Executive Summary
Ecological Interactions Report

Willapa Bay and Grays Harbor – two coastal estuaries in the southwest corner of Washington State – provide a substantial percentage of the nation's oysters, and the shellfish industry is central to the local economies of Pacific and Grays Harbor counties. In recent years, shellfish growers have contended with many ecological stressors that threaten the future viability of the industry, including ocean acidification, mortality events caused by harmful algal blooms and summer heat waves, and invasive species. The increased uncertainty generated by these large-scale environmental changes has also contributed to conflicts between shellfish growers and regulators about aquaculture practices and their impacts on protected species and habitats.

The Washington Coast Shellfish Aquaculture Study

To make progress on the most pressing of these regulatory conflicts in the bays, the Washington Coast Shellfish Aquaculture Study (WCSAS) – a three-year program of integrated engagement and research guided by stakeholders and scientists, coordinated by Washington Sea Grant (WSG) and funded by the Washington State Legislature and other grants – was initiated in 2018. ***The goal of WCSAS was to sustain shellfish aquaculture in the region under changing environmental conditions by establishing a collaborative, ecosystem-based management framework that addresses two key challenges: perceived conflicts between shellfish farming and eelgrass habitat conservation, and the lack of effective burrowing shrimp pest management on shellfish farms.*** Central to this endeavor is a shared foundation of information for developing and evaluating management and adaptation strategies. To that end, WSG commissioned a series of reports synthesizing the scientific and management literature related to system-scale environmental challenges in Willapa Bay and Grays Harbor. This report focuses on the biology, ecology, and interactions between three important ecosystem engineers in Willapa Bay and Grays Harbor: cultivated shellfish, eelgrass, and burrowing shrimp.

WILLAPA-GRAYS HARBOR
ESTUARY COLLABORATIVE

Main Findings

Chapter 1 introduces the estuaries, the people who live alongside them, and the shellfish industry that connects people and place. Located a mere 25 km apart, Willapa Bay and Grays Harbor combined represent 37% of the estuarine wetland area in all of Washington State. Oceanographically, marine inputs are evident near the mouth of Willapa Bay, where variation in water properties (i.e., salinity and pH) tracks summer coastal upwelling. The food resources that fuel productive oyster lands near the mouth of Willapa Bay are derived from the ocean, and phytoplankton communities differ along the estuarine axis. ***Though often described as pristine, the estuaries have been influenced and altered by various historical and recent human activities***, including containment of the Columbia River, large-scale dredging, diking, industrial logging, contaminants and pollution, and the introduction of Spartina cordgrass and other invasive and/or non-native species.

Coastal Indigenous peoples have lived alongside Willapa Bay and Grays Harbor since time immemorial. In the 1850s, Euro-American settlers began arriving to what is now Pacific County in search of oysters to feed the California gold rush, and to Grays Harbor County in pursuit of opportunities in the logging industry. ***The growth of commercial oyster harvesting and industrial logging led to overexploitation and declining water quality, both of which depleted wild stocks of native oysters (Ostrea lurida) in the 19th century.*** This prompted a shift toward increasingly formalized oyster cultivation on private tidelands – a livelihood that has been central to the local culture and economy for over 125 years.

Currently, shellfish aquaculture occupies approximately 23% of the intertidal area of Willapa Bay and about 3% of the intertidal area of Grays Harbor, with the actual area under cultivation at any given time likely lower. ***Pacific oysters (Crassostrea gigas) and Manila clams (Ruditapes philippinarum) are commercially produced primarily using on-bottom culture techniques, though several off-bottom methods are also in use.*** Reported landings of Pacific oysters were about 2 million kg (fresh shucked weight) annually from 1980 to 2005. Since 2012, annual landings of Manila clam have stabilized at about 500,000 kg in-shell weight and represent about 19% of shellfish production by weight. The shellfish industry is also an important direct and indirect source of jobs, income and revenue in southwestern Washington, accounting for 15-24% of the total labor-earned income in Pacific County – one of the most seafood-dependent counties in the nation.

Shellfish aquaculture in the estuaries operates within a complex policy and regulatory context. Tidelands can be privately or publicly owned, but activities affecting water or wildlife are managed within a multi-level system that includes private tideland owners, local governments, state agencies, tribes, federal agencies, NGOs and public input. More recently ***the communities surrounding Willapa Bay and Gray Harbor have experienced demographic and economic shifts, bringing new residents from more urban areas with different livelihoods and environmental values and limited understanding of the importance of working waterfronts to rural coastal communities.***

Chapter 2 focuses on the biology and ecology of three prominent shellfish species in the estuaries: native oysters, Pacific oysters, and Manila clams. Native oysters typically occur at lower tidal elevations in Willapa Bay, and their current distribution is patchy and sparse. Pacific oysters typically occur at higher elevations and are cultivated throughout Willapa Bay and Grays Harbor. Though Pacific oysters are better able to withstand freezing air temperatures at low tide, native oysters spawn at cooler water temperatures than Pacific oysters and they are more tolerant of fluctuating salinity. Both native and Pacific oysters recruit naturally in Willapa Bay and prefer recruiting on shell substrate. Recruitment typically occurs from May to July for native oysters and from late July to August for Pacific oysters, but this can vary depending on summer temperatures that influence the timing of spawning. The two species have distinct reproductive cycles and growth rates. Native oysters brood larvae and have a slower growth rate as adults, while Pacific oysters complete all of stages of larval development in the plankton and, after planting, are typically ready for harvest within three years. Oysters in Washington State are generally more limited by predators, parasites, and pests than by microscopic disease-causing pathogens, although harmful algal blooms associated with summer mortality have been increasing in frequency. Common predators include crabs, oyster drills, sea stars, and flatworms, while burrowing shrimp that destabilize the sediment and bury the oysters are a major pest in the estuaries. ***Oysters are ecosystem engineers that influence water properties, carry out benthic-pelagic coupling, stabilize sediments, and create structural habitat for benthic and nekton species within the estuaries. Their filter feeding plays an important role in cycling materials in the water column and their biodeposits return organic material to the sediment.***

The other major commercial shellfish species in the region is the non-native Manila clam. Like oysters, clams settle at highest densities in the south part of Willapa Bay where water residence time is longer, while lower settlement occurs closer to the mouth of the bay. Manila clams are tolerant of a wide range of temperatures and salinities, but they cannot withstand freezing temperatures or excessive freshwater inputs. Unlike many other bivalves, their filtration rates increase continuously with temperature, even past the optimum filtration rate. Manila clams spawn when temperatures reach approximately 13-14 °C, and their larvae are abundant as early as May with an extended reproductive period through the summer. Habitats with shell or gravel tend to have higher clam recruitment, while non-native eelgrass usually reduces clam recruitment and condition. Predators of Manila clams include moon snails, crabs, sea stars, and various species of birds and fish. A major pest is burrowing shrimp, which destabilize sediments and compete with clams for space. ***Like oysters, their filter feeding plays an important role in cycling materials in the water column and Manila clams also contribute to nitrogen regeneration and sediment aeration.***

Chapter 3 reviews the biology and ecology of *Zostera marina* (native eelgrass) and *Z. japonica* (non-native eelgrass). ***Z. marina and Z. japonica are estimated to cover 16-32% and 8-13% of the intertidal area of Willapa Bay, respectively,*** though estimates vary widely by measurement methods. *Zostera marina* is generally distributed lower in the intertidal zone than *Z. japonica*, a distribution that is an outcome of better tolerance of low-tide conditions by *Z. japonica* and larger body size and competitive ability for *Z. marina*. *Z. marina* often overlaps with oyster aquaculture and *Z. japonica* often overlaps with clam aquaculture in Willapa Bay. Competition between *Z. marina* and *Z. japonica* can occur in the mid-to-low intertidal zone, but several studies show *Z. marina*'s larger size provides an advantage when desiccation is not a problem. Eelgrass can reproduce asexually and sexually and follow either annual or perennial life history strategies. Most populations of *Z. marina* (including those in Willapa Bay) are perennial and have dynamics dominated by asexual clonal branching. *Z. japonica* tends toward an annual (i.e., sexual) life history type, by comparison, in which seeds germinate, flower, and die within one growing season. Light availability is one of the greatest limiting factors for eelgrass, but distribution and growth can also be affected by wave exposure, currents, turbidity, sediment composition, physical and chemical disturbances, temperature and salinity. In the two estuaries, the biggest anthropogenic threats to eelgrass are reduction in light availability due to shading from overwater structures and physical disruption to plants or sediments. However, eelgrass is quite resilient. ***Though cumulative effects from multiple stressors can cause irreparable damage, healthy eelgrass beds can recover from disturbances that reduce density by more than 20-fold.***

Native eelgrass plays a central role in many ecosystem functions within the estuaries, including stimulating and stabilizing nutrient, carbon and sulfur cycling in sediments. Fewer studies have addressed whether *Z. japonica* confers the same ecological benefits. Within Willapa Bay, both eelgrass species are ecosystem engineers that reduce current velocity and stabilize sediment. ***Eelgrass meadow habitat supports***

diverse biological communities that are distinct from unvegetated habitats but share some overlap with other structured habitat such as oyster beds. Differences between macrofaunal communities in *Z. japonica* and *Z. marina* have also been observed and may be due to differences in tidal elevation and vegetation. Finally, eelgrasses fuel both plant-based and detritus-based food webs.

Chapter 4 describes the biology and ecology of the two predominant species of burrowing shrimp found in Willapa Bay and Grays Harbor: ghost shrimp (*Neotrypaea californiensis*) and mud shrimp (*Upogebia pugettensis*). Ghost shrimp are typically found higher in the intertidal zone than mud shrimp, especially in areas where the two species co-occur. Ghost shrimp create a series of connecting shafts and chambers with multiple surface openings marked by small mounds of ejected sediment, whereas mud shrimp dig simpler Y-shaped mucus-lined burrows with two openings to the surface. Both species are well adapted to low-oxygen conditions and feed on particulate organic matter, though ghost shrimp are generally classified as deposit feeders and mud shrimp are considered suspension feeders. Although both species are sexually dimorphic and have slightly skewed adult sex ratios, mud shrimp tend to have a faster life history compared to ghost shrimp: they produce more eggs that hatch earlier in the year, and have a shorter larval development period, faster juvenile growth and shorter life spans. Larvae of both species are flushed out of coastal estuaries and into the nearshore coastal ocean where they develop through several zoeal stages before returning to the estuaries as post-larvae. Ghost shrimp settle and recruit broadly, while mud shrimp tend to settle and recruit to areas with adult conspecifics. ***Mud shrimp populations have drastically declined since 2001, while ghost shrimp populations have mostly increased since 2009.*** Multiple explanations have been proposed for these changes, including parasitic isopod infection, increased sedimentation, declines in predator populations, and changes in freshwater inputs.

As ecosystem engineers, burrowing shrimp alter the soft sediment environments they inhabit and thus the ecosystem services provided. Their burrows greatly enhance sediment surface area and permeability, thereby increasing the exchange of oxygen, dissolved inorganic nitrogen and other nutrients in the environment, and potentially buffering against eutrophication. Their burrowing activities also alter the suitability of soft sediments for other benthic organisms by disrupting biofilms and/or destabilizing the substrate. However, for some infauna, their mucous-lined burrows enhance trophic resources. Finally, burrowing shrimp influence the food web by acting as primary and secondary consumers and by providing food to many estuarine predators, including crabs, gray whales and multiple fish species.

Finally, Chapter 5 examines the two-way ecological interactions between each group of ecosystem engineers before considering cross-habitat comparisons across all of them. Much of the regulation of shellfish aquaculture practices in Washington State concerns its interactions with eelgrass habitat. ***On the one hand, shellfish beds potentially benefit eelgrass in several ways:*** (1) oysters remove particulate matter from the water column and can reduce turbidity, thereby potentially increasing light availability for eelgrass; and (2) by depositing feces and pseudofeces that increase local nutrient concentrations and organic content.

On the other hand, shellfish aquaculture methods can negatively impact eelgrass, though the nature of the impact varies by culture method. Bottom culture can compete with eelgrass for space, and mechanical harvesting can physically damage plants by uprooting rhizomes or cutting blades, tangling blades or increasing sedimentation, contributing to an overall decrease in eelgrass biomass – at least in the short-term. Longline culture can impact eelgrass via entanglement and sediment accretion, while suspended bag culture can cause shading. Finally, stake and rack culture can cause shading, erosion and increased sedimentation. However, eelgrass is generally able to recover from pulse disturbances due to shellfish aquaculture. ***At an overall landscape scale and based on long-term historical trends, eelgrass is found at expected amounts on oyster beds in Willapa Bay, despite concerns about spatial competition and disturbances caused by aquaculture activities.***

Looking at the effects of eelgrass on cultivated shellfish, ***eelgrass can influence bivalve production by altering water flow and food availability, reducing or enhancing predation, stabilizing sediment and buffering pH***; however, the effects are both site-specific and species-specific, in terms of both shellfish species and eelgrass species. Dense beds of eelgrass slow the flow of water immediately above and adjacent to shellfish beds, which could limit the delivery of water-column resources. Conversely, reduced water flow could directly supply organic particulates from microalgae or senescing eelgrass, thereby increasing food availability for shellfish.

Most studies of shellfish and burrowing shrimp interactions have focused on the impacts of shrimp on shellfish survival. ***Dense populations of burrowing shrimp can render entire plots of tideland unsuitable for shellfish culture.*** Their burrowing activity destabilizes the substrate and expels sediment at the surface. This interferes with feeding or leads to suffocation and death if the oysters' gills and ciliary tracts become clogged. In terms of eelgrass and burrowing shrimp interactions, areas of overlap worldwide have been studied frequently to better understand their relationship. ***Interactions between burrowing shrimp and eelgrass are often antagonistic, but the dominant competitor (i.e., which wins) is inconsistent.***

The most common comparisons across all three groups of species have focused on the diversity of community assemblages. In both Willapa Bay and Grays Harbor, ***the highest diversity of benthic macrofauna community assemblages is found within eelgrass beds and bottom-culture oyster plots, while the lowest amount of diversity was found within ghost shrimp beds.*** By comparison, the diversity of community assemblages was most similar between the eelgrass beds, oyster beds, and mudflat habitats, indicating similarities of nekton communities across these three habitats.

Next Steps and Recommendations

As a place-based, collaborative and interdisciplinary approach to landscape-scale adaptive management, EBM is well-suited to the complexity of resource management in Willapa Bay and Grays Harbor. Though this report reviews the state of the science regarding the biology and ecology of the key ecosystem engineers in the estuaries, competing interpretations of the science and its implications remain. In some cases, additional research addressing key information gaps can help reconcile different perspectives or shed light on important tradeoffs. ***Future research should generally prioritize two areas: (1) enhanced understanding of the ecological role of each ecosystem engineer and the interactions between them to help characterize the tradeoffs between shellfish production, eelgrass protection, and burrowing shrimp management and anticipate the impact of changing environmental conditions; and (2) social science studies related to environmental history, traditional and local knowledge, and the impacts of economic and demographic changes.***

In many cases, however, underlying value-based conflicts have simply been framed as scientific conflicts, with each side claiming the other side is not using "good science." ***As progress toward EBM continues in Willapa Bay and Grays Harbor, constituents should acknowledge the value of consulting the "best available science" to inform decision-making and resolve technical disputes, while recognizing that it cannot reconcile competing values.***

Future Research Priorities to Support EBM in Willapa Bay and Grays Harbor

- Consistent mapping and monitoring of each habitat type to assess disturbance, resilience and recovery at the landscape scale
- The ecosystem services of each shellfish species and the environmental factors related to increased production/restoration and decline
- The ecological role of native versus non-native eelgrass
- The comparative vulnerability and resilience of eelgrass species to different shellfish cultivation practices and emerging invasive species (i.e., European green crab)
- Burrowing shrimp recruitment dynamics and the vulnerability of different burrowing shrimp life stages to support the development of pest management tactics
- The environmental history of the region and the traditional and local knowledge of tribal members and multigeneration shellfish farmers
- The economic value of different cultivated shellfish species and cultivation techniques
- The impact of economic and demographic changes on the shellfish industry

For more information contact Nicole Naar, Social Science and Education Specialist at Washington Sea Grant at nanaar@uw.edu

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Sea Grant
WASHINGTON

Washington Sea Grant
3716 Brooklyn Ave NE
Seattle, WA 98105
seagrant@uw.edu
wsg.uw.edu
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