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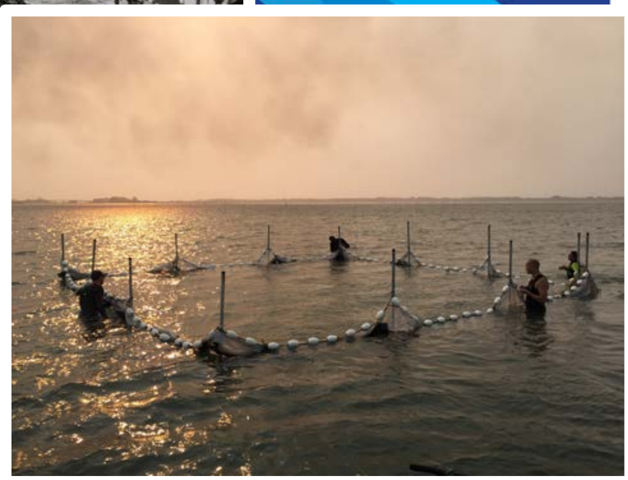
Comparative Habitat Use of Estuarine Habitats with and without Oyster Aquaculture

Prepared for:

National Marine Fisheries Service
November 2019



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Comparative Habitat Use of Estuarine Habitats with and without Oyster Aquaculture
DRAFT REPORT

Project funded by Saltonstall-Kennedy Act Grant Award NA16NMF4270254

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November 2019

Note: These data and related items of information have not been formally disseminated by NOAA, and do not represent any agency determination, view, or policy

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1.0 INTRODUCTION

Humboldt Bay is located approximately 260 miles north of San Francisco and is California's second largest estuary. The bay is 14 miles long, 4.5 miles wide at its widest point, and approximately 25 square miles in size (excluding its tributaries and sloughs). Humboldt Bay comprises three distinct sub-basins: (1) North Bay (or Arcata Bay), (2) Entrance Bay (or Central Bay), and (3) South Bay (Figure 1). Both the north and south segments are extremely shallow with large, mostly vegetated, mudflats exposed during low tides. Habitat within each of these sub-basins is a mixture of unconsolidated sediment (or mudflats), native eelgrass (*Zostera marina*) beds, coastal marsh habitat, macroalgae, and subtidal habitat in channels that drain the Humboldt Bay.

Shellfish aquaculture[1], native eelgrass, and mudflat habitat have co-existed in Humboldt Bay for at least the last 60 years of commercial shellfish production, and for more than 120 years since the first attempts to introduce cultured shellfish in 1896 (Barrett 1963). Native eelgrass is a common perennial aquatic plant that creates three-dimensional habitat structure and forms extensive intertidal and subtidal beds in estuaries and coastal areas. Eelgrass beds are an important component of coastal ecosystems because they stabilize coastal sediments, provide direct and indirect food sources for marine species, and act as a nursery for fish and invertebrates (Phillips 1984, Short et al. 2000). Shellfish aquaculture provides several ecosystem functions that are comparable to eelgrass, such as prey resources, water quality benefits, and habitat structure (DeAlteris et al. 2004 and Dumbauld et al. 2009). In a recent review of the existing literature, Rumrill (2017) identified 8 ecosystem functions typically assigned to eelgrass beds, shellfish culture, or both (Table 1).

Table 1. Ecosystem Functions associated with Eelgrass and Shellfish Habitat

Ecosystem Function	Units	Eelgrass Beds	Shellfish Culture
Primary production of organic material	$g\ m^{-2}\ yr^{-1}$	●	
Trapping of sediments and erosion control	$mm\ yr^{-1}$	●	●
Improvements of water quality and enhanced flux of nutrients	$g\ m^{-2}\ yr^{-1}$	●	●
Sequestration of carbon	$g\ m^{-2}\ yr^{-1}$	●	●
Provision of diverse heterogenous habitat for invertebrates, fish, and birds	?	●	●
Nursery areas for juvenile fish and invertebrates	Hectare	●	●
Forage areas for waterfowl and seabirds	Hectare	●	●
Secondary production of food for human consumption	$$$		●
Adapted from: Rumrill 2017			

[1] This report uses the general term "shellfish aquaculture" for commercial operations related to Pacific oysters (*Crassostrea gigas*), Kumamoto oysters (*C. sikamea*), and Manila clams (*Venerupis [Ruditapes] philippinarum*) grown in Humboldt Bay – also commonly referred to as bivalves. Another term commonly used is mariculture, which is used synonymously in the literature to refer to shellfish (bivalve) aquaculture operations.

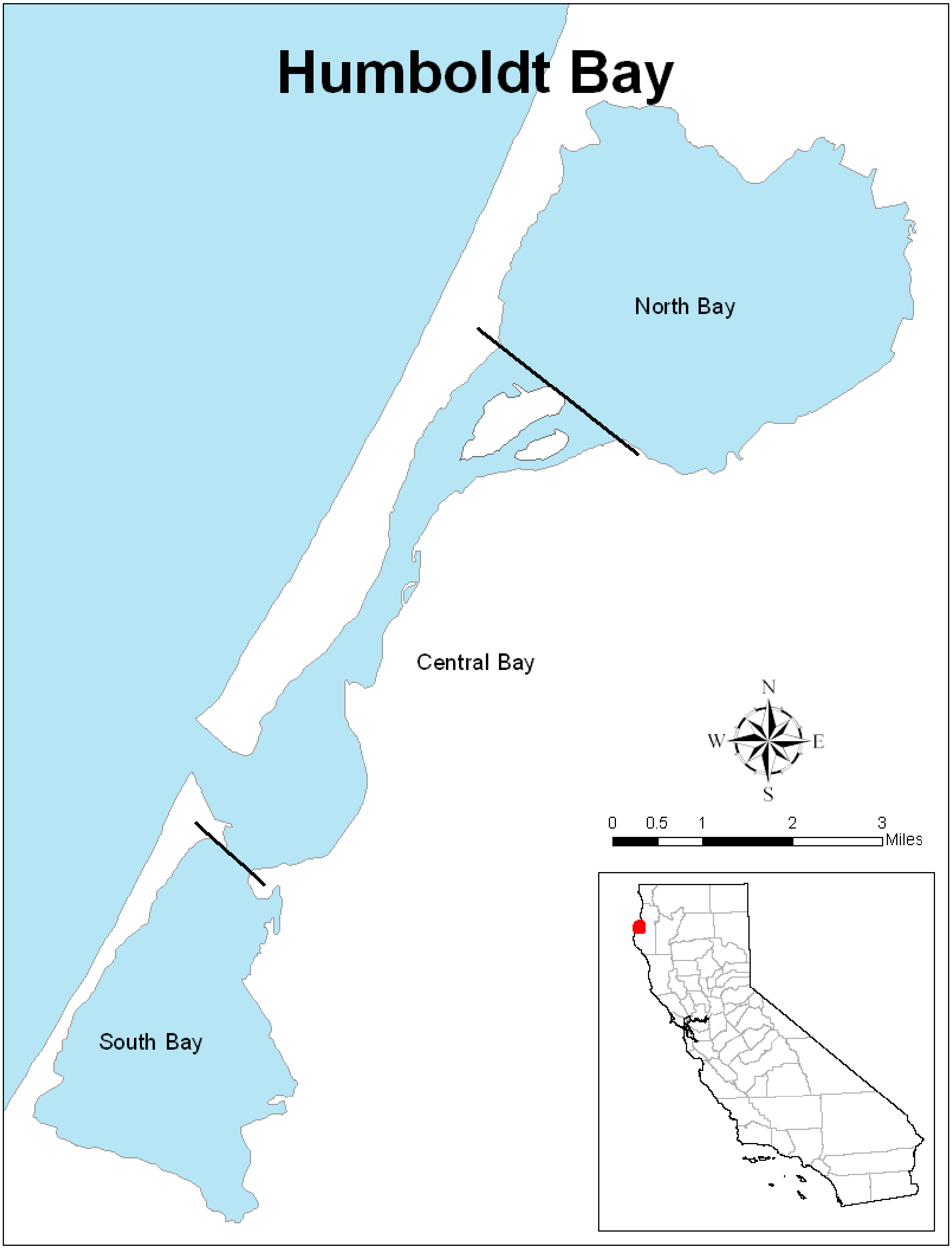

Figure 1. Sub-Basins of Humboldt Bay, California
Source: Pinnix et al. (2005)

Numerous studies on the U.S. West Coast have documented differences in species diversity and abundance associated with estuarine habitat types with and without oyster culture (Simenstad and Fresh 1995, Pinnix et al. 2005, Hosack et al. 2006, McKindsey et al. 2007, D'Amours et al. 2008, Forrest et al. 2009, Dumbauld et al. 2009, Ferraro and Cole 2007, 2011, 2012). However, due to the relatively recent transition to off-bottom culture within West Coast estuaries, few studies have addressed how and whether off-bottom oyster culture affects species use and abundance, or whether these differences affect the overall food web ecology of the system (but see Rumrill and Poulton 2004).

The "Comparative Habitat Use of Estuarine Habitats with and without Oyster Aquaculture Project" (the Comparative Habitat Project), addresses the goal of providing research on the environmental impacts of shellfish aquaculture by furthering the understanding of how fish and invertebrate communities are affected by the presence of cultch-on-longline oyster aquaculture. Cultch-on-longline is a culture method that braids a piece of cultch with oyster seed into a line that is approximately 100 feet long (i.e., the term "longline"), suspends the longlines approximately 1-foot above the sediment surface, and then grows the oyster seed on the longline for 18 to 36 months before harvest. During the study (2017-2018), the cultch-on-longline plots in Humboldt Bay were set up either with each row spaced 2.5-ft apart or with five rows spaced 2.5-ft apart then a 5-ft gap between groups of five lines (Figure 2).

The Comparative Habitat Project builds upon previous work performed in Humboldt Bay, studies conducted in other West Coast estuaries, and current efforts to understand the interactions between shellfish aquaculture and estuarine habitats. The Comparative Habitat Project also explored the utility of Ecopath with Ecosim (EwE) modeling software to evaluate the effect that oyster culture has on the food web and commercial fisheries.

1.1 Project Goals and Objectives

The Comparative Habitat Project supports the Saltonstall-Kennedy (S-K) Grant Program objectives by identifying an appropriate balance between competing economic and ecosystem uses of Humboldt Bay to support commercial fisheries, oyster culture, and other uses related to the viability of working waterfronts. The goal of the Comparative Habitat Project was to determine whether oyster culture alters invertebrate and fish assemblages or productivity of habitats where oysters are grown commercially in Humboldt Bay. The objectives used to reach this goal include the following:

- Does oyster culture alter fish assemblages in Humboldt Bay?
- Does oyster culture alter invertebrate assemblages (prey resources) in Humboldt Bay?
- Does oyster culture alter the food web in Humboldt Bay?

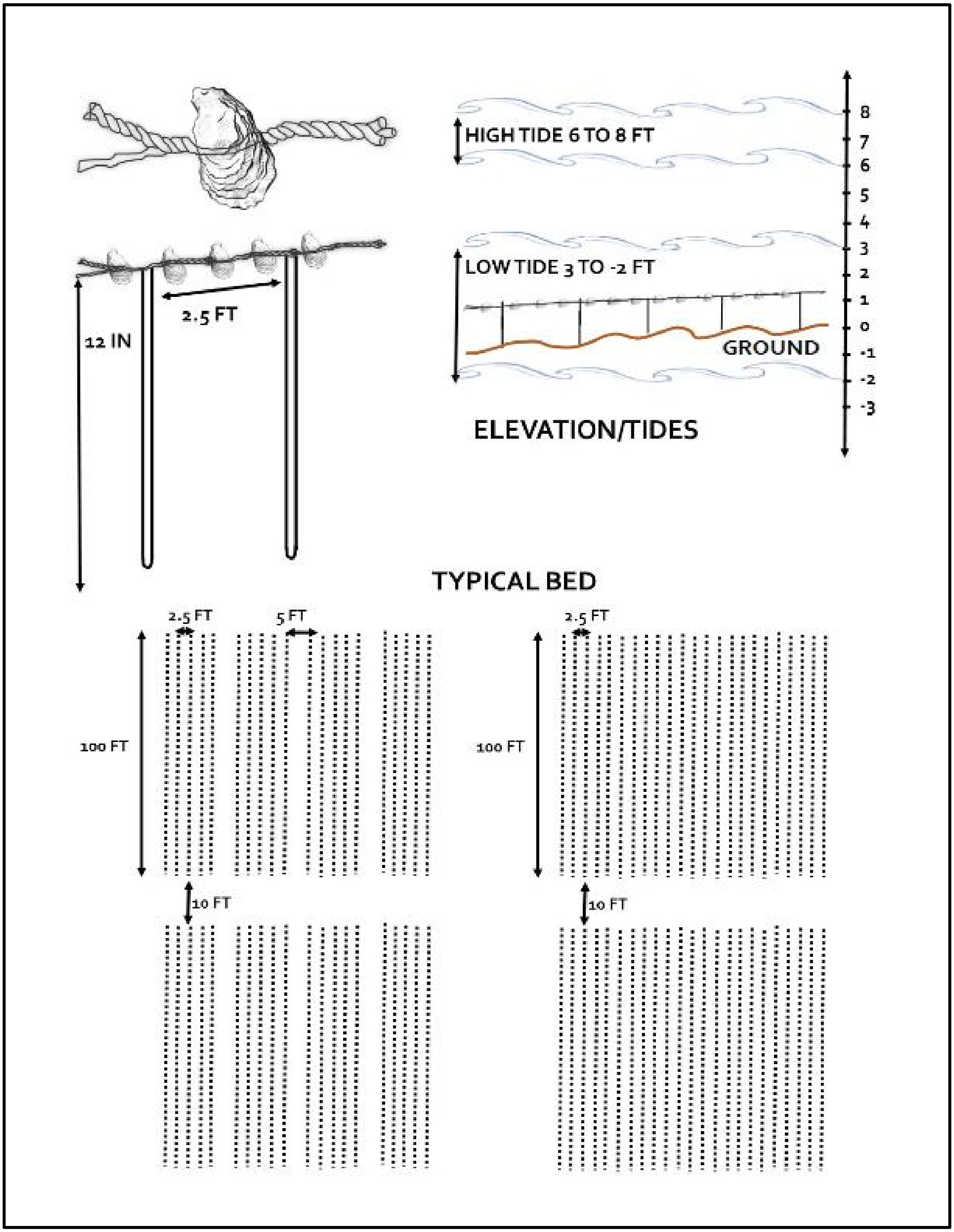

Figure 2. Example of Cultch-on-Longline Culture Methods

1.2 Background

Humboldt Bay is recognized for being a valuable nursery habitat for a diverse assemblage of fish and invertebrates, including commercially important species and their prey. Juvenile and/or early adult life stages of English sole (*Parophyrus vetulus*), speckled sanddab (*Citharichthys stigmaeus*), copper rockfish (*Sebastes caurinus*), black rockfish (*Sebastes melanops*), bocaccio (*Sebastes paucispinis*), lingcod (*Ophiodon elongatus*), northern anchovy (*Engraulis mordax*), Pacific herring (*Clupea pallasii*), and Pacific sardine (*Sardinops sagax*) were collected in Humboldt Bay by Pinnix et al. (2005). Larval life stages of English sole, speckled sanddab, bocaccio rockfish, black rockfish, lingcod, Pacific herring, and longfin smelt (*Spirinchus thaleichthys*) have also been observed in Humboldt Bay (Barnhart et al. 1992). These fish are supported by a mosaic of habitat in the bay, which includes native eelgrass, oyster culture, and mudflat habitat.

Humboldt Bay is also recognized for its commercial fisheries and shellfisheries operations. Although it has diminished from historical highs, commercial fishing has been a significant part of the local economy around Humboldt Bay for centuries. Currently, over 200 commercial vessels list Eureka (Central Humboldt Bay) as home port, and an additional 500 commercial vessels from other ports use Humboldt Bay each year (Humboldt Baykeeper 2019). In 2017, commercial landings at Eureka totaled 14,945,906 pounds, valued at over $19.5 million or approximately 10% of the total state landings value (CDFW 2018). Significant Humboldt Bay fisheries include dover sole (*Solea solea*), sablefish (*Anoplopoma fimbria*), pink shrimp (*Pandalus borealis*), and Dungeness crab (*Cancer magister*). In fact, Dungeness crab landings accounted for over 50% of the landings value at Eureka in 2017 (CDFW 2018).

Shellfish aquaculture has occurred in Humboldt Bay since the early 1900s (Barrett 1963). Currently, operations are located in North and Central bays, and include approximately 314 acres approved for aquaculture that are used by four different companies and another 177 acres that may be approved for culture activities (Figure 3).[2] Coast Seafoods/Pacific Seafood (Coast) is the largest company operating in North Bay, and operates within approximately 274 acres of intertidal habitat in North Bay and 1.01 acres of subtidal habitat in Central Bay. Current culture methods used in Humboldt Bay include cultch-on-longline, basket-on-longline, rack-and-bag, nursery rafts or Floating Upweller Systems (FLUPSYs), clam rafts, and intertidal nursery areas. The Comparative Habitat Project focused on effects from cultch-on-longline culture methods, as discussed above.

2 The Humboldt Bay Harbor, Recreation and Conservation District released a Final Environmental Impact Report for a Pre-Permitting Project for shellfish aquaculture in February 2016 (Harbor District 2016). The Harbor District is continuing to negotiate with tideland owners to allow the intertidal portions of the Pre-Permitting Project to move forward.

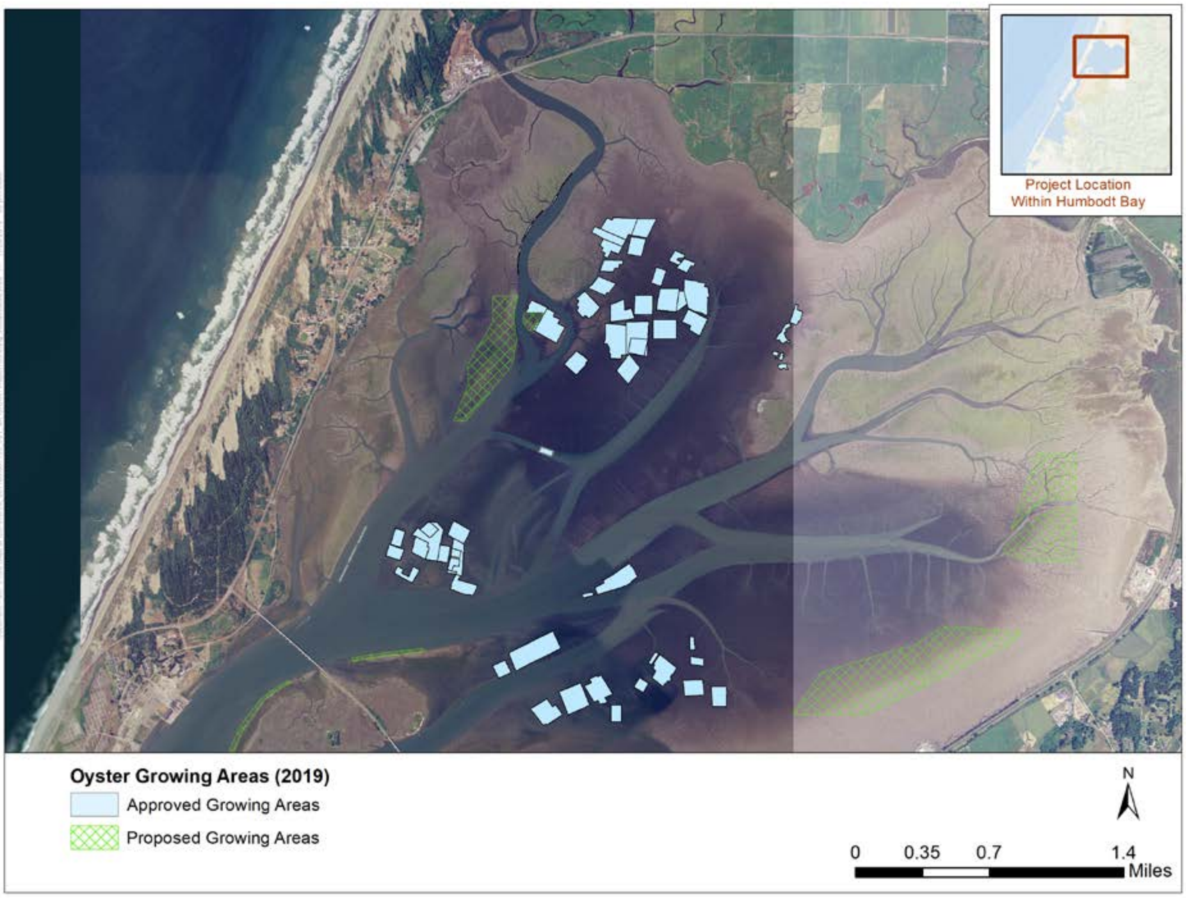

Figure 3. Shellfish Aquaculture Areas Currently used in Humboldt Bay

Best available science for agencies to address regulatory issues is limited for shellfish aquaculture on the West Coast, forcing agencies to be cautious about potential and perceived impacts to habitats, communities, and organisms (Dumbauld et al. 2009). The regulatory process in California is complex and involves multiple state (e.g., CA Department of Fish & Wildlife, CA Fish & Game Commission, etc.), local (e.g., Humboldt Bay Harbor District), and federal (U.S. Army Corps of Engineers) agencies (Earth Resource Technology, Inc. 2018). The permits and reports associated with this regulatory process often requires relevant scientific data to establish or prove limited impact to ecosystem functioning. At the present scale within West Coast estuaries, shellfish aquaculture appears to be more sustainable than other human activities (e.g., coastal development for urban or commercial purposes), which can degrade and eliminate estuarine function (Dumbauld et al. 2009, Coen et al. 2011). Management decisions for the regulation of shellfish aquaculture should consider both temporal and spatial scales. In addition, the functional value of a mosaic of habitats, including shellfish beds with edges and corridors, should be considered in terms of the potential to add ecosystem functions to an estuary. According to Coen et al. (2011), this concept of a habitat mosaic "may be an area where innovative practices and best management practices (BMPs) developed by [shellfish] growers in association with scientists can be applied to conserve and even enhance the functional value" of estuarine habitats.

The Comparative Habitat Project provides an understanding of the interactions between species use and various habitat types in Humboldt Bay, and the importance of different habitat types in providing prey and nursery resources for commercially important species (e.g., rockfish, California halibut, Dungeness crab). This information can be used to improve assessments of shellfish aquaculture operation interactions and influence on estuarine productivity related to sustainable commercial fisheries, and to develop BMPs that provide the highest benefits to these species. For example, understanding when sensitive life stages are potentially present in oyster culture areas (e.g., Pacific herring larvae) and how to avoid these areas in order to support the continued sustainability of Pacific herring populations in Humboldt Bay.

1.3 Relevant Work

The Comparative Habitat Project also integrated and compared study results with previous and current work in Humboldt Bay and other West Coast estuaries (Table 2). The comparison to relevant literature will allow regulators and the public to have a better understanding of the habitat values provided by shellfish, eelgrass, and mudflats as they relate to ecosystem preservation, recreation, and economic opportunities. This understanding will allow for more informed decision-making within coastal fishing communities and assist in maintaining sustainable shellfisheries practices.

Table 2. Literature used to Compare Project Results

Citation	Goal of the Study(ies)	Physical/ Chemical Structure	Invertebrates	Fish
Trianni 1996	Compared benthic invertebrate infauna in Humboldt Bay between oyster bottom culture sites, sites where oyster shell had been deposited, and natural habitat		●	
Simenstad and Fresh 1995	Reviewed available information about the impacts of intertidal aquaculture activities on benthic and epibenthic communities on the West Coast		●	
Rumrill and Poulton 2004	Analyzed the effects of off-bottom oyster culture in Humboldt Bay on eelgrass metrics and benthic communities	●	●	
Pinnix et al. 2005	Assessed different gear types in capturing fish in eelgrass, oyster culture, and mudflat habitats of Humboldt Bay			●
McKindsey et al. 2007	Reviewed literature throughout the West Coast to understand potential positive ecosystem services of cultured bivalves, in addition to the negatives		●	
Ferraro and Cole 2007, 2011, 2012	Determined associations between benthic macrofauna and habitat (including eelgrass, burrowing shrimp, oyster, and mudflat) in West Coast estuaries	●	●	
Hudson et al. 2018	Assessed the impact of shellfish aquaculture on seagrass habitats and provided data supporting the interest in expanding shellfish aquaculture while also protecting the ecosystem		●	●
● = topic included in the study or studies cited.				

The work described in this report relied on the methods and results from previous studies, most notably Pinnix et al. (2005) and Hudson et al. (2018). The findings of these studies are described more thoroughly below.

Pinnix et al. (2005) used a variety of methods within North Humboldt Bay to characterize the fish assemblages associated with three primary habitats: eelgrass, oyster culture, and mudflat. Sampling gear included a shrimp trawl, beach seine, purse seine, cast net, fyke net, and minnow trap. Analysis of the catch data revealed that the shrimp trawl and fyke net were the most effective gear in answering the questions of interest. Both the shrimp trawl and fyke net had significantly greater catch per unit effort of fish (CPUE) in oyster culture than in mudflat and eelgrass habitats. For the fyke net, species richness and diversity were significantly greater in the oyster culture and eelgrass habitats, than in the mudflat habitat. There were no significant differences in species richness or diversity for the shrimp trawl. Diversity was characterized by both the Simpson's Index and the Shannon-Wiener Index (Magurran 1988). The study documented the baseline fish community within North Humboldt Bay, with shiner perch (*Cymatogaster aggregata*), English sole, northern anchovy, speckled sanddab, and Pacific herring caught in the largest numbers. The use of multiple sampling methods also revealed individual biases and limitations for each gear type. For example, the shrimp trawl could not be used directly within the oyster culture habitat due to potential damage to the aquaculture gear. Other methods had low catches or a limited variety of species caught. The insight gained in the Pinnix et al. (2005) study was used to inform the methodology and interpretation of results presented in this report.

The work described by Hudson et al. (2018) was funded by a previous S-K Grant (NA15NMF4270318). This study sought to compare the effects of shellfish aquaculture between four different bays along the Pacific coast: Samish Bay (WA), Willapa Bay (WA), Tillamook Bay (OR), and Humboldt Bay (CA). Data collected characterized seagrass coverage/growth, fish and invertebrate abundance and diversity, predation intensity, environmental DNA, and spatial relationships between seagrass and aquaculture habitats. Sampling occurred across a transition from eelgrass (primarily *Zostera marina*) into oyster culture habitat.

The results of the Hudson et al. (2018) study indicated that eelgrass shoot density varied among estuaries, with Humboldt and Willapa bays having significantly lower densities than Samish and Tillamook bays. In addition to density, eelgrass morphology can be significantly different based on geographic location with size of plants varying by up to two orders of magnitude based on geography (Ruesink et al. 2018). Epibenthic samples in Willapa and Humboldt bays were dominated by harpacticoid copepods, along with cyclopoid copepods (*Cyclopina* spp.), calanoid copepods (*Eurytemora americana*), and polychaetes. In Samish and Humboldt bays, few differences in epibenthic community between oyster culture and edge/eelgrass strata were detected. Fish and macroinvertebrate abundance and diversity were measured through minnow trap catches and underwater video sightings. Underwater video data from Humboldt Bay proved unusable due to the turbid environment and resulting low visibility. Minnow trap catches in Humboldt Bay (201 individuals) were second behind Samish Bay and were dominated by shiner perch, shore crabs (*Hemigrapsus* spp.), and Pacific staghorn sculpin (*Leptocottus armatus*).

Spatial analysis of the eelgrass and aquaculture habitats in Humboldt Bay was also completed in the Hudson et al. (2018) study. The process relied on aerial imagery to classify eelgrass beds, comparing these "observed" values to modeled predicted values based on environmental and physical characteristics. Observed values for eelgrass area were greater than predicted values inside and outside of aquaculture. While this process is informative, it should be noted that the data was almost a decade old and would need to be updated for a more accurate analysis of the spatial distribution of eelgrass within Humboldt Bay. As a final step, a subset of all the data collected was included in a Habitat Suitability Index (HSI) to quantify ecosystem functions in mixed oyster culture and eelgrass habitats. For Humboldt Bay, HSI results were comparable between eelgrass and aquaculture, although eelgrass had slightly higher abundances of epibenthic fauna while aquaculture had higher macroalgal densities. However, the HSI is meant to be used as a tool to assess habitat value and is somewhat data-limited so should be viewed as a model and not absolute values.

2.0 FIELD SAMPLING EFFORT

Field research was carried out to focus on two primary research questions regarding the effects of aquaculture to invertebrates and fish populations (Appendix A). To address invertebrates, research sites throughout North Bay were identified and sampled to assess assemblages and abundances of invertebrates in areas with eelgrass or mudflat habitats and with or without aquaculture present. Sites were sampled in summer and winter seasons to characterize temporal differences in invertebrate assemblages.

Fish populations were assessed using a novel sampling technique of enclosure netting. This sampling method was developed to address sampling challenges associated with off-bottom aquaculture which creates conflicts with many types of fish sampling gear. Another type of sampling, use of underwater video, was also assessed, however it was determined to be non-viable for Humboldt Bay due to low visibility in the water column. Field sampling occurred during 4 low tide series spread throughout the year. Sites were identified and sampled to assess assemblages and abundances of invertebrates in areas with eelgrass or mudflat habitats and with or without aquaculture present. Additional sampling occurred using fyke nets and minnow traps to evaluate differences in sampling methods and support comparisons to other data collection efforts using those methods.

3.0 ECOSYSTEM MODELING WORKSHOP

During efforts to develop an ecosystem model for Humboldt Bay, it was identified that it is premature to develop a full model due to a lack of information to support food web interactions and insufficiently organized environmental data. Therefore, a workshop was convened to identify potential data sources that could be integrated and analyzed to support future development of an ecosystem model (Appendix B). This workshop identified potential management scenarios, data needs and data resources that may support future development of an ecosystem model for Humboldt Bay.

4.0 STAKEHOLDER OUTREACH

Outreach and education focused on engaging relevant stakeholders and sharing sampling results, including formal and informal efforts in the Arcata and Eureka area in concert with Coast Seafoods/Pacific Seafood, the Humboldt Bay Harbor, Recreation, and Conservation District (the Harbor District), the Wiyot Tribe, and Humboldt State University (HSU). Representatives from each entity participated throughout the project. The Comparative Habitat Project also engaged other project partners during the outreach and education phase, including the U.S. Fish and Wildlife Service (USFWS), Pacific Shellfish Institute (PSI), and Oregon State University (OSU).

5.0 SUMMARY

The main study questions of the Comparative Habitat Project addressed whether oyster culture alters invertebrate and fish assemblages or productivity of habitats where oysters are grown commercially in Humboldt Bay. The approach to answering these questions included a series of field studies, workshops, and stakeholder outreach. Below is a summary, by study question, of the main results of the project.

5.1 Does oyster culture alter fish assemblages in Humboldt Bay?

This study indicates that there is a potential benefit from the presence of aquaculture gear when compared to estuarine habitats without gear present. Differences in taxanomic groups present and their abundances occur between vegetated and unvegetated sites. Observations from earlier research efforts focused in the same geography and habitat groups are consistent with these observations.

The timing and abundance of fishery species varies seasonally with some species and life stages occurring during relatively short periods of time within the bay. Sampling suggests that some early juvenile life stages for certain species (Pacific herring, northern anchovy and topsmelt) may be more abundant in areas with oyster culture. Additional sampling during the periods when these species are present in the bay would be required to confirm an association, however it is postulated that in-water structure associated with oyster culture may create refuge from tidal currents and facilitate retention of species in areas with oyster gear that might otherwise be redistributed.

5.2 Does oyster culture alter invertebrate assemblages (prey resources) in Humboldt Bay?

As described in Appendix A, the field research associated with this project indicates that invertebrate assemblages are not significantly affected by the presence of aquaculture gear. Other associations, including effects of estuarine habitat and tidal elevation, were detected as significant variables affecting taxa present and abundance. This information suggests that off-bottom aquaculture has limited interaction with invertebrate populations and may be having no significant affect where underlying estuarine habitats are intact.

5.3 Does oyster culture alter the food web in Humboldt Bay?

This research question continues to be a work in progress as additional data is developed about interactions between aquaculture and components of the food web the understanding of food web effects from aquaculture will improve. The current study suggests that invertebrate and fish populations may not be significantly affected by the presence of aquaculture, however important questions remain regarding the interactions of aquaculture with eelgrass habitat and the potential for aquaculture activities to affect other fauna including large migratory fish, marine mammals and birds. These species may avoid or be attracted to aquaculture areas due to mechanisms independent of prey abundance or availability. Appendix B addresses potential future development of an ecosystem model for Humboldt Bay including management questions, data needs and data resources.

6.0 REFERENCES

Barnhart, R.A., M.J Boyd, and J.E. Pequegnat. 1992. Ecology of Humboldt Bay, California: An Estuarine Profile, U.S. Fish and Wildlife Service, Biological Report 1, Washington, D.C., 121 pp.

Barrett, E.M. 1963. The California oyster industry. Scripps Institution of Oceanography Library. http://scilib.ucsd.edu/sio/

California Department of Fish and Wildlife (CDFW). 2018. 2017 Final California Commercial Landings. https://www.wildlife.ca.gov/Fishing/Commercial/Landings#260042120-2017. Accessed May 10, 2019.

Coe, Hannah C. 2019. Effects of longline oyster aquaculture on benthic invertebrate communities in Humboldt Bay, California. Master's thesis. Humboldt State University, Arcata, California.

DeAlteris, J. T., B. D. Kilpatrick, and R. B. Rheault. 2004. A comparative evaluation of the habitat value of shellfish aquaculture gear, submerged aquatic vegetation and a non-vegetated seabed. Journal of Shellfish Research 23:867–874.

Duffy, J. E., S. L. Ziegler, J. E. Campbell, P. M. Bippus, and J. S. Lefcheck. 2015. Squidpops: A Simple Tool to Crowdsource a Global Map of Marine Predation Intensity. PLOS ONE 10(11):e0142994.

Dumbauld, B. R., J. L. Ruesink, and S. S. Rumrill. 2009. The ecological role of bivalve shellfish aquaculture in the estuarine environment: A review with application to oyster and clam culture in West Coast (USA) estuaries. Aquaculture 290(3–4):196–223.

Ferraro, S. P., and F. A. Cole. 2007. Benthic macrofauna–habitat associations in Willapa Bay, Washington, USA. *Estuarine, Coastal and Shelf Science* 71(3):491–507.

Ferraro, S. P., and F. A. Cole. 2011. Ecological periodic tables for nekton usage of four US Pacific Northwest estuarine habitats. *Estuarine, Coastal and Shelf Science* 94(1), 36-47.

Ferraro, S.P. and F.A. Cole. 2012. Ecological period tables for benthic macrofaunal usage of estuarine habitats: Insights from a case study in Tillamook Bay, Oregon, USA. Estuarine, Coast and Shelf Science 102-103:70-83.

Forrest, B. M., N. B. Keeley, G. A. Hopkins, S. C. Webb, and D. M. Clement. 2009. Bivalve aquaculture in estuaries: Review and synthesis of oyster cultivation effects. Aquaculture 298(1–2):1–15.

Hosack, G. R., B. R. Dumbauld, J. L. Ruesink, and D. A. Armstrong. 2006. Habitat associations of estuarine species: Comparisons of intertidal mudflat, seagrass (Zostera marina), and oyster (Crassostrea gigas) habitats. Estuaries and Coasts 29(6):1150–1160.

Hudson, B, D. Cheney, B. Dumbauld, J.R. Cordell, F. Tomas Nash, and S. Kramer. 2018. Quantification of functional relationships between shellfish culture and seagrass in US West Coast estuaries to inform regulatory decisions, Final Report. National Oceanic and Atmospheric Administration Fisheries Saltonstall-Kennedy Grant Program (Grant NA15NMF4270318).

Humboldt Baykeeper. 2019. Wildlife: Fisheries Resources. https://www.humboldtbaykeeper.org/humboldt-bay-information/wildlife/48-fisheries.html). Accessed on May 10, 2019.

Magurran, A.E. 1988. Ecological diversity and its measurement. Croom Helm, London.

McKindsey, C. W., M. R. Anderson, P. Barnes, S. Courtenay, T. Landry, and M. Skinner. 2006. Effects of shellfish aquaculture on fish habitat. Fisheries and Oceans.

Phillips, R. 1984. The ecology of eelgrass meadows in the Pacific Northwest: a community profile. US Fish and Wildlife Service, FWS/OBS-84/24, Washington, D.C.

Pinnix, W. D., T. A. Shaw, K. C. Acker, and N. J. Hetrick. 2005. Fish communities in eelgrass, oyster culture and mudflat habitats of north Humboldt Bay, California, Final Report. US Fish and Wildlife Service, Arcata, California Technical Report 2.

R Core Team (2016). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

Ruesink, J.L., Stachowicz, J.J., Reynolds, P.L., Boström, C., Cusson, M., Douglass, J., Eklöf, J., Engelen, A.H., Hori, M., Hovel, K. and Iken, K., 2018. Form–function relationships in a marine foundation species depend on scale: a shoot to global perspective from a distributed ecological experiment. Oikos, 127(3), pp.364-374.

Rumrill, S. 2017. Ecosystem Services and Functions Provided by Eelgrass and Commercial Shellfish Mariculture. Presentation to NOAA Eelgrass working group on April 11, 2017. Seattle, Washington.

Rumrill, S. S., and V. K. Poulton. 2004. Ecological Role and Potential Impacts of Molluscan Shellfish Culture in the Estuarine Environment of Humboldt Bay, CA. Page 79. South Slough National Estuarine Research Reserve, Charleston, OR.

Simenstad, C. A., and K. L. Fresh. 1995. Influence of intertidal aquaculture on benthic communities in Pacific Northwest estuaries: Scales of disturbance. Estuaries 18(1):43–70.

Short, F.T., D.M. Burdick, C.A. Short, R.C. Davis, and P.A. 2000. Developing success criteria for restored eelgrass, salt marsh and mud flat habitats. Ecological Engineering 15:239-252.

Trianni, Michael S. 1996. The influence of commercial oyster culture activities on the benthic infauna of Arcata Bay. Doctoral dissertation, Humboldt State University. Arcata, California.

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