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Potential Future Impacts of Sea Level Rise on Shellfish Mariculture in Humboldt Bay

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Opportunities, Challenges, and Recommendations

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Disclaimer

This document was produced in the Senior Practicum Class, EMP 475 Spring 2014, by students in the Environmental Management and Protection/ Planning Option in the Department of Environmental Science and Management at Humboldt State University. Any views or opinions presented are solely those of the authors and do not represent the University.

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Executive Summary

Humboldt Bay is among the largest producers of oysters in the United States. As shellfish production is a vital component of the local economy, iy is important to understand how this industry is likely to be affected by sea level rise. This report examines the existing conditions for oyster cultivation in Humboldt Bay, how, according to the best available scientific information, conditions are expected to change as a result of sea level rise, and how these changes could influence oyster cultivation opportunities in the future.

We conducted research using both published sources and interviews with local professionals. We began by determining a baseline of the habitat requirements for oyster cultivation, which was compared with the habitat conditions present in Humboldt Bay. The current conditions and water quality present in Humboldt Bay were found to be ideal for oyster mariculture. A local fisheries biologist and hydrologist were consulted to gain information about how these conditions might change as sea level rise occurs. After consulting with experts and the best currently available literature, we believe that SLR will not have a direct negative impact on the water chemistry and overall water quality present in Humboldt Bay in the near future, but it will be important to begin collecting local data and monitoring for changes in water conditions over longer periods of time. As the volume of water within the bay continues to increase as sea level rise occurs, threats to oyster health and water quality will arise mainly from the surrounding landscape.

Much of the shoreline around the bay was heavily modified with earthen dikes during the late 1800s and early 1900s, and currently only 25% is natural. The bay now takes up a much smaller footprint than it did historically, and industry, agriculture, and grazing all have thrived on the enclosed lands. Several communities of varying sizes are located around the bay. A large portion of the artificial shoreline is in disrepair, and several of these areas have already experienced the impacts of SLR during extreme winter high tides and storm events. The integrity of shoreline

infrastructure will continue to be tested as the volume of water in Humboldt Bay increases, and the landscapes behind them are increasingly at risk.

Certain on-shore areas containing hazardous materials, especially industrial brownfields and wastewater treatment facilities, will pose a greater threat to water quality in the bay as sea level rises. While larger sites that are potential sources of contaminants are better documented and accounted for, less well known sites such as residential septic systems in the community of Fairhaven could pose risk to the oyster industry. These locations along the peninsula must be monitored and planned for to ensure that fecal coliform or other bacteria are not entering the bay. In addition, the City of Arcata's wastewater treatment plant relies heavily on its bayside location, but its dikes have already been breached by storm surges in recent years. Recently, the City of Arcata received a Climate Ready Grant from the California Coastal Commission to fund and permit protective living shorelines and sea level rise adaptation measures around this vital infrastructure.

In order to adapt to an increasing volume of water, the footprint of Humboldt Bay will need to expand. Raising and maintaining dikes and artificial shoreline is expensive. As the responsibility for repair and upkeep of dikes falls upon individual landowners, a regional approach to planning involving all stakeholders and landowners will be critical to forming an integrated adaptation plan and deciding where to shore up dikes and where to retreat. One approach could be to strategically return some areas to tidal influence, to help reduce pressure on significant diked resource areas or infrastructure elsewhere. Such renewed tidally influenced areas would provide ecosystem services and possibly support some expansion of mariculture. If Humboldt Bay' high water quality can be sustained, the oyster industry, including other supporting operations such as hatcheries and processing facilities, will have the opportunity to expand in future. It is further possible that mariculture operations involving other species might be initiated and help to diversify the oyster based economy. In order to make the most informed planning decisions, there is a need for more local monitoring of sea level rise on Humboldt Bay.

We suggest that a Humboldt Bay-wide regional planning approach will be of benefit for mariculture operations seeking to adapt to sea level rise into the future. Bay planning could be coordinated by local government entities such as the Humboldt Bay Harbor, Recreation, and Conservation District and Humboldt County, so that all manner of stakeholders, landowners, and communities around the bay may form a common vision for the future of Humboldt Bay and coordinate their adaptation efforts.

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Introduction

Humboldt Bay has had a rich history of human interaction, as it has provided a source of shelter, food, fertile land, and other resources. Indigenous peoples thrived here for thousands of years recognizing not only Humboldt Bay's bounty of resources, but also its significance as a sacred landscape. Local tribes, in particular the Wiyot People, lived largely in balance with the landscape, without having a lasting physical impact on Humboldt Bay or its ecosystems. The majority of European settlers, who began arriving in the mid 1800's, brought with them a different world view. They ignored any prior rights the Wiyot might have claimed and proceeded to modify Humboldt Bay and surrounding lands to best suit their needs and their ideas for economic prosperity. By the end of the century, the remaining Native American community had been marginalized in their ancestral homeland (Wiyot Tribe, 2014).

Beginning in the 1850s, European settlers quickly began establishing shipping channels, bayside communities, and modifying the shoreline of Humboldt Bay to support agriculture. Soon after, railroads and timber mills were established.. Historical maps representing Humboldt Bay from 1870 compared to aerial images of the bay's current extent reveal how heavily the geography of this area has been modified, and how the size of the bay itself has been greatly reduced (Figure 1). Presently, little natural shoreline remains and much of the various types of man-made shoreline structures such as earthen dikes and railroad berms have gone unrepaired for up to one hundred years (Laird 2013).

Figure 1*: 1870 Humboldt Bay shorelines with an estimated 60 miles of shoreline. While the Bay's shoreline is slowly subsiding, 18.6 inches of the sea level is rising per century in the North Spit (Russell &Griggs, 2012). Image from Laird 2013.*

Humboldt Bay has provided a plethora of marine resources for settlers over the years, resulting in a local economy supported in part by a large commercial fishing fleet (Higgins 2009). However, the commercial fishery has been greatly reduced in recent years, with much of the fleet moving to other locations including Trinidad Bay to the North (Revitalization Plan 2003). Today, much of the marine based economy in Humboldt Bay depends upon mariculture, or the raising of marine species such as oysters or other shellfish for market sale. The bay is known to exhibit ideal conditions for mariculture and is currently home to one of the leading producers of oysters in the U.S., Coast Seafood Company.

It is clear that sea level rise (SLR) will affect Humboldt Bay, the question is how much and how quickly. Landowners in coastal communities, especially those built on and around heavily modified shorelines, wish to know how they might be affected and what might be the best options for future planning and development. While the impacts of SLR and climate change will be dynamic and are largely unpredictable for a specific location, decision makers can make preparations on a local level based on known conditions and hazards. Proactive planning efforts involving areas of impact over which humans have some degree of influence will help to form a more resilient community that will be prepared when more hazard events occur (Beatley 2009).

Marine based economies, such as those of Humboldt Bay could be most vulnerable to the impacts of sea level rise due to their geographic vulnerability and reliance on natural marine processes. This report investigates how sea level rise will potentially impact mariculture on Humboldt Bay, and specifically oyster mariculture, as this is largest branch of the industry in this region. Several oyster farming operations are well established primarily throughout North Bay and their success relies on the favorable habitat conditions present in the bay. Oyster mariculture is a large contributor to the local economy and previous research indicates that the industry has potential to grow and expand into the future under the right conditions (Carter-Griffin et. al 2010).

Research and Methods

The research reported in this document was carried out between January and April 2014. We reviewed the literature through online databases and Federal, State, and Regional Agency reports, and interviewed local mariculture industry experts, resource scientists, and environmental agency staff (HSU Institutional Review Board permission # 13-121).

We began our research by developing a conceptual model of the problem of SLR for oyster cultivation (Figure 2). Based on this framework, we first determined the ideal habitat conditions for growing Pacific Oysters. We then identified the current habitat conditions present on Humboldt Bay in terms of habitat, water quality, and climate, and compared them with the ideal conditions. This helped us to gain an understanding of the limiting factors for oyster mariculture on Humboldt Bay, water quality in particular. Next, we focused on how sea level rise (SLR) is expected to affect Humboldt Bay and its surrounding shoreline and terrestrial landscape, and what the implications of such impacts on oyster habitat might be.

We interviewed several local experts in the fields of fisheries biology, hydrology, and brownfields in order to determine how changes in sea level and tidal influences within the bay could affect the conditions that allow for oyster mariculture. In addition, a local mariculture expert was an important source of information regarding the intricacies of raising oysters and the current state of the industry. With some understanding of how conditions for mariculture within the bay are likely to be affected by sea level rise, we focused our attention to the terrestrial landscape along the bay's shore and surrounding areas that might be impacted by sea level rise and in turn impact oyster mariculture. We started with brownfields known to contain hazardous materials, and municipal wastewater treatment facilities, and then researched less well documented areas such as septic systems. Then, we analyzed potential challenges or opportunities that might result from SLR-caused inundation of agricultural and grazing lands, and areas of shoreline under tidal influence.

We synthesized this information in order to determine which impacts might occur on their own, and which might be cumulative if or when they occur simultaneously. We then worked to determine which impacts of sea level rise will pose the greatest threat to oyster production and where planning efforts could best be focused. Since the exact impacts and severity of sea level rise on Humboldt Bay cannot be predicted, we decided it best to identify which impacts are most likely, and recommend planning for them to ensure the viability of mariculture into the future.

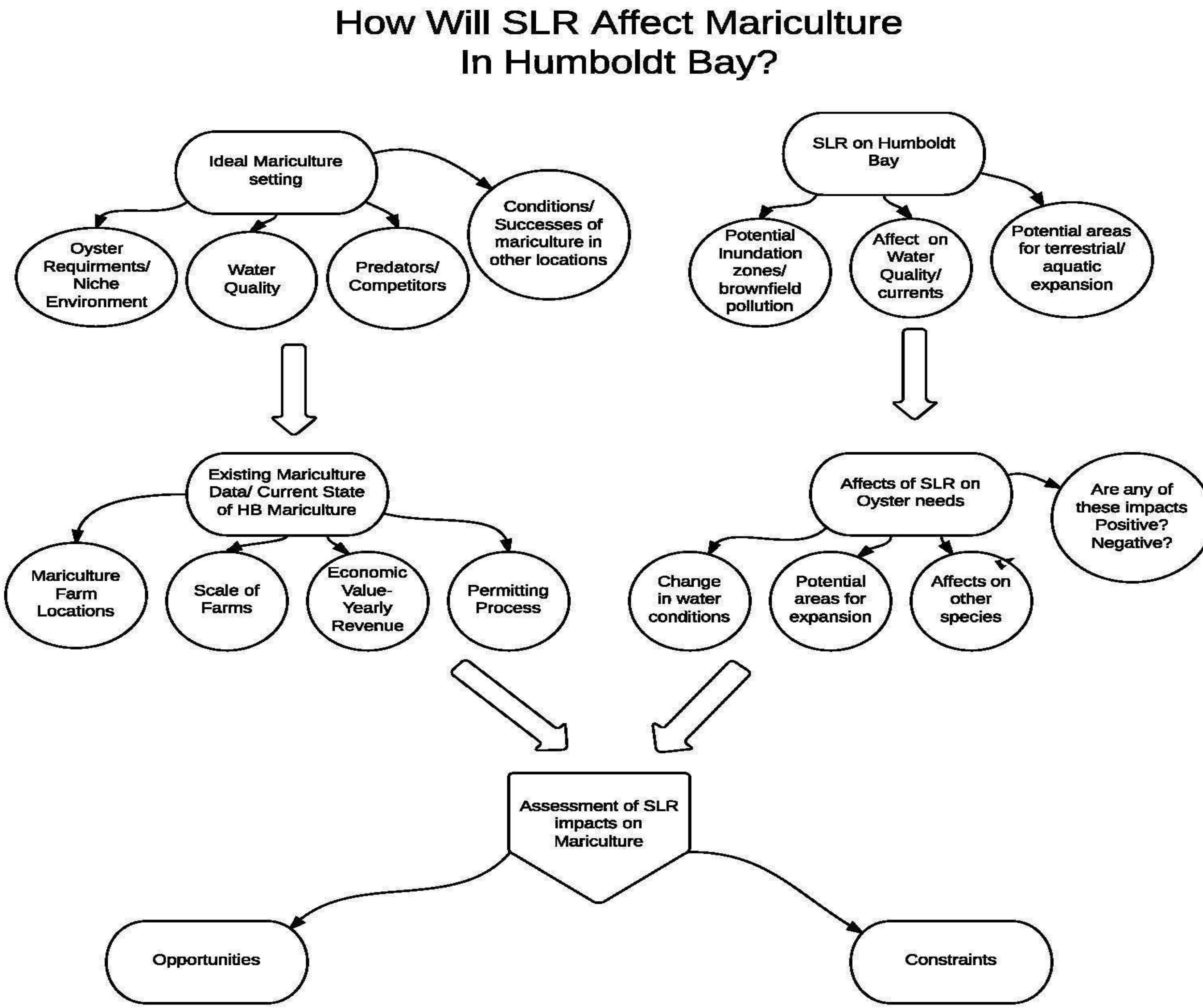

Figure 2. *Flowchart depicting research design.*

Existing Conditions

Climate

Humboldt County has a temperate climate. Temperature around the bay is averages 53 degrees Fahrenheit and typically only varies by ten degrees from summer to winter (Humboldt County, 2013). The Humboldt Bay area gets less than 33 inches of rain annually, most of which is received from November through March. The region's cool coastal climate, with a cool fog layer during summer months and high precipitation during winter months allows the waters of Humboldt Bay to maintain thresholds of relatively stable temperatures (Barnhart et al, 1992).

The winds in the area are consistent and strongly influence tidal patterns on the Pacific Ocean. In the California North Coast Air Basin, dominant winds follow a seasonal pattern, especially in coastal areas such as Humboldt Bay (Western Regional Climate Center, 2008). During the summer, strong north to north-westerly winds are common and allow cool, ocean bottom waters to rise to near shore waters. Consequently, a fog layer occurs due to cool air and water vapor condensation, aiding to the area's relatively cool conditions all year round (Barnhart, 1992). Throughout the winter, storms from the South Pacific increase the percentage of days winds are from southerly quadrants (Humboldt County General Plan Update, 2012). These climatic conditions have a strong influence on water quality in Humboldt Bay.

Water and Habitat Conditions

Wigi, or Humboldt Bay in Wiyot traditional language, has supported a variety of fish, mammals, invertebrates, and bird species (Wiyot Tribe, 2014; Barnhart, 1992). The Bay originally encompassed about 10, 931 hectares but development of infrastructure such as dikes and activities like dredging have reduced the Bay's total area to around 7,290 hectares at mean high tide. The conversion of Bay habitat to other land uses has led to a decrease in habitat and species variety. Salt marsh reduction, as a result of dredging, has also decreased the Bay's tidal prism, altering fish and wildlife habitat. Shoreline habitat alteration has affected wetlands over the last century, altering the lengths of time during which wetlands are inundated with water, changing biological and chemical components of water, and increasing human interaction with these habitats (Barnhart, 1992). In the last century, Pacific Eelgrass has been recognized as a feature of wetlands that not only provide critical habitat, but other ecosystem services.

Eelgrass beds are an important component of shoreline habitat. Eelgrass occurs mainly in the intertidal zone, and plays important roles in the ecosystem, such as capturing sediment, which increases water clarity. Furthermore, eelgrass creates characteristic microclimates within the water column and provides food and shelter for a diverse range of species. Eelgrass beds, therefore, aid in maintaining biodiversity and water quality within the bay.

Superior water quality in Humboldt Bay makes the area ideal for oyster cultivation. Approximately 41% of Humboldt Bay's water volume is replaced by tidal influences daily, with complete replacement occurring about once every week (Costa 1982; Anderson 2008a). Salinity in the Bay is similar to the near shore waters in the ocean ranging from about 25 to 34 parts per thousand, or ppt. During the rainy seasons, the salinity is lowered due to runoff from the land. Higher salinity levels in the bay are associated with offshore upwelling along with high evaporation rates, which typically occur during the summer months around the bay. Hypersalinity, salinity that is higher than seawater, can occur in late summer months (Eicher *et al.,* 2012.)

Water temperatures in the bay vary widely with time of day, season, stage of tide, depth, distance from the mouth of the bay, and the offshore oceanic water conditions. The temperature for Humboldt Bay ranges from approximately 48 to 68 degrees Fahrenheit (8.9 to 20 degrees Celsius.) Measurements of pH ranged from a low of 7.42 in October of 2004 to 8.54 in November of 2003 (Pinnix *et al*, 2005.) Dissolved oxygen is relatively low in the deeper channels of Humboldt Bay, but waters are generally near saturation in shallow waters that cover the mudflats around the bay (Eicher *et al.,* 2012).

History of Mariculture on Humboldt Bay

Before European settlement, Native Americans harvested the region's native Olympia oyster *(Ostrea conchaphila)* from Humboldt Bay. Prospectors from the gold rush who settled in the area established commercial oyster fisheries that rapidly consumed the slow-growing Olympia oyster stock (Poor, 2011.) By the late 1850s, the native oyster population was significantly lowered due to overharvesting.

In the 1880s, the first published report of oyster cultivation in Humboldt Bay noted that the operations were composed exclusively of native oysters *(O. conchaphila)* (Humboldt Standard, 1931). Humboldt Bay did not support notable mariculture operations until the 1950s, after Pacific (*Crassostrea gigas*) and Kumamoto (*Crassostrea gigas Kumamoto*) oysters were introduced to the region. The primary method of cultivation from the 1950s to 1996 was ground culture, in which oyster beds are located directly on the bay's floor. During this time, about 500 to 600 acres of the bay were used for oyster production. By 2006, the majority of Humboldt Bay oyster companies had converted from ground cultivation methods to off-bottom, long line systems. Oyster cultivation today utilizes about 450 acres of Humboldt Bay (Eicher *et al.,* 2012). The transition from ground culture to long line systems has proven to be more ecologically and economically sustainable for a number of reasons. Not only do the lines eliminate the need to hydraulically harvest the oysters from the bay's floor, which decreases turbidity, but they also remove the oysters from predation that had previously been an issue. Using off-bottom methods of oyster cultivation also creates a more sustainable industry by promoting faster growth rates, increasing survival, improving shell shape and appearance, and increasing product consistency in the cultivated oysters (Walton et al. 2012.)

Figure 3: *1963 Hand harvesting Pacific oysters from a soft-mud bed, Arcata Bay. Source: California Department of Fish and Wildlife.*

Pacific Oyster Mariculture Requirements

The Pacific Oyster (*C. gigas*) thrives in Humboldt Bay, an indication of the Bay's health and water quality. The habitat requirements needed to farm oysters in a natural bay environment include food availability from coastal upwelling, certain levels of salinity, pH, temperature, water circulation, water depth, and siltation and substrate composition (Barnhart et al, 1992). Together the water quality and temperate ambient climate promote healthy oyster populations and, therefore, enable industrial oyster production on the Bay.

The Pacific Oyster is a bivalve, benthic species with a rough, highly fluted shell known to reach a maximum width of 10 inches. The typical width of an adult spans between 4-5 inches (Pauley et al, 1988). Juvenile and adult oysters are mainly found in lower inter-tidal estuarine areas at a depth of 13 feet (Whatcom County, 2014). They can also be found on rocky, mud or mud-flat at estuarine bottoms.

A crucial food source for Pacific oysters comes from micro-algae blooms of phytoplankton associated with offshore upwelling events (Barnhart et al, 1992). The constant circulation of water within the Bay allows for nutrient-rich waters to enter from offshore, providing phytoplankton and nutrients to oysters. The Pacific oyster is most susceptible to changes in water temperature and salinity levels. Due to the wind patterns and ocean currents of the Pacific Northwest, oyster success is high. They tend to survive under temperatures ranging from 4 to 24 degrees Celsius (39.2 to 75.2 degrees Farenheit), with a temperature for optimum yield of 20 degrees Celsius (68 degrees Farenheit) (Pauley et al, 1988). Salinity levels contribute to certain biological functions such as feeding and degree of shell opening, and the varying salinity levels in the bay cause by offshore upwelling events contributes to oyster success. (Pauley et al, 1988). Optimum salinity for Pacific Oysters occurs at 25-35 ppt (Pauley et al, 1988).

Sea Level Rise

Introduction

We focused on relative or local sea level rise (SLR) as it pertains to Humboldt Bay, rather than total mean global or regional/eustatic sea level rise. Local sea level rise takes into account the factor of tectonic uplift, or vertical land movement, that occurs around Humboldt Bay due to its position at the southern end of the Cascadia Subduction Zone. Continuing research by the Humboldt Bay Vertical Reference Group and Cascadia Sciences suggests that the land beneath Humboldt Bay is subsiding, so this factor must be taken into account when considering the local rate of sea level rise in the bay (Cascadia 2013). Some of the effects of sea level rise can already be witnessed around Humboldt Bay and its networks of sloughs and tributaries, especially during king tide and storm events. These types of events, such as in 2003 when a 9.51 foot winter high tide combined with a storm surge to overtop earthen dike along Mad River Slough, flooding 600 acres of pasture (Figure 4), are well documented in Aldaron Laird's *Humboldt Bay Shoreline Inventory, Mapping, and Sea Level Rise Vulnerability Assessment* (Laird 2013). In 2006, Humboldt Bay was even declared to be in a state of emergency by former Governor Schwarzenegger after a 9.49 foot high tide and heavy rainfall allowed the Bay to overtop several sections of dike around the Arcata Wastewater Treatment Facility in North Bay.

Figure 4. *Flooding of pastureland next to Mad River Slough as a result of earthen dikes being overtopped in 2003 (Times Standard 2003, Laird 2013).*

SLR on Humboldt Bay

During this century, California sea levels north of Cape Mendocino are predicted to rise at an increasing rate, with estimates of -4 cm to 23 cm for 2030, -3 cm to 48 cm for 2050, and 10 cm to 143 cm for 2100 (CO-CAT 2013). Yet, these are averaged rates for the entire State and could be significantly different on Humboldt Bay due to local tectonic activity that may cause land to rise or subside. Research suggests that the land beneath Humboldt Bay is subsiding. Information from the National Oceanic and Atmospheric Administration (NOAA) tide gage located on the North Spit suggests that current relative sea level rise is occurring at a rate of approximately 4.7 mm/yr (Gilkerson 2012). Recent estimates suggest that the regional SLR is approximately 2.3 mm/yr (Burgette and Weldon, 2009), and that the North Spit in the vicinity of the tide gage appears to be subsiding at a rate of approximately 2.4 mm/yr (Gilkerson 2012).

As mentioned above, many areas around Humboldt Bay have and continue to experience water levels comparable to future predictions when winter extreme high tides occur. The effects of these high tides are compounded by storm surges and heavy rainfall, which are already capable of overtopping various types of shoreline infrastructure and damaging the adjacent land or infrastructure. There is a lack of comprehensive information regarding the state and fortitude of the Bay's shoreline structures, and no one group or agency is responsible for monitoring their upkeep (Laird 2013). With repair and maintenance responsibilities solely in the hands of private landowners and cities, efforts around the Bay to either fortify shoreline structures or return the land to tidal influence in order to prepare for SLR have been uncoordinated. This parcel by parcel approach is expensive and could ultimately lead to more problems and fewer options for solutions as the rate of SLR increases.

Legal obstacles come into play, as California Coastal Commission and federal regulations are very limiting in terms of shoreline fortification and rebuilding. Thus, it will prove beneficial to the Harbor District and the communities and industries surrounding Humboldt Bay to develop a holistic planning process that takes into account the entire Bay shoreline, rather than individual sections. No matter what is decided in terms of fortifying or returning dikes to tidal influence, a regional approach is necessary to facilitate a future for Humboldt Bay that benefits both the natural system, and all those involved in the process.

An additional factor to consider is the eventual occurrence of a major Cascadia Subduction zone earthquake. The San Andreas fault zone, the Mendocino fracture zone, and the southern end of the Cascadia subduction zone "all meet within the offshore and coastal regions of Humboldt County, at what is known as a 'triple junction'" (County General Plan, 2012). Such a major tectonic event as is expected to occur in the near future, or even a smaller local earthquake, could dramatically shift the geologic structure around Humboldt Bay, and cause some of the discussed threats to occur in a matter of hours. The impacts of such an event on mariculture are cannot be predicted, however, limiting sources of toxic pollutants within the tsunami run-up zone would be beneficial.

Potential Impact on Water Chemistry

In order to examine how sea level rise could potentially affect the water chemistry and water quality that supports successful oyster production, we first set out to determine the ideal conditions for growing oysters, and compared them to the conditions present in Humboldt Bay. Greg Dale, Operations Manager of Coast Seafoods, was a vital source of information regarding the specific growing conditions present in Humboldt Bay and known obstacles. With this understanding of present and ideal conditions for oysters, we then consulted with a fisheries biologist and a hydrologist to obtain a professional opinion as to how certain oyster habitat requirements might be altered as a result of sea level rise. Below, table 1.1 provides a summary comparison of the ideal oyster habitat to the conditions present in Humboldt Bay.

	Ideal	**Humboldt Bay**
pH	7.7-8.1	7.42-8.54
Salinity	20-35 ppt	25–34 ppt
Temperature	39-75 °F	48° to 68° F (8.9° to 20° C)
Turbidity	~7 ntu, or up to ~55 ntu during mass spawnings	<30.0 ntu
Depth	< 10 meters	−1.0 ft to 1.0 ft (−0.3 m and 0.3 m)

Table 1 Ideal habitat conditions of *Crassostrea gigas* and averages in comparison to Humboldt Bay. NTU= nephalometric turbidity units (Compiled from 1. Barnhart et al, 1992. The Ecology of Humboldt Bay, California: An Estuarine Profile 2. Lannig, Gisela et al, 2010. Impact of Ocean Acidification on Energy Metabolism of Oyster, Crassostrea gigas 3. Samain, Jean-François; McCombie, Helen. 2008. Summer Mortality of Pacific oyster Crassostrea gigas: the Morest Project.)

Dissolved oxygen levels

Dissolved oxygen (DO) levels are measured by the amount of oxygen molecules concentrated in the water at milligrams per liter. In Humboldt Bay, DO is relatively low in the deep channels, but it is typically near saturation in the shallow waters that spread out over the mudflats (Barnhart et al. 1992). A hypoxic condition, low DO levels that cannot support marine habitat, can occur if additional nutrients are found in the water and heating up of surface stratified waters on mudflats occurs. DO levels can be affected by a myriad of factors relating to human causes and natural causes, most of them resulting from water temperature, nutrient inputs from development, upstream drainage, and tidal prism of the Bay (Wellandsen 2011).

Temperature

Varying temperature can influence the amount of oxygen that dissolves in the water. Water temperatures vary with time of day, season, stage of the tide, depth, and distance from the Bay mouth, wind, and near shore water conditions. Humboldt Bay water temperatures range from 48° to 68° F (8.9° to 20° C) (Barnhart et al. 1992; Humboldt State University 2008). Due to moderately stable coastal temperatures, Humboldt Bay's circulation allows water temperature to remain relatively low. As noted above, ocean saltwater circulates to replace 41% of the Bay's volume per day, which may vary depending on freshwater input (Costa 1982; Anderson 2008a). As sea level rise and tectonic uplift occur, inundation and tidal prism expansion may allow for more volume in the Bay to be replaced, increasing water column stratification and thus altering the water chemistry in Humboldt Bay (Anderson, 2014). This would change the habitat suitability of the Pacific Oyster.

Nutrient input

Nutrient inputs from surrounding agricultural lands and urban runoff could prove problematic to oyster cultivation if sea level rise were to occur. Excessive amounts of nutrients in water, or eutrophication, can be detrimental to marine life, and produces algae blooms that consume oxygen and reduce dissolved oxygen levels to a degree that may be harmful to oysters (Chesapeake Bay, 2012). Wind is also a highly influential factor in nutrient transportation of the Bay's water. The highest amount of nutrient input occurs during upwelling while a moderate amount of nutrient input occurs during storm events and low nutrient input occurs during low wind seasons (Barnhart et al, 1992). Natural nutrient inputs, which are at healthy levels for oyster production, occur when coastal upwelling occurs, and when rain events bring nutrients into the Bay from tributaries.

Depth

The increase in water depth within Humboldt Bay may alter water chemistry through increased vertical stratification. Because of the Bay's drainage structure, its elevation is gradual and therefore allows deeper penetration of warmer waters during summer and late fall seasons. The thermocline that separates colder, denser waters at depth from warmer waters near the surface allows for mixing during wind events. Phytoplankton, an important food source for oysters, are more present in near surface, warmer waters and due to increased stratification may produce more nutritional sources for oysters. Bay depth and its effect on oysters due to sea level rise is not expected to be significant enough to consider mitigation (Anderson, Bjorkstedt 2014).

Dissolved oxygen is an intricate part of water circulation and a good indicator for changes in water chemistry which influence Bay water temperature, circulation, eelgrass habitat, and ultimately oyster success. However, according to information from an interview with a local marine fisheries scientist, DO levels are not expected to change dramatically in the short term (less than 50 years). Thus the foreseeable levels of change in water quality are expected to have little effect on oyster production.

Potential Impact on Habitat

The habitats present in and around Humboldt Bay will be impacted by sea level rise to varying degrees as they begin to adapt. Rising sea levels will increase the amount of regularly flooded salt marsh, ocean beach, and estuarine beach. Most landscapes, including developed land and freshwater marshes around Humboldt Bay, will decrease in acreage as more water becomes regularly present in the Bay (USFW, 2011.)

Some of the established eelgrass beds in Humboldt Bay are likely to shift and change as the water level in Humboldt Bay increases. As the water depth increases around the Bay, eelgrass is likely to move inland to more suitable locations. Since the regulatory protection of this species is often strict due its role as fish habitat, oyster farmers must be sure to monitor how its distribution begins to change.

Climate change in conjunction with SLR will also have the potential to affect the benthic habitat of Humboldt Bay, changing the structure of the characteristic mud flats as temperatures increase. The 'lagoon effect' that occurs in North Bay could increase with warmer water temperatures, and reduce circulation and water quality.

The increase in sea level conditions can cause a transition of "shallow tidelands towards the upland shore", where subsidence of the Bay and increased sea level can lead to inundation of private and public properties beyond the levees (Huppert et al, 2013). The effect of sea level rise on inundated areas may return grazing lands to mud flats or tidal marshes, allowing eelgrass to habituate the newly inundated coastal area.

Eelgrass Related Habitat

Pacific eelgrass is a perennial aquatic grass that grows in estuaries along the Western Coast of North America. This species can be found from the Sea of Cortes to the coasts of Alaska, as well as coastlines on other continents. Eelgrass is believed to be critical foraging habitat and/or cover for a large diversity of fish and invertebrate species, including endangered species (HBHRCD, 2006.) This poses as a major constraint to oyster cultivation in Humboldt Bay due to the protection of the species as critical habitat for several different threatened or endangered species of fish, including Coho salmon (*Oncorhynchus kisutch*) and Chinook salmon (*Oncorhynchus tshawytscha*), and migratory birds such as the Brant geese (*Branta bernicla*)(HBWAC and RCAA, 2005). Although there is controversy among stakeholders about the ecological significance of the eelgrass beds in and along Humboldt Bay, mariculture operations must comply with guidelines of the Endangered Species Act and Coastal Act to protect Eelgrass beds, and the marine species utilizing it as crucial nesting habitat (HBHRCD, 2006.) As areas around the Bay face inundation and a return to tidal influence, there is potential for eelgrass beds to move inland or spread in size. A recommendation in planning for this event is to emphasize the need for a local jurisdiction to plan for and monitor the spread and movement of eelgrass habitat. On going monitoring will allow planners and oyster farmers to compare the locations and movement of Eelgrass from year to year.

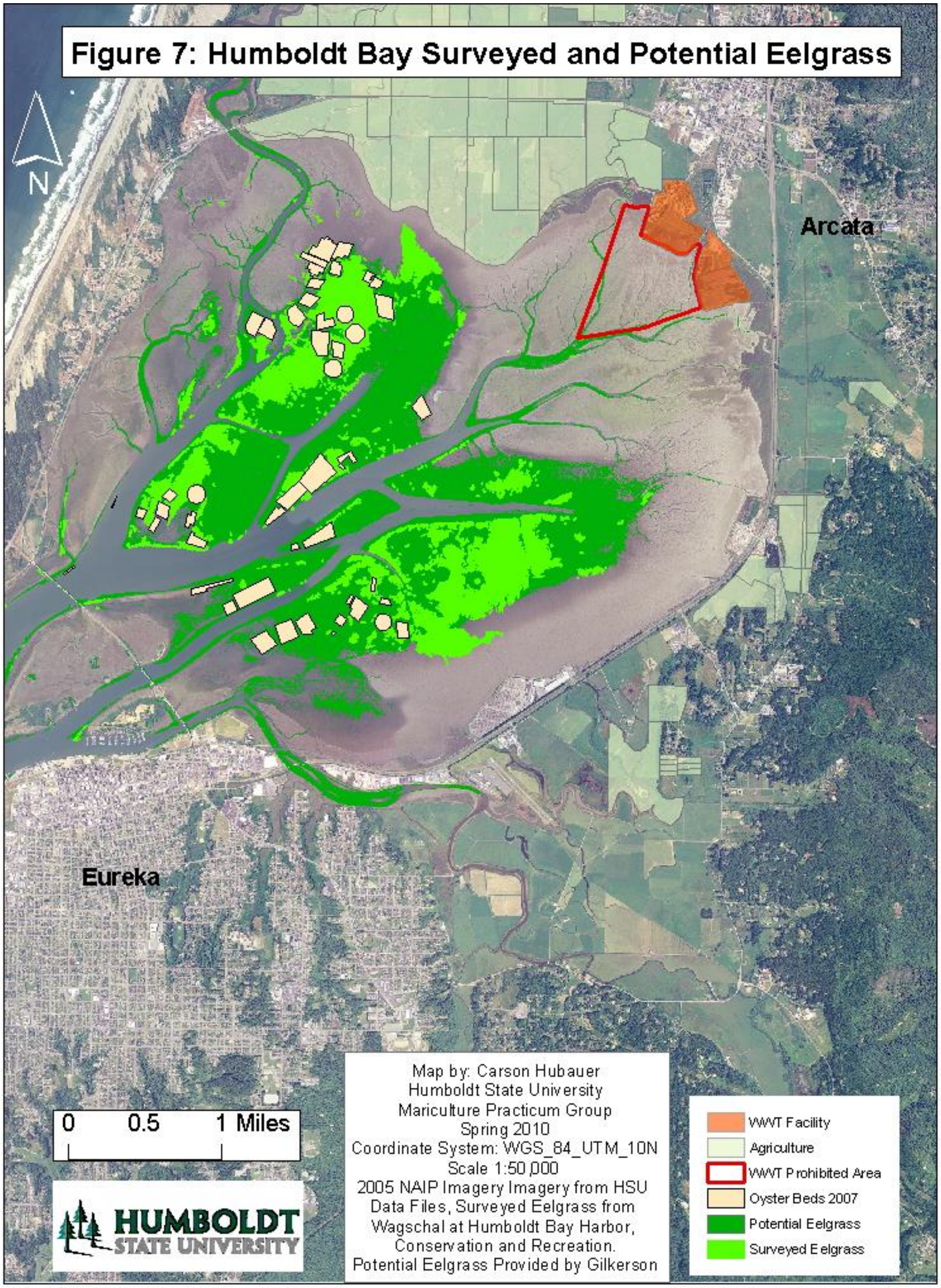

Figure 5: Map of Humboldt Bay Surveyed and Potential Eelgrass. (Carter-Griffin et al. 2010.)

Potential Impacts of SLR on Surrounding Lands

As previously discussed, Humboldt Bay has been heavily modified over the last century, and today, 75% of the shoreline is comprised of artificial structures (Laird 2013). A comparison of the historic shoreline structure from 1870 with its status in 2009 is provided below (Figure 4).

Unfortunately there is no single government or private entity responsible for maintaining artificial shoreline infrastructure around Humboldt Bay, and so extremely costly repairs fall on private landowners and nearby cities. In addition, vital infrastructure such as waste water treatment facilities have been constructed on lands reclaimed from the Bay, and several defunct industrial sites with are now on land that is protected by failing shoreline infrastructure.

Historically, a number of industrial sites relating to the timber industry operated around the Bay, many of which have left a legacy of hazardous materials that were never cleaned up. Brownfields such as these are "real property, the expansion, redevelopment, or reuse of which may be complicated by the presence or potential presence of a hazardous substance, pollutant, or contaminant" (Small Business Liability Relief and Brownfields Revitalization Act 2002). Brownfields contain materials that pose a health risk to human health and the health of the natural environment. Humboldt County maintains records on the location and status of known brownfields.

It is important to identify the locations of these brownfields and to assess the level of threat they might pose to oyster cultivation with sea level rise. Humboldt County maintains records of brownfields on the shoreline of the Bay, including several decommissioned pulp mills sites that harbor toxic substances (see Figure A.) Several of these sites have received attention or funding for clean up (Whitney 2014). Inundation of any of these areas could severely affect the mariculture operations on Humboldt Bay. If toxins are released, it is likely that oysters and other shellfish in the Bay would not meet federal or state guidelines for safe human consumption. However, as these brownfield sites are documented, and some are actively undergoing cleanup, they do not pose a severe threat. The Environmental Protection Agency is currently involved in the process of removing toxic chemicals from the decommissioned Samoa Pulp Mill site (EPA 2014).

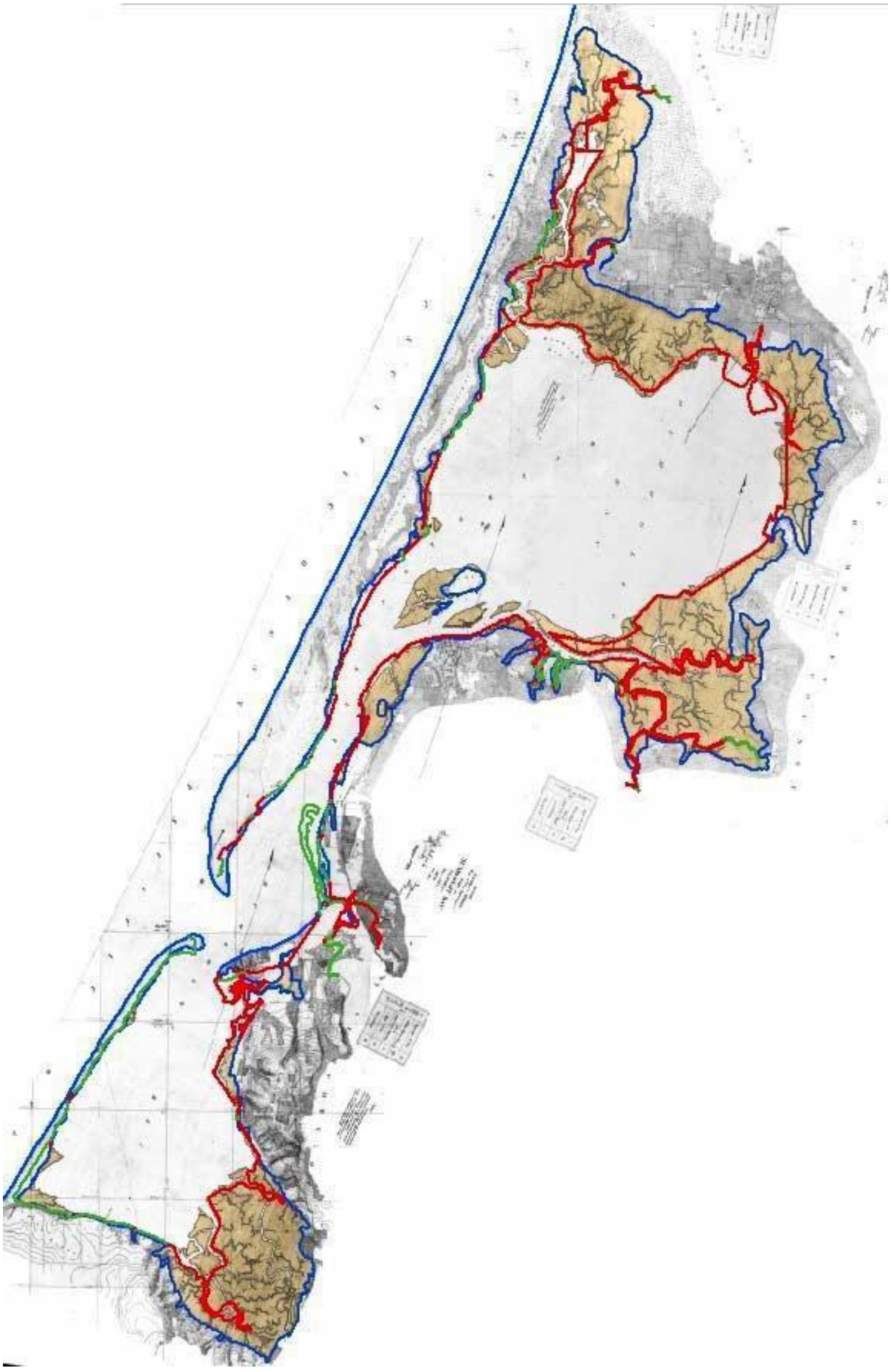

Figure 6: *1870 USCGS survey of Humboldt Bay, with 1870 shoreline (blue) and 2009 shoreline (red for artificial and green for natural) serves to illustrate the magnitude of change to the Bay (Laird 2013.)*

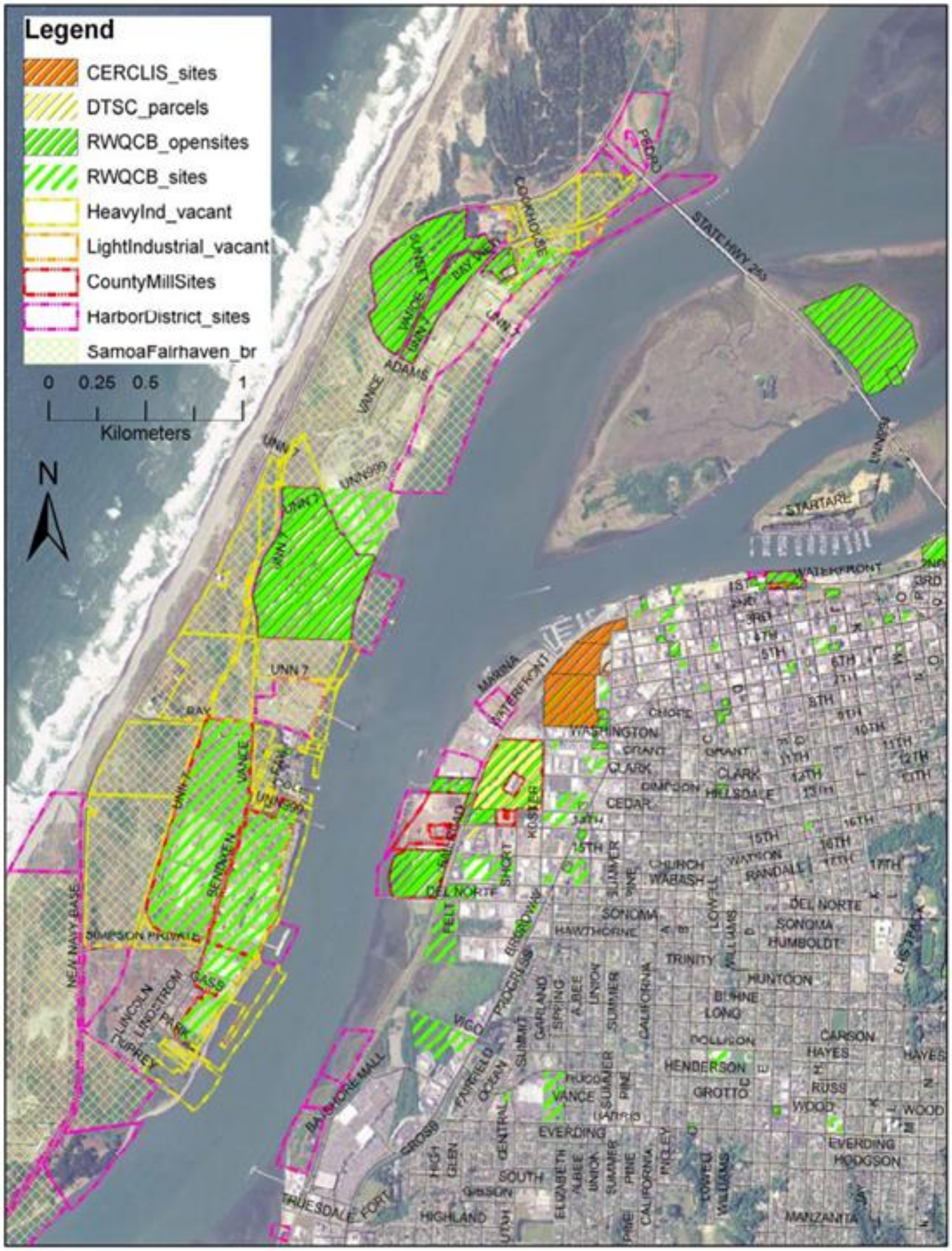

Figure 7: *Example of brownfield GIS for the Eureka, Samoa and Fairhaven area. RWQCB: California Regional Water Quality Control Board; CERCLIS: The federal Comprehensive Environmental Response, Compensation, and Liability Information System; DTSC: Department of Toxic Substances Control. (Whitney, 2010.)*

In addition, communities around the bay have constructed critical infrastructure such as wastewater treatment facilities and septic systems that are at risk to inundation from sea level rise and could release harmful substances into the Bay. For example, Lynnhaven River in Chesapeake Bay, Virginia which was nationally and internationally known for producing quality oysters, no longer may produce oysters commercially due to high bacterial contamination of fecal coliform from sanitary sewer overflows, failing septic systems, and stormwater discharge from suburban development (Morris *et al*, 2013).

While large wastewater treatment plants such as the Arcata facility are well managed and monitored, others have seen far less scrutiny, such as on-site septic systems in the community of Fairhaven. Additionally, the town of Samoa "has two wastewater collection, treatment and disposal systems which are quite old and are operating at about 70% of capacity" (Samoa Master Plan 2002). Without adequate monitoring and consideration given to upgrading these systems, they pose a risk to human health and oyster operations if they leach fecal coliform or other dangerous bacteria into the Bay.

Figure 8: *Overtopped Dikes in Arcata Wastewater Treatment Facility 2006* (Laird 2013)

The cities of Eureka and Arcata both have wastewater treatment plants located along the bay, with the Arcata Treatment Plant being in closest proximity to commercial oyster beds. While this facility and its interaction with the bay is frequently monitored, it remains directly at risk to sea level rise due to the facility's unique treatment system and its reliance on the current geographical state of the bay. The image above shows the Arcata Wastewater treatment system and overtopping of the Bay's northern dike due to a high rainfall with succession of maximum high tide in 2006 (Laird, 2013). Since these plants cannot be readily moved to more inland locations, it will prove increasingly important to monitor the integrity of the facility's shoreline infrastructure so as to avoid inundation and overtopping. Planners must determine how to best invest in this infrastructure so that it may continue to function as the water level rises in the Bay, or determine the best course of action for relocation.

Much of the land surrounding Humboldt Bay at risk to sea level rise is fertile agriculture and pastureland that was previously reclaimed from the Bay. During rain events, storm water runoff brings nitrate, phosphate, and less common ammonium nutrients into the Bay (Barnhart *et al*, 1993). These nutrients can be advantageous to oyster productivity, but could also pose a risk to oyster success, if excessive amounts enter the Bay due to inundation and rising groundwater tables. Impacts on water chemistry for oyster success may need to consider these land uses and their location relative to potentially inundated sites.

While agricultural lands do not pose a direct threat to mariculture, the way in which they are planned for will inevitably contribute to future conditions for mariculture in Humboldt Bay. In 2003, a storm surge combined with a winter high tide reaching 9.51 feet, overtopped a reinforced earthen dike along Mad River Slough and flooded 600 acres of pasture with salt water (Laird 2013). After this event, millions of federal dollars were spent to repair shoreline infrastructure. With SLR such events are likely to become more common and funding will be harder to come by. Unless the entirety of the bay's shoreline is to be fortified, assessment must be made as to which areas of at-risk farmland and infrastructure are most critical and feasible to protect and which are cost prohibitive to maintain that might better be returned to tidal influence.

Efforts to return areas to their former tidal influence, such as those by the City of Arcata at McDaniel Slough, provide example of one aspect of a bay-wide approach to sea level rise adaptation that could benefit oyster mariculture. The city has restored a 212-acre area around McDaniel Slough to "restore tidal flow and fish passage to former salt marsh wetlands and enhance associated wildlife habitat in the McDaniel Slough and Janes Creek region on Humboldt Bay" (Coastal Conservancy 2012). Whereas continuing to fortify artificial shoreline structures along former tidelands can effectively create steep walls that drop off into a basin, restoring tidal influence allows natural processes to help reduce the impact of storm surge and increasing water level.

Oyster mariculture operations can benefit from this restoration of tidelands because if done strategically, it can allow sea level rise to expand the Bay's footprint in a more natural way, creating more marine habitat and potentially more space to raise oysters or support associated operations. Planning for agriculture lands at risk to sea level rise could even take the approach of planning strategically for locations of possible future marine and mariculture based operations that contribute to the growth and success of the oyster mariculture industry.

Analysis of Impacts

Opportunities, Challenges and Recommendations

Opportunities and Recommendations

As sea level rise on Humboldt Bay continues to occur, there will undoubtedly be opportunities for the oyster mariculture industry to expand and further establish itself as an integral part of the local culture and economy. So long as collaborative planning processes can take place between oyster producers, management agencies, and other stakeholders around Humboldt Bay, the negative impacts of sea level rise to oyster mariculture can be minimized. With proper planning and implementation of mitigation techniques pertaining to the known impacts of SLR, the mariculture industry has potential to expand production on more acreage across the Bay. Further, some lands immediately around Humboldt Bay could be well suited for mariculture related operations if returned to tidal influence.

Both the oyster mariculture industry and the Humboldt Bay Harbor Recreation and Conservation District have the opportunity to initiate a regional planning effort that can change the course of management on Humboldt Bay. This type of landscape planning could focus on the overall health of the Bay and its shoreline habitat, with a focus on protecting the integrity of the oyster mariculture industry and the natural habitat by which it is supported. Yet, currently there are several information gaps and a lack of SLR monitoring data that will be required before this kind of planning can take place. An opportunity now exists to begin some of the monitoring efforts discussed in this report, so that more accurate locally gathered data could represent the impacts of SLR and guide decisions.

Such a process will likely require a slow shift in the public and private industry perspective of Humboldt Bay that has been based on its historical use as part of the timber industry. While lands that were reclaimed from the Bay during early years of European settlement have allowed agriculture and ranching to flourish many of these lands are now facing ecological changes such as subsidence and saltwater intrusion. The cost of maintaining artificial shoreline protecting these fertile lands may prove to be too great to justify continued investment, by private landowners or agencies. Yet, this shift in land use does not inevitably mean that landowners must give up or stop using their land, but rather begin using and tending the land towards different goals. If local governments and planning efforts can begin to put more of a monetary value on the management of former agricultural lands for ecosystem services or if expansion of mariculture becomes feasible, then landowners will begin to have incentives to consider adapting to new land uses.

Challenges and Recommendations

While the continuing impacts of sea level rise will allow a number of opportunities for oyster mariculture, there are also a number of challenges that can potentially hinder the planning process. The challenges that have been identified are not largely due to the direct impacts of a rising water level in Humboldt Bay, but rather are existing threats from shoreline infrastructure, industrial legacies, hazardous materials, and current political and economic constraints. In addition, a lack of data and up-to-date information on some of these existing threats will likely hinder the start of a regional planning process. In order to gain a clearer understanding of these issues, it will be important to begin gathering more data and implement monitoring efforts. Since water quality is likely the most directly limiting component of oyster production, monitoring should begin to take place around areas that threaten this condition. While not known to currently have a negative impact on water quality, septic systems and wastewater treatment areas of Fairhaven and Samoa should be monitored as sea level increases, for the possibility of human waste leaching out and releasing harmful bacteria and viruses into the water.

Monitoring the interactions between these wastewater systems and the bay is imperative because if contamination begins to occur, it may be too late to stop it from continuing. Actual impacts to water temperature, salinity, and pH, are also lesser known, and should be monitored regularly so that changes can be noted over time.

Based on the research compiled for this report, we believe that water acidification due to lowered pH will not occur within Humboldt Bay to the extent that is detrimental to oyster mariculture, as has been the case in other parts of the Pacific Northwest. Another aspect of water chemistry that warrants focus is dissolved oxygen level in the bay. The increased volume of water, and increased tidal prism, could eventually lead to an increase in dissolved oxygen levels, which could have positive direct effects on the conditions available for oysters. However, monitoring this factor is important because it could also be indicative of how changing dissolved oxygen levels will affect other species in the bay, especially phytoplankton, and in turn impact oyster mariculture.

Political and legislative factors, as well as economic and cultural factors, form a different type of constraint to oyster mariculture and planning in terms of SLR. State regulations have been a limiting factor to expansion of oyster mariculture operations in the past, and will likely continue to be in the future. Regulations limiting impacts to eelgrass are one example. Efforts could be made by local decision makers to work with the California Coastal Commission in developing regulations that pertain more specifically to the conditions in Humboldt Bay, so that the presence of eelgrass does not automatically hinder mariculture operations, if sufficient fish habitat is still present in the Bay. Reliable current local data must first be obtained before this initiative can begin.

As mentioned under the Opportunities section, there is a prevailing perspective from landowners and private industry that Humboldt Bay should continue to support timber and agriculture as it has in past century, so important to do so wherever possible. However, with SLR, maintaining dikes and levees to the same degree as in the past may become cost prohibitive for landowners. A regional planning process could begin with public outreach to discuss these issues, especially with bay-side landowners, so that a holistic vision of the future of Humboldt Bay can be formed. Without preemptive planning, all stakeholders will be at the mercy of the forces of nature. This is important to emphasize because while sea level rise might appear to be a slow gradual process, the major impacts already manifest themselves during large storm events, when the increased amount of water in the bay combines with extreme high tide and storm surge.

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