash dams to an increase in, shrimp populations aside from a time correlation, it is likely that an increase of sediment reached Willapa Bay (through flushing) as a result of the splash dams. This would have created an abundance of habitat that the burrowing ghost shrimp prospered within. To this day the shrimp prefer the type of muddy open sediments that this would have created. When the splash dams were removed, either by dynamite or removing a few key logs, the riverbed and sediments were scoured as the water flushed the basins. The graphics below in Figure 4 depict identified streams and rivers across Western Oregon that once had splash dams. To my knowledge a similar inventory project has not been undertaken in Washington State; however the practice appears quite common on both sides of the Columbia River throughout historical literature.

Figure 4. Splash Dam and Log Drive sites in Western Oregon

Source: Miller, Undated (Figures 4 and 5)

Figure 5: Splash Dam on the Upper Coos River, 1947

As logging practices became increasing mechanized the industry also became more efficient in their transportation. Eventually as jobs were replaced by machines and road building splash damn logging and water transportation became a thing of the past. It is likely that the ecological effects of these early practices, particularly in relation to sediment transport and salmon habitat continue to affect the Willapa Bay watershed today. While there is no data, which can specifically correlates a rise in the shrimp populations to increased sediment in the Bay, it appears that this practice may have created more habitat that shrimp enjoy.

Hydro-Electric Power on the Columbia River

Another large-scale change in the watershed landscape was the construction of the Bonneville dam, which began in 1934 and opened in 1938. A second powerhouse was constructed from 1974-1981 (Bonneville Dam, Wikipedia). The primary purpose of the dam, which is situated 40 miles east of Portland Oregon, is to generate electrical power. Despite its world- record size at construction, the Bonneville Dam was exceeded in size by the construction of subsequent dams upstream, becoming the smallest of seven locks at different locations upstream on the Columbia and Snake Rivers. This dam construction blocks migration of green and white sturgeon to their spawning grounds, although there are depressed small pockets of populations isolated upstream above the dams. Native salmon species and steelhead are able to breach the dam via fish ladders to travel upstream on their spawning cycles. Historically sea lions and seals were known to hunt as far as 200 miles upstream from the mouth of the ocean but they are cut off from this system also. "The Columbia River basin is in fact the most hydroelectrically developed river system in the world to date. This river system is home to more than 400 dams and generates more than 21 million kilowatts of energy" (Center for Columbia River History, Undated).

Results from a three-year hydrographic study of Willapa Bay revealed in 2004 that its estuarine waters were highly variable and fluctuated with ocean conditions (up-welling and down-welling) as well as intrusions of buoyant Columbia River freshwater (Banas, et al, 2004). These fluctuations influence salinity levels and perhaps other water quality parameters, which may affect populations of burrowing ghost shrimp in either a positive or negative manner. Prior to the construction of the Bonneville dam in the mid 1930s and subsequent dams constructed upstream, it is plausible that this restricted flow into Willapa Bay over time making less freshwater intrusion to Willapa Bay from the Columbia River mouth plume.

Anecdotal information suggests that perhaps this was one more reason for an increase in the population of burrowing shrimp in the 1950's. It may have been a cumulative effect of the many dams, which altered the water chemistry (Oyster Grower 3, personal communication) in addition to the sediment changes from logging practices. A conflicting viewpoint was stated by another of the region's oyster growers (Oyster Grower 2, personal communication) who relayed that the "shrimpiest" beds that his company has are actually found at river mouths, which would suggest that the shrimp are tolerant of freshwater. Whether the shrimp react positively or negatively to freshwater, the construction of the dams on the Columbia River altered those flows and in turn the salinity levels in Willapa Bay. This was a major environmental change, compounded by additional changes within the watershed in the years, which preceded a significant rise in the shrimp populations. I believe this was, and continues to be, a likely influence in shrimp population dynamics though the relationship is not thoroughly defined.

Over-Fishing at the Mouth of the Columbia River

Burrowing Shrimp populations also may have risen due to declines in their natural predators: salmonids, sturgeon, English sole, and other finfish. These species were overharvested in the late 1800s and early 1900s (Oyster Grower 3, Personal Communication). Commercial fisherman in the Columbia River region caught sturgeon, both white and green, though white sturgeons have a higher commercial value. The commercial fishery for white sturgeon began in the Columbia in the early 1880s and reached its peak at 52 million pounds in the year 1892. At about the same time the salmon harvest also peaked. A technique known as the "gang line" was often employed and was particularly efficient in catching sturgeon. This practice was damaging for both the white and green sturgeon. A line with a series of hooks was placed along the bottom of the river, which is where sturgeon feed. The hooks would snag their bodies, as opposed to luring them with bait. The practice was banned in 1899 but by that year, the sturgeon (both green and white) populations were essentially decimated. The numbers remained low until brood stock-size fish — seven feet in length and about 150 pounds — were protected, and that was not until 1950. Populations began to rebound in the 1970s but have not recovered to their estimated abundance of the late 19th century (Northwest Power and Conservation Council, Undated).

The commercial fishing industry grew rapidly alongside the development of canneries on the shores of the Columbia. In 1866, the first of many canneries began operating, there were two commercial fishing boats on the river. The number of commercial boats jumped to 100 by 1872, 250 by 1874, 500 in 1878, and 1,200 in 1881 (Northwest Power and Conservation Council, Undated). Commercial fishing reached its sustained peak period in the Columbia River in the 1880s. In 1883 and 1884, the catch totaled more than 42 million pounds, and more than 620,000 cases of salmon were packed each year (Northwest Power and Conservation Council, Undated). Green sturgeons, while not commercially important, were often caught as by-catch in these harvests.

By the late 1800s salmon harvests and production at canneries began to decline. In 1890, for example, the total catch was 29.6 million pounds, the pack was 435,744 cases, and just 21 canneries remained in operation (Northwest Power and Conservation Council, Undated). This is significant to shrimp populations because of the predacious relationship these fish have on the native burrowing shrimp. Commercial salmon fisherman often caught more than the canneries could handle and canneries didn't set landing limits until the mid-1880s. Excess fish were often dumped back into the river. Many of these would wash up on shore and rot, providing food for gulls and bears and producing an omnipresent stench. Astoria, Oregon, at the mouth of the Columbia River, had a long-standing reputation for its fishy odor (Northwest Power and Conservation Council, Undated). Rotting fish also provided breeding grounds for disease organisms like the typhoid bacillus. In those days it was not uncommon for as many as 500 salmon to be dumped back in a single night. In her book The Trail Led North, Martha Ferguson McKeown quotes a cannery foreman describing life in Astoria in the 1880s:

> There wasn't no laws regulating what happened to the fish. The fishermen tried to catch all they could. The canneries agreed to take them. Every man tried to live up to his contract. Everyone aimed to make all he could. Folks in Astoria got pretty sore, but that was about the smell more

> than about the salmon being wasted. (Northwest Power and Conservation Council, Undated)

The troll fishery began on the lower Columbia in the early 1900s and steadily increased in both the number of boats and the number of fish harvested. Many gillnetters adopted hooks and lines at least partly to be able to fish on Sundays, when the gillnet fishery was closed. In contrast, the troll fishery had no such regulation. Around the turn of the century, gasoline engines became available for fishing boats, and this increased their range and the effectiveness of fishing. Gasoline-powered boats could range farther than the traditional sail-powered craft in search of fish, including large areas of the ocean. By 1915 there were 500 trolling boats based in the lower Columbia, and by 1919 the number doubled, perhaps boosted by a shortage of flax for nets imposed by the advent of World War I (Northwest Power and Conservation Council, Undated). It was also in 1915 that the number of gillnet boats peaked on the lower Columbia, at 2,856.

Viewed in hindsight, this overfishing appears reckless and greedy, but in the context of the time this was not the case. In fact, in that era it was not uncommon to believe that the supply of all natural resources - fish, trees, water and land for agriculture - essentially was limitless, as the bounds had not yet really been tested. As well, fisheries science was new and little was understood about life cycles and the importance of adequate spawning and rearing habitat or brood stock. The primary causes of the 150-year decline of salmon, steelhead and other commercial fish are familiar — water pollution, overfishing, dams, habitat destruction, etc. Ineffective or lax regulation also played a part by allowing overfishing as well a misperception that stocks were limitless. The decline of the burrowing ghost shrimp predator's populations played a role in the increase of shrimp populations noted in Willapa Bay in the 1950s. There are similarities in the timing and overexploitation of harvesting of the shrimp predators (many finfish species and the harvest of timber in this era. Mechanization enabled great harvests for both the timber and fish industries.

Because of a combination of these overexploitations, and maybe others, shrimp populations increased during the 1950s and 1960s. This prompted oyster farmers in the region to find a method for control in order to continue growing oysters at their commercial scale as illustrated in Figure 6. The scale and the techniques for growing oysters have changed little over the last 60 years since.

Figure 6. A helicopter sprays carbaryl on oyster beds in Willapa Bay

Helicopters apply Carbaryl over the Willapa Bay mudflats.

Source: Steve Nahl/The Oregonian

Oysters: Biology, Cultivation and History

Pacific Oysters are commonly grown directly on the ground (a technique referred to as ground culture); on long lines suspended off the ground; or in racks or bags. By far, ground culture is the most dominant growing technique in Willapa Bay (Oyster Grower 3, Personal Communication). The mid 1850s saw the commercial oyster harvest boom in Washington State due in large part to the overharvesting of oysters native to San Francisco Bay and demand for the bivalves during the California Gold Rush. Boats loaded with oysters from Washington travelled to San Francisco where people paid quite well for them- up to $20.00 per plate or around $400.00 in contemporary dollars (Peter-Contesse, T., & Peabody, B., 2005). This was a major blow to the native Olympia oyster population in both coastal and Puget Sound waters as Washington oysters were then overharvested and their native reef structure was reduced. The potential for profits was great. Early shellfish farmers in this region prevailed though and became more efficient about harvesting. They began to grade oysters according to size for harvest, thereby preserving future crops (Puget Sound Action Team, 2003). When Washington became a state in 1895 the federal government handed the rights to sell the tidelands as private property to the state. The Bush and Callow Acts (passed in 1890 and 1895 respectively) gave private property owners the right to own tidelands and cultivate oysters. This allowed establishment of many private shellfish companies and rooted aquaculture farming techniques as a way of life for many Washingtonians.

The Pacific oyster (*Crassostrea gigas)* was introduced to the commercial shellfish industry over several decades in the late 1800s to the early 1920s. As a much hardier species, which also had a longer shelf life, Pacific oysters could be transported longer distances (Puget Sound Action Team, 2003). This introduction was another blow to Olympia oyster populations as the hardier non-native Pacific species slowly outpaced them in sales. The commercial scale oyster industry was born and the era of harvesting natural populations began to be phased out. Poet Jay Bolster captured the Pacific Northwest love of oysters with his *Ode to the Olympia Oyster* in which he called them "food of the gods" and identified the Pacific Northwest region as the "nearest place to paradise" (Steele, 1957).

This iconic bivalve and namesake of Washington's capital city, is a mollusk or a shelled invertebrate in the same phylum as the mussel, clam, snail, and octopus. Oysters are further classified as a bivalve, which means that their shell is held together by an elastic hinge and is created by the secretion of calcium from within. Oysters are designed to thrive in the intertidal zone. By closing their shells when the tide goes out they are able to keep water in their shells surviving the difficult life of low tide and this makes them easy to transport as well. When the tide is up and they are submerged oysters open their shells and using their gills filter tiny phytoplankton from the water around them for food. As filter feeders, oysters are capable of filtering 8-12 gallons of water per day. Multiplying this filtering effect by thousands of oysters allows for the filtration of large volumes of water per day, which is known to help take up nutrients from the water and improve turbidity (Peter-Contesse, T., & Peabody, B., 2005). This filtration and nutrient sequestration provides an ecosystem service, which can be valued. There are slight variations in the reproductive habits of different oyster species but the majority release both eggs and sperm to the surrounding water. Oyster larvae spend on average about three weeks without a shell drifting as part of the phytoplankton community before attaching to the substrate shell (Blanton et al, 2001).

Oyster Reefs and Ecosystem Services

Oyster reefs were once a dominant feature of temperate estuaries like Willapa Bay. A 2009 report released by the Nature Conservancy concluded "…oyster reefs are one of, and likely the most, imperiled marine habitats on earth…(Beck et al, 2009)." Showing significant decline, even referred to as functionally extinct, this poses risk to both the economic and ecological health of coastal estuaries. Centuries of intensive fisheries extraction, the introduction of non-native shellfish, coastal development (filling and dredging), timber harvest practices and increased anthropogenic pollution sources upland have all contributed to the decline of native oyster reefs (Beck et al, 2009).

Because oyster reefs serve as ecosystem engineers (by creating habitat and conditions that other plant and animal species within estuaries depend upon), this loss is quite significant. Other ecosystem services provided by oyster reefs include water filtration, nutrient removal, and shoreline protection (from erosion). While there is also ecosystem service value retained in the current commercial oyster industry in terms of filtration and habitat, the intensive harvesting practices (including dredging and harrowing which move the oysters from bed to bed and disrupt sediment respectively), of the single shell Pacific oyster market have changed the way that oyster reefs function in Willapa Bay and elsewhere.

Native oysters or even non-native oysters left to flourish would naturally clump and build into a reef over time. Years of harvest without returning shells left no place for spat (tiny oyster seed) to settle in Willapa Bay (Feldman et al, 2000). The natural reef was replaced with a single scatter layer of ground shell or cultch (Feldman et al, 2000). It is through cultivation practices and market demands that the industry has moved to grow single oysters on tidelands. While this has allowed easier harvest, and responded to market demands it likely has also allowed greater susceptibility to shrimp colonization over time due to exposure of muddy sediments (Feldman et al, 2000).

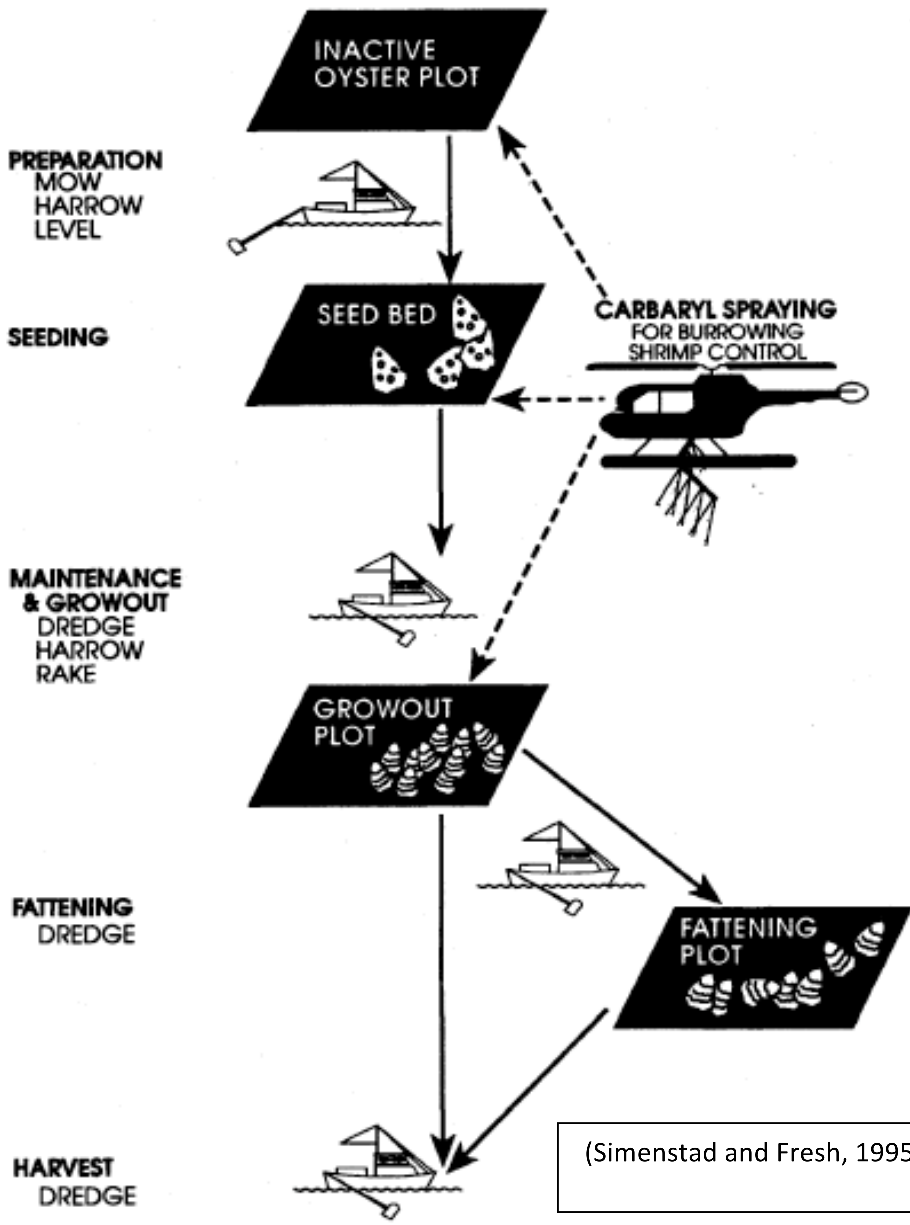
For millennia, people have used shellfish for food, ornamentation, currency, mineral resource, and even to pave roads (Beck et al, 2009). Globally, it is estimated that 85% of native oyster reefs have been lost (Beck et al, 2009). Oyster reefs are at 10% of prior abundance in most bays worldwide and deemed functionally extinct with less than 1% of prior abundance for in many bays and eco-regions (particularly in North America, Australia and Europe) (Beck et al., 2009). The loss of native oyster reefs is of global significance. Although the Nature Conservancy Report (2009) details many conservation and restoration strategies, it is likely that a perception among managers and stakeholders exists that there is not a major problem with a decline of native oyster reefs. Valuing and recognizing oysters for the reef habitat and ecosystem services provided may strengthen the case for recovery. Balancing the need and sustainable methods for aquaculture/oyster harvest with a baseline reef habitat is tricky given market demands and the efficient mechanization of large-scale commercial harvest.

Native oysters in the Willapa Bay region are known to have crashed in the late 1800s (Cheney and Mumford, 1986). Subsequently, oyster producers focused on the culture of eastern (*Crassostrea virginica*) and Pacific oysters as early as 1895 in Willapa Bay. Fattening beds are sometimes harrowed in the spring to partially lift sunken oysters and break large clusters into smaller ones. Oysters can grow too large for both the raw half shell and shucked markets. Bottom culture oysters are sometimes handpicked at low tide and put in large bins, which are then lifted onto barges at high tide. The alternative is to use a mechanical drag dredge to skim the bed surfaces to harvest bottom culture oysters, thus exposing and disrupting the sediment. Significant harvest occurs in the winter months. Triploid oysters (which are sterile and produced from a hatchery) are popular for harvest in the summer due to better meat quality. During the spawning season over the summer months oyster meat quality decreases as the organism devotes more energy to spawning (Booth, 2010).

Reports from the mid to late 1800's suggest that the native Olympia oyster once grew up to 1 meter thick in the low intertidal and sub-tidal channels of Willapa Bay (Simenstad and Fresh, 1995). Once Pacific oysters were introduced the nature of the oyster habitat changed from a thick reef structure to a thin layer of oysters over sediments. Many modern day markets for oysters' request single shelled oysters as well.

Oyster populations in their native reef formation would be less likely to be affected by the habits of burrowing ghost shrimp. But this would not be a good fit for market demands. Natural reefs were relatively impenetrable to burrowing shrimp and provided an elevated substrate for newly settled spat (Feldman, et al, 2000). Oyster plots in Willapa Bay are repeatedly disturbed- by harrowing, dredging, leveling and sprayed with carbaryl- though the intensity varies by grower, environmental condition and plot locations as previously stated. Figure 7 below details a general sequence for ground cultured Pacific Oysters in Willapa Bay. It should be noted however that this model is based primarily on practices within Willapa Bay and practice vary dramatically between growers.

Figure 7. A general sequence for the ground culture of Pacific Oysters in Willapa Bay



(Simenstad and Fresh, 1995).

Commercial Values of Pacific Oyster Industry

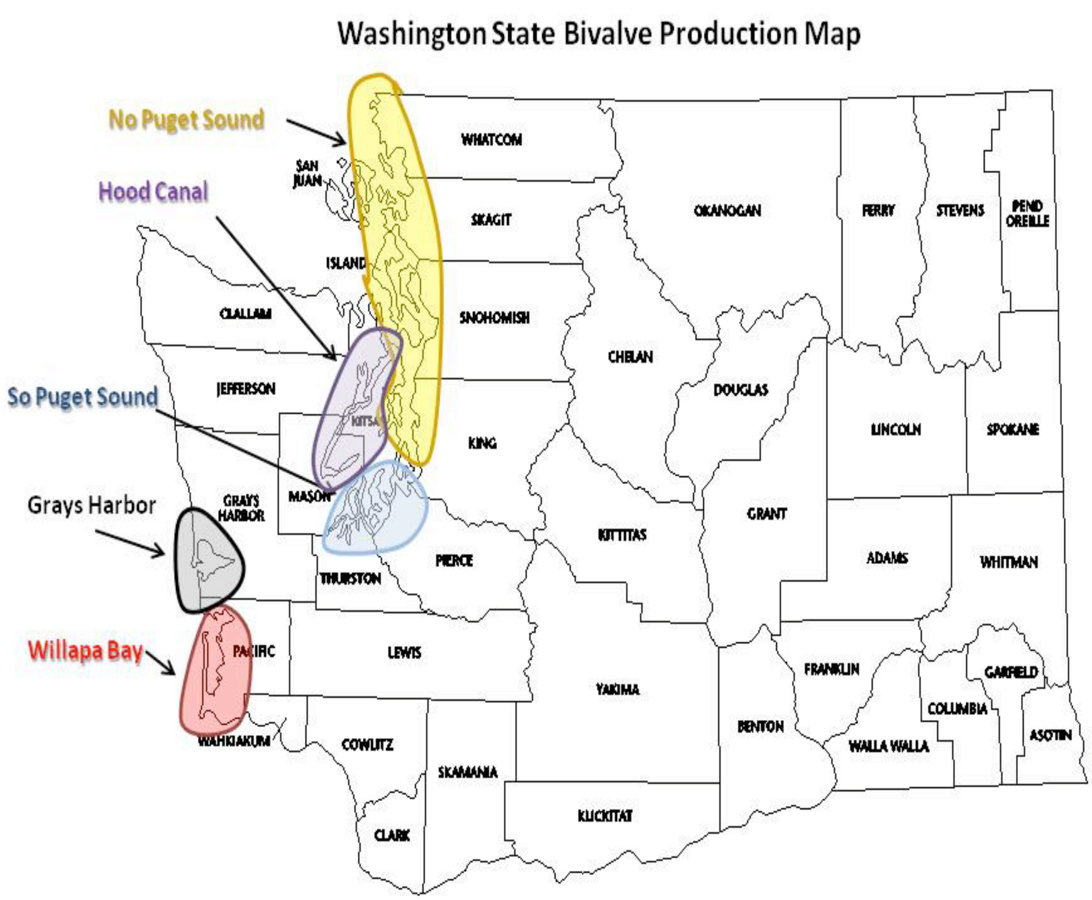
Since the early 1930's Pacific oysters have been the dominant oysters grown in all areas of Washington state accounting for 98% of all cultured oysters (Simenstad and Fresh, 1995). The shift to culturing a single species with great economic value has produced opinions on both ends of the spectrum. Intense single species aquaculture, like monoculture practices in other industries such as agriculture, can promote estuarine conditions indicative of a stressed ecosystem. Others stress that single species aquaculture can promote biodiversity and produce successfully without harmful effects to common species. Growers as an industry tend to be staunch advocates for maintaining or improving water quality in the face of increasing development as ultimately their product depends upon it. To judge whether the economic benefits and job opportunities of the oyster industry are an acceptable trade-off for ecological disturbance is a subjective process.

Ground culture oyster production can result in the direct disturbance of the substrate. To reduce density, some growers transplant oysters several times over the typical three-year harvest cycle. Harvesting and transplanting is frequently done with a mechanical dredge, as it is more cost effective than harvesting or transplanting by hand. How and to what extent oysters are treated and moved around depends on many factors including growth rates, planting density, environmental conditions, plot locations and grower preferences. Long line or stake and rack culture is generally used on ground that is marginal for bottom culture (meaning that the substrate is too soft) and this is a more expensive method. Bottom culture tends to produce higher yield compared to other methods averaging 1540 gallons per hectare-1 (Feldman et al, 2000) and requires less labor than other methods.

In 2005 Washington produced 77 million pounds of oyster meat, 8.5 million pounds of Manila clam meat, 2.1 million pounds of mussel meat, and .85 million pounds of Geoduck clam meat for a total of 88.5 million pounds of bivalve meat (Booth, 2010). Oysters are marketed as fresh, smoked or frozen but mostly sold fresh both shucked and in the shell. The most valuable oyster is a single one it its shell. Clusters are typically shucked with the meats graded for size and packed in containers. Shell size, shape and appearance in addition to meat quality are all recognized as important variables in the oyster marketplace. Smaller live single oysters are used in the raw bar market while large singles are sold for barbequing and other cooked dishes. Most of the large growers sell directly to domestic and international seafood wholesalers and distributors. Some growers sell to other producers or retailers who then resell. Growers are also able to sell directly to restaurants or to the public through retail store or over the internet (Booth, 2010). Recent estimates value the oyster industry at $25-27 million statewide and estimate that it is responsible for the direct and indirect employment of over 1700 workers in the region (Feldman et al, 2000).

The economic values of the oyster industry are significant both historically and in the present day. Growers depend upon clean water and while the industry does produce ecosystem benefits over many decades the habitat has been significantly altered in Willapa Bay. Mechanized harvest practices have allowed growth to the current level of commercial operation and may offset some of the benefits of a native oyster reef. This industry was historically based on harvest of natural populations of native Olympia oysters. This region is currently troubled with a lack of a natural set and relies primarily on hatchery oyster seed. The current commercial operations rely on a monoculture of Pacific oysters due in part to market demands and biological characteristics of this hardy but introduced species. Harvest of the native Olympia oyster is impractical and not cost effective as they are not as hardy of a species either to grow or transport. While the oyster industry is significant to the growers, processors, hatchery workers, shuckers and others involved in this rural industry it is not without impacts over time on the ecological characteristics of the bay and it is sensitive to the implications of neighboring industries as well (fisheries and timber).

Figure 8. Washington Bivalve Production Regions



www.ipmcenter.org/cropprofiles/docs/WABivalves.pdf

Burrowing Shrimp & Carbaryl

Beginning in 1963 oyster growers in Willapa Bay began spraying oyster beds in the tidelands with the insecticide carbaryl as a way to kill populations of burrowing ghost and mud shrimp. Many growers contend that the periodic control of the shrimp is necessary to maintain the current commercial oyster industry because high densities of shrimp destabilize the substrate. As a result, the oysters placed on shrimp dominated plots either sink and/or are smothered by sediment. These thallinassid shrimp (primarily *Neotrypaea* and *Upogebia*) appear to have been a problem since at least 1929 when they were reported to be hindering oyster culture and infesting some plots to such a degree that oysters were becoming uneconomical to harvest (Feldman et al, 2000). Carbaryl is a non-persistent organocarbamate pesticide (NPIC, 2000). While the spraying of these shrimp has certainly been controversial it is also unique to this region, highly regulated, and being phased out by 2012. Both California and Oregon banned this practice within the last two decades and use of the pesticide even terrestrially is illegal in several European countries (Wikipedia, 2011).

Extensive research shows that carbaryl is very effective at killing the target species of burrowing shrimp (with an 80-100% effectiveness rate), but it also kills and has sub-lethal impacts on non-target organisms. Mortality depends on the specific taxa, the concentration applied, and the duration of exposure, though crustaceans are particularly sensitive when it is applied in a marine environment. Data on the non-target impacts of carbaryl application suggest that estimates are highly variable (large confidence interval) and are likely conservative since they are based upon observation at the surface sediment. Observed invertebrates killed during applications include the mud and ghost shrimp, worms, Dungeness crab, and other crab species. Observed fish killed by the application include gunnels, sculpin, gobys, sticklebacks, and starry flounder (Simenstad and Fresh, 1995). Another study found additional non-target impacts included Staghorn sculpin (*Leptocottus armatus*), English and sand sole (Parophyrs vetulus and *Psettichthys melanostictus*), shiner perch (*Cymatogaster aggregata*), and starry flounder (*Platichtyys stellatus*) (Feldman et al, 2000).

It is interesting to note that many of the non-target species killed in the Carbaryl application are also known predators of the shrimp. Mortality varies depending on the number of fish in the area during the application, how much of water coverage is on the oyster beds and species abundance. Fish that survive the application are unlikely to die as a result of consuming contaminated taxa (Feldman et al, 2000).

Figure 9. Ghost Shrimp Burrows

(Courtesy: Pacific Shellfish Institute)

At densities of 30 or more shrimp burrows per square meter both large oysters and smaller oyster seed shell is known to sink into sediment. Note the appearance of burrows in Figure 9 above. The time to death for oysters is longer at lower shrimp densities but growers report that yield over several years are severely impacted if burrow densities exceed 10 per sq. meter (Booth, 2010). Long line cultivation is sometimes used as a technique to reduce oyster mortality (suspending the oysters on staked lines above the sediment) but this increases labor costs and requires more equipment to tend and harvest. In cases where the shrimp density is very high, however, the long line stakes have also failed in the past (sinking into the mud). While some growers report success with long line method it is not as cost effective for harvest and tidal currents as well as storms can dislodge the stakes (Booth, 2010). One interview suggested anecdotally that growing practices such as mechanized dredging, which is used to both move the oysters around to different plots and to harvest perpetuates that shrimp's presence. By exposing the mud sediment on an annual basis, the shrimp habitat is renewed with the scrape of the dredge (Oyster Grower 1, 2010).

Figure 10. Burrowing Ghost Shrimp

(Courtesy: Pacific Shellfish Institute)

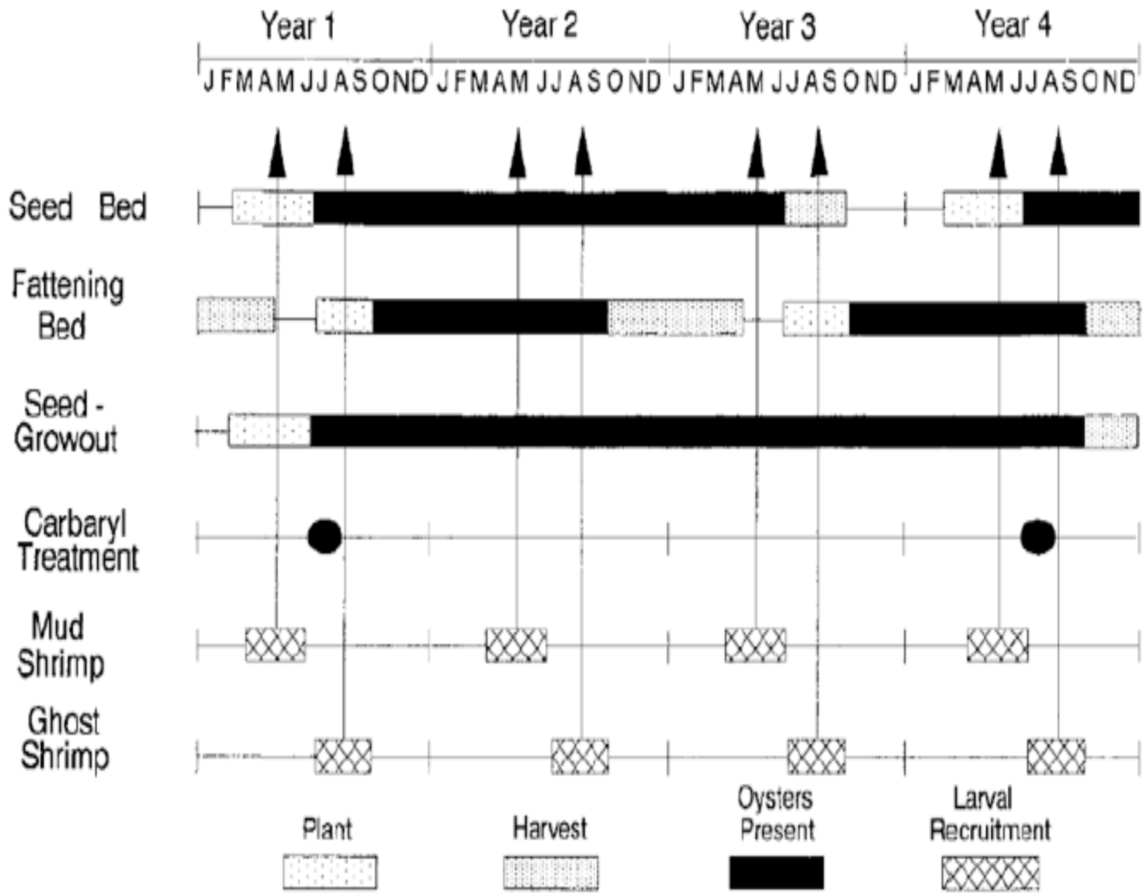
Burrowing shrimp (see Figure 10) are native to the west coast with a large range. The accidental introduction of a foreign parasite (Orthione griffenis) from ballast water in the early 1980's may be responsible for a recent decline in the populations of mud shrimp. O. griffenis currently parasitizes up to 80% of the mud shrimp in most PNW estuaries (Booth, 2010).

Carbaryl can currently be applied at 5-7.5lbs per acre in the Willapa and Grays Harbor estuaries on beds with a shrimp density greater than the threshold of 10 burrows per sq. meter on limited acreage per year. Applications are made both by hand and helicopter in the early morning low tides of July and August. Growers must apply for a permit each spring. Carbaryl is applied according to label instructions and at the authority of several Washington state agencies including the Washington Department of Ecology, The Washington State Department of Health, and the federal Environmental Protection Agency. Limitations include not spraying on more than 800 acres and maximum wind speed of 10 miles per hour plus a buffer of 200 ft around targeted beds. A treated bed remains farmable for several years after the application though harvest of the oysters is restricted for one year following the application. Applications later in the season would capture more of the juvenile shrimp but is avoided so as to not impact migrating salmon and steelhead (Booth, 2010).

Under the burrowing shrimp carbaryl control program mud and ghost shrimp are treated as a single entity though there are distinctive life history characteristics and behaviors between the two species (Feldman et al, 2000). Both are infaunal burrowers, meaning they burrow into the sediment but their reproductive habits, and feeding strategies vary. This complexity adds to controversy and may limit to some degree the effective management of these shrimp.

Staghorn sculpin (*Leptocottus armatus*) are one of the most important predators of these shrimp, as they are known to restrict the distribution of the shrimp. Other predators include Cutthroat trout (*Salmo clarkii*), Dungeness crab (*Cancer Magister*), and Western gulls (*Larus occidentalis*) Pacific Herring (Clupea pallasii), Gray whales (*Eschrichtius robustus*), several salmonids species including Keta, and Chinook (*Oncorhynchus tshawytscha and o. keta*), White and Green Sturgeon (*Acipenser medirostris* and *A. transmoutanus)*.

Figure 11. The complexity of shrimp and oyster life histories.



The overlap of shrimp and oyster lifecycles and chemical treatment in Willapa Bay. Source: Feldman et al, 2000

Growing practices and the environmental history of the Bay (including effects from surrounding industries) play large roles in the population dynamics of the burrowing shrimp. Several practices including splash damns, the removal of the native oyster reefs, commercial scale monoculture of a non-native oyster species, dredging and, harrowing have all contributed to muddy habitat for the shrimp. While there are ecosystem services and habitat values from the Pacific oyster industry via habitat creation and nutrient sequestration, both market demands for single shelled oysters and cost effective labor practices lend themselves to a habitat which is also suitable for burrowing shrimp. Both over harvesting of natural finfish predators and logging practices in the watershed have also contributed significantly to this history and current controversy.

Green Sturgeon

In 2001, the National Marine Fisheries Service (NMFS) received a petition requesting Endangered Species Action listing of the Green Sturgeon (*Acipenser Medirostris*) as either a threatened or endangered species. In response an ESA status review was initiated (Adams, 2002) and this species has been defined and listed in two distinct population segments since June 2006. The northern population segment is listed as “threatened” and the southern population segment is listed as a “species of concern,” and both utilize Willapa Bay. Green sturgeon are anadromous fish without much commercial value having inferior meat quality to the White sturgeon. Despite their listed status there is relatively limited data on their population, life history and biology. They are very long-lived and large fish. They spend more time in marine waters than any other sturgeon. The majority are thought to spawn in the Klamath, Sacramento and Rogue rivers of California and Oregon respectively. Males do not spawn until they are 15 years old and females begin to spawn at 17 years of age and at that only once every 5 years. Adults migrate in to rivers to spawn from April to July. Eggs are spawned on rocky bottom substrates and juveniles spend 1 to 4 years in freshwater. After Green sturgeon enter the ocean they migrate north to the cool coastal estuaries of Washington and British Columbia. Neither much feeding or spawning are thought to occur with these migrations (Adams, 2002), however anecdotal evidence and work by Brett Dumbauld in published in 2008 suggests evidence of feeding by

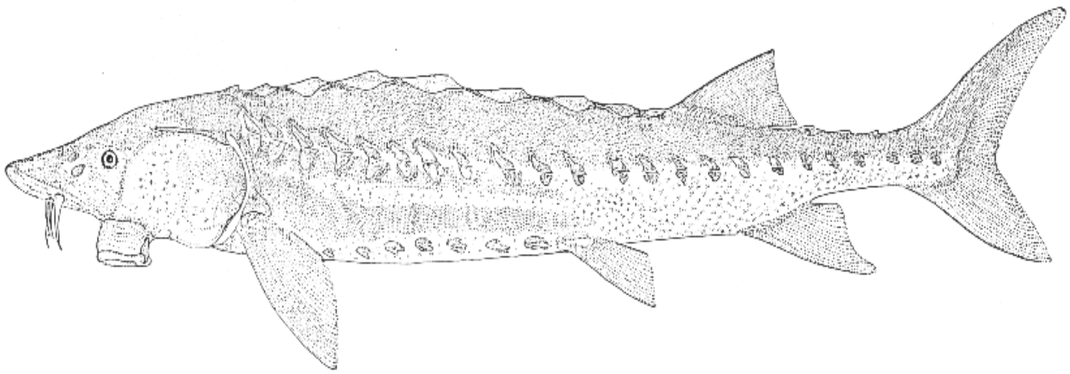
Green sturgeon in the Willapa Bay estuary by the presence of distinctive pits created while the fish forage (Dumbauld, 2008). Most of the harvest of Green sturgeon occurs on these migrating population concentrations via by-catch and is unintentional.

The National Marine Fisheries Service identified two distinct population segments (DPS) based on the fish's fidelity to distinct spawning sites. The northern population segment was found during this status review to have insufficient information to show that they are in danger of extinction or would likely to become so in the foreseeable future. However, the review also concluded that they face considerable threats to their populations and was therefore placed on the candidates list and will have their status reviewed again within five years. The Southern populations segment did not have declining population trends but did face a number of potential threats to their populations. These concerns included concentration of spawning habitat, lack of population data, harvest concerns, and loss of spawning habitat. Of extreme concern was the unknown harvest impact on populations in coastal rivers and estuaries. Both the northern and southern population segments are known to utilize the Willapa Bay estuary (Adams, 2002).

Little is known about the feeding habitats of Green sturgeon beyond general information. Adults captured during the NMFS review for ESA status substantiated that adults are benthic feeders on invertebrates, including shrimp, mollusks, amphipods, and even small fish (Adams, 2002). Sturgeons are among the largest and most ancient of bony fish. They are placed, along with paddlefishes and numerous fossil groups, in the infraclass Chondrostei, which also contains the ancestors of all other bony fishes. They have a cartilaginous skeleton and possess large ossified plates, called scutes, instead of scales. Sturgeons are highly adapted for preying on benthic organisms (e.g. clams, shrimp, etc.), which they detect with a row of extremely sensitive barbells on the underside of their snouts. They protrude their extraordinarily long and flexible "lips" to suck up food.

Green sturgeon are similar in appearance to the white sturgeon, except the barbells are closer to the mouth than the tip of the long, narrow snout. The body color is olive green with a stripe on each side. Sturgeon live a long time (40-50 years), delay maturation to large sizes (125 cm total length/ 4 + feet), and spawn multiple times over their lifespan but not until 15-17 years of age. This life history strategy has proven to be successful in the face of normal environmental variation in the large river habitats where spawning occurs. The sturgeon's long lifespan, repeat spawning in multiple years, and high fecundity allows them to persist through periodic droughts and environmental catastrophes. Adult green sturgeon do not spawn every year, and only a fraction of the population enters freshwater where they might be at risk of a catastrophic event in any year (US Bureau of Reclamation, 2008). Note the unique features of the Green Sturgeon in the graphic below (Figure 12).

Figure 12. Green Sturgeon.



Source: US Bureau of Reclamation, 2008

Harvest of Green sturgeon occurs during by-catch of two commercial fisheries: gill netting of salmon and by-catch of commercial white sturgeon. As previously mentioned, the commercial fisheries in the late 1800's in the Columbia River region for White sturgeon collapsed when mortalities exceeded the sustainability of the stock. The white sturgeon fishery collapse might have caused an accompanying decline in Green sturgeon however this data is unavailable and therefore uncertain and anecdotal at best. The total harvest of green sturgeon in the Columbia River, Washington coastal areas and the Oregon and California fisheries declined to 1192 fish in the 1999-2001 from a high of 6871 in the 1985-1989 (Adams, 2002). The commercial fishing of white sturgeon continues to this day and was valued at $10.1 million in 1992 (Wikipedia, Undated) and sells currently for ~$10.00-$12.00 per pound. The flesh of Green sturgeon is considered inferior and is therefore not assigned a commercial value.

Analysis of 95 Green sturgeon stomachs from the California to British Columbia revealed that those fish with items in their guts (many were empty) fed on benthic prey items and fish. Burrowing shrimp (mostly *Neotrypaea californiensis*) were identified important food items for white and especially green sturgeon in Willapa Bay where they represented 51% of the biomass ingested. It is necessary to develop non-lethal investigative gut sampling methods now that the sturgeon is an ESA listed species. Further evidence of the Green sturgeon's feeding habit is found in the form of feeding pits which can be observed in intertidal areas dominated by burrowing shrimp. There is significant evidence (Dumbauld, 2008) that these "predator pits" can have an effect on the density of burrowing shrimp. These Green sturgeon predators are thought perhaps to have had an important top down population control effect on the shrimp populations when they had a more significant population.

Despite the evidence that has been presented here: that these threatened and species of concern ESA listed fish feed on the same shrimp that are controlled with Carbaryl, my literature review and associated interviews reveal that it is unlikely that these control methods are much of a limiting factor for Green sturgeon populations. It is difficult to say with certainty because of limited before and after population data. This lack of data is a product of their low commercial value, inferior flesh and their biology (by spending lots of time out at sea they are difficult to track). Though the present day Columbia River White sturgeon fishery is arguably one of the most healthy sturgeon fisheries worldwide, Whites dominate Greens in the Columbia estuary while Green sturgeon are known to be more dominant in the Willapa estuary (Dumbauld, 2008).

Declines in shrimp predator populations (including the Green sturgeon) have been suggested as one reason that the shrimp population increased historically. It is likely that this was a contributing factor based on the ecology of each of the species but not the only factor. Other possibilities include loss of additional predators, watershed changes resulting in freshwater and sediment dynamics (related to hydropower and the timber industry). Using Green sturgeon as an alternative control method for the shrimp (by penning over oyster beds) is problematic given their ESA status, the nature and flux of tides, and their biological desire to stay in the marine waters far more than other types of sturgeon.

It has been questioned whether the Carbaryl applications in oyster growing areas threaten populations of sturgeon (Dumbauld, 2008). The answer to this depends largely on space. Given that ~21% of Willapa Bay is used for oyster cultivation (3642 hectares) and a smaller percentage of the beds are actually treated with Carbaryl (324 hectares/annually). Extensive shrimp beds exist outside of the oyster beds (and treated oyster beds) so much so that it is unlikely that the availability of uncontaminated food (shrimp) is the limiting factor in the green sturgeon's population (Dumbauld, 2008).

There are other significant challenges to the green sturgeon (by-catch, anthropogenic impacts to spawning and rearing habitat, predation on eggs, larvae, and juveniles in streams) that make it tough for this small population to recover. This coupled with poor data makes their population difficult to track. Enhancements to the sturgeon population are worth investigating to restore this important benthic predator and this could have a symbiotic benefit for the oyster industry. This would be difficult to implement given their Endangered Species Act status and their elusive nature. Because these fish are long lived, have a delayed maturity, and only spawn intermittently in distant streams it would be difficult to set up a supplemental hatchery program. There is no evidence to support that the carbaryl spray impacts the fish but their population decline may contribute to higher shrimp population given the predator/ prey relationship.

Dungeness crab

Peak harvest for the commercial Dungeness crab in coastal Washington is during January and February, which means big swells and storms. The season runs from December 1st- September15th. Dungeness crab are typically harvested anywhere from 12-200 feet from the surface with an average of 60ft deep (Suderman, 2011). Washington State licenses 238 commercial fisherman and 30 tribal fishermen for the coastal crab fishery on an annual basis. There are literally tens of thousands of pots out catching crabs during the season. The crab is named for Dungeness Bay- to the north in the Strait of Juan de Fuca near Port Angeles, Washington but its habitat ranges from Alaska to Santa Barbara, California including the Pacific Coast shelf and Puget Sound.

These crustaceans shed their shells up to 12 times before getting to a harvestable size, a process called molting. Before and after molting the crab develops its shell. While the shell is hardening and it is in a soft shell stage they actually inflate themselves slightly with water to make it larger and grow into it. When crabs are in this soft shell stage handling more easily damages them. The major molting takes places in the late summer and early fall so the commercial fishery is closed during this time. When the crab is mature and their shell is hard their meat yield is about 25% of their weight- making them one of the highest yield ratios of any food crab (Sudermann, 2011) and underscoring their importance as a commercial fishery.

Each year crabbers estimate that they take about 90% of the harvestable catch. By throwing back females and smaller males (less than 6.25 inches across the shell) the fishermen have reached a relatively stable harvest level (Sudermann, 2011). The record catch for Dungeness crab in Washington was 25 million lbs (during 2004-2005) though the average over the last three years is about 9.5 million lbs. The Washington Department of Fish and Wildlife states that the commercial Dungeness crab fishery is one of the most important in the state. The average ex-vessel value of is approximately 19.9 million/yr (WDFW, Undated). The Dungeness crab is typically priced between $5.00 and $7.00 per pound retail. Fluctuations in harvest levels are likely due to varying ocean conditions including water temperature, food availability, and ocean currents (WDFW, Undated).

In 1997 Congress granted management authority for the crab industry to the states of Washington, Oregon and California outside state waters (3-200 miles offshore). While harvest levels have not been a large issue for the coastal fishery a pot limitation program was implemented in the 1999-2000 season to slow the competitive nature of the fishery. Prior to this implementation 50% of the season total was landed in the first 3-4 weeks of the 9-month season. Additional harvest rights were upheld in 1994 by a federal district judge who ruled that Washington treaty tribes can harvest up to 50% of harvestable shellfish in their usual and accustomed fishing grounds which is approximately 50% of the Washington state coastline (WDFW, Undated).

Willapa Bay is an important nursery area for Dungeness crab. Larvae released into the coastal waters settles into onto benthic habitat in the Bay beginning in early spring. The highest settlement of crab larvae is in oyster shell and eelgrass habitat in coastal estuaries (Doty, 1990). Nearly all of the newly settled juvenile crab known as Young of Year (YOY) are killed shortly after spraying if they are present on the sprayed beds. It is possible that crabs on adjacent beds are also killed. Re-colonization is known to occur within one month on sprayed plots. Crab mortality depends on the type and extent of habitat in the area and the timing of the carbaryl application. One researcher in the area developed a worst-case scenario model to estimate the impact of the carbaryl applications on the Dungeness crab in Willapa Bay from 1985-1987. He estimated 3-4% of the YOY crab would be killed with the assumption that 2400 hectares are under ground culture and the acreage treated with carbaryl was 111-145 ha annually (Doty, 1990). If this scenario and the average harvest statistics hold true it appears that the carbaryl applications though lethal to juvenile crab do not ultimately affect the population of Dungeness crab.

The replacement of burrowing shrimp habitat with oyster beds, while providing a high quality-rearing habitat for crabs, does suggest that more crabs survive than if the oyster shells were not present (Simenstad and Fresh, 1995). However, if the native oyster reef were intact crab populations would be likely to respond accordingly. By improving the habitat structure the oyster industry might be mitigating the impacts of carbaryl on crabs by increasing crab production (Simenstad and Fresh 1995). However, if the oyster industry wasn't spraying carbaryl and the oyster reef existed there would perhaps be less need to mitigate and consistent crab habitat as the dredging of oysters currently disrupts the habitat. If the industry could leave some oyster reef structure intact perhaps that would work towards mitigating impacts to Dungeness crab populations. This may not economically advisable however, and the bottom line is that harvest levels of Dungeness crab do not appear to have been affected in a negative manner since the spraying began.

Ecological Economics and the Future

The oyster industry in Willapa Bay does provide tangible ecosystem service benefits in the form of nutrient sequestration, habitat value, and water filtration. There is not adequate data to compare the difference in benefits derived from the modern day single introduced species commercial scale harvest to the historic native oyster populations that grew in reefs. It is likely however that both provide the above mentioned ecosystem services with unknown variation. There are externalities associated with the modern day harvest in the form of Carbaryl application, which is likely to be replaced with a different control method (perhaps chemical but not necessarily) in 2012. Other externalities include the replacement of the Olympia oyster with the Pacific oyster and regular disruptions to the Bay sediment from harrowing and dredging.

These externalities did not exist historically and occur now as a cost of the industries scale. There are costs associated with the spraying of Carbaryl to many other ecologically important species (and some commercially important such as Dungeness crab, and Salmon). It is difficult to evaluate the costs to species, which are not commercially important because it involves assigning non-market value and assessing intrinsic worth.

While a chemically based control regime may well be the most economically efficient and effective method at controlling the target organism, it can also be viewed as a market failure in economic terms. A market failure refers to a concept within economic theory where the allocation of goods and services by a free market is not efficient. The existence of a market failure is often associated with externalities and at times this is used a justification for government intervention in a particular market. Valuing the externalities caused by the application of Carbaryl is a difficult and subjective undertaking. However the fact the legal settlement that bans Carbaryl aquatic applications in this part of Washington State is evidence of such a market failure.

There are barriers, which prevent change amongst the stakeholders (oyster growers) including increased labor and equipment costs associated with alternative growing methods and scaling back production. The amount of value that is assigned to the targeted shrimp and non-target organisms that are impacted is largely subjective as previously discussed. Therefore whether a remedy is warranted to correct this market failure is also a matter of opinion in addition to factoring in those costs of alternative growing methods.

As noted earlier the relative economic contributions are difficult to fully characterize because wages and jobs associated with the industry quickly multiply outside of the Pacific county region. There is a tangible contribution to the local economy by the shellfish industry however, which is undoubtedly extremely important to those who make their living and livelihood this way. This industry has grown in scale and changed in its economic impact over its storied past.

We live in an era of shifting baselines where residents may not remember the time where native oyster reefs dominated the Willapa Bay and Olympia oysters were harvested from a wild set and consumed at a smaller scale. There has been tremendous landscape scale change within this ecosystem over the last 200 years and the oyster industry has grown, with some costs, to be very successful commercial industry. Any ecosystem can be altered over time through persistent disturbance and an estuarine bay is no exception. Cultivation of single non-native species at the current mechanized scale is a major transition from the Bay 200 years ago. Even given the relative “newness” of this change in the context of history generations have still made their way of life and livelihood as oyster farmers.

“Management strategies that fail to consider the tolerance of estuaries to anthropogenic disturbance such as that posted by intensive aquaculture may well threaten the sustainability of estuarine resources and ecosystem processes upon which coastal economies depend (Simenstad and Fresh, 1995).” Ultimately the health of the oyster industry depends on the health of the estuary itself, which is built from the summation of all species within that system and must also take in to account the past and present activities throughout the watershed.

Future research is suggested to include an assessment of the feasibility of a sustainable certification or organic label for the industry, and the feasibility of Green Sturgeon enhancement. As a market fix, a sustainable or organic label could offset additional costs incurred by changes in growing practices and increased labor costs by fetching a higher price for the product. Green Sturgeon enhancement, if economically and ecologically feasible, could decrease shrimp populations while mutually benefiting the goals of restoring an ESA listed species.

Conclusions and Recommendations

The Willapa Bay estuary ecosystem is complex and the demands on its resources many. The land use and development patterns in the surrounding watershed have likely contributed to the current conditions within the Bay- particularly the pest management issues. The Bay has been home for nearly a century to intensive aquaculture and prior to that was the home of native oyster reefs. While there are similarities between oyster farming and native oyster reefs from an ecosystem service perspective (in terms of nutrient sequestration and filtration capabilities) there are differences in harvest and growing scales that may also have contributed to a changed ecosystem which favors burrowing shrimp.

A combination of activities over the last 150 years has resulted in great changes. The forested slopes surrounding the Bay have been cut several times over. The native oysters are no longer common or food source within the Bay, nor do their reefs provide consistent habitat structure. The current commercial scale of aquaculture results in more frequent disturbances of the oyster beds. A large sector of the market favors single shell oysters rather than clusters which leaves growers relying on the cost effective ground culture method. The river systems have been scoured of sediment and changed as a result of early timber harvest practices. The resulting increased sediment load affects ecosystem processes and physical characteristics of habitat for predators of the burrowing ghost shrimp among other species. The largest river system in the region, the Columbia, has been tamed with the placement of over 400 dams throughout all reaches of its watershed, which has contributed to changes in freshwater dynamics and salinity within Willapa Bay. The mouth of the Columbia saw an intense period of unregulated overfishing for finfish, which are predators for the burrowing ghost shrimp. While it is difficult to attribute any one of these factors solely to an increase in burrowing shrimp populations there is consensus among diverse stakeholders that populations of native burrowing shrimp increased in the 1950’s and 1960's. I believe this is due to the sum of these and perhaps other watershed scale anthropogenic changes.

Whether perpetuated by the oyster industry's dredging, brought on by changes in water chemistry or more available substrate, or even imperceptible shifts in the marine food chain or ocean conditions, shrimp populations reached a level such that they were interfering with the ability to successfully harvest Pacific oysters at a commercial scale. In response, many growers but not all, begun to rely on periodic control of the shrimp through the application of the insecticide Carbaryl. While imperfect in that Carbaryl kills more than just the desired target, this practice has been authorized and regulated for many years by several Washington state agencies and ultimately the Environmental Protection Agency. This will change in 2012, due to a legal settlement. How that change materializes and what form of control is used in the future is unknown at this point. Several alternatives are in the process of being assessed for their feasibility. Imidacloprid, another insecticide, looks like a promising alternative but it too is imperfect in that it has to be applied at higher rates in order to be effective and even so is somewhat ineffective when compared to Carbaryl (Researcher 1, Personal Communication 2011). The use of a different pesticide to control shrimp populations is not likely to a satisfy those who raised the Carbaryl lawsuit (Researcher 3, Personal Communication 2011).

There is ample evidence that the application of Carbaryl is toxic and does kill juvenile Dungeness crab. While that is true, it also appears true that this practice has not affected the harvest or populations of crab harvested off the

Pacific Coast of Southwestern Washington since the practice began. Harvest has been for the most part steady and reliable based on the numbers provided above. The commercial oyster industry does provide habitat for juvenile crab in the Bay and this may well mitigate some of the crab losses due to the carbaryl spraying but there are documented mortalities as a result of the chemical treatment.

There is also evidence presented within that the Green sturgeon, which has been listed as species of concern and threatened (per northern and southern population segment respectively) feeds upon the shrimp, which are controlled with the Carbaryl application. Given this, it is easy to posit that the control of shrimp with this pesticide does not help recover this population. This is an elusive fish, which is difficult due to the fact that it is not particularly valuable commercially and because it spends a lot of time out at sea. While challenging, and perhaps not practical given their biology, there is an argument to start a hatchery enhancement program for the Green Sturgeon since they are a natural predator for the shrimp in question. The control of the burrowing ghost shrimp does not appear one of the main factors influencing the population- given the large region the fish inhabit, and the relatively small percentage of the beds that are sprayed for shrimp control.

It is inherently difficult to separate the effects of the commercial oyster industry from the carbaryl applications. There is habitat value gained by having the oysters in beds as proven with species abundance and diversity studies. However, the persistent disturbance of eelgrass habitat (via dredging, harrowing, and leveling) and the replacement of oyster reefs with ground single shell oyster culture may have actually promoted the expansion of burrowing shrimp by allowing these disturbance orientated shrimp to colonize stressed eelgrass habitats. (Simentsad and Fresh, 1995)

"Aquaculture management should consider the industry and economic asset as an ecological force," (Simenstad and Fresh, 1995). This is the fundamental base of ecological economics. The oyster industry is an ecological force because it influences important estuarine processes and it is also an obvious economic force for these rural communities. Management of the aquaculture industry in this region as a whole has largely been geared to look at the oysters (and other shellfish) as natural resources not evaluated or managed as a disturbance (Simenstad and Fresh, 1995) nor taking into account the industry is primarily based on a non-native species. There has been a tendency to focus on effects of water pollution and navigation rather than considering the environmental costs and benefits of aquaculture on other estuarine resources. Typically effects of certain aquaculture practices have been questioned only when another commercially important species such as the Dungeness crab are at risk. This analysis contrasts risk of a commercially important species with an endangered but not commercially important species (the Green Sturgeon).

The oyster industry should seek to minimize its impacts within an ecological context in order to support the health of the estuary system that it depends upon. It is survival. The loss of native oyster reef/ replacement with a non-native species grown at a commercial scale has ecological implications that may ultimately be contributing to the issue with the native shrimp pests. There is likely room for mitigation but it may come at the cost of the current size and scale of operations.

Holistic evaluation of this industry and this region involves looking at history as well as neighboring ecosystems and multiple resource extraction based industries. In order to evaluate future proposed alternatives the implications on multiple species (those commercially important and those deemed not commercially important) should to be evaluated and taken into consideration. The history and degree to which the industry and this region has changed over the last 150 years needs to be appreciated, further assessed and taken into account. Future management decisions will likely include ecological and economic compromise. It is a remarkable story to date and the future appears to hold that promise as well.

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