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Management Recommendations for Restoration of the Degraded Olympia Oyster, *Ostrea lurida* Carpenter 1864 in Tomales Bay, CA

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This Master's Project

**MANAGEMENT RECOMMENDATIONS FOR RESTORATION
OF THE
DEGRADED OLYMPIA OYSTER
OSTREA LURIDA CARPENTER 1864
IN TOMALES BAY, CALIFORNIA**

by

Carolyn McCauley Gibson

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Chapter 1: Introduction

Estuaries are biologically productive, dynamic ecosystems that act as an interface between marine and riparian upland environments. They provide protection, biogeochemical cycling, and habitat for a diverse range of biota. Estuaries are nutrient sinks and sources, with riparian freshwater and oceanic saltwater mixing to create a highly productive zone. Their sheltered situation between upland and coast provides a sort of nursery for marine and aquatic biota, with abundant invertebrate populations supporting species of higher trophic levels. Such a far-reaching influence merits consideration for conservation and preservation; estuaries endure a variety of threats, from ocean acidification to coastal development and sedimentation to non-native species invasions. Fortunately, the efforts of the National Oceanic and Atmospheric Administration's (hereafter NOAA) National Marine Sanctuary Program and other natural resource agencies recognize the value of estuaries and provide some much-needed protection and mitigation. This research focuses on protection for a particular resource in a particular National Marine Sanctuary, as discussed below.

1.1 Background

The following sections discuss the role of the National Marine Sanctuaries in resource protection in the Pacific Region and provide background information on the Tomales Bay estuary, within the boundary of Greater Farallones National Marine Sanctuary.

1.1.1 Role of National Marine Sanctuaries and Greater Farallones

In 1972, Congress passed the National Marine Sanctuaries Act in an effort to set aside certain marine ecosystems of particular value. Such areas are of biological and conservational significance, with some consideration for human value as well (NOAA, 2013). Currently, there are thirteen national marine sanctuaries and one marine national monument protected under the Act, several of which are undergoing boundary expansions (NOAA, 2013). NOAA's Office of National Marine Sanctuaries, which is

within the Department of Commerce, manages these sanctuaries; the sanctuary offices regulate and minimize wildlife disturbance, prohibit oil and gas production and extraction, issue multi-use and exemption permits, and work with stakeholders such as shipping companies and fishermen to promote sustainability within each sanctuary's boundaries. Sanctuaries are an effective resource management strategy, as they set aside biologically productive and significant marine ecosystems to prioritize conservation. Some commercial practices, including shipping, fishing, and tourist activities are permitted within sanctuaries; sustainable practices and utilitarian conservation remain at the forefront (NOAA, 2013). As a result, marine habitats and their dependent populations can sufficiently recover or flourish within these designated areas.

Greater Farallones National Marine Sanctuary (hereafter GFNMS or the Sanctuary) off the coast of California is one such entity that oversees estuarine resource protection. Created in 1981, GFNMS provides protection for numerous marine resources, including those around the Farallon Islands, for which it is named, and numerous bays and estuaries including Tomales Bay (GFNMS, 2015). GFNMS is an area of major marine biodiversity due to the presence of the California Current. This current produces upwelling events, which spur blooms of phytoplankton that fuel the marine, estuarine, and coastal ecosystems within GFNMS boundaries (Kimbrow, 2009). GFNMS is a feeding and nursery ground for 36 species of cetaceans and pinnipeds, a significant seasonal population of great white sharks, thousands of seabirds and shorebirds, both resident and migratory, and numerous benthic invertebrates (GFNMS, 2015).

In accordance with the National Marine Sanctuaries Act, GFNMS prioritizes resource protection, scientific research, and outreach and education to best manage the marine environment within its boundaries (GFNMS, 2015). Its proximity to major ports, including San Francisco and Oakland, require GFNMS to also consider the socioeconomic needs; minimizing the impacts of human enterprises, such as commercial shipping, enables GFNMS to effectively protect the sensitive marine ecosystem and its inhabitants (GFNMS, 2015). Figure 1 shows the recently expanded boundary of the Sanctuary; which includes both offshore and coastal habitats from the San Francisco Bay Area north to Sonoma and Mendocino Counties (GFNMS, 2015).

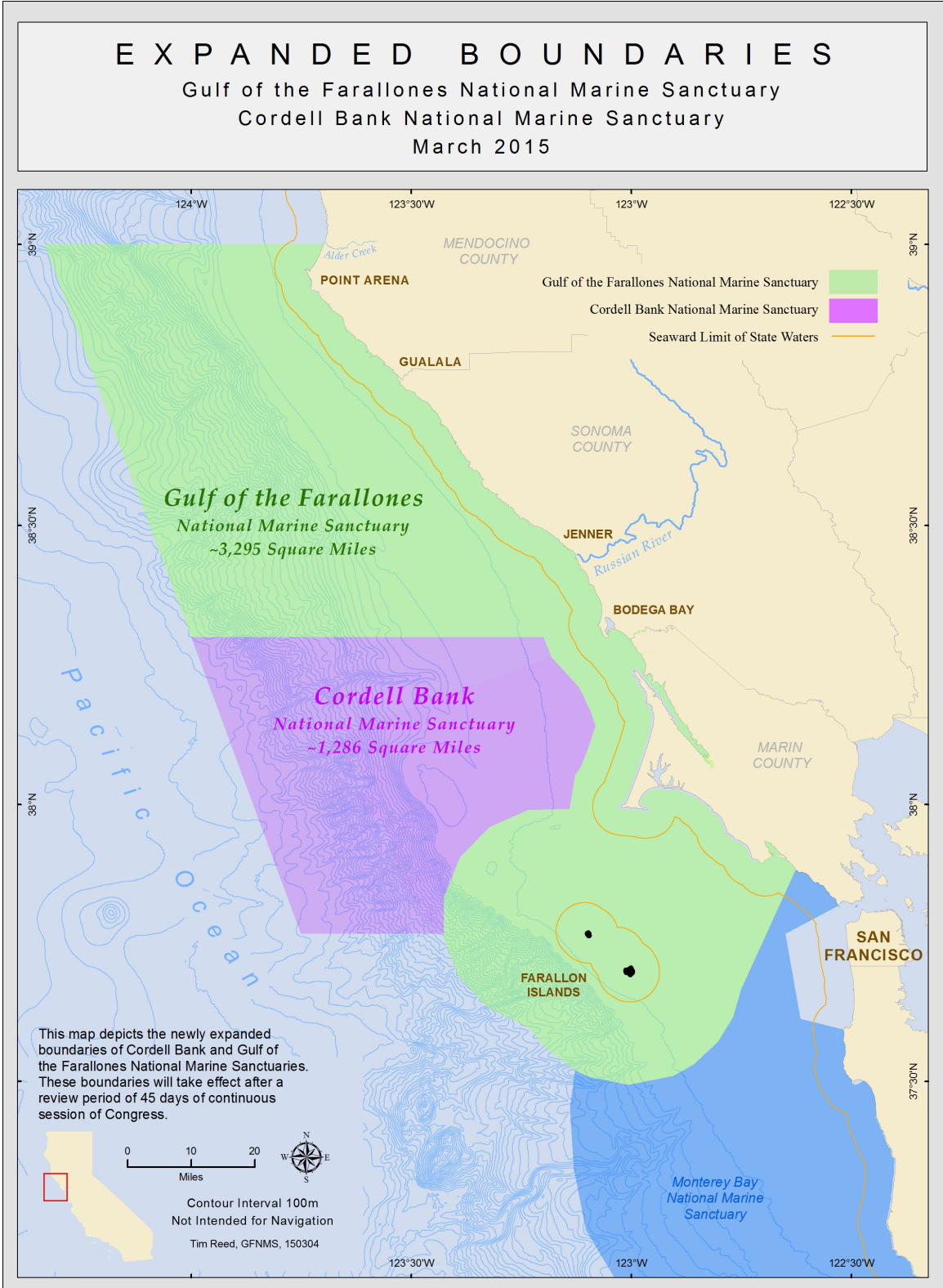


Figure 1: Map of the extent of the Sanctuary along the California coast (Map courtesy of Tim Reed, NOAA, 2015).

1.1.2 Tomales Bay Estuary

Tomales Bay is a protected estuary within the jurisdiction of Greater Farallones National Marine Sanctuary; located in western Marin County of California, it is a unique estuarine ecosystem. The bay is situated between an extensive inland watershed and a significant seasonal upwelling zone within the California Current off the adjacent Pacific coast (Deck, 2011; Kimbro, 2009). Tomales Bay includes a variety of microhabitats: seagrass beds, intertidal zones, subtidal zones, and tidal wetlands can be found within and around its shorelines. These habitats are jointly regulated by GFNMS and several state and federal agencies. GFNMS works to minimize human disturbance to this sensitive ecosystem and promote the ecological integrity of the bay. The GFNMS jurisdiction ranges from the submerged habitats within Tomales Bay up to the mean high water line (GFNMS and CSLC, 2013). Despite the joint protections afforded to Tomales Bay by GFNMS, the bay and its watershed remain highly disturbed as a result of past and present human activities, including mining, settlement, and agriculture. Such disturbances compromised the status of one of the bay's foundation species, the Olympia oyster, *Ostrea lurida*.

1.2 Olympia Oyster Ecology and Degradation

The following sections provide an overview of Olympia oyster ecology and degradation within Tomales Bay.

1.2.1 Olympia Oyster Ecology

The Olympia oyster, *Ostrea lurida* Carpenter 1864 (hereafter Olympia oyster), is a small calcifying mollusk once found in abundance throughout the Pacific Coast estuaries of North America (White et al., 2009; Groth and Rumrill, 2009; Pritchard et al., 2015), including Tomales Bay. The “Carpenter 1864” references a conclusion drawn by researchers in the twentieth century of the genetic similarity between *Ostrea lurida* and its very similar southern relative, *Ostrea conchaphila* (Carson, 2010). Like other bivalve species, Olympia oysters are ecosystem engineers, as their establishment and creation of three-dimensional substrate provides habitat and protection for other organisms (Kimbro

et al., 2006). The reef structures formed by populations of oysters are nurseries and feeding grounds for numerous species of invertebrates, fish, birds, and mammals, enhancing the biodiversity of the Tomales Bay estuary (Tolley et al., 2005). In addition, reefs of settled Olympia oysters ease coastal erosion and buffer the estuary's shallows and vegetation from wave surge (Deck, 2011). This small species contributes a great deal to the overall health and function of the estuary, and for these reasons is considered a foundation species.

1.2.2 Species Degradation

Climate change and anthropogenic carbon emissions create uncertainty as to the survival and adaptation of the Olympia oyster. Projected impacts of ocean acidification as a side effect of climate change could prove quite devastating to the Olympia oyster, as well as to all calcifying marine organisms (Kurihara, 2008). Anthropogenic emissions of carbon dioxide (CO₂) and greenhouse gases accumulate in the atmosphere at imbalanced concentrations, and as a result, much of the atmospheric carbon dioxide now sinks into the oceans (Gazeau et al., 2007). This leads to ocean acidification; such high concentrations of CO₂ entering ocean water cause a lowering in pH, thereby acidifying the ocean and threatening the survival of calcifiers like the Olympia oyster. Marine calcifiers derive carbonate ions and bicarbonate from the surrounding ocean water to construct their shells or other structures (Guinotte et al., 2008). Calcifiers rely upon the carbonate ions present in ocean water to create calcareous structures such as shells (Doney et al., 2009); the imbalance in ocean chemistry due to excessive concentrations of carbon dioxide decreases the availability of carbonate and other essential ions. While little is guaranteed as to the severity or long-term impacts of ocean acidification, it is evident that the issue poses a great threat to Olympia oysters.

While the future impacts to Olympia oyster populations from ocean acidification is less certain, it is clear that two current degraders, sedimentation and invasive species, pose a more dire threat; fortunately, each is also manageable. It is worth noting that current populations of the species are particularly sensitive due to declines in its historic range. The exploitation of the species in Tomales Bay began in the mid-nineteenth century, when settlers of the San Francisco Bay Area overfished Olympia oyster to meet

the demands of a thriving commercial market (Booker, 2006). The slow-growing, small species could not sustain this market, and thus the populations in Tomales Bay collapsed. Currently, wild Olympia oysters can be found in sparse abundance in the bay, but little effort to restore or cultivate them commercially inhibits their resurgence.

Land development and agricultural practices in the Tomales Bay watershed significantly degraded Olympia oyster habitat through sedimentation; historic mining and logging activities began the inflow of sediment into Lagunitas, Olema and Walker Creeks in the mid-nineteenth century before major agricultural enterprises were established in Marin County (Niemi and Hall, 1996). While logging and mining practices in the watershed declined, rangeland agriculture further exacerbated the sediment problem in Tomales Bay and continues to do so. Land clearing to accommodate cattle removed much of the riparian vegetation in the watershed, resulting in an influx of massive quantities of fine sediment into Tomales Bay and its watershed due to soil destabilization (Niemi and Hall, 1996). By the early to mid-twentieth century, sediment accumulation increased to more than 5 millimeters (mm) depositing per year, reducing tidal marshes through progradation (Rooney and Smith, 1999). Fortunately, these high rates of sediment influx to Tomales Bay and its watershed decreased after the mid-1950s as a result of damming and restoration efforts, but land erosion continues to add fine sediment such that these water bodies remain listed as 303d, or “impaired” under the Clean Water Act (Rooney and Smith, 1999; Hwang et al., 2013). Fine sediment continues to plague the Olympia oyster by creating severe stress on both juvenile and adult oysters, inhibiting settlement and establishment on the seabed.

The replacement of Olympia oysters with Eastern oysters, *Crassostrea virginica*, further reduced efforts to restore Olympia oyster populations. In response to the overharvest of and lack of sufficient populations of Olympia oysters, growers imported the Eastern oyster by 1870, as this species met both the market demands of Bay Area enterprises and the quality standards of Bay Area consumers (Booker, 2006). Eastern oysters proved insufficiently adapted to the oceanographic conditions of Tomales Bay and the U.S. West Coast, which prompted their replacement (Forrest et al., 2009). In the early to mid-twentieth century, a second non-native species replaced Eastern oysters: the Pacific oyster, *Crassostrea gigas*. This larger, adaptable oyster species thrived in

Tomales Bay to the further detriment of Olympia oysters, and current aquaculture enterprises continue to cultivate the Pacific oyster in large quantities (Kirby, 2004).

While the cessation of harvest in favor of Eastern and then Pacific oysters should encourage resurgence in Olympia oyster numbers, the accidental introduction of two invasive oyster drill species to Tomales Bay continues to curb oyster populations through predation and competition. It is noted that nearly half of non-native species introductions in western U.S. estuaries result from oyster aquaculture, and Tomales Bay is no exception (Forrest et al., 2009). The Atlantic oyster drill, *Urosalpinx cinerea*, is the more aggressive of the two drills present and is widely distributed throughout Tomales Bay; this species “hitchhiked” with imports of Eastern oysters in the nineteenth century and continued to thrive (Kimbrow and Grosholz, 2006). The Japanese oyster drill, *Ocenebra inornata*, similarly arrived in Tomales Bay via importation of Pacific oysters in the twentieth century; while impactful upon the trophic processes of the bay ecosystem, it is less directly impactful upon Olympia oysters than the Atlantic drill (Buhle and Ruesink, 2009). However, its effects are not to be overlooked.

These three degraders in addition to historical overfishing reduced Olympia oyster populations in Tomales Bay. The ecological integrity, habitat and water quality of the bay are subsequently compromised. To restore the oyster populations and mitigate these issues, changes in resource management and human practices of both Tomales Bay and its watershed are necessary.

1.3 Ecological Relevance and Restoration

As one of the custodians of Tomales Bay, GFNMS is responsible for maintaining and restoring the ecological integrity of this estuary and its inhabitants. The Olympia oyster is one such inhabitant, and its presence in the bay provides invaluable ecosystem services that cannot be overlooked or replaced. The restoration of healthy, self-sustaining Olympia oyster populations within the bay improves water quality and biodiversity; therefore, it is within the scope of the GFNMS Management Plan to participate in and facilitate restoration efforts where possible. The degradation of the Olympia oyster in Tomales Bay is a direct result of human activity; therefore, the Sanctuary is the

appropriate agency to lead restoration efforts. Collaboration with other agencies and research institutions, including the National Park Service, California State Parks, California Department of Fish and Wildlife, California State Lands Commission, and Bodega Marine Laboratory, is essential to design an effective restoration plan.

GFNMS can and should begin the process of Olympia oyster restoration in Tomales Bay. This research provides the necessary first step towards restoration through the consolidation of data and relevant studies, the identification of issues to ensure restoration success, the acknowledgement of data gaps, and recommendations to address restoration barriers. Thorough site evaluation and data collection is necessary to address the aforementioned data gaps that could inhibit restoration. An example of such a gap is a mapped location and abundance of both Olympia oyster populations and invasive oyster drills within Tomales Bay. The lack of data can be rectified through collaboration with those researchers currently working with this species in Tomales Bay. Ocean acidification requires close collaboration with researchers and coastal agencies to better understand the possible effects on Olympia oysters in Tomales Bay, but some preventative measures during restoration projects could mitigate the impacts of this large-scale process.

1.4 Research Summary

This research addresses the effective restoration of Olympia oyster populations in Tomales Bay, Marin County, California. Chapter 2 provides background information on the Tomales Bay estuary, regional history, and ecology of the Olympia oyster. Following this background discussion, each of the three aforementioned degraders of Olympia oyster populations in Tomales Bay is presented: ocean acidification (Chapter 3), sedimentation (Chapter 4), and invasive species (Chapter 5). Each of these issues creates numerous barriers that require the attention of managers. Chapter 6 presents overall Research Conclusions and Chapter 7 identifies management recommendations to effectively begin the restoration of the Olympia oyster in Tomales Bay.

Chapter 2: Tomales Bay, Olympia Oyster Ecology, and Threats to the Species

This chapter presents background information for the Tomales Bay Estuary, its regional history, ecology of the Olympia oyster, and threats to the oyster within Tomales Bay resulting from ocean acidification, sedimentation and invasive species.

2.1 Tomales Bay Estuary

An overview of the Tomales Bay estuary is provided in the sections below in terms of geography, oceanography, watershed, seagrass beds (hereafter referred to as the eelgrass species *Zostera marina*) and jurisdiction.

2.1.1 Geography

Tomales Bay is a narrow bay located within a submerged valley along the San Andreas Fault in western Marin County, California; at 38.20° N, 122.90° W, Tomales Bay is approximately 48 kilometers north of the city of San Francisco (Niemi and Hall, 1996). The bay is about 22 kilometers long and very shallow, with an average depth of three meters (Niemi and Hall, 1996), although the mid-channel is much deeper. It is oriented northwest to southeast, with the northwestern mouth opening into the Pacific Ocean. Tomales Bay includes an extensive range of microhabitats, including freshwater riparian zones, tidal wetlands, mudflats, soft-bottom subtidal zones, seagrass beds, and rocky intertidal areas (Niemi and Hall, 1996). Because of the influx of freshwater from its watershed and constant inflow of ocean water, Tomales Bay is a brackish estuary, with a variable salinity and pH characteristic of such water bodies (Kimbrow et al., 2009). The complex oceanography responsible for the biodiversity of Tomales Bay is discussed in the following section.

2.1.2 Oceanography

Tomales Bay is a low-inflow estuary, which means that the entry of both freshwater and ocean water is limited and varies seasonally (Kimbrow et al., 2009; Cloern et al., 2012). As is characteristic of estuaries, Tomales Bay experiences dynamic seasonal variations in salinity, temperature, and pH as a result of the presence of both fresh and salt water (Sansone et al., 1998). The average salinity is approximately 30 to 35 PSU with some variation between seasons; there is also some variability in salinity throughout the bay due to freshwater influx and water residence time (Johnson, 1967). Water temperatures vary seasonally, with an average range between 10° Celsius and 20° Celsius (Deck, 2011). Ocean water and tides affect the hydrology and chemical oceanography most significantly near the mouth of the bay, while the inner bay is subject to a great influence by fluvial and watershed processes (Deck, 2011; Rooney and Smith, 1999). In general, the salinity and temperature both increase from the mouth of Tomales Bay to the inner bay; this is because residence time is greater in the inner bay areas due to limited access to the ocean (Deck, 2011). Fluvial input from Lagunitas and Walker Creeks are significant sources of freshwater, sediment, and nutrients, impacting the aforementioned biogeochemical processes throughout the bay (Rooney and Smith, 1999). Due to the wet winters and dry summers characteristic of its Mediterranean climate, Tomales Bay receives greater amounts of freshwater from its watershed during the winter, with less flowing into the bay during the summer months (Deck, 2011). It is during these drier summer months that a large-scale oceanographic phenomenon significantly affects Tomales Bay's hydrology and biology: upwelling.

The California Current, a cold-water eastern boundary current, brings cold, nutrient-rich water southward along the west coast of the North American continent. This current contributes to significant upwelling events offshore of California; wind-driven surface currents displace the warm surface water and forces dense, saline, and nutrient-rich water up to shallower depths (Kimbrow et al., 2009). This process is referred to as upwelling; upwelling events produce high rates of primary productivity and phytoplankton blooms, fueling the food chain of coastal and estuarine waters. In Tomales Bay, upwelling occurs during the summer and early fall, from late June to October (Kimbrow et al., 2009); during this period, greater tidal exchange causes a more

thorough mixing and exchange within the bay, in which phytoplankton explode in numbers as a result of the influx of nutrients (Kimbrow et al., 2009). These events also temporarily lower the pH in the bay; as is typical with estuaries, Tomales Bay experiences variable pH as a result of the interplay between fresh and marine water (Kimbrow and Grosholz, 2006). Upwelling plays a major role in the oceanography and hydrology of Tomales Bay, and its influence on primary productivity drives the food chain as well. However, it is important to consider oceanographic conditions on a smaller, more regionalized scale as well, as Olympia oyster restoration success could vary site-by-site.

Three oceanographically distinct regions characterize Tomales Bay: the outer bay, middle bay, and inner bay. An understanding of these three regions is helpful to managers, as the conditions found in each could play a major role in site selection for Olympia restoration. The outer bay includes the mouth of the bay to approximately eight kilometers southeast, with water of similar salinity, turbidity, and water residence time as the nearby coastal ocean water entering through Tomales Point (Sansone et al., 1998) and (Kimbrow et al., 2009). Walker Creek, a major freshwater tributary, enters Tomales Bay near the mouth in the outer bay region, and deposits a significant quantity of fine sediment to the seabed near its delta (Rooney and Smith, 1999). The hydrology of this region is significantly influenced by the tides (Sansone et al., 1998) and (Kimbrow et al., 2009); the residence time of outer bay water is shorter than that of the middle or inner bay because of the tidal influence and proximity to the nearby ocean (Deck, 2011). The middle bay, which is located 10 to 14 kilometers from the mouth of the bay, is characterized by intermediary water conditions; nutrients are plentiful in the region to promote and support primary productivity, and can be lower in pH during the upwelling season (Kimbrow et al., 2009). The water in the middle bay is “older” than that of the outer bay; as it flushes inward from the ocean, the water remains in the middle bay for a longer amount of time, depleting it of some of its nutrients and warming its temperatures slightly (Kimbrow et al., 2009). The middle bay’s oceanographic and hydrologic conditions are the least extreme of the three regions due to sufficient mixing of both the freshwater influences from the inner bay and the oceanic influences from the outer bay (Rooney and Smith, 1999).

Finally, the inner bay region of Tomales Bay is found 16-20 kilometers from the mouth, with the Lagunitas Creek delta forming the southeastern boundary (Kimbrow et al., 2009). The inner bay experiences the highest influx of freshwater from Lagunitas Creek, and therefore salinity is lower during the winter and spring months (Sansone et al., 1998). However, the inner bay becomes highly saline and lower in pH during the summer due to warmer air temperatures and subsequent evaporation of freshwater; this region of Tomales Bay is highly dynamic in water composition. In addition, the water here is very slow to mix with the outer and middle bay due to weakened tidal influence, so temperatures are warmer and riparian nutrient concentrations are often higher in the inner bay (Sansone et al., 1998). Lagunitas Creek introduces significant nutrient loads into Tomales Bay during the wet season; agricultural practices in the creek's watershed cause higher concentrations of methane, nitrates, and fecal coliform runoff into Tomales Bay (Lewis et al., 2004). Figure 2 shows the approximate boundaries of the outer, middle and inner bay regions of Tomales Bay.

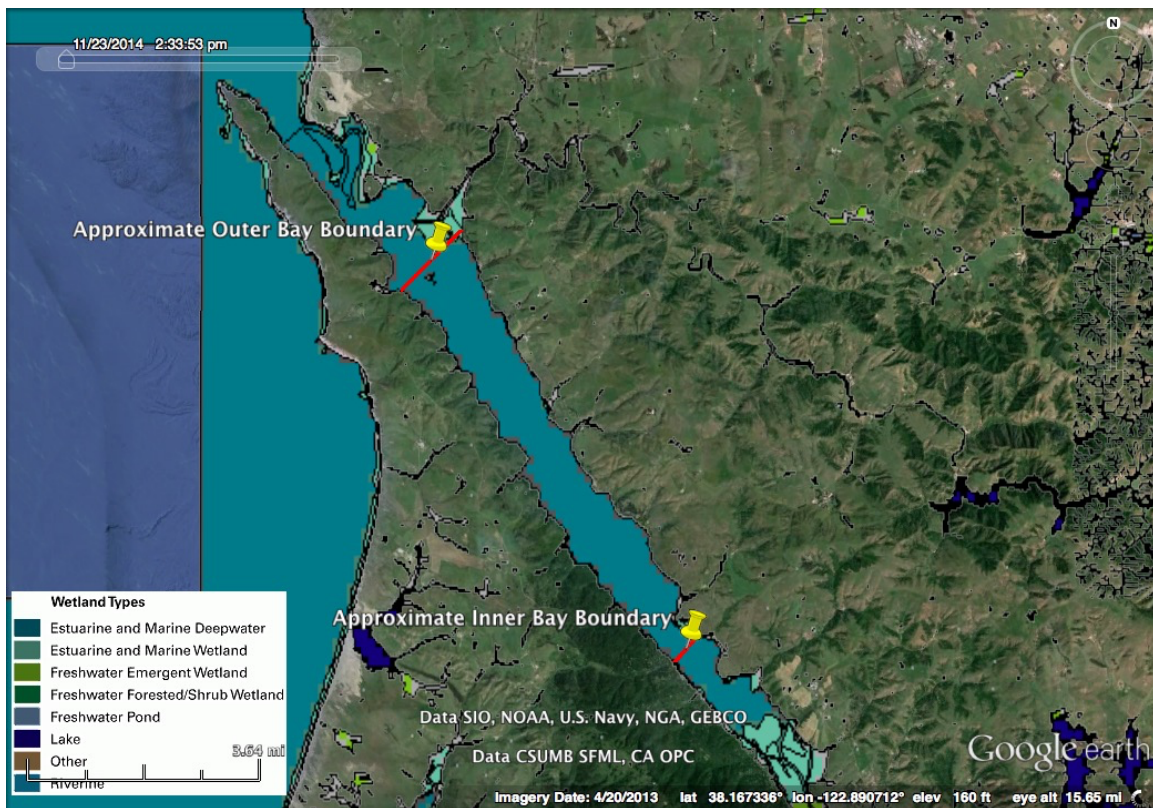


Figure 2: Map of approximate boundaries of the inner and outer regions of Tomales Bay. The wetland types depicted in the above key show the various habitats in and around the bay and its creek mouths.

Physical and chemical oceanography plays an essential role in shaping the biotic structure of Tomales Bay, and the seasonal variability in these processes requires bay inhabitants to adapt to various abiotic conditions. The *Olympia* oyster is an estuarine benthic species requiring specific conditions to spawn and settle, so an understanding of the typical physical conditions found in Tomales Bay is necessary to ensure restoration success. Chapter 2.3 discusses the conditions required by juvenile and adult *Olympia* oysters.

2.1.3 Watershed

The Tomales Bay Watershed is extensive, including two major creeks and one smaller tributary draining an area of 255 square miles (Laughlin, 2009). Figure 3 shows the Tomales Bay Watershed and its drainage area, which includes three creeks: Lagunitas Creek, Walker Creek, and the lesser Olema Creek. While each of these creeks have their own watershed, they ultimately drain into Tomales Bay, thus are part of a larger hydrologic system known as the Tomales Bay Watershed (TBWC, 2005). A population of approximately 11,000 people lives in this watershed's boundaries (Laughlin, 2009). Land ownership within the Tomales Bay Watershed region is divided amongst private landowners, private dairy farms and ranches, parklands under various agency jurisdictions, and residential areas (TBVMP, 2013).

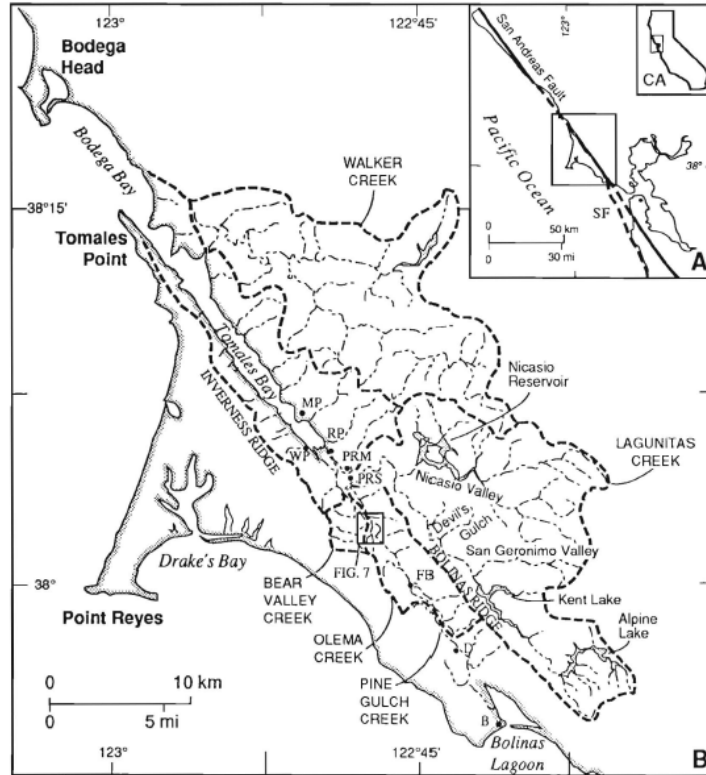


Figure 3: The Tomales Bay geographical situation and drainage basin (Niemi and Hall, 1996).

Road construction within the Tomales Bay Watershed began in the 1850s, as miners and ranchers required ways to transport their goods to San Francisco and required the streams for navigation as well as for materials (TBWC, 2005). By the 1960s, Marin County relied on bed material from the watershed’s streams to build roads: Bear Valley Road and Sir Francis Drake Boulevard are two such roadways initially paved with Lagunitas Creek sediments (TBWC, 2005). Lagunitas, Walker, and Olema Creeks contribute significant amounts of freshwater to Tomales Bay, playing a major role in the hydrology and chemical oceanography of the bay through this water delivery as well as through the deposition of fine sediment.

Lagunitas Creek is the largest freshwater tributary to Tomales Bay, contributing more than 50% of the total drainage from the watershed to the bay (TBVMP, 2013). It meets its terminus near the head of Tomales Bay, in the southeastern-most end of the bay (Niemi and Hall, 1996). The upper watershed of Lagunitas Creek is steep in terrain and largely forested, with woody vegetation acting as riparian buffers along the creek (IRWMP, 2014). The valley areas of the Lagunitas watershed, once similarly forested,

converted to grassy rangelands for livestock grazing to support a viable dairy industry. The conversion is also due to the existence of logging and paper mill industries within the western Marin region during the mid-nineteenth century to early twentieth century (TBWC, 2005).

Walker Creek is the second largest tributary of freshwater to Tomales Bay, flowing from the northwestern region of the Tomales Bay Watershed to the eastern shore of the bay; the mouth of this creek is less than 10km from the mouth of Tomales Bay itself (Niemi and Hall, 1996). Walker Creek and its associated watershed contribute approximately 35% of Tomales Bay's total freshwater input (TBVMP, 2013). While agriculture and cattle ranching persist to the present, mining and logging industries dominated the Walker Creek watershed in the mid-nineteenth century (TBWC, 2005). Mercury and gold mining persisted until the 20th century, destabilizing large quantities of sediment and depositing concentrations of mercury in the sediment of the creek bed (TBWC, 2005).

Olema Creek is the smallest of the creeks within the Tomales Bay Watershed, flowing into Tomales Bay from the south via Lagunitas Creek (Niemi and Hall, 1996), thus its inclusion with the larger Lagunitas Creek. Olema Creek is significant to include in the greater Tomales Bay Watershed because it drains the Bolinas Ridge and Inverness Ridge on the western shore of Tomales Bay (Niemi and Hall, 1996). Currently, parklands and private dairy farms are the predominant land use practices within the Olema Creek region.

The Tomales Bay Watershed contributes not only freshwater to the bay, but also sediment and nutrients that continue to shape the geology, oceanography, and biodiversity of this estuary. A further discussion of the watershed follows in Chapter 2.2 and Chapter 4.

2.1.4 Eelgrass

Eelgrass beds are one of the microhabitats found in Tomales Bay; historically, these beds extended through almost four square kilometers of the bay (Huntington et al., 2008). Eelgrass, also known as *Zostera marina*, is a marine plant species (or seagrass) that grows in dense mats in the intertidal zone of the bay; typically found in soft

sediment, eelgrass can also anchor to rockier substrate (Huntington et al., 2008). The plant contributes valuable services to the abiotic and biotic processes of Tomales Bay, making it a key foundation species. Eelgrass creates habitat and provides physical and biological services to the estuarine system (Huntington et al., 2008). Eelgrass improves water quality through the anchoring of sediment and the filtration of the water column. It is also important to note the carbon sequestration ability of marine plants, including phytoplankton and eelgrass (TBVMP, 2013). In addition, eelgrass beds are nurseries for commercially important fish species, including coho salmon (a federally-listed Endangered Species), rockfish, and several coastal pelagic species including Pacific herring; the beds also provide habitat for other benthic invertebrates.

As a marine plant, eelgrass requires sufficient light, water temperature, and nutrient concentrations to reproduce and thrive; however, studies show that the species is most sensitive to water temperature and the amount of light available, with significant die-offs resulting from a limitation of either factor (Kaldy, 2014; Huntington et al., 2008). Eelgrass is in decline in Tomales Bay due to watershed-related water quality offenses; nutrient loading fuels the growth of macroalgal species that out-compete eelgrass for light and space (Huntington et al., 2008). To improve water quality and protect the eelgrass beds from further degradation, collaboration among relevant agencies proved useful.

Because of the significant role played by eelgrass in Tomales Bay, several agencies, including GFNMS, the California Department of Fish and Wildlife (CA DFW), and the California Coastal Commission (CCC). Eelgrass beds are found in the intertidal zone of Tomales Bay, which is within the regulatory jurisdiction of GFNMS and, in some areas of the bay, California State Lands Commission and National Park Service (TBVMP, 2013). The prohibition of disturbance to eelgrass beds from boating, moorings, anchorage, and fishing activities ensures that these microhabitats can reach their maximum extent and continue to contribute to the biodiversity of the bay (TBVMP, 2013). The adaptive management strategies and collaborative protections afforded to eelgrass beds could be extended to Olympia oyster populations in the future, as oyster beds provide very similar ecosystem services and contributions to biodiversity.

Eelgrass is significant to the restoration of Olympia oyster populations in Tomales Bay. Historically, eelgrass beds and oyster beds grew concurrently, or in proximity to

one another (Forrest et al., 2009). Eelgrass beds stabilize sediment and oxygenate the water column; they stimulate productivity and nutrient cycling important to supporting other biota (Forrest et al., 2009; Huntington et al., 2008). Olympia oysters, as filterers, improve water quality and clarity through the removal of phytoplankton, nutrients, and other suspended materials from the water column, thus enhancing conditions for eelgrass (Forrest et al., 2009). As a result, the extent of eelgrass in Tomales Bay could increase due to the improvement of overall water quality. Similarly, the presence of oyster beds could buffer against storm surge and other events that might damage or destroy eelgrass beds in the intertidal zone (Meyer et al., 1997), so the placement of Olympia oyster beds in proximity to eelgrass during restoration projects should be considered.

2.1.5 Jurisdiction

The diversity of estuarine habitats, aquatic and terrestrial species, and human uses of Tomales Bay result in a complex jurisdiction. A total of eleven agencies regulate, permit, and protect the natural and anthropogenic interests of the bay; acknowledgement and understanding of their interrelation is important to facilitate future Olympia oyster restoration.

The complexity and confusion in jurisdictional boundaries resulted in the formation of the Tomales Bay Interagency Committee (TBIC) to better address some of the environmental issues within the bay (TBVMP, 2013). Olympia oyster restoration will likely require the involvement of many of these agencies, so their inclusion in this document is necessary. The TBIC includes the following list, which is also found in the Tomales Bay Vessel Management Plan (TBVMP, 2013):

- Greater Farallones National Marine Sanctuary (GFNMS)
- California Coastal Commission (CCC)
- California Department of Boating and Waterways (CA DBW)
- California Department of Fish and Wildlife (CA DFW)
- California Department of Public Health (CDPH)
- California Department of Transportation (Caltrans)
- California State Lands Commission (CSLC)
- California State Parks (CSP)

- Marin County Sheriff's Office
- National Park Service/Pt. Reyes National Seashore/Golden Gate National Recreation Area (NPS/PRNS/GGNRA)
- State Water Resources Control Board/Regional Water Quality Control Boards (SWRCB/RWQCB)

It is important to note that the TBIC does not include all agencies with the ability to regulate within Tomales Bay; the United States Coast Guard is one such entity, and other local agencies may have similar authorities to those listed above as part of the TBIC (TBVMP, 2013). However, this document focuses on those agencies whose mandates, regulations and policies could impact Olympia oyster restoration.

GFNMS plays a significant role in resource protection for this estuary. Under the National Marine Sanctuaries Act, the Sanctuary regulates the submerged lands and water up to the mean high water line within its designated federal boundaries, which includes Tomales Bay (TBVMP, 2013). It prohibits disruptive activities in the bay such as the placement of structures or vessel moorings, anchoring in protected areas, boat discharge, dredging, buoy installations, and any wildlife disturbance (TBVMP, 2013). However, GFNMS can allow certain activities that are otherwise prohibited, such as research and the installation of buoys, through the issuing of permits (TBVMP, 2013). This jurisdiction overlaps with that of other state and federal agencies, including California State Lands Commission (CSLC) and the California Department of Fish and Wildlife (CA DFW); under the authorities granted by the Public Resources Code of California, this state agency manages all state-owned tidelands, submerged lands, and seabed of state waterways. The CSLC also issues leases for moorings, aquaculture, and other permanent structures in or along the bay (TBVMP, 2013). GFNMS and CA DFW share many responsibilities in the resource protection of Tomales Bay, and will likely be the most closely involved in any oyster restoration activities.

2.2 Regional History

2.2.1 Land Uses in Tomales Bay Region That Affects Olympia Oysters

Historical and current land uses in west Marin County dramatically affect the habitat and water quality of Tomales Bay. Hunting and gathering, mining, logging, agriculture, and fishing are some of the practices employed by settlers of the region over millennia; the rich natural resources sustained first a thriving indigenous culture succeeded by enterprising American settlers from the mid-nineteenth century to the present (Booker, 2006). Unfortunately, the exploitation of the Tomales Bay region degraded watersheds and the bay itself through nutrient and sediment loading and habitat loss. Olympia oysters are one such species that endured both population decline as well as habitat loss due to land use practices. The following sections discuss the historical degradation sustained by this species and the bay due to agriculture and aquaculture; a discussion regarding the current status of the Olympia oyster and its Tomales Bay habitat also follows.

Agriculture

For thousands of years, the native Ohlone people of western Marin County practiced hunting and gathering techniques for subsistence. This included the collection of Olympia oysters and other fish and invertebrates from Tomales Bay, as is evidenced through the presence of large shellmounds in the region (Booker, 2006). However, the arrival of Europeans to the North American West Coast, beginning with the Spanish in the 1500s (Niemi and Hall, 1996), marks a transition from hunting and gathering to agriculture.

The discovery of gold in California watersheds in 1849 attracted thousands of American settlers to the San Francisco Bay Area. During the mid-nineteenth century, many of them established ranches and farms in Marin County near Tomales Bay; others founded logging and mineral mining enterprises along Lagunitas and Walker Creeks (Niemi and Hall, 1996). In addition to the removal of redwood trees for timber and excavation of upland soils for minerals, large acreages of land in the Point Reyes and Tomales Bay regions were cleared and divided into cattle and sheep ranches to supply the

growing population of the Bay Area with meat and dairy products (Niemi and Hall, 1996). The land clearing to create pastures for livestock destabilized massive quantities of sediment and soil throughout western Marin County, with significant consequences for Tomales Bay.

Historical and current agricultural activities within the upper Lagunitas and Walker Creek watersheds (each part of the greater Tomales Bay Watershed) continue to load fine sediment into the streams and creeks (Niemi and Hall, 1996). As riparian and upland vegetation is removed to create rangeland, sediment destabilizes and erodes into streams. This sediment then flows downstream to Tomales Bay, leading to sedimentation of the bay floor and the loss of intertidal and subtidal habitats (Niemi and Hall, 1996). While present-day ranchers attempt to maintain cattle fences and avoid riparian areas, the ongoing grazing by livestock continues to cause erosion throughout the region. Chapter 4 discusses sedimentation and its consequences for Olympia oysters and restoration efforts in Tomales Bay in greater detail. . Effects on the species from aquaculture are discussed below.

Aquaculture and Historical Overfishing

Aquaculture in Tomales Bay began during the Gold Rush era in the mid-nineteenth century, as the settlers of the San Francisco Bay relied upon bivalves as an affordable source of protein (Booker, 2006). The native Ohlone people of the region subsisted off of bivalve species for thousands of years, but they were collected rather than cultivated (Niemi and Hall, 1996). Abundant populations of native Olympia oysters in both San Francisco and Tomales Bays sustained commercial fishing by Bay Area settlers throughout the mid-nineteenth century, but the slow-growing species could not meet the demands of early aquaculture (Booker, 2006). Olympia oysters are a small species, reaching a maximum size of approximately five centimeters (White et. al., 2009); the high demand for large numbers of oysters, along with the species' slow growth rate, contributed to the collapse of this commercial fishery and of Olympia oyster populations in the region. Furthermore, declining water quality of major estuaries like San Francisco Bay rendered many Olympia oyster harvests unfit for human consumption (Booker, 2006).

By the early twentieth century, the Olympia oyster fishery collapsed; while some cultivation continued, the large-scale harvesting ceased due to insufficient oyster stocks. Bay Area harvesters looked for other means to meet the commercial and local demands for oysters (Ramsay, 2012). One of these means was replacement: *Crassostrea virginica*, the Eastern oyster, was imported from the American East Coast to replace the Olympia oyster fishery (Kirby, 2004). Refrigerated rail cars successfully imported the Eastern oyster from the East Coast to West Coast estuaries such as Willapa Bay in Washington and Tomales Bay in California (Kirby, 2004). By 1870, the Eastern oyster replaced most of the remaining harvest of Olympia oysters in the San Francisco Bay Area. A larger, faster-growing species, the Eastern oyster met both the commercial demands of aquaculture industries as well as the palatable demands of consumers (Kirby, 2004; Polson and Zacherl, 2009). However, the Eastern oyster did not thrive as well as expected in San Francisco and Tomales Bays, and by the mid-twentieth century could no longer sustain commercial fisheries. The unfamiliar water conditions led to decreased breeding of Eastern oysters, thus a second oyster fishery collapse occurred (Carlton, 1992). Again, aquaculture had to adjust its production.

With Olympia oyster populations too small to sustain harvest and Eastern oyster populations unable to survive in West Coast estuaries, oyster growers sought a new species to replace both of these bivalves. Fisheries in the Pacific Northwest began importing *Crassostrea gigas*, the Pacific oyster, in the early to mid-twentieth century; by 1930, growers in San Francisco and Tomales Bays followed suit (Ruiz et al., 1997). The Pacific oyster, a native of Japan, was transported via shipping to Tomales Bay and flourished throughout the region. Pacific oysters grow and reproduce very quickly; most importantly they adjusted well to the water conditions of Tomales Bay (Polson and Zacherl, 2009). By the mid-twentieth century, the goal by regional aquaculture to cultivate a sustainable oyster was finally achieved, and today that industry is a multi-million dollar one for California (Booker, 2006). Unfortunately, the success of this non-native fishery comes at a price: the ecological integrity of estuary ecosystems and the status of Olympia oyster populations.

Current Fisheries and Status of Olympia Oysters in Tomales Bay

Currently, there are twelve commercial aquaculture leases in effect in Tomales Bay, covering an area of approximately 500 acres of the bay (TBVMP, 2013). Oyster aquaculture in this estuary is an enormous moneymaker for California, with 20% of the state's commercial oysters produced here (TBVMP, 2013). The growers holding these leases primarily cultivate Pacific oysters, with Eastern oysters being the second-most productive species grown in Tomales Bay (TBVMP). Olympia oysters, the only native species, are not grown commercially by any of the aforementioned leaseholders. While some wild populations of Olympia oysters rebounded in Tomales Bay since the overharvesting of the nineteenth and twentieth centuries, they are sparse and at great risk from ocean acidification, sedimentation, and invasive species.

Because there is no commercial cultivation of or demand for Olympia oysters, there is little interest in restoring the species in Tomales Bay. However, educating the local community and aquaculture industry in the region about this species and the benefits of its restoration could promote support for any restoration projects in the future. If conditions detrimental to Olympia oysters in the bay are addressed and mitigated, then perhaps populations could rebound to levels suitable for commercial production in the future.

2.3 Species Ecology

Knowledge of the study species' biology and role in the Tomales Bay estuary is necessary to construct a comprehensive restoration plan. An overview of the ecology of the Olympia oyster is provided in the sections below in terms of biology, ecosystem services and ecological niche, and range and habitat.

Table 1 provides a summary of the general conditions in which Olympia oysters thrive. Discussion of each of the included parameters follows in forthcoming sections of Chapter 2.

Table 1: Physical conditions required for *Olympia* oyster survival and reproduction (Buselco, 1989; Deck, 2011).

Preferred Habitat Conditions	
Depth Range (m)	0.5m above - 1.0m below Mean Lower Low Water
Water Temperature Tolerance (°C)	6° C (winter) to 20° C (summer)
Reproduction Temperature Threshold (°C)	16° C
Salinity (PSU)	25-35 PSU
Substrate Size (mm)	8mm (medium gravel) to 256mm (cobble)

2.3.1 General Ecology

Biology

As a member of the phylum Mollusca, the *Olympia* oyster is an estuarine oyster species found in estuaries along the Pacific Coast of North America (White et al., 2009). It is a small species, with most adults reaching an average maximum size of five centimeters (White et al., 2009). A protandrous hermaphroditic species, the *Olympia* oyster begins life as a male and switches its sex multiple times during its life cycle (Kimbrow and Grosholz, 2006; Wasson et al., 2014), and like most other bivalve species, undergoes a multi-stage development (Kurihara, 2008). Adult oysters spawn within a narrow range of water temperatures; this temperature-dependence is discussed further in Section 2.3.1.2. Biological development differs slightly from that of other closely related oyster species in that *Olympia* oyster females are oviparous: fertilized larvae develop within their mother's mantle prior to release into the surrounding water (Camara et al., 2009). Most bivalve species simply spawn their gametes into the water column, but *Olympia* oyster larvae are already fertilized and undergoing development upon release (Wasson et al., 2014). This is an important survival tactic, as these more mature larvae have an increased chance of survival once afloat in the estuary's waters (Kimbrow, 2009). In Tomales Bay, where *Olympia* oysters are at a disadvantage due to a variety of degraders, this advanced larval development is a significant help to population resurgence. Figure 4 shows the small oyster as it appears in estuaries like Tomales Bay.

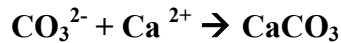


Figure 4: Olympia oysters on rocky substrate (Image courtesy of Oregon Department of Fish and Wildlife).

During the larval maturation stage, oyster larvae spend a few days to weeks within the water column undergoing development to reach the juvenile stage. This phase, referred to as the pelagic or planktonic phase, is longer than that of other bivalves, so Olympia oyster larvae are more developed at the time of settlement on hard, relatively flat substrate (Buselco, 1989; Hopkins, 1935). In Tomales Bay, this settlement period occurs in June and August (Seale and Zacherl, 2009). Following settlement, the larvae continue the calcification process to develop calcium carbonate shells; this calcification continues throughout the juvenile life stage (Kurihara, 2008). These settled juveniles continue their maturation into adults; juveniles reach their full size in approximately four years (Ramsay, 2012; Kimbro, 2006; Kurihara, 2008). Calcification is an important process during each of the Olympia oyster's developmental stages and is discussed at length in this document.

The Olympia oyster is a calcifying species, meaning it develops a hard, calcium-based structure to protect their soft internal organs (Gazeau et al., 2013). During calcification, Olympia oysters derive carbonate ions from the surrounding water column to produce calcium carbonate; this compound secretes from the oyster's extrapallial cavity and builds an external shell structure (Gazeau et al., 2013). Depending upon the development stage of the oyster, calcium carbonate is secreted as calcite or aragonite during shell formation (Fabry et al., 2008). The difference between these two compounds

is discussed in subsequent paragraphs. The chemical reaction for calcification is described as follows (Gazeau et al., 2007):



Typical of most bivalves, Olympia oysters begin the calcification process during the larval phase, during which the vulnerable planktonic oyster is adrift within the water column and subject to predation (Gazeau et al., 2013) and (Kurihara, 2008). Fortunately for the larvae, their mother rears them within her mantle for a longer than average period, reducing the amount of time the larval oysters are exposed within the water column (Camara et al., 2009). During this larval life stage, the oyster individual uptakes carbonate ions from the water to produce aragonite shells. Larval and juvenile oysters produce shells composed of aragonite, while adult oyster produce calcite shells (Kurihara, 2008). Aragonite is a less complex, weaker calcification product (Fabry et al., 2008). After a few weeks, the larval oysters enter the settlement stage, during which they attach themselves to a hard substrate and continue to develop their shells, now producing calcite instead of aragonite, a more durable substance (Kurihara, 2008). Calcification continues throughout the juvenile stage, until the oyster reaches adulthood and its average size of five centimeters (Kurihara, 2008; White et al., 2009).

Calcification creates hard substrate not only for the oyster itself, but also for the estuary. Aggregates of Olympia oysters form reef-life structures that provide invaluable biotic and abiotic ecosystem services, thus creating a niche for the species within an estuary.

Ecosystem Services and Ecological Niche

Adult Olympia oysters, like other benthic oyster species, are ecosystem engineers. Their enhancement (and sometimes creation) of hard substrate within estuaries greatly increases the biodiversity of these ecosystems, as oyster beds provide habitat for other invertebrates, increase food availability, and enhance natural barriers against the stresses of coastal oceanographic processes (Kimbrow, 2006). Olympia oysters are primary sessile species, meaning they attach directly to the substrate and increase that substrate's overall

surface area (Kimbrow and Grosholz, 2006). This increased availability of submerged substrate encourages the settlement of secondary species, which aggregate atop *Olympia* oyster individuals (Kimbrow and Grosholz, 2006). As juvenile oysters settle upon this existing substrate in the estuary, they form calcareous shells and accumulate in high densities, by which they expand the overall surface area of that substrate (Kimbrow, 2006). The result is large reef-like structures in the intertidal and subtidal zone. These beds act as nurseries for other invertebrate species, including molluscs and crustaceans; this attracts more complex organisms such as juvenile and adult fish, shorebirds, seabirds, and mammals (Grabowski et al., 2005).

The intertidal and subtidal areas of estuaries experience a variable range in pH, salinity, temperature, and water level due to the oceanographic and climatic processes dominant in such ecosystems; the engineering of habitat by species like *Olympia* oysters greatly reduces the severity of these stressors upon other resident estuarine organisms (Kimbrow, 2009; Beck et al., 2001). The formation of hard structure and habitat within estuaries improves species biodiversity and enhances the biogeochemical processes essential to estuary productivity. This service provided by *Olympia* oysters sets the foundation for a healthy and durable coastal ecosystem.

The *Olympia* oyster is a filter feeder, siphoning phytoplankton and other planktonic organisms as well as other suspended particulate matter from the water column for food and nutrients (Kimbrow, 2006; Forrest et al., 2009). It is capable of filtering particles between a range of 4 and 100 μ m (Forrest et al., 2009). In addition to their role as ecosystem engineers, the species are filterers and improvers of water quality of the estuaries in which they settle and develop (Beck et al. 2011; Dumbauld et al., 2009). They filter the surrounding estuarine waters for phytoplankton, their main source of food; other suspended particulate matter such as sediment and nutrients are also filtered out of the water column (Ramsay, 2012). This filtering enhances water quality in a variety of ways; oysters are a much-needed resource to protect these sensitive coastal ecosystems. Furthermore, their eventual excretion enriches the benthic sediments through nutrient addition (Forrest et al., 2009), a secondary ecosystem service.

The clarity of the water is greatly improved and maintained through oyster filtration. This increased clarity in turn enhances the growth of estuarine vegetation, such

as eelgrass, and promotes primary productivity (Ramsay, 2012), (Kimbrow, 2009). This oyster filtration process also inhibits eutrophication within Pacific estuaries, an increasingly common and severe problem (Dowd, 2004). Eutrophication occurs when an excessive amount of nutrients or toxins accumulate within a body of water, resulting in an explosion of phytoplankton growth (Dowd, 2004). This growth creates toxic water quality conditions; fortunately, the presence of Olympia oysters helps mitigate this issue through the consumption of both the nutrients and the phytoplankton (Dowd, 2004).

The turbidity of water, dependent upon the amount of suspended sediment and other matter, is reduced as oysters capture and filter sediment and organic matter; these components are eventually digested and thereafter deposited onto the estuary bed (zu Ermgassen et al., 2012). This reduction could be of huge benefit to an estuary like Tomales Bay, where fine sediment is a major pollutant. The nutrient-rich sediments filtered from the water column and subsequently deposited are valuable to microbial organisms and other invertebrates; as discussed above, the sediment is also enriched and safeguarded from erosion through the addition of these biodeposits (Ramsay, 2012). The removal of organic particulate matter from the water column leads the scientific community to view Olympia oysters and other bivalve species as carbon sequesters (Ramsay, 2012), a role that aids in the stabilization of the carbon chemistry of seawater and estuarine water.

Filtration and the subsequent improvement of water quality is a significant ecosystem service provided by Olympia oysters. This process varies in efficiency; as a smaller species, Olympia oysters filter a lesser water volume than some of its larger relatives like the Pacific or Eastern oyster (zu Ermgassen et al., 2012). Temperature of the surrounding water as well as the concentration of particulate matter also affects the filtration rate of Olympia oysters (zu Ermgassen et al., 2012), so oceanographic conditions need to be favorable for these oysters to provide significant benefits.

Despite the narrow parameters within which Olympia oysters reproduce, develop, and thrive, the ecosystem services provided by this species are quite significant and beneficial.

Range and Habitat

Olympia oysters require a specific range of abiotic conditions, including salinity, water temperature, and food availability. They determine where and when both larvae and adults establish habitat within estuaries like Tomales Bay. During site selection for restoration activities, the meeting of these parameters is essential to better ensure project success.

It is first important to note that the historic range of the Olympia oyster in Tomales Bay is poorly documented, and thus complicates both advocacy for and proceeding of restoration projects. Habitat loss due to sedimentation limited the range of this species; this data gap could possibly be addressed through site-specific sediment surveys discussed at length in Chapter 7.4.

As an estuarine species, the Olympia oyster experiences daily fluctuations in water quality and composition due to tidal influences. While adapted to survive the variability of its surroundings, the species thrives and reproduces within a particular range of parameters. Salinity is one such factor; Olympia oysters prefer a salinity of 25 or higher (Buselco, 1989), which is typical in Tomales Bay. However, the inner bay region of Tomales Bay seasonally experiences lower salinity due to freshwater influx from Lagunitas Creek. Olympia oysters can survive short periods submerged in such conditions, but eventually mortality rates increase as exposure time increases (Buselco, 1989). Other stressors caused by low salinity in Tomales Bay include decreased reproduction, reduced food availability, and increased predation by invasive species (Wasson et al., 2014).

Water temperature plays a vital role in the survival and establishment of Olympia oyster populations, as most of the species' metabolic processes are highly temperature-dependent (Deck, 2011). Adult oysters tolerate water temperatures as low as 6° Celsius during the winter, while their temperature tolerance during the summer reaches approximately 20° Celsius (Buselco, 1989). While the range in which survivorship occurs is wide, Olympia oysters require a much narrower temperature range for spawning. Male and female Olympia oysters will not spawn until the water temperature reaches a minimum temperature of 16° Celsius (Buselco, 1989), so spawning can become difficult in estuaries where tidal flushing is not consistent. In Tomales Bay, the warmer

inner bay region is one such location where excessively water temperatures and poor tidal flushing (Kimbrow et al., 2009) could be an issue for Olympia oyster reproduction and establishment. The aforementioned abiotic conditions dictate not only how Olympia oysters behave but also where they can settle and aggregate.

Olympia oysters populations are typically found within the intertidal and low subtidal regions of estuaries (Deck, 2011). This range includes approximately 0.5 meters above Mean Low Water and 1.0 meter below Mean Low Water (Deck, 2011). In Tomales Bay, this region is further described as that area above eelgrass beds but below the shoreline (Kimbrow and Grosholz, 2006). The species thrives when submerged; while short-term exposure to the air, such as during intertidal periods, is tolerable, longer exposure times can lead to increased mortality rates (Wasson et al., 2014). Desiccation results from excessive exposure to the air, leading to oyster death. The exposure to air temperatures exceeding the species' survival threshold also contributes to higher mortality rates. Fortunately, the intertidal and low subtidal regions of estuaries like Tomales Bay provide ample periods of total submersion to adequately support Olympia oyster aggregations. Other factors within these estuary zonations, such as hard substrate and water quality, must be of certain condition to adequately support Olympia oysters.

Bed material, or the sediment found on the seafloor or estuary bed, is a critical component of Olympia oyster habitat. The species prefers harder, rockier substrate, such as rocks and cobbles, for settlement and establishment; juvenile oysters settle on intertidal rocks and cobbles to continue calcification and development into adulthood (Kimbrow and Grosholz, 2006). Empty oyster shells are the ideal habitat, as larval oysters attach to these shells and continue development into juveniles (Wasson et al., 2014). In Tomales Bay, there is an abundance of Pacific oyster shells as a result of commercial cultivation, so the larval Olympia oysters utilize those for development (Wasson et al., 2014). Hard substrate of these types is found in both the intertidal and low subtidal regions of Tomales Bay, but other regions such as mudflats and manmade structures also support some oyster populations (Grabowski et al., 2005). In areas of low substrate availability, a possibility in estuaries, dead oyster shells supplement absent rocks and cobbles to adequately support aggregates of juvenile and adult Olympia oysters (Grabowski et al., 2005).

When larval oysters settle, or attach, it's relevant to note that they often do so on the underside of the substrate. This positioning is likely due to the way larval oysters swim, with their velum (also known as the foot) facing upwards (Hopkins, 1935). It is important to note this tendency towards the underside of substrate, because estuaries like Tomales Bay are often substrate-limited due to sedimentation. As fine sediment accumulates, the availability of substrate upon which oysters can attach is reduced (Deck, 2011; Hopkins, 1935). Substrate availability and size are of critical importance to Olympia oysters, as each provides the needed habitat for individuals to settle, develop, and later reproduce. However, disturbed habitats such as Tomales Bay may not adequately provide the rocky intertidal cobbles preferred by the species, as sedimentation and interspecies competition creates limitations (Deck, 2011). Fortunately, Olympia oysters can adapt to such conditions, settling on old oyster shells or other atypical substrate. This substrate tolerance may be helpful to restoration efforts when determining if substrate availability at potential sites in Tomales Bay are limited in this way.

Finally, adequate tidal flushing is important for Olympia oysters, particularly in a partially enclosed linear bay like Tomales Bay. The tides move ocean water into Tomales Bay through the mouth, delivering phytoplankton and nutrients into the bay and flushing them throughout the basin (Grabowski et al., 2005). Adequate water velocity ensures that the clarity and food availability remain high, which supports Olympia oysters (Grabowski et al., 2005; Deck, 2011). As discussed in Chapter 2.1.2, Tomales Bay includes three distinct oceanographic regions: the outer, middle, and inner bay (Kimbrow et al., 2009; Sansone et al., 1998). The conditions of the middle bay tend to produce the largest Olympia oysters found throughout Tomales Bay; the salinity, water temperature, and substrate availability seem most suited to the species (Deck, 2011). However, larval oysters (which remain in the water column prior to settlement) seem to prefer the inner bay region, which is unusual due to the water quality and invasive species issues that prevent adult settlement there. It is possible the larvae prefer the inner bay due to less water turbulence and tidal flushing; they are better protected from washing out into the open ocean, as is a risk to larvae in the middle and outer bays (Deck, 2011). Thus the oysters require a “middle ground,” in which the water quality remains dynamic but not so much that larvae cannot mature to adulthood.

2.4 Threats to Olympia Oysters in Tomales Bay

Olympia oysters face three major threats in Tomales Bay, which are ocean acidification, sedimentation, and invasive species. This research discusses each of these issues at length, as each requires addressing by managers at Greater Farallones National Marine Sanctuary and other relevant agencies to ensure the development of best management practices for oyster restoration.

Of the three threats to Olympia oysters, ocean acidification is of the greatest scale as well as the least understood. A direct result of excessive carbon emissions to the atmosphere, ocean acidification reduces the pH of ocean water and limits the availability of carbonate necessary for Olympia oysters to create their shells (Kurihara, 2008). As a result, Olympia oysters face two threats: developmental complications and shell dissolution. A lack of carbonate ions makes the production of a high-quality shell difficult for an oyster, leaving the individual susceptible to predation and other risks (Gazeau et al., 2013; Kurihara, 2008). The process of ocean acidification and its implications for both Olympia oysters and Tomales Bay are discussed in Chapter 3.

Agriculture and land development in western Marin County, both historically and presently, erode massive quantities of sediment that enter the creeks and streams of the Tomales Bay Watershed. To accommodate rangeland agriculture and dairies, ranchers and landowners cleared large swaths of land; removing riparian vegetation and upland vegetation destabilizes the soil (Niemi and Hall, 1996). This loose sediment erodes downhill into creeks such as Lagunitas and Walker Creeks, flowing downstream to deposit into Tomales Bay. As a result, much of the intertidal and subtidal zones as well as mudflats are smothered with several feet of fine sediment (Forrest et al., 2009), reducing the availability of Olympia oyster habitat. In this way, sedimentation is a significant threat to the restoration and survival of Olympia oysters in Tomales Bay. Sedimentation and its effects are further discussed in Chapter 4.

The third threat to Olympia oysters discussed in this document is invasive species. Tomales Bay hosts several invasive species resulting from human activities, compromising the ecological integrity and trophic interactions of the estuary (Kimbrow et al., 2009). Two of these species, the Atlantic oyster drill (*Urosalpinx cinerea*) and the

Japanese oyster drill (*Ocenebra inornata*), pose the greatest threat to Olympia oyster restoration. Both of these species are “hitchhikers:” they arrived alongside imported Eastern and Pacific oysters in the late nineteenth and early to mid-twentieth centuries (Kimbrow and Grosholz, 2006). Each of these drills preys on Olympia oysters and inhibits the expansion of the species’ range in Tomales Bay. Chapter 5 discusses the invasive species problems in Tomales Bay, as this issue is arguably the most obstructive to restoration efforts.

Chapter 3: Ocean Acidification

3.1 Background

Currently, much of the global public's concern over climate change focuses on anthropogenic fossil fuel emissions and the resulting warming of the lower atmosphere. However, global warming is not the only process resulting from fossil fuel dependence; ocean acidification is now known as the other major consequence of carbon and greenhouse gas emissions occurring on a global scale (Doney et al., 2009). Studies show that the oceans absorb one-third of all atmospheric CO₂; the excess CO₂ from anthropogenic sources results in a decrease of pH and the disruption of both organic and inorganic chemistry within ocean systems (Gazeau et al., 2007). These declines and disruptions have serious implications for estuarine ecosystems like Tomales Bay and, in particular, the marine calcifiers such as Olympia oysters that inhabit them.

3.2 Chemistry of Ocean Acidification

As anthropogenic emissions of carbon dioxide (CO₂) and greenhouse gases accumulate in the atmosphere in excessive concentrations, an imbalance in atmospheric and aquatic chemistry occurs. Under normal conditions, atmospheric CO₂ sinks and sequesters through natural processes such as photosynthesis, respiration, and the recycling of nutrients to the deep ocean (Gazeau et al., 2013). While terrestrial ecosystems sequester carbon and produce half of the world's oxygen, marine environments play an equally important role. Phytoplankton is responsible for the uptake of vast quantities of atmospheric CO₂, photosynthesizing it to produce the other 50% of atmospheric oxygen while also sequestering carbon to the deep ocean. Wetland species, such as eelgrass, play similar roles (Gazeau et al., 2013; Kroeker et al., 2013).

However, greenhouse gases are now present in unprecedented concentrations in the lower troposphere; industrialization, deforestation and other landscape alterations necessary to accommodate the growing global population diminished the capacity of some terrestrial sinks (Doney et al., 2009). As a result, one-third of the CO₂ emitted from

anthropogenic sources now sink into the oceans (Gazeau et al., 2007). This increase in CO₂ leads to ocean acidification; such high concentrations of CO₂ disrupt the organic and inorganic chemistry of ocean water and cause a lowering in pH, thereby acidifying the ocean and threatening the biological functioning of its calcifying organisms.

Knowledge of the chemical processes involved in ocean acidification is necessary to understand its impacts upon species such as the Olympia oyster. First, it is important to note that ocean acidification is caused by a decline in ocean water pH; pH is determined by the concentration of hydrogen ions in a solution (Kurihara, 2008). The higher the hydrogen ion concentration, the lower the pH, and therefore the more acidic the solution (or water body). The average pH of ocean water is around 8, but this varies throughout the global ocean (Gazeau et al., 2013). Estuaries, for example, typically exhibit a lower pH than the ocean, an effect discussed in Section 3.3. Under typical conditions and concentrations, atmospheric CO₂ gas enters the surface waters of the ocean, where it becomes aqueous carbon dioxide; these two compounds can then interact to form H₂CO₃, or carbonic acid. The carbonic acid can then dissociate further into free hydrogen ions and HCO₃⁻, which is also known as bicarbonate. A final dissociation reaction can occur, in which two free hydrogen ions and CO₃²⁻, or carbonate, form (Doney et al., 2009). This complex series of reactions is shown below:



The inorganic compounds formed by the above interaction between atmospheric carbon dioxide and seawater, including aqueous CO₂, carbonate, and bicarbonate are essential for calcifying organisms to form their shells (Fabry et al., 2008). However, the excessive concentration of atmospheric CO₂ from anthropogenic emissions results in an imbalance in the above reaction, reducing the availability of carbonate and bicarbonate in shallow water depths.

3.3 Effects of Ocean Acidification on Estuaries and the Abiotic Environment

Ocean acidification affects the oceanographic and physical processes characteristic of coastal ecosystems and estuaries. Because such processes are interconnected and often synergistic in their impacts, the altering of oceanography and physical processes within estuaries is highly significant to the survival of species like Olympia oysters as well as to the maintenance of estuary biodiversity (Gazeau, 2013).

This review focuses on the effects of ocean acidification on Olympia oysters, which are native to the Pacific Coast of North America; this region is greatly impacted and regulated by the California Current System (Gruber et al., 2012). The California Current is an eastern boundary current that brings cold, nutrient-rich waters from the Gulf of Alaska south along the North American West Coast (Gruber et al., 2012). Typically, this type of oceanographic currents is lower in pH due to its carbon-rich content; upwelling events along the California Coast add to this acidity (Gruber et al., 2012). Upwelling occurs when wind-driven surface currents displace the surface waters of the ocean with cold, nutrient-rich waters from depth; this process greatly increases primary productivity and food availability along the California Coast (Gruber et al., 2012). The low-pH waters of the California Current, coupled with the carbon-rich upwelled waters, add to the overall acidic pH of the coastal regions. Upwelling and the phytoplankton associated with the California Current is key to the growth and survival of estuarine species such as the Olympia oyster (Kimbrow, 2006).

Estuaries like Tomales Bay typically experience highly variable pH and salinity levels due to the inputs of salt and fresh water (Gazeau et al., 2013). The influx of freshwater from watersheds and precipitation often temporarily reduce pH and salinity. Such a low pH can be due to variety of sources: agricultural influences, higher nutrient contents, sediment, respiration, and reduction-oxidation reactions within bordering estuarine wetlands (Gazeau et al., 2013). As freshwater is low in salt content, its introduction into the estuary by watersheds and precipitation reduces overall salinity. This decrease in salinity is then balanced by estuarine tidal activity that brings in more alkaline, saline ocean water (Gazeau et al., 2013). However, seasonal upwelling events introduce acidic, nutrient-rich water into estuaries from the ocean, so the overall pH

decreases further during specific times of the year (Gruber et al., 2012). Such fluctuations in water chemistry makes estuaries highly dynamic ecosystems; fortunately, marine organisms such as Olympia oysters adapted to tolerate this variability in pH and salinity. As phytoplankton-rich waters enter these estuaries, including Tomales Bay, Olympia oyster populations enjoy greater food availability (Hettinger et al., 2013). This supports adult populations while also increasing the survival and growth rates of juvenile oysters (Hettinger et al., 2013).

Increases in the input of carbon dioxide from the atmosphere to the surface ocean leads to ocean acidification, as higher concentrations of hydrogen ions and carbonic acid are produced (Gazeau et al., 2007). As mentioned above, the California Current System and seasonal upwelling events deliver acidic, nutrient-rich water to Tomales Bay, promoting biodiversity and primary production. Ocean acidification will cause a further reduction in pH of this somewhat acidic water as well as alter the estuary's salinity, oxygen availability, chemical composition and primary productivity rates (Hettinger et al., 2013; Bakun, 1990). Upwelling events adjacent to Tomales Bay could also intensify as a result of ocean acidification due to increased CO₂ from the atmosphere and from the deep ocean (Doney et al., 2009; Sanford et al., 2014). Further studies will clarify the effects of upwelling intensification on Tomales Bay ecology.

3.4 Effects of Ocean Acidification on Olympia Oysters and Restoration Efforts

3.4.1 Calcification

As the atmospheric concentration of CO₂ increases, inorganic reactions attempt to balance themselves through redistribution; the ocean is a sink for the excessive CO₂ unabsorbed by the atmosphere (Kurihara, 2008). The concentration of CO₂ in the shallower depths of the ocean is projected to exceed approximately 750 parts per million by the end of this century, a concentration that exceeds the tolerance of many shellfish species (Talmage et al., 2010). Excessive concentrations of atmospheric CO₂ entering the surface water imbalances the chemical reaction discussed in Section 3.2 and results in a reduced availability of carbonate and bicarbonate; more carbonic acid and dissociated hydrogen ions form instead. The pH decreases as concentrations of carbonic acid and

hydrogen ions increase. This pH decrease causes the acidification of the surface ocean (Gazeau et al., 2013), which is of great concern due to its impacts on calcification and marine calcifying organisms.

Calcifiers rely upon the carbonate ions present in ocean water to create calcareous structures such as shells (Doney et al., 2009). When these ions are no longer sufficiently present, the biological consequences for Olympia oysters and calcifying flora and fauna are significant. Observed responses include decreases in shell size and density, declines in reproduction, and increases in rates of mortality among populations (Hettinger et al., 2012). An understanding of calcification will clarify the impacts of ocean acidification on Olympia oysters.

Marine calcifying organisms include a wide range of molluscs and invertebrate microfauna; such species derive carbonate ions and bicarbonate from the surrounding ocean water to construct their shells or other structures (Guinotte et al., 2008). Stable carbon chemistry is essential for the Olympia oyster to undergo calcification, and carbonate must be present in sufficient concentrations in estuary or ocean water for calcification to occur. The availability of carbonate ions is affected by several physical properties, including water temperature, water pressure, and the concentration of carbon dioxide in the water (Fabry et al., 2008). Under normal conditions, carbon dioxide sinks into the oceans from the atmosphere and interacts with ocean water in the following reaction (Doney et al., 2009):



Calcifying organisms, including Olympia oysters, use carbonate (CO_3^{2-}) and calcium ions from the water column to produce their calcium carbonate shells (Kurihara, 2008). However, as the amount of atmospheric CO_2 entering ocean water increases, the formation of carbonate reduces. The higher concentration of CO_2 produces more carbonic acid and hydrogen ions, reducing pH and carbonate ion concentrations (Gazeau et al., 2007). Thus, calcification declines as the availability of carbonate ions decreases, aragonite and calcite become undersaturated, and pH increases. This leaves Olympia oysters much more vulnerable as their shells can no longer form to a sufficient size and

thickness for protection against external conditions or predators (Fabry et al., 2008). Degradation of this nature could cause Olympia oyster populations in Tomales Bay to further decrease in number, as weak shells leave the species atypically vulnerable to predation by native and non-native predators (Sanford et al., 2014; Fabry et al., 2008). To complicate this problem, the impacts of ocean acidification on Olympia oysters vary across multiple life stages.

The larval and juvenile stages of Olympia oyster are at greatest risk of calcification issues caused by ocean acidification (Kurihara, 2008; Guinotte et al., 2008). Figure 5 shows the impacts of ocean acidification upon each stage of development of an oyster species (Kurihara, 2008).

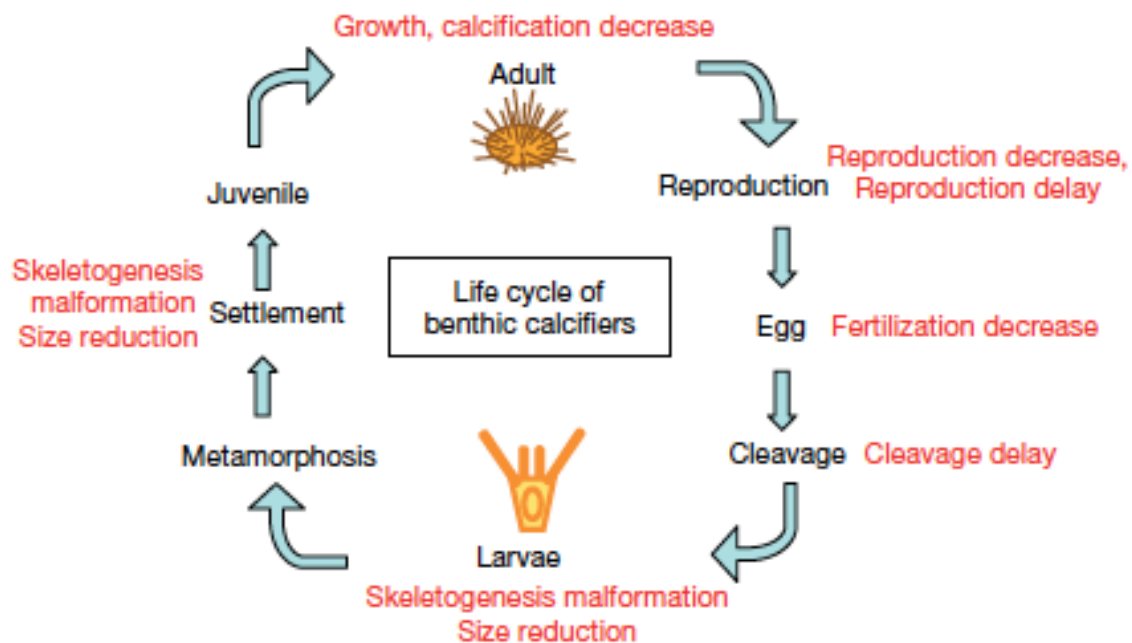


Figure 5: Observed impacts of ocean acidification on each stage of development of calcifying molluscs and echinoderms (Kurihara, 2008).

Low pH and warmer water temperatures create physical and physiological stress in larval Olympia oysters, a stage at which significant amounts of energy are expended for development (Hettinger et al., 2012). The surrounding acidity in the water and lack of carbonate ions makes calcification much more difficult for the larval and juvenile oysters, leading to increases in mortality among populations (Kurihara, 2008; Miller et al., 2009). Those larvae that do survive to the juvenile stage form shells of a poor quality due to

elevated CO₂ (Kurihara, 2008). As previously mentioned, calcification by organisms such as *Olympia* oysters produces structures made of calcium carbonate; aragonite and calcite are two forms of calcium carbonate found in their shells (Kurihara, 2008).

Such declines in survival and juvenile establishment affect the entire oyster population with lasting consequences. Larval oysters must now spend a greater amount of time floating within the water column, as decreased concentrations of carbonate make the calcification process and subsequent settlement much slower and more energy consuming (Camara et al., 2009; Kurihara, 2008). This increased duration of exposure within the water column increases the likelihood of death from exposure or by predation of larvae. Those larvae that enter the juvenile stage and subsequently settle to continue development may be less fit to survive to adulthood due to stressful conditions and the formation of weak calcareous structures (Kurihara, 2008; Gazeau et al., 2013). Juvenile *Olympia* oysters rely upon their aragonite shells for protection, feeding, and other bodily processes (Kurihara, 2008). The difference between aragonite and calcite is discussed in Section 3.4.2. Adult bivalves are better equipped to handle ocean acidification, as they can self-regulate their internal pH, but suffer from physiological stresses under acidified conditions (Kurihara, 2008). However, adults are not immune to the effects of acidification; they are not only at risk of smaller populations, and difficulties in reproducing and feeding but also shell dissolution, which is discussed in Section 3.4.2, (Kurihara, 2008).

3.4.2 Shell Dissolution

The decline in calcification rates is not the only risk to calcareous structures in the face of ocean acidification. Bivalves, including *Olympia* oysters, could experience shell dissolution if pH decreases below a critical level (Gazeau et al., 2013; Waldbusser et al., 2011). Shell dissolution could threaten the entire estuarine ecosystem of Tomales Bay, as the hard substrate formed by oyster beds provides essential ecosystem services. The absence of oyster beds could negatively affect the physical structure and biodiversity of estuaries.

The first risk of dissolution occurs in juvenile *Olympia* oysters; they produce shells composed of aragonite, while adult oysters' structures are typically made of calcite

(Kurihara, 2008). Calcite and aragonite, two forms of calcium carbonate secreted by bivalves, become undersaturated in concentration due to excessive CO₂ levels (Feely et al., 2004). Aragonite is less complex in structure and a more soluble form of calcium carbonate; the juvenile Olympia oysters are therefore at a greater risk of dissolution in acidified conditions (Guinotte and Fabry, 2008). According to recent studies, the saturation horizons of aragonite and calcite continue to shift to shallower depths, higher latitudes and within closer proximity of the coastal regions (Guinotte et al., 2008); this places great stress on estuaries like Tomales Bay and their inhabitants, as neither is adapted to higher concentrations of carbonic acid, hydrogen ions, or CO₂. It is important to note that despite the shoaling of aragonite and calcite, the impacts of increased pH happen over time; shell dissolution does not occur upon immediate immersion in such acidified waters (Gazeau et al., 2013). Most studies show that Olympia oysters and other bivalves experience a decrease in both shell size and shell thickness over a period of months in conditions of decreased pH (Gazeau et al., 2013). The slow rate of this process could give Olympia oysters some time to adapt to more acidic conditions.

3.4.3 Implications

The effects of ocean acidification are of great concern due to their compromising the health and structure of estuaries. Olympia oysters are ecosystem engineers; their creation of calcium carbonate structures provides habitat for other estuarine organisms as well as coastal protection (Kimbro, 2006). Ocean acidification will reduce this hard, calcareous substrate and create conditions inhospitable for the replacement of such a loss by calcifying species (Gaylord et al., 2011). Similarly, the absence of filtering services provided by large numbers of Olympia oysters and other bivalves fosters conditions in which eutrophication or hypoxia occur, further degrading water quality (Dowd, 2004). The ecosystem services provided by Olympia oysters are invaluable, as they encourage biodiversity within estuaries like Tomales Bay (Kimbro, 2006). The loss of these services resonates throughout the food chain and alters physical processes of Tomales Bay (Kimbro, 2006), a devastating consequence that will affect all dependents of this ecosystem.

The potential for a crippling of calcification ability by young and adult oysters, as well as the dissolution of aragonite and calcite-based shells, leaves Olympia oysters vulnerable to predation and non-native species invasions. Figure 2 summarizes the biophysical effects of reduced pH on molluscan species, including Olympia oysters; it is evident that a pH decline exceeding 0.5 units will cause grave issues for shelled molluscs, including reductions in calcification, filtration rate of the surrounding water (referred to below as the clearance rate), and reproductive and immune behavior (Gazeau et al., 2013).

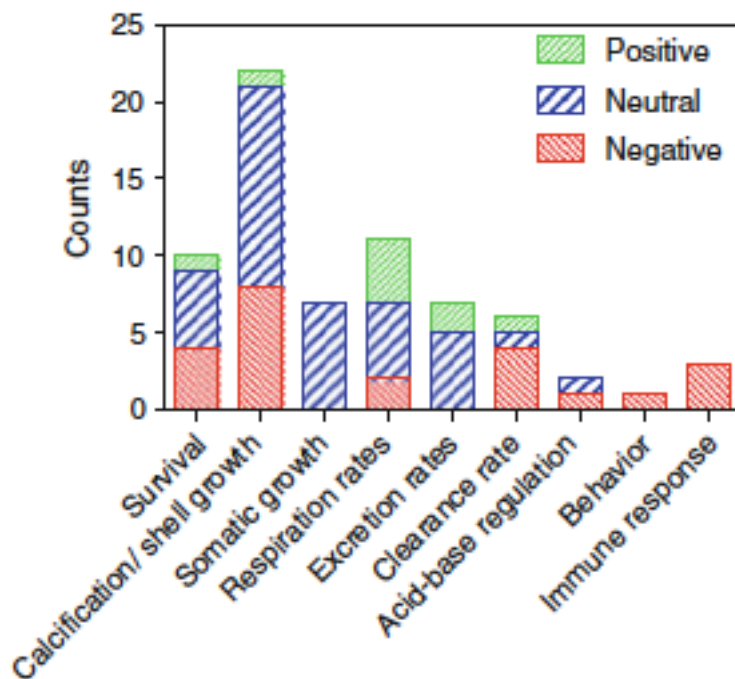


Figure 6: The effects of ocean acidification on juvenile and adult oyster species (Gazeau et al., 2013).

As calcification suffers in waters with a lower pH, the shells produced by individual oysters are thinner and weaker; predators such as crabs or drilling snails can more easily penetrate this shell and consume the exposed oyster (Sanford et al., 2014). Another side effect of ocean acidification is an increase in non-native species invasions within estuaries (Sanford et al., 2014). Non-native invaders can often adapt quickly to unfamiliar or atypical conditions; in estuaries, such acidified conditions are increasingly common as a result of climate change and could foster species invasions (Sanford et al., 2014). The invasive species issue in Tomales Bay, discussed in depth in Chapter 5, could

become much worse if managers do not mitigate their invasions before ocean acidification can enhance them.

3.5 Need for Further Studies and Long-term Monitoring

The Olympia oyster inhabits estuaries where pH fluctuates fairly widely throughout the day due to tidal flow and freshwater influx as well as throughout the year due to upwelling events; it is possible this species could endure some decline in pH with minimal effects to its calcified structure (Gazeau et al., 2013; Talmage et al., 2010). However, the projected decline in pH as CO₂ emissions continue to increase (Guinotte et al., 2008) may exceed the tolerance threshold of Olympia oyster populations (Gazeau et al., 2013). More studies are needed to accurately predict the short and long-term impacts of ocean acidification upon calcification, as well as the degree of severity (e.g., how much will the pH decline). Ocean acidification will exacerbate current stresses upon this species in addition to creating new ones; species-specific studies are needed so environmental managers might mitigate the impacts (Kurihara, 2008).

While ocean acidification is a reality, the effects are less clear and require further investigation so that appropriate protections might be taken to ensure that restoration efforts of the Olympia oyster in Tomales Bay are not futile. The management recommendations in Chapter 7 provide guidance for addressing ocean acidification when undertaking restoration efforts.

Chapter 4: Sedimentation

4.1 Background

The Gold Rush era marks the onset of land development in the western Marin County region responsible for much of the ongoing water quality issues in Tomales Bay. Large-scale modifications to the landscape to accommodate logging, mining, and agriculture continue to destabilize and erode upland soils that enter creeks and streams, flowing downstream to deposit in Tomales Bay (Niemi and Hall, 1996). Other pollutants, including nitrate and fecal coliform, compromise the water quality of the bay; were riparian buffers still present to filter and cycle these nutrients, the pollutant concentrations in the bay would be significantly lower (Lewis, 2004; Miller et al., 2006). Nutrient loading can cause eutrophication or hypoxia, but research shows that the tidal range of Tomales Bay minimizes these events at present (Gee et al., 2010). Furthermore, these nutrients have little effect on the health of Olympia oyster populations; sediment, however, poses a much greater threat to the species' restoration and survival.

4.2 Origins of Sediment

In response to the growing population and commercial enterprises of the San Francisco Bay Area following the 1850s Gold Rush, settlers of the Point Reyes and Tomales Bay regions utilized the area's natural resources, especially lumber, minerals, and land. By the mid-nineteenth century, ranches and dairy agriculture took root in the Lagunitas and Walker Creek uplands; this vegetated and forested area was cleared of its riparian vegetation to create pastures and rangeland (Niemi and Hall, 1996; Fischer et al., 1995). Similarly, mercury mines and redwood lumber mills along subsidiary creeks in the greater watershed were built in the late nineteenth and early twentieth centuries (Laughlin, 2009) to provide minerals, lumber and paper to the City of San Francisco. To move lumber and minerals from rural western Marin County to the city, developers began constructing roads in the watershed in the 1850s (TBWC, 2005). Despite the economic contributions to the local economy and the connectivity between communities, these

developments seriously compromised the health of the Tomales Bay ecosystem through sediment destabilization and erosion.

Agriculture in the Tomales Bay Watershed, which includes the bay, Lagunitas, Walker, and Olema Creeks, finds its beginnings in the mid-nineteenth century, with many of the practices continuing today. By 1860, ranchers partitioned the open spaces of land to house beef and dairy cattle as well as other livestock; these animals require extensive grass pastures for grazing (Booker, 2006; Huntsinger, 1996; Niemi and Hall, 1996). To accommodate the grazing needs of these animals, the ranchers and other land developers removed most of the vegetative cover in the upland and riparian corridors of the Tomales Bay Watershed. Section 4.3 discusses the effects of vegetation removal as well as the erosive processes that cause sediment to deposit in Tomales Bay.

To facilitate the movement and economy of Marin County residents, land developers built roads connecting the rural agricultural areas to the Highway 101 corridor. Such development began in the late nineteenth to early twentieth century (Niemi and Hall, 1996). Until the 1960s, Marin County relied on gravel and sand from the watershed's streams as road materials: Bear Valley Road and Sir Francis Drake Boulevard are two roadways initially paved with Lagunitas Creek sediments (TBWC, 2005). Currently, approximately 11,000 people live within the Tomales Bay Watershed boundaries (Laughlin, 2009). The population is growing, and subsequently putting greater demands for development and access throughout the region. Access to and from western Marin County greatly increased the amount of impermeable surfaces as well as interrupted channel flows, and further development could do the same damage. Tomales Bay and its watershed are now listed as impaired water bodies for sediment pollutants under Section 303d of the Clean Water Act (TBWC, 2005). Despite the efforts of county, state, and federal agencies to curb sedimentation and shift landowners away from the antiquated rangeland practices that encourage it, mass erosion continues and threatens to health of Tomales Bay's intertidal and tidal estuarine ecosystems.

4.3 Erosion and Watershed Loading

While oceanographic processes, such as daily tides and storm events, deliver sediment to Tomales Bay through the bay mouth, much of it enters the bay from the watershed (Smith et al., 1989). Studies show that approximately 95% of the bed sediment in Tomales Bay is fluvial in origin (Rooney and Smith, 1999). The delta regions of both Lagunitas and Walker Creeks show marked accumulation of sediment, meaning the sediment that flows downstream in the creeks deposits at the mouth and along the alluvial fan that extends a few kilometers outward from the delta (Rooney and Smith, 1999). The input of sediments from both Lagunitas and Walker Creeks accumulates in Tomales Bay at a rate of 35-50 feet per year (Marcus, 1989). Progradation of the inner and middle bays is most noted, and is subsequently addressed in this chapter.

Vegetation removal in Lagunitas Creek's watershed (the largest contributor to the Tomales Bay Watershed) began in the early twentieth century and continued into the mid 1960s (Laughlin, 2009) as rangeland and livestock agriculture took hold. Managers should understand the basic structure and function of riparian ecosystems when considering the restoration and protection of their downstream wetland dependents. In a watershed, the upland or terrestrial environment includes the headwaters, where woody trees such as redwoods abut the creek (Laughlin, 2009). The transport is the next phase of a watershed, where the creek moves water from the headwaters downstream towards the deposition. Riparian vegetation here is often smaller in size than that of the upper watershed; shrubs, small trees (such as willows and alders), and some grassier plant species line the creek banks and catch both nutrients and sediment. However, the water flow in this area is often higher, resulting in a greater erosion of fine sediment into the transport (Laughlin, 2009; Marcus, 1989). Finally, the depositional zone is where the creek ends, widening into a delta as it empties its water and sediment load into a larger water body. Tomales Bay is the deposition for Lagunitas, Walker, and Olema Creeks; Lagunitas and Walker Creeks have visible deltas at their mouths in Tomales Bay, and their sediment load is dispersed throughout the bay (Rooney and Smith, 1999). The depositional zone often features wetland vegetation, such as reeds, sedges, and other salt-

tolerant plants (TBWC, 2009). Figure 6 shows the structure of riparian vegetation zones, and outlines the numerous benefits provided by these systems.

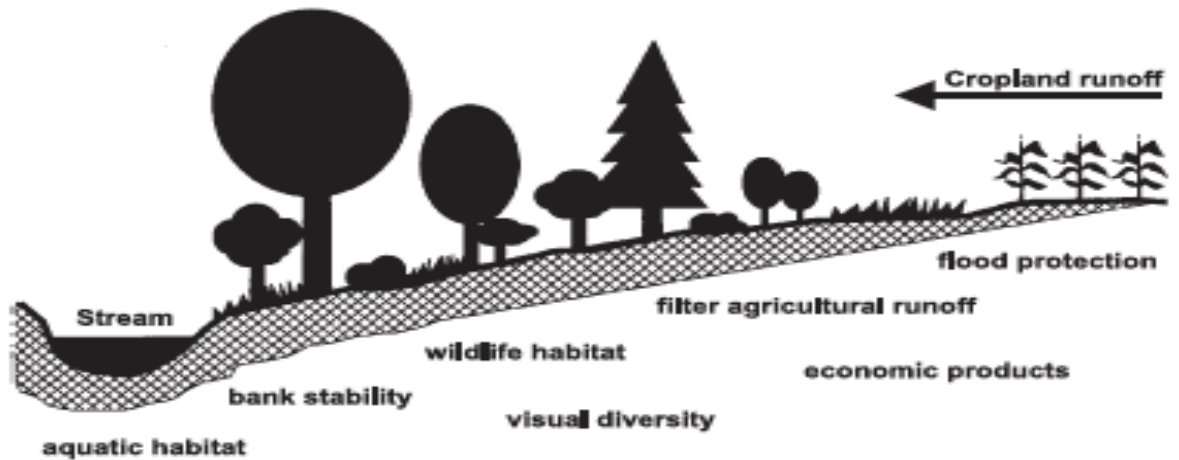


Figure 7: Structure of a riparian corridor with vegetation type and placement shown (Image courtesy of the U.S. EPA, 2003).

The structure of riparian ecosystems plays a significant role in the water and habitat quality of the downstream wetlands and estuaries.

Riparian buffers, such as riverine vegetation and soils, act as filters for the stream: they ensure better water quality through the catching of nutrients and toxins in the soil, with vegetation preventing erosion, which in turn maintains proper channel form and flow. Riparian ecosystems act as type of a catchment and filtration plant as well as a protective interface between upland and wetland ecosystems (Marcus, 1989). The ecosystem services provided by riparian areas are invaluable, as they maintain and improve the health of freshwater, upland, and wetland ecosystems. When vegetative cover is removed, very fine soils (including silt, clay, and some sands) are exposed and erode downhill into the watershed's streams. A lack of riparian vegetation and increased scour from the incoming sediment enables stream bank erosion when peak flows are high (Marcus, 1989), adding more sediment to the streambed. If channels become filled in with sediment or are undercut, water cannot reliably move downstream. Bank erosion and collapse can occur as the channel moves sporadically, and this erosion, coupled with trampling and grazing prevents riparian buffers from reestablishing along the watershed's creeks and streams (Niemi and Hall, 1996). As cattle trample vegetation and graze soil-

anchoring grasses, the exposed sediment loosens and moves downhill with the aid of wind, water, and gravity. The fine particles end up in the low-lying streams and creeks of the watershed, flowing downstream to eventually accumulate in Tomales Bay (Rooney and Smith, 1999). The mass erosion events in this region are evident in the steady accumulation of fine sediment particles.

Other mass erosion events at work in the Tomales Bay Watershed include rilling and gullying of upland hills and slopes, evident to passersby in the Point Reyes and Tomales Bay region (Niemi and Hall, 1996). The constant trampling of vegetation by cattle and livestock in managed rangelands as well as in unfenced areas of the watershed create a downward sliding of hillsides, adding more sediment to the depositional reaches of Lagunitas and Walker Creeks. Similarly, road construction causes sedimentation on a large scale. As discussed in Section 4.2, roads create impermeable surfaces. Although a more permeable material than concrete or asphalt, gravel taken from the creek beds caused channel incision and damage to riparian corridors (Laughlin, 2009). These roads and other local accesses are now paved with asphalt, and create serious issues for the watershed. Impervious structures deflect sediment and water into the streams, compromising water quality and filling in streambeds with eroded soils.

Furthermore, the Tomales Bay Watershed's streams are transected and interrupted by dams and the aforementioned roads, preventing headwaters from reaching their natural transport and deposition zones (Niemi and Hall, 1996). Riparian corridors are dramatically modified or destroyed completely, as construction across streams forces the removal of trees and vegetation. Despite efforts by Marin County and the California Department of Transportation to build culverts and dams for sediment capture, water flow is still restricted. As the depositional zone for Lagunitas and Walker Creeks, Tomales Bay accumulates sediments from the watershed; the integrity of the bay's estuarine tidal marshes is at serious risk due to eroded sediment filling in these areas and preventing tidal fluctuations from inundating the flats (Marcus, 1989). While roads, dams, and reservoirs provide necessary services to the residents of Marin County, they negatively impact the Tomales Bay Watershed and modify riparian corridors essential to regulating sedimentation and toxin input. To complicate this issue, Tomales Bay's water quality is also at risk, as are the tidal habitats required by Olympia oysters.

4.4 Effects of Sediment on Olympia Oyster Establishment and Survival

Olympia oysters require hard, rocky substrate in the intertidal and low subtidal zones of Tomales Bay for settlement. Substrate of these types provide enough complex structure and shelter upon which juvenile oysters settle and mature into adulthood, and also ensure their environment is properly aerated and not at risk of smothering (Kimbrow, 2008). Sedimentation threatens Olympia oysters in several ways, first through progradation of intertidal, subtidal, and mud flat habitats near the Lagunitas and Walker Creek mouths in Tomales Bay (Niemi and Hall, 1996). Progradation means that sediment in these deltaic depositional areas of Tomales Bay accumulates upward and outward, resulting in the filling in of intertidal and tidal wetland areas (Niemi and Hall, 1996; Wasson et al., 2014). Additionally, the accumulation of fine sediment in Tomales Bay covers hard substrate such as the aforementioned rocks and cobbles, limiting the availability of material for oyster settlement. Finally, fine sediment could potentially smother existing Olympia oyster populations, reducing populations of Tomales Bay (Deck, 2011). As erosion continues in the Tomales Bay Watershed, sedimentation could result in significant degradation not only to the tidal ecosystems of Tomales Bay but also to Olympia oysters.

Mass erosion in the Tomales Bay Watershed, accelerated by agriculture, contributes fine sediment into major creeks and streams that ultimately deposit in Tomales Bay. The accumulation rate in certain regions of the bay, coupled with weaker tidal flushing, cause the sediment to build up on the bay bed. This process is referred to as sedimentation. As discussed in Chapter 2, Tomales Bay features three oceanographically and biophysically distinct regions: the inner, middle, and outer bays (Kimbrow et al., 2009). Sedimentation is variable across the three regions, with the creek deltas showing the greatest rate of both sedimentation and progradation. The Lagunitas Creek delta is in the inner bay, while the Walker Creek delta is along the transition between the middle and outer bay regions. Each of these delta regions experiences the severest sediment accumulation rates due to their proximity to the watershed (Rooney and Smith, 1999). This discrepancy is explained by the fluvial origins of the sediment discussed in Section 4.1. Erosion from human and natural activities in the upper

watershed causes sediment to flow downstream and settle in a fan-like pattern at the creek mouths in Tomales Bay (Rooney and Smith, 1999). The middle bay region and depositional zones where the creeks meet Tomales Bay display moderate to severe sediment accumulation (Rooney and Smith, 1999). The inner bay is similarly affected by sedimentation, though tidal influence plays a greater role in the sedimentation issue of this region. Because the inner bay is flushed by tides more slowly and less frequently, sediment accumulates and is not evenly distributed or removed from the region (Forrest et al., 2009). Thus, sedimentation is an issue for the entire Tomales Bay basin, and is not a location-specific issue.

Sedimentation in Tomales Bay threatens the existence of tidal marshes, mudflats, and the rocky intertidal zones. Since the agricultural developments in the late nineteenth century, erosion in the bay's watershed continues to flush sediment into the major creeks and tributaries, which flow downstream to deposit in Tomales Bay. As the sediment deposits and accumulates more widely due to increased volume, it "fills in" the shallow tidal marshes that line the shores of Tomales Bay (Niemi and Hall, 19996). This progradation and loss of tidal and mud flats is particularly prominent in southeastern Tomales Bay, where Lagunitas Creek reaches its mouth (Niemi and Hall, 1996). Fortunately, ongoing wetland restoration and conservation in this area near the Giacomini wetland preserve counteracts some of the sedimentation issues. Tidal marshes are not the only at-risk habitat of Tomales Bay; rocky intertidal and subtidal habitats are at risk of burial by fine sediment. This habitat burial not only degrades substrate quality and limits availability, but also decreases water clarity and oxygen content (Wasson et al., 2014). It is these impacts that are of greatest threat to *Olympia* oysters.

Sedimentation would be less of an issue for Tomales Bay if the grain size of incoming sediment was coarser and rockier, but the fine particulates threaten *Olympia* oyster habitat and overall water quality (Wasson et al., 2014) quite significantly. The species requires complex substrate like rocks, cobbles, oyster shells, and coarse bed material in the intertidal to subtidal regions of Tomales Bay in order to settle and establish adult populations. Fine sediment accumulates and buries these preferred structures, making it very difficult for larval oysters to find suitable places to settle (Wasson et al., 2014). While adult *Olympia* oysters can endure burial by coarse

sediment, they cannot tolerate the finer particles; metabolic processes become very difficult for oysters when such fine sediment becomes the predominant bed material and is suspended in the water column (Wasson et al., 2014). Empty oyster shells are preferred to rocks as settlement substrate, but they are often buried first when sedimentation occurs and no longer provide suitable habitat (Wasson et al., 2014). Fine sediment thus reduces Olympia oyster recruitment in Tomales Bay, limiting population growth and reestablishment. Because the larval oysters have nowhere to settle, they remain in the water column for longer than average periods and are thereby subject to predation or tidal flushing (Kimbrow et al., 2009; Wasson et al., 2014). Mortality rates therefore increase as a direct result of sedimentation.

Fine sediment directly degrades Olympia oyster habitat and populations through the reduction of available habitat. Erosion in the Tomales Bay Watershed brings fine-grained sediment downstream to Tomales Bay, where it buries rocky intertidal and subtidal habitat and worsens water quality (Wasson et al., 2014; Niemi and Hall, 1996). The result is a loss of Olympia oysters populations: larval oysters cannot settle and thus do not survive to adulthood, while adult oysters are buried in smothering, fine-grained sediment inhibiting respiration and reproduction (Wasson et al., 2014). The acute effects of sedimentation in Tomales Bay make this issue a significant one for managers to consider prior to undertaking any restoration efforts for Olympia oysters.

4.5 Need for Further Studies and Long-term Monitoring

To best address the sedimentation issue in Tomales Bay and its watershed, further studies and long-term monitoring are needed. Studies that identify the areas of greatest erosion in the Tomales Bay Watershed could help managers develop or enforce more stringent policies, such as a strict Total Maximum Daily Load, to curb the amount of sediment entering Tomales Bay Watershed bodies, including Lagunitas, Walker, and Olema Creeks as well as their tributary streams. Additionally, better land management practices by ranchers and developers could prevent unnecessary further erosion; studies that identify specific ranches or rangelands and development areas with significant

erosion fill a data gap required by managers to best mitigate sedimentation of Tomales Bay.

Long-term monitoring of sedimentation and progradation of Tomales Bay will help determine if any policies or management strategies to mitigate sediment are effective. Long-term monitoring could provide valuable data as to where fine sediment accumulation in Tomales Bay is the greatest, and if after the enforcement of a TMDL or more stringent policies that accumulation rate slows. Site identification is critical, especially when oyster restoration is under consideration. Furthermore, long-term monitoring of identified Olympia oyster populations and their habitat quality is a data gap that could provide useful information as to where restoration projects might be the most successful.

Further study and monitoring of sedimentation in Tomales Bay and its watershed provide needed regional and site-specific information regarding the seriousness of the issue and also provide a gauge of the success of any new (or better-enforced) policies related to sediment control. Section 7.1.2 describes management recommendations specific to the combatting of sedimentation in Tomales Bay with the goal of ensuring viable habitat for Olympia oyster restoration.

Chapter 5: Invasive Species

5.1 Background

Of the three major degraders of *Olympia* oysters in Tomales Bay, invasive species are the most impactful. This research focuses on the impacts of two invasive oyster drills in Tomales Bay, both of which create a variety of issues for restoration projects. These oyster drills include the Atlantic oyster drill, an extremely aggressive and highly invasive species that primarily preys on small and juvenile *Olympia* oysters (Deck, 2011; White et al., 2009). A second invasive drill is the Japanese oyster drill, whose effects are most noticeable in the disruption of trophic interactions in Tomales Bay (Kimbrow et al., 2009) rather than by predation or competition. Both arrived in Tomales Bay by “hitchhiking;” the importation of Eastern and Pacific oysters in the late nineteenth and early twentieth centuries inadvertently brought the drills from their native estuaries, and the two invaders subsequently flourished in Tomales Bay (Ramsay, 2012). In this research, it is important to note that the non-native species discussed are also invasive, indicating that the net effect on Tomales Bay and *Olympia* oysters is negative (Kimbrow, 2008; White et al., 2009). This chapter examines the introduction, ecology, and specific effects of these two species on both *Olympia* oysters and the ecological integrity of Tomales Bay.

Rapid transit and expansion of human civilizations contribute to globalization and international connectivity. Individuals, natural resources and manufactured products now move across oceans and continents daily; while the economic benefits are obvious, these enterprises also include the inadvertent transport of potentially harmful non-native species. Shipping and aquaculture (particularly oyster aquaculture) are arguably the most significant vectors of invasive species worldwide, as both activities include large amounts of water, microorganisms, and other invertebrates with their intended cargo (Carlton, 2010; Williams, 2007). Aquaculture of non-native oysters in estuaries is widely regarded as one of the worst vectors of invasive species ever caused by humans (Forrest et al., 2009), and Tomales Bay is the poster child for this issue of inadvertent species and habitat degradation by invasive species.

In the case of Tomales Bay, the import of Eastern oysters for commercial cultivation brought larval and adult oyster drills in the oyster and water-filled containers. The drills then entered Tomales Bay and thrived; in fact, conditions in Tomales Bay so supported Atlantic oyster drills that the species might be larger in size and in greater densities compared to those found in native Long Island, New York estuaries (Grosholz and Ruiz, 2003). Furthermore, these invasive drills appear to thrive in the same conditions that threaten the survival of *Olympia* oysters in Tomales Bay: water quality problems, sedimentation, and warmer water temperatures are better-tolerated by the Atlantic and Japanese oyster drills (Booker, 2006). The adaptability and tolerance of these species could complicate *Olympia* oyster restoration efforts.

While ocean acidification and sedimentation directly impact the long-term settlement and survival of *Olympia* oysters, invasive species such as the Atlantic and Japanese oyster drills have much acuter effects on both Tomales Bay and its native oysters: the interruption of trophic levels, competition, and predation (Kimbrow et al., 2009). Furthermore, oyster drills pose an immediate threat to restoration projects; until they are removed, many sites in Tomales Bay cannot support *Olympia* oyster restoration. Fortunately, the issue of invasive species is also the easiest to address due to its species-specific and site-specific nature (whereas ocean acidification and sedimentation require the consideration of larger spatial and temporal scales), and the management recommendations in Chapter 7 provide a framework for the Sanctuary and other relevant agencies to move forward with invasive species removal.

5.1.1 Atlantic Oyster Drills: Introduction to Tomales Bay and Species Ecology

The Atlantic oyster drill, *Urosalpinx cinerea*, arrived in Tomales Bay by the late nineteenth to early twentieth century, shortly after fisheries and California-based fishing commissions began importing Eastern oysters to replace the collapsing *Olympia* oyster fishery (Booker, 2006). While the Eastern oyster did not adapt well to conditions in West Coast estuaries, the hitchhiking Atlantic oyster drill thrived (Ramsay, 2012). This small mollusc is a gastropod, or snail, and preys upon Eastern oysters. When large colonies of Eastern oysters and spat were transported in water-filled railcars from Long Island estuaries to California, adult drills came along with their prey and were subsequently

introduced to Tomales Bay and other local estuaries (Ruiz et al., 1997). The drills found in Tomales Bay agreeable: warmer water temperatures and an abundance of prey (both farmed and wild oyster species), and a lack of predators encouraged population explosions (Lord and Whitlatch, 2013), leading to a severe infestation throughout the bay. The behavioral biology and ecology of the Atlantic oyster drill is discussed here to provide a brief background to the Sanctuary as well as emphasize the severity of the invasive species problem in Tomales Bay.

The Atlantic oyster drill is a gastropod mollusc found in soft-bottom estuaries of northeastern North America; it typically can be found in both the intertidal and subtidal regions of the estuary (Cohen, 2011). A member of the molluscan family Muricidae, this snail prefers to prey upon bivalves, such as Olympia oysters (Faasse and Lighthart, 2009). The species is approximately 30 millimeters in size, with females laying long strands of fertilized egg cases on hard submerged substrate in the spring and summer months. After one to two months, small snails emerge from these egg capsules to feed on any sessile invertebrates near their hatch site (Cohen, 2011). Figure 7 below shows the Atlantic oyster drill as it appears in San Francisco Bay; similar specimens are found in Tomales Bay.



Figure 8: Appearance of the Atlantic oyster drill (Image courtesy of Andrew N. Cohen, Center for Research on Aquatic Bioinvasions; Cohen, 2011).

The mild oceanographic conditions and availability of food for juvenile snails in Tomales Bay ensures that many of them mature to adulthood, the life stage in which they are particularly more threatening to *Olympia* oysters.

The feeding mechanism of Atlantic oyster drills explains the species' name; individual snails have radula, which are tooth-like structures in the snail's mouth that can drill into the shell of their oyster or other bivalve prey (Cohen, 2011; Federighi, 1931). Further facilitated by chemical secretions, the snail successfully bores into its prey to reach the soft inner tissue of the oyster, which it then consumes (Harding et al., 2007). The Atlantic oyster drill is rapacious, as one individual can consume up to one oyster per week (Lord and Whitlach, 2013). The abundance of prey in Tomales Bay supported drill populations and enabled them to flourish; today the species is well established, with high densities in the inner bay regions (Kimbrow et al., 2009). This range significantly limits where *Olympia* oyster restoration in Tomales Bay can occur. Chapter 7 discusses options for dealing with the Atlantic oyster drills, either through eradication or avoidance; their concentration in the inner bay region makes avoidance a possibility.

The inner bay region of Tomales Bay harbors the highest densities of invasive Atlantic oyster drills in the entire bay (Kimbrow et al., 2009). This is because the warmer temperatures, shallower water and variable salinity appear to support the metabolism and reproductive rates of the drill, thereby enabling populations to grow (Kimbrow et al., 2009). Furthermore, there are few predators found in the inner bay that might consume the Atlantic oyster drill and curb its population growth; Tomales Bay's native rock crab does not tolerate the variable salinity of the inner bay, and thus remains in the middle or outer bay regions (Kimbrow, 2008; Kimbro et al., 2009), where it does act as a top predator. This is unfortunate for *Olympia* oysters, because the rock crab typically does eat gastropods and might otherwise consume the Atlantic oyster drill in the inner bay were it not for the oceanographic limitations (Kimbrow, 2008). The Atlantic oyster drill is found in less dense populations in the middle bay region, however, predators studies do not yet indicate why the drills are less prevalent there (Kimbrow et al., 2009). Another invasive species, the European green crab, further complicates the food web involving *Olympia* oysters and Atlantic oyster drills. The trophic interactions and the consequences of invasive species interfering with them are discussed in greater detail in Section 5.1.3.

5.1.2 Japanese Oyster Drills: Introduction to Tomales Bay and Species Ecology

The Japanese oyster drill, *Ocenebra inornata*, arrived in Tomales Bay in the early twentieth century. Eastern oysters failed to support a viable fishery in the San Francisco Bay region due to poor acclimation to the regional oceanographic conditions; fisheries then imported Pacific oysters from Japan to fill the void in the oyster market (Ruiz et al., 1997). The Pacific oyster thrived and is cultivated as the primary oyster species along the West Coast of North America, including in the Tomales Bay estuary. Similar to the arrival of Atlantic oyster drills, the Japanese oyster drill invaded Tomales Bay with the implanting of Pacific oyster spat from Asia (Ramsay, 2012), establishing a foothold in the bay as a predator of native Olympia oysters and a second interrupter of the bay's trophic levels. While its effects are less severe than its Atlantic counterpart (Kimbrow, 2008), the Japanese oyster drill is nonetheless a presence felt in Tomales Bay and merits consideration by Sanctuary restoration efforts.

A relative of the Atlantic oyster drill, the Japanese oyster drill is a boring marine gastropod native to Japan and northern Asia (Lützen et al., 2012). The reproductive cycle is similar to the Atlantic species; after mating events in the spring and summer, female drills lay long strands of fertilized eggs that subsequently hatch into juvenile snails after one to two months (Lützen et al., 2012). As its name suggests, the Japanese oyster drill uses its radula to pierce the shells of oysters and bivalves to access and eat the inner flesh (Harding et al., 2007). In Tomales Bay, the Japanese oyster drill does consume bivalves such as native Olympia oysters, but little is documented aside from its coinciding range with Atlantic oyster drills in the inner bay, with some records indicating its presence in the middle bay as well. The Japanese drill is subject to predators like the native rock crab (Lützen et al., 2012), so it is less of a dominating force than the Atlantic oyster drill. Figure 8 shows the Japanese oyster drill and its predation technique.



Figure 9: Appearance of the Japanese oyster drill (Image courtesy of the Washington Department of Fish and Wildlife).

The Japanese oyster drill's range in Tomales Bay is not as well documented as that of the Atlantic oyster drill, but it is likely found in greatest numbers in the inner bay region, where native rock crabs are scarce (Kimbrow, 2008; Kimbro et al., 2009). The abundance of drills in the inner bay explains why there are few to no Olympia oyster populations there, and any restoration efforts should focus on the removal of these snails if avoiding the region is not a desirable option for the Sanctuary. The Japanese oyster drill's greatest act of degradation to the Olympia oyster in Tomales Bay is its interruption of trophic interactions, a problem discussed in Section 5.1.3.

5.2 Impacts on Olympia Oysters and Tomales Bay

5.2.1 Predator-prey Relationship

First and foremost in the complex interactions between invasive oyster drills and Olympia oysters is one of predator and prey. This relationship is very straightforward, and the impacts on Olympia oysters are acute. As discussed in Section 5.1.1 and 5.1.2, the Atlantic and Pacific oyster drills are formidable predators: one Atlantic drill can consume up to one oyster a week, a rate by which it can decimate entire Olympia oyster aggregations (Lord and Whitlatch, 2013). In Tomales Bay, where historic overfishing and

habitat loss already limit Olympia oyster numbers, the aggressive feeding by invasive drills could further exacerbate recovery.

Using its radula and chemical secretions, oyster drills bore holes into the shells of small Olympia oysters and then eat the oyster flesh inside said shell (Cohen, 2011). In their native range, the Atlantic and Japanese oyster drills consumed oysters of a smaller size and thinner shell density. While there are other bivalves in Tomales Bay upon which the invasive drills might feed (in the case of the Japanese oyster drill, its native prey the Pacific oyster), the Olympia oyster is a target because of its smaller size and thinner shell (Lord and Whitlatch, 2013). In particular, juvenile Olympia oysters may be at greatest risk due to their size and weak shells (Buhle et al., 2009). While the drills do eventually seek larger bivalves upon reaching adulthood (Lord and Whitlatch, 2009), the damage done to Olympia oysters during their juvenile or early adulthood stage may be too great for Tomales Bay Olympia oysters to endure.

The predator-prey relationship between invasive oyster drills and Olympia oysters in Tomales Bay represents the most immediate means of degradation upon the oysters. Unfortunately, further degradation caused by the drills' disruption of the estuary's food web further complicates oyster restoration and recovery.

5.2.2 Trophic Level Interruptions in Tomales Bay

Trophic levels describe the positions at which organisms are found in an ecosystem's food chain, with primary producers typically found at the bottom and apex predators at the top. When invasive species arrive in an ecosystem, the typical trophic interactions are disrupted, as the invasive consumes lower level organisms unchecked because the native predators do not recognize the invasive as a threat (Kimbrow, 2008). The interruption of trophic cascades by Atlantic and Japanese oyster drills is perhaps more detrimental to Olympia oysters than predation, as these interruptions affect interconnected food webs throughout the bay and compromise the biodiversity of the bay's microhabitats.

In Tomales Bay, the trophic levels relevant to this research include the native Olympia oyster that an intermediate consumer, the native rock snail, preys upon throughout the intertidal and low subtidal zones of the estuary. The native rock crab is

the top predator, consuming the rock snails (Kimbrow, 2008). This food web drives trophic cascades in Tomales Bay: the native rock crabs limit rock snail populations, enabling sufficient numbers of *Olympia* oysters to survive and reproduce (Kimbrow, 2008) and (Kimbrow et al., 2009). However, the importation of Eastern and Pacific oysters introduced invasive oyster drills that compete with and replace the native snails as the intermediate consumer of *Olympia* oysters in Tomales Bay. In the inner bay, where extreme salinities limit the presence of native crabs, the invasive Atlantic and Japanese oyster drills essentially run rampant (Kimbrow et al., 2009). The drills subsequently increase in population, as there is no native predator present to keep their numbers low and thus the drills consume all *Olympia* oysters in their range. Further interrupting the food web, invasive European green crabs act as a top predator in the inner bay; more tolerant to saline conditions than the native crab, the European green crab is found in large numbers in inner Tomales Bay (Kimbrow, 2008). However, it is an ineffective check on oyster drill numbers because it does not seem to successfully prey upon them (Kimbrow, 2008). The presence of invasive oyster drills significantly interrupts the natural food web and trophic cascades typically found in Tomales Bay.

The invasive species issue does not seem as dire in the middle and outer bay regions of Tomales Bay. This is fortunate, as these regions provide better quality habitat for *Olympia* oysters; there is rockier substrate, native predators, and preferable water quality, particularly in the middle bay and transitional outer bay (Kimbrow, 2008). Tidal flushing and distance from creek mouths may explain why areas of rocky substrate remain available in the middle and outer bay regions. Research shows that the invasive oyster drills occur less densely here because of the presence of native rock crabs, which will consume them (Kimbrow, 2008). Additionally, native rock snails are prevalent in the middle and outer bays, ensuring the continuation of natural trophic interactions and cascades involving *Olympia* oysters. This continuity for the Sanctuary and restoration participants to understand when selecting sites for *Olympia* oyster restoration; until invasive oyster drills are removed, selecting sites where they are absent and the ecological integrity is preserved is ideal.

Atlantic and Japanese oyster drills are prime examples of a detrimental non-native species. Because their net effects on the Tomales Bay ecosystem are negative, the two

snails are considered invasive, and thus compromise the biodiversity and ecological integrity of this estuary. Their invasions of Tomales Bay quickly lead to a population explosion of both drill species, particularly in the inner bay, where few native predators and supportive biophysical conditions enabled the oyster drills to thrive. As a result, the Olympia oysters face further degradation as the drills prey upon juvenile and small adults at an unsustainable rate (Kimbrow, 2008; Lord and Whitlatch, 2013). The invasive oyster drills not only prey upon Olympia oysters but also interrupt the established trophic interactions between the oyster and its consumers in Tomales Bay (Kimbrow et al., 2009). By replacing native rock crabs and outcompeting intermediary consumers like the rock snail, invasive oyster drills compromise the Olympia oyster food web, resonating throughout the entire estuary ecosystem (Kimbrow, 2008, Jensen et al., 2007). To successfully restore Olympia oysters, the Sanctuary must consider where oyster drill densities are highest and either remove them from or avoid such locations (Buhle et al., 2009). Unfortunately, any mitigation or reduction of Atlantic and Pacific oyster drill populations could be counteracted by climate change, a possibility discussed in Section 5.2.2.

5.2.3 Projections for the Future

Excessive anthropogenic emissions of carbon, methane, and other greenhouse gases lead to warming of global temperatures and enhance climate change processes. As these gases accumulate and remain in the lower troposphere, the surface temperature of the Earth rises. This temperature increase causes issues such as ocean acidification and global warming, which occur on large spatial and temporal scales. However, the more acute effects of climate change are noticeable in the increase of non-native species invasions (Lord and Whitlatch, 2013). These invasions are becoming more frequent and more severe, particularly in sensitive ecosystems like estuaries. In Tomales Bay, warmer air and water temperatures enable existing invasive species like the Atlantic and Japanese oyster drills to expand their range and increase in population size (Lord and Whitlatch, 2013), a response that could cause significant damage to Olympia oyster restoration projects.

Climate change already manifests itself in Northern California and the California Current region; surface water temperatures are increasing steadily, particularly during the summer months (Sanford et al., 2014). Atlantic oyster drills thrive in warmer water temperatures: their metabolism increases, thus enabling the snails to move faster, reproduce more, and consume more Olympia oysters (Lord and Whitlatch, 2013). This vitality strengthens the oyster drills' foothold as the top predators in Tomales Bay, and severely impact both trophic cascades and Olympia oyster beds (Kimbrow, 2008). If the warming trend continues, then the invasive oyster drills could expand their range beyond the inner bay and inner-to-middle transition zones and further degrade Olympia oyster populations and habitat. The potential for such a compromising event to occur emphasizes the need for invasive species removal as part of the management plan for restoring Olympia oysters.

As discussed in Chapter 3, ocean acidification is a major consequence of climate change that threatens the very survival of calcifying species like the Olympia oyster. The decreased availability of carbonate in ocean water due to acidifying conditions means bivalves create thinner, weaker shells (Sanford et al., 2014; Fabry et al., 2008). This places Olympia oysters at great risk of increased predation by invasive species. Invasive Atlantic and Japanese oyster drills can bore more easily into these thin and weak shells, thus reducing oyster populations further and more quickly (Lord and Whitlatch, 2013). This is a great risk for Tomales Bay's Olympia oysters, an estuary with variable pH due to the freshwater influx and upwelling events offshore (Kimbrow and Grosholz, 2006). In weakening the biological fitness of calcifying organisms, ocean acidification promotes invasive species at the expense of Olympia oysters.

5.3 Need for Further Studies and Long-term Monitoring

The data gaps regarding invasive species behavior and range in Tomales Bay require further study to best address oyster drill invasions and successfully restore Olympia oysters. Conducting site-specific studies to identify where invasions are the most severe, in proximity to Olympia oysters could help GFNMS and involved agencies to mitigate and remove the oyster drills. Furthermore, long-term monitoring is needed

due to the high numbers of both Atlantic and Japanese oyster drills; avoidance and eradication of the oyster drills during Olympia oyster restoration projects requires multiple seasons' worth of data to best determine where restoration should occur as well as the success rate.

First, researchers acknowledge a lack of data that might explain why Atlantic and Japanese oyster drills established large populations in the inner bay and not in other locations within Tomales Bay (Kimbrow, 2008). While the habitat quality sustains both oyster drills extremely well in the inner bay, similar conditions exist near the mouths of Lagunitas and Walker Creeks (Rooney and Smith, 1999). Site-specific studies examining the extent of Atlantic and Japanese oyster drills would help clarify when and where Olympia oyster restoration might occur. To ensure that the oyster drills do not significantly expand their range beyond the inner bay (and thus compromise further the intertidal and subtidal habitats of the entire Tomales Bay estuary), further studies and long-term monitoring are needed. Chapter 7 discusses in greater detail several recommendations the Sanctuary and managers might implement in regards to site-specific invasive species research.

Long-term monitoring is a recommended "best practice," because it ensures that accurate data is used to design and execute viable management options. The dynamic nature of non-native species invasions, the enhancement of invasions by climate change, and the interconnected nature of trophic levels require adaptive management strategies and comprehensive restoration plans. Chapter 7 proposes management recommendations for the Sanctuary and other agencies to consider as counteractive measures against the invasive oyster drill issue in Tomales Bay.

Chapter 6: Research Conclusions

6.1 Key Research Conclusions

6.1.1 Ocean Acidification

Anthropogenically-enhanced climate change poses daunting and inevitable challenges for restoration projects, particularly those involving an estuarine calcifying species like the Olympia oyster. The species plays an invaluable and irreplaceable role as an ecosystem engineer through the creation, enhancement, and protection of habitat preserves the ecological integrity of estuaries like Tomales Bay (Kimbrow, 2006). Ocean acidification directly threatens the continued production of calcareous substrate (Gaylord et al., 2011) by rendering estuary pH too acidic. The lowering of pH inhibits key organic reactions, such as the formation of carbonate and bicarbonate (Gazeau et al., 2013), and could possibly render estuaries an uninhabitable place for Olympia oysters. Water quality dictates much of the species' behavior, and its degradation directly affects their survival rate (Sanford et al., 2014). The species' physiological and metabolic processes are consequently hindered, thus the survival of calcifying molluscs is at great risk.

The inhibition of calcification in both juvenile and adult Olympia oysters is an observed reality resulting from ocean acidification, and leaves the species weak in the face of a long battle in which adaptation is essential (Kurihara, 2008). The increased rate of non-native species invasions as a result of climate change will greatly reduce Olympia oyster populations if restoration efforts do not address this issue (Grosholz, 2002). A second threat, total shell dissolution, is an impact that requires further research, as the pH threshold which Olympia oysters can tolerate over long periods of time remains unknown. However, the Sanctuary and managers should acknowledge these oysters as a foundation species in need of vulnerability assessments to best prepare for climate change.

Ocean acidification is a reality both today and tomorrow, but research needs to catch up in order to adequately restore and protect Olympia oysters in Tomales Bay. Species-specific assessments in particular could provide much-needed answers to some of the complex questions regarding ocean acidification. The management

recommendations in Chapter 7 provide some structure for moving forward and mitigating the realities our future climate holds.

6.1.2 Sedimentation

The expansive Tomales Bay Watershed drains much of Marin County into Tomales Bay, contributing the freshwater that makes the bay such a biodiverse and dynamic estuarine system (Laughlin, 2009). However, freshwater inflow is not the only delivery from the creeks and streams: fine sediment eroded from the upper watershed regions steadily degrades water quality and smothers the rocky intertidal and subtidal zones of Tomales Bay (Wasson et al., 2014). Decades of rangeland and livestock agriculture destabilized huge quantities of fine-grained sediment, and these practices continue to do so at the cost of estuarine habitat. Removal of riparian vegetative buffers and destabilized hill slopes due to livestock grazing promote the downstream movement of sediment and nutrients that would be otherwise anchored in the upland (Rooney and Smith, 1999); the settlement of eroded material in Tomales Bay significantly alters the estuarine microhabitats.

Sedimentation threatens the existence of tidal marshes, mudflats, and intertidal habitats found along the fringes of Tomales Bay. The accumulating sediment causes progradation to occur, so tidal wetland areas are filled in and lost (Niemi and Hall, 1996). The deltas of both Lagunitas and Walker Creeks continue expanding as sediment fans out from the creek into the bay, promoting major losses of rocky, shallow intertidal zones as well (Rooney and Smith, 1999). The once-rocky bed material is replaced with finer-sized sands, silts, and other particles (Niemi and Hall, 1996), greatly altering the shallower benthic habitats where Olympia oysters, eelgrass, and other native species are found.

Habitat loss is a direct result of sedimentation, while an indirect result is the loss of Olympia oysters populations of Tomales Bay. Larval oysters struggle to settle upon suitable substrate and mature to adulthood, while adult oysters are buried and unable to metabolize or reproduce (Wasson et al., 2014). The populations of Olympia oysters, already struggling to survive ocean acidification and invasive species, are further decreased. Furthermore, restoration efforts are complicated because existing rocky substrate becomes limited or unavailable; imported foreign substrate may be a

requirement to encourage oyster settlement and rehabilitation. These acute effects of sedimentation in Tomales Bay call for adjustments in land use as well as site evaluation prior to undertaking any restoration efforts for Olympia oysters.

Sedimentation in Tomales Bay requires additional studies and long-term monitoring to identify the areas of greatest erosion in the Tomales Bay Watershed and the subsequent development or improvement of policies such as a Total Maximum Daily Load. Changes in land management practices by ranchers and developers are also needed to curb the high rates of erosion throughout Marin County. Chapter 7 discusses at depth the recommendations managers and the Sanctuary might consider or implement to mitigate the sedimentation problem faced by Tomales Bay and the Olympia oyster populations there.

6.1.3 Invasive Species

The invasive Atlantic and Japanese oyster drills are the most egregious degraders of Olympia oysters in Tomales Bay, as each significantly alters the structure of food webs and interspecific relationships while also voraciously preying directly upon oyster populations. The first to arrive in Tomales Bay, the Atlantic oyster drill, preys on small and juvenile Olympia oysters at an alarmingly high rate and competes with native consumers for the role as a top predator (Deck, 2011; White et al., 2009). Its relative, the Japanese oyster drill, adds to the degradation by contributing to the disruption of trophic interactions in Tomales Bay (Kimbrow et al., 2009). The presence of these two invasive snails greatly compromises Olympia oyster restoration.

Both species of oyster drills prey upon bivalve species such as the Olympia oyster, whose small size and habitat in the intertidal zone make them particularly vulnerable to predation (Cohen, 2011). The concentration of Atlantic oyster drills in the inner Tomales Bay region renders the area unsuitable for oysters until eradication can occur; the high feeding and reproductive rates of the oyster drills would overwhelm any efforts to reestablish oysters in the area (Lord and Whitlatch, 2013). However, the effects of these two invaders are not limited to Olympia oysters; entire trophic level processes suffer as a result of invasive species' presence.

The oyster drills prevent the natural trophic interactions of Tomales Bay from occurring, as the invasive species replace the native rock snail as an intermediate consumer of Olympia oysters (Kimbrow et al., 2009). In addition, the native rock crab that typically preys upon those native intermediate consumers does not affect the invasive oyster drills, and thus these two snail populations increase unchecked with no natural predator (Kimbrow et al., 2009). The predator-prey relationships in Tomales Bay directly affect the population size of Olympia oysters, and the disruption of trophic levels greatly degrades them.

Invasive species such as the Atlantic and Japanese oyster drills have acute effects on Tomales Bay and native Olympia oysters through predation, trophic level interference, and competition (Kimbrow et al., 2009). The oyster drills pose an immediate threat to restoration projects; until they are removed, many sites in Tomales Bay cannot support Olympia oyster restoration. Additionally, the continued warming of water temperatures and sedimentation likely fosters population growth of these two invasive snails (Kimbrow et al., 2009), so their removal should be a high priority for the Sanctuary and other Olympia oyster stakeholders. Fortunately, the issue of invasive species may be a simpler one to mitigate due to its species-specific and site-specific nature. However, more studies that clarify the location, population densities, and species behavior are needed. The management recommendations in Chapter 7 provide guidance to the Sanctuary and other relevant agencies to both resolve the data gaps and move forward with invasive oyster drill removal.

Chapter 7: Management Recommendations

7.1 Introduction

The degradation of the Olympia oyster in Tomales Bay is an environmental problem rooted in three major offenders: ocean acidification, sedimentation, and invasive species. These three degraders, coupled with decades of overfishing and habitat loss, require a multi-faceted management strategy to ensure that oyster restoration is successful in Tomales Bay.

This chapter provides the Sanctuary and other relevant agencies with two types of management recommendations: general strategies and issue-specific recommendations. The first type of management recommendations discussed in this chapter is general strategies the Sanctuary might employ to begin the restoration process. These recommendations include the formation of advisory committees and the use of spatial analysis and map tools to address data gaps; they provide the needed first steps towards restoring Olympia oysters in Tomales Bay by clarifying what is available and what is needed in terms of data, funding, and geography. The issue-specific recommendations pertain to each degrading factor, and provide strategies to mitigate or eradicate the threats posed by each of them. Such a management structure enables the Sanctuary to target each issue individually and therefore more effectively. Furthermore, the three degrading factors are synergistic in their overall effect on Olympia oysters and on the ecological integrity of Tomales Bay; they compound upon each other and exacerbate the threats to oyster and estuary habitat (Wasson et al., 2014). Fortunately, the combination of general management strategies with targeted efforts could mitigate and even eliminate some of these exacerbations.

Both the general and the issue-specific management recommendations should be considered by the Sanctuary in order to effectively and successfully restore Olympia oyster populations in Tomales Bay. Such a focused approach to restoration ensures that all of the factors at play are addressed and mitigated as strategically as possible. Two appendices supplement this management section: the Tomales Bay Oyster Habitat map and the Site Evaluation Tool. The habitat map, a tool developed by Sanctuary staff,

highlights those areas in Tomales Bay that may be suitable for Olympia oyster populations should restoration occur there. Several layers narrow down the available habitat in the bay and hypothesize locations in which oysters might survive and thrive. The second appendix includes as a reference the Site Evaluation Tool, which was developed by a team from the San Francisco Bay and Elkhorn Slough National Estuarine Research Reserves, University of California at Davis, the State Coastal Conservancy, California Department of Fish and Wildlife, and the Smithsonian Environmental Research Center in an effort to restore and conserve Olympia oyster populations (Wasson et al., 2014). This “do-it-yourself” guide enables the Sanctuary to conduct much-needed research and data collection about Olympia oysters in Tomales Bay in a site-specific manner, thus clarifying potential restoration sites.

To restore the degraded Olympia oyster is a goal the Sanctuary should prioritize because it is within the Sanctuary’s scope of management: the oyster is a native foundation species whose presence improves the water quality and biodiversity of a federally protected estuary (Coen et al., 2007). Therefore, the supporting background information from Chapters 1-6 and the recommendations in Chapter 7 can be used to supplement the Sanctuary’s existing management plan for resource protection in Tomales Bay.

7.2 General Management Recommendations

Despite the complexity of the three issues affecting Olympia oysters, there are general strategies available to the Sanctuary to facilitate the start of restoration and support it throughout the lengthy process. These strategies include a presentation of this document and its findings to the Sanctuary Advisory Council, as members might be interested in supporting restoration efforts or participating in an advisory capacity. This action relates to the recommended formation of a technical advisory committee, or TAC, comprised of interagency members, researchers, and consultants with relevant experience who can best advise the Sanctuary as to data gaps or misinformation, funding, and permitting required to proceed with Olympia oyster restoration. Next, the Sanctuary has several spatial analysis and data collection tools available to address some of the spatial data gaps that exist in Tomales Bay; these tools provide the needed first steps towards restoring Olympia oysters by clarifying where efforts might be possible. These general recommendations are both applicable to and supportive of those specific to ocean acidification, sedimentation, and invasive species. The TAC can advise and provide support for each of these issues if its membership is appropriately diverse; similarly, the spatial analysis tools provide useful data related to all three of the Olympia oysters' degraders.

7.2.1 Technical Advisory Committee (TAC)

A Technical Advisory Committee (hereafter TAC) provides technical and scientific guidance to the Sanctuary; as stated in its name, it is an advisory entity whose purpose is to help the Sanctuary achieve its long-term goal of restoring Olympia oysters in Tomales Bay. The diversity of jurisdictions and complex degrading factors complicates proposed projects, so an interdisciplinary, interagency TAC is a valuable resource for the Sanctuary to overcome these obstacles and develop a comprehensive management plan. Furthermore, there are many data gaps that exist in this area of research; for example, little data is available as to the historic range of Olympia oysters in Tomales Bay. The TAC would greatly help the Sanctuary to fill some of these gaps. At this time, a Sanctuary Advisory Council (SAC) working group is not recommended to

assist with Olympia oyster restoration. While the public's input is valuable, the Sanctuary needs the advice and recommendations from those scientists and resource managers experienced in Olympia oyster and estuary restoration rather than by community members. Studies show that most community-based restoration efforts are small in scale and often less successful than those developed and overseen by researchers and agencies (Wasson et al., 2014), so the Sanctuary should prioritize the formation of a TAC rather than a SAC working group.

At its formation, the TAC should include the following staff from the Sanctuary: Superintendent Maria Brown, Deputy Superintendent Brian Johnson, Resource Protection Coordinator Karen Reyna, Program Analyst Max Delaney, Marine GIS Analyst Tim Reed, and a to-be-determined Project Coordinator. These staff members have the necessary knowledge of the Sanctuary's jurisdictional and financial capabilities and how these capabilities pertain to Olympia oyster restoration. The resource protection team has significant experience undertaking restoration in the Sanctuary's estuaries; furthermore, these staff members participate in interagency collaboration on a daily basis, thus can recommend who is best suited for inclusion on the TAC. In addition, Executive Director Chris Kelley and Grants Manager Nicole Lungerhausen of the Farallones Marine Sanctuary Association are needed to assist with the obtaining of funding and community support for Olympia oyster restoration efforts in Tomales Bay.

The TAC should also include representatives from the following research institutions and agencies:

- California Coastal Commission (CCC)
- California Department of Fish and Wildlife (CA DFW)
- California State Coastal Conservancy
- California State Lands Commission (CSLC)
- California State Parks (CSP)
- Elkhorn Slough National Estuarine Research Reserve (ES NERR)
- Farallones Marine Sanctuary Association (FMSA)
- California State University Monterey Bay, Moss Landing Marine Laboratory (MLML)

- National Park Service/Pt. Reyes National Seashore/Golden Gate National Recreation Area (NPS/PRNS/GGNRA)
- San Francisco Regional Water Quality Control Board (SF RWQCB)
- San Francisco National Estuarine Research Reserve (SF NERR)
- University of California, Davis Bodega Marine Laboratory (BML)

It is important to note that the TAC members' participation might be staggered; as the planning for oyster restoration begins and projects commence, members from some of the above entities can participate as needed. However, each of the above agencies and institutions has invaluable knowledge of Olympia oysters and Tomales Bay or legal jurisdiction in the bay or watershed, so their inclusion is necessary. A TAC comprised of the above representatives requires the Sanctuary to take a more site-specific approach to Olympia oyster restoration by considering the administrative characteristics, such as agency jurisdictions, as well as the biogeophysical characteristics of a site. The scientists and researchers from Bodega Marine Lab and the two National Estuarine Research Reserves have years of experience studying Olympia oysters in degraded estuaries as well as experience in their restoration, so their lead should be followed during the restoration of Tomales Bay. Individuals such as Dr. Edwin Grosholz and his research team, Dr. John Largier, Dr. David Kimbro, Matthew Ferner and Anna Deck could co-lead the TAC with the Sanctuary and thus guide any restoration projects towards a more successful outcome. Marilyn Latta from the State Coastal Conservancy, whose experience includes Olympia oyster restoration in San Francisco Bay, would also be a valuable member on the TAC

The above list of agencies, organizations, and institutions is not exhaustive and should adapt to include other members as Olympia oyster restoration progresses. The TAC might also decide to divide into subcommittees to address each of the three degraders, coming together as one large committee to provide updates and recommendations to one another. The Sanctuary should act as both organizer and co-leader through the Project Coordinator, but defer to those research and science-based individuals whose participation and recommendations throughout the restoration process ensure its overall success.

7.2.2 Tomales Bay Native Oysters Potential Restoration Sites Map

Tomales Bay is 22 km long with extensive coastline and varying coastal habitats, from eelgrass beds to rocky intertidal areas to muddy tidal marshes. To determine where Olympia oyster restoration is optimal is a daunting task and one that requires careful consideration of the biological and physical conditions found at each site.

To facilitate this task, the Sanctuary can use the Tomales Bay Native Oysters Potential Restoration Sites Map (Reed and Gibson, 2015); this tool uses Olympia oyster's preferred depth range and substrate type (gravel-sand, cobbles, gravel, and shell litter) as proxies for oyster habitat. Because conditions such as water temperature and salinity are more variable, they are not included in this map. Furthermore, there is little relevant data available that shows the historic range of the oysters in the bay prior to aquaculture and sedimentation. Therefore, depth range and substrate type are the only means available for this stage of the project. Of these two proxies, depth range is the most rigid; Olympia oysters tolerate or adapt to a wider range of biophysical conditions and implantation or installation of suitable substrate can address any sediment inadequacies, but depth range in the intertidal to low subtidal zones is a limiting parameter for oyster survival. The map then uses various layers to show where protected areas, including eelgrass beds and mooring zones, are no-go for oyster restoration. In addition, layers that show the jurisdictional boundaries of the major agencies and aquaculture operations show where restoration efforts could be more complicated due to permitting and interagency collaboration. Some of the aquaculture areas may not be leased from the State of California in the future, so investigating the habitat suitability in the inactive aquaculture areas might be a worthwhile venture. Spatial analysis shows regions where oyster restoration might be possible in the bay: the outer bay adjacent to eelgrass beds, in the middle bay region near Hog Island Oyster Company, and in some areas of the inner bay; thus the 22 km of Tomales Bay narrows to a much smaller sample size for site selection. The Tomales Bay Native Oysters Potential Restoration Sites Map should be used during a meeting of the TAC to demonstrate where further site investigation is needed in Tomales Bay to plan restoration projects. Prior studies indicate that the outer bay and inner bay are unsuitable due to oceanographic processes and invasive species, so there is clearly some discrepancy here that requires addressing before a final decision is made. A

second tool, the Site Evaluation Tool, tests the hypotheses presented by the Tomales Bay Native Oysters Potential Restoration Sites Map.

7.2.3 Site Evaluation Tool

The Site Evaluation Tool can be used to further the investigation for suitable restoration sites in Tomales Bay. The tool is the result of research led by San Francisco National Estuarine Research Reserve and Elkhorn Slough National Estuarine Research Reserve, and guides users to the collection of Olympia oyster population abundance, density, recruitment rates, and other related data to give managers a sense of how suitable a site is for Olympia oyster restoration (Wasson et al., 2014; Grosholz et al., 2007). The Site Evaluation Tool supports this document's emphasis on site-specific surveys and evaluation to design restoration plans that directly address the degrading factors at a site and rectify them prior to Olympia oyster reintroduction.

Use of the Site Evaluation Tool narrows the focus of the Sanctuary and TAC to a few locations; some of those sites might be within the areas highlighted by the Tomales Bay Native Oysters Potential Restoration Sites Map or in other locations, such as the middle bay region, known to researchers as capable of supporting Olympia oysters (Kimbrow et al., 2009). Its use in recent and ongoing projects in San Francisco Bay led to new findings of Olympia oysters in unexpected locations thought inhospitable (Wasson et al., 2014); similar results may follow in Tomales Bay. Furthermore, the Site Evaluation Tool fills data gaps for the Sanctuary and its partners during restoration, including the locations and population dynamics of wild oyster populations and invasive oyster drills. It is not well documented where both Olympia oyster aggregations and invasive oyster drills are most dense, so this tool provides a solution to that issue before restoration projects begin, which is a better strategy to achieve long-term success. The knowledge of both species' population ecology and dynamics is invaluable, so use of this tool is beneficial to restoration in many ways.

7.2.4 Conclusion

The management recommendations of this section are general in nature and relate to the structuring of a restoration plan for Olympia oysters in Tomales Bay. They

encourage collaboration among stakeholders, governmental and private sector, through a TAC, and develop an adaptive but strong framework that promotes successful, site-specific restoration projects. In addition, these recommendations promote the use of spatial analysis tools to facilitate data collection and site selection, which is particularly useful since the Project Coordinator and TAC members cannot always be onsite in Tomales Bay. The TAC is particularly valuable in that it guides the Sanctuary towards an ideal long-term outcome; interdisciplinary expertise and cooperation to achieve a common purpose enable the TAC to advise the Sanctuary how to proceed with best management practices in regards to Olympia oyster reestablishment in Tomales Bay.

7.3 Recommendations for Ocean Acidification

7.3.1 Overview of the Issue

Ocean acidification is difficult to manage because of the immense spatial and temporal scale on and during which it occurs. The spatial scale issue is twofold; high carbon emissions are not location-centric, and the subsequent acidification is not restricted to one ocean or body of water (Cayan et al., 2007). The burning of fossil fuels and resulting carbon emissions is a global epidemic: developing and established nations alike are emitters of greenhouse gases, and the sources of emitted pollution are located worldwide. While efforts to curb these emissions have been made, they are largely insufficient and possibly too late to halt ocean acidification (Doney et al., 2009). Furthermore, ocean acidification is not limited to one ocean or to coastal waters along one continent; it is occurring throughout the world's oceans in varying degrees of severity. The carbon dioxide (CO₂) entering the oceans and lowering pH is atmospheric in origin, and currently human attempts to sequester the CO₂ do not adequately reduce the atmospheric or aqueous concentrations (Doney et al., 2009). Thus, the spatial scales of ocean acidification's causes and effects are enormous and therefore very challenging to mitigate.

The temporal scale during which ocean acidification occurs is coincidentally great, because CO₂ accumulated in the atmosphere over decades and the effects of that accumulation are just now being realized in the oceans (Feely et al., 2004). As greenhouse gases continue to enter the atmosphere, albeit via cleaner methods than those of the Industrial Revolution in the mid-eighteenth century, the consequences extend decades and centuries into the future; were all global emissions to cease today, the current atmospheric concentrations of CO₂ will still cause a significant reduction in oceanic pH by 2100 (Hofmann et al., 2010). Ocean acidification's negative effects on inorganic and organic aquatic chemistry, estuaries and calcifying species (such as Olympia oysters) began decades ago and are now beginning to show themselves to a greater extent: coral bleaching, the shoaling of calcite and aragonite in coastal waters, the reduced calcification rates of shelled organisms, and the observed decline in ocean pH clearly indicate that ocean acidification is no longer a possibility, it is a reality. The long-

term projections do not suggest possible outcomes, but rather outline what will happen to marine ecosystems and marine species in the near future. The damage is done, and thus mitigation and adaptation to adjust to this newfound ocean reality are of paramount priority.

As discussed in Chapter 3, marine calcifying organisms face unique risks in the face of ocean acidification. In the case of the Olympia oysters of Tomales Bay, the species inhabits an already-acidic estuary with frequent fluctuations in pH due to upwelling events and fluvial input (Kimbrow et al., 2009). Ocean acidification further reduces estuarine pH, exceeding the adaptive abilities of the oysters, thus leading to two acute symptoms (Harley et al. 2006). Reduced ability to undergo calcification, or create calcareous structures like shells, is one of the risks already observed in current studies involving Olympia oysters and other calcifying molluscs (Kurihara, 2008). As oceanic pH declines, so does the availability of carbonate and bicarbonate ions essential for calcification (Gazeau et al., 2007). Thus Olympia oysters produce thinner, weaker shells such that the species cannot adequately protect itself. Furthermore, ocean acidification inhibits adult oysters' ability to produce fit offspring, and this inability compromises the long-term survival of populations (Kurihara, 2008). The second threat of ocean acidification is a projected one: shell dissolution. If pH continues to decline at current rates, then calcium carbonate-based structures such as shells will inevitably dissolve (Feely et al., 2004).

Despite the dire threats of ocean acidification, several mitigation strategies described below provide the Sanctuary with a framework for moving forward with best management practices to ensure that Olympia oyster restoration in Tomales Bay is successful in both the short-term and long-term.

7.3.2 Participation of Climate Researchers and Experts in TAC

To assess the current status of Olympia oysters in Tomales Bay in regards to both observed and projected impacts from ocean acidification, the Sanctuary-led TAC should address these data gaps that currently exist in the literature as well as seek a better understanding of the observed and projected effects on the species as ocean acidification progresses. To acquire this understanding, the TAC needs participants with the

appropriate background and knowledge to lead the Sanctuary towards a viable solution. The use of a TAC would not only promote partnerships and collaboration between agencies and research institutions but also facilitate the obtaining of essential climate change-related data.

Some of the members recommended to participate in the TAC, as discussed in Section 7.2.1, include oceanography and ecology researchers from University of California, Davis Bodega Marine Laboratory or the California Ocean Science Trust, whose areas of research include the effects of ocean acidification on the physical and biological environment. The Sanctuary should also encourage the participation of its Ocean Climate Initiative staff, as their experience in climate impacts and adaptation for the San Francisco Bay Area could extend to Tomales Bay. The inclusion of these members in this advisory body ensures that the Sanctuary is aware of current research efforts and any findings relevant to Olympia oyster restoration in Tomales Bay while collaborating with external institutions. Furthermore, these participants' deeper understanding of the oceanography and species ecology at work would help the Sanctuary construct a more effective and adaptive restoration plan for the Olympia oyster.

The Sanctuary should consider reaching out to relevant partner agencies, institutions, or individuals whose participation in the TAC might improve the success of Olympia oyster restoration projects. The recent restoration efforts of Olympia oysters in San Francisco Bay and ongoing research by Bodega Marine Lab students shows that the Sanctuary's goal of restoring the species in Tomales Bay would likely be well-received and of great interest. Therefore, it is important for the Sanctuary to take advantage of this interest and extend the invitation for these parties' to participate in the TAC.

7.3.3 Collaborate with University of California, Davis Bodega Marine Laboratory

Much of the current Olympia oyster restoration occurring in Oregon and Washington State are community-based projects focused on creating or adding hard substrate to enhance oyster habitat (Wasson, 2010). Unfortunately, many of these projects may prove ineffective because they lack the in-depth understanding of Olympia

oyster physiology and behavioral biology; similarly, the projects don not address the root of the problem: why hard substrate is absent in the first place (Wasson, 2010). Therefore, it is recommended that the Sanctuary work closely with scientists and researchers with field expertise when designing and planning for oyster restoration in Tomales Bay.

Bodega Marine Lab (BML) currently conducts research both in Tomales Bay and with Olympia oysters as the study subject. The Grosholz Lab and the Largier Lab both include research related to Olympia oyster ecology and the oceanographic processes (TAC) should bring the identified data gaps in regards to Olympia oyster densities, recruitment, survivorship, and population locations to these researchers and collaborate with them to answer such questions. If their research or knowledge does not address these data gaps, then the Sanctuary might suggest or support additional projects that can provide answers. The opportunity to serve each other's interests promotes a healthy partnership between the Sanctuary and BML while also bettering science.

7.3.4 Olympia Oyster Vulnerability Assessment

Climate change and ocean acidification affect individual species and habitats differently; while calcification reduction and shell dissolution affect all calcifying bivalves, the severity and reaction is unique amongst species (Kurihara, 2008). The Olympia oyster has a different physiology and adaptive ability than the Eastern or Pacific oyster, for example, and therefore the species merits its own vulnerability assessment to accurately prepare for both the inevitability of ocean acidification and the less certain future of restoration.

The Sanctuary's Ocean Climate Initiative and partner organizations recently conducted and produced vulnerability assessments as part of their climate change adaptation strategies; much of this work focused on the impacts of sea level rise on specific keystone and foundation species and habitats. The use of vulnerability assessment is also an ideal approach for preparing for ocean acidification in Tomales Bay. By focusing on what may happen to individual estuarine microhabitats under acidified conditions, such as the intertidal and subtidal zones, the Sanctuary could focus resources on addressing these data gaps while eventually preparing a specific and thorough adaptive management plan. Therefore, the Sanctuary should work with the

Ocean Climate Initiative and its partners on two additional studies: a species-specific Olympia oyster vulnerability assessment and a Tomales Bay intertidal-subtidal vulnerability assessment.

First, a species-specific vulnerability assessment is an important strategy the Sanctuary should undertake to prepare successful restoration plans for Olympia oysters in Tomales Bay. Historically, Olympia oysters provided valuable ecosystem services to Tomales Bay, enriching habitat quality and biodiversity. If restored, the oysters could resume this role, and this value merits a species-specific assessment. Much of the existing research examining the effects of ocean acidification on bivalves is general and provides an overarching projection in regards to decreased calcification and eventual shell dissolution; less information and studies specific to Olympia oysters and these side effects exist. Olympia oysters may react differently to lower pH than other bivalves due to their different physiology, reproductive methods, and habitat (Kurihara, 2008). For example, female Olympia oysters brood their young within their mantle and release the developed larvae into the water column; the stage of larval development for this species is more advanced than its relatives (Kurihara, 2008). This hardiness and the presence of a basic aragonite shell could better equip the larval oysters to survive in acidified conditions. Survival could lead to adaptation, so this is an important reason to focus on Olympia oyster-specific vulnerabilities. However, Olympia oysters cannot survive without suitable habitat, so the Sanctuary should include habitat assessment to best plan for ocean acidification.

Olympia oysters inhabit the rocky intertidal and low subtidal zones of Tomales Bay (Deck, 2011). They coexist with other invertebrates, fish, shorebirds, seagrass, and phytoplankton. Ocean acidification undoubtedly threatens the biodiversity and integrity of these zones, as reduced pH may increase mortality events, reduce species' ranges, and negatively affect water quality. The health of its intertidal and subtidal zones reverberates throughout Tomales Bay, thus supporting the need for habitat vulnerability assessments. The Sanctuary could work with its Ocean Climate Initiative, BML, or other partner agencies and organizations to determine exactly how these tidal zones will respond to ocean acidification. Changes to key parameters like water temperature, salinity, and primary productivity could profoundly affect these tidal zones and render

them inhabitable for oysters (Wasson, 2010). Thus habitat assessments would supplement Olympia oyster restoration projects by eliminating certain areas of Tomales Bay as incapable of sustaining oyster populations under future conditions.

Vulnerability assessments bridge the data gaps that exist regarding the reactions of both Olympia oysters and Tomales Bay to ocean acidification. Therefore they are a viable strategy the Sanctuary should consider as part of its oyster restoration plans.

7.3.5 Long-term Research and Monitoring

Ocean acidification occurs on vast spatial and temporal scales. To adequately understand its current and future impacts on both Olympia oysters and Tomales Bay, long-term research and monitoring are needed. This need translates to possibly moving forward with restoration in the bay and using the project sites as reference sites (Wasson et al., 2014), while also continuing current research in controlled settings. A reference site provides real time, on-the-ground data and observations on the reaction of Olympia oysters and their habitat to the gradual acidification process (or perhaps a decline in the rate of acidification if carbon emissions begin to decrease or significant sequestration efforts move forward). Use of reference sites also allows for adaptive management, in which the Sanctuary can adjust its restoration methods and framework to encourage success rates.

As discussed in Section 7.2.1.3, Olympia oysters might gradually adapt to the lower pH conditions in which most populations will find themselves with ocean acidification. Current research in progress, such as the cultivation of both oyster spat and juveniles under reduced pH conditions (Kurihara, 2008), may determine if the lower pH encourages physiological or behavioral adaptation. However, evolutionary adaptation is a slow process; whether the Olympia oyster can adapt quickly enough to survive in a changing climate is a major question mark. Long-term studies and monitoring are the best tools available to managers to mitigate and adjust if necessary.

7.4 Recommendations for Sedimentation

7.4.1 Overview of the Issue

Sedimentation of Tomales Bay is the result of ongoing erosion throughout its extensive watershed; land development in the forms of agriculture, commercial and residential developments altered the once-forested landscape and thus destabilized enormous quantities of fine sediment (Niemi and Hall, 1996). Riparian corridors that both trap sediment and filter nutrients prior to entry to Lagunitas, Walker, and Olema Creeks fell victim to development activities. As this fine sediment enters the Tomales Bay Watershed (which includes the aforementioned creeks), it scours the channel bed and banks, eroding further sediment and resulting in a weakened riparian zone (Niemi and Hall, 1996). The sediment moves downstream to the creeks' mouths in Tomales Bay. There it deposits in wide alluvial fans, slowing prograding the tidal marshes and rocky smothering the rockier intertidal zones (Niemi and Hall, 1996). Chapter 4 discussed at length erosion, deposition and sedimentation of Tomales Bay, and determined that their overall effects are negative for both Tomales Bay and Olympia oysters. The oysters' preferred habitat, the rocky intertidal to low subtidal zones, fill in with fine sediment and cannot support populations. Tomales Bay experiences a decline in water quality and loses not only its intertidal and subtidal microhabitats but also its fringing wetlands (Rooney and Smith, 1999) and tidal marshes.

To address the issue of sedimentation in Tomales Bay, the Sanctuary should consider a range of strategies in both Tomales Bay and within the watershed. Those strategies relevant to Tomales Bay proper include habitat studies and substrate implantation. While the effects of sedimentation are arguably the most acute in Tomales Bay (particularly as they relate to Olympia oysters), the most effective means of combatting this issue is to go to its source in the Tomales Bay Watershed. Therefore, much of the sedimentation management recommendations relate to regulatory changes or enforcements in the Tomales Bay Watershed rather than in the bay itself. However, neither type of strategies outweighs the other in terms of relevance or prioritization; they should be considered concurrently.

While the Sanctuary's jurisdiction does extend upstream into Walker Creek (TBVMP, 2013) it does not include the upper watershed areas of western Marin County where most of the erosive activities occur. Therefore it cannot mandate or solely carry out restoration activities in the upper watershed. However, the partnerships that exist between the Sanctuary and other local and state agencies encourage collaboration on restoration projects. Because Tomales Bay is within the Sanctuary's jurisdictional boundary and is negatively affected by upstream pollution and degradation, the Sanctuary could call for policy changes, restoration activities, and other mitigation means on the grounds that a federally protected entity is under threat. Furthermore, sedimentation threatens the bay's biodiversity, which includes several threatened or endangered species. The recommendations of this section provide the Sanctuary and other agencies with a variety of strategies that could decelerate or possibly halt sedimentation of Tomales Bay and the associated loss of Olympia oyster habitat.

7.4.2 Management of Tomales Bay

Habitat Studies in Tomales Bay

Olympia oysters prefer hard substrate for settlement: oyster shells, cobbles, boulders, and other rocky or otherwise erect structures provide optimal conditions for settlement, reproduction, and filtration (Deck, 2011). The mid-intertidal to low subtidal zones in Tomales Bay, which extend from approximately 0.5 meters above Mean Lower Low Water to 1.0 meters below Mean Lower Low Water, typically provide substrate of this kind and thus are appropriate Olympia oyster habitats (Deck, 2011). However, the resulting sedimentation of the bay from eroding upland sediment threatens the existence of these habitats. Fine sediment accumulates on the bay floor, covering the rocks and cobbles on which oysters aggregate. Additionally, the deltas of Lagunitas and Walker Creeks expand under this increased volume of incoming sediment, gradually prograding until the fringing tidal marshes and mudflats disappear (Wasson et al., 2014). Both of these side effects of sedimentation degrade and decrease habitat for Olympia oysters, complicating any restoration efforts. If accumulating sediment buries the naturally occurring oyster beds, rocks and cobbles, then there is nowhere for the Sanctuary to

implant oyster spat or juvenile oyster during restoration projects. Site-specific studies that survey sedimentation may address this issue.

It is recommended the Sanctuary or TAC conduct sediment surveys at two types of locations: those where wild oysters naturally occur and those potential oyster restoration sites. Potential restoration sites can be determined by first using the Tomales Bay Native Oysters Potential Restoration Sites Map followed by extensive data collection using the Site Evaluation Tool. The sediment surveys should characterize the dominant particulate size of the bed material at each site, as well as the sediment accretion rate over time. The particulate size determines if Olympia oysters can naturally recruit there; if a site is primarily fine to very fine sediment, then it likely cannot support a sustaining oyster population without human intervention. To further support this finding, surveys should determine the sediment as it will determine if a potential site is suitable in the long-term: if sediment is not accumulating significantly over time, then implanting hard substrate may be a viable strategy (Wasson, 2010). However, if the accretion rate appears rapid or noticeable, then the Sanctuary should avoid that site until erosion in the upper watershed decreases. It is important to note that addressing the sedimentation problem at its source should be of greatest priority. If upper watershed erosion continues unchecked, then even those sites with low sedimentation rates will eventually suffer with respect to habitat quality.

Substrate Implantation

If fine sediment size is the only inhibiting biophysical condition, adding hard substrate is one possibility to encourage Olympia oyster settlement. The addition counteracts the detrimental effects of sedimentation by providing the initial habitat attractive to settling oysters. Additionally, natural oyster beds provide coastal protection and buffering of the fringing tidal marshes from storm surge; restoring intertidal and subtidal oyster beds through substrate implantation enhances the ecological functioning of Tomales Bay. These beds could also trap incoming sediment and thus slow down the rate of sedimentation (Niemi and Hall, 1996; Wasson, 2010). Other oyster restoration projects in Oregon and Washington estuaries show moderate success in both settlement and recruitment rates following substrate implantation, although each emphasize careful

consideration of site conditions prior to adding materials (Wasson, 2010). In addition, the type of substrate added to these estuaries played a role in overall recruitment success (White et al., 2009). The lessons learned from these projects provide reference information for Tomales Bay and are relevant to any projects the Sanctuary pursues. Again, extensive surveys and data collection of the biogeophysical conditions at each site is essential and ensures strategic placement of added substrate.

Olympia oysters naturally recruit to larger, rockier substrate; their preferred habitat is empty oyster shells (McGraw, 2009; Trimble et al., 2009), which in Tomales Bay includes both non-native Pacific oyster shells and Olympia oyster shells. The larval oysters, or spat, complete their planktonic phase upon settlement on a surface, after which they continue development and calcification (Kurihara, 2008). Ideally, the spat do not travel far from large aggregates of adult oysters and can then settle on or adjacent to existing oyster reefs. The success of recruitment ensures continued reproduction and population growth. If the Sanctuary pursues habitat enhancement through the addition of substrate, that substrate should be large quantities of empty Olympia oyster shells placed in the low intertidal to mid subtidal zones at determined locations in Tomales Bay.

Placed in the low intertidal and subtidal zones, Olympia oyster shells provide adequate settlement substrate while also mimicking historical and natural conditions (White et al., 2009). If Olympia oyster shells are unavailable in sufficient quantities, then other species' shells could be substituted; in Washington's Yaquina Bay, Willapa Bay, Fidalgo Bay, and Puget Sound, managers used Pacific oyster shells to encourage Olympia oyster settlement (Trimble et al., 2009; White et al., 2009; Dinnel et al., 2009). While initially successful in these reference sites, the use of another species' shells poses some issues for Olympia oyster restoration in Tomales Bay. First, using empty Pacific oyster shells could cause Olympia oyster recruitment to unintended locations where live Pacific oysters grow, subjecting the Olympia oysters to shallower depths, warmer water temperatures, and both native and invasive predators (Trimble et al., 2009). Other risks of non-native shell use include the spread of disease or parasites, an issue avoided through shell sterilization prior to submersion (McGraw, 2009); the risk and time-intensive processes associated with use of foreign shells strengthen the case for Olympia oyster shell use as added substrate.

When deciding whether to set spat or adult oysters on added substrate in Tomales Bay, the Sanctuary and TAC should defer to the expertise of Bodega Marine Lab researchers and those with experience in successful Olympia oyster restoration. Typically, restoration projects use one of the two strategies: adding substrate with adult oysters or planting lab-raised juvenile oysters (White et al., 2009). Many of the aforementioned reference projects in Washington and Oregon used oyster spat to some success, but this is a risk in Tomales Bay, as some of the potential restoration sites may not have spawning adults close by, a characteristic greatly encouraged by restoration managers to facilitate settlement (Brumbaugh et al., 2009; McGraw, 2009). Furthermore, the significant tidal flushing in the middle to outer bay regions could be problematic for the pre-settlement larvae (Kimbrow et al., 2009). Therefore, the Sanctuary should seek advice from knowledgeable researchers and experienced oyster restoration managers before proceeding further with substrate implantation and oyster settlement.

7.4.3 Management in the Tomales Bay Watershed

Targeting Erosion in the Watershed

To effectively manage sedimentation in Tomales Bay, the Sanctuary needs to look to the source of the issue. Livestock grazing and ranging erode the hill slopes and riparian corridors of the upper Tomales Bay Watershed; trampling and grazing removes the vegetation needed to anchor fine sediment and thus mass erosion occurs (King et al., 2010). The expanse and diversity in land ownership complicate riparian and watershed management, but collaborative efforts between the Sanctuary and agencies like the Regional Water Quality Control Board (hereafter RWQCB), Marin County Department of Public Works, California Coastal Commission and Point Reyes National Seashore to identify areas where erosion is most acute and promote better management practices could alleviate the sedimentation of both Tomales Bay and its contributing creeks.

Identifying areas in the uplands of Lagunitas and Walker Creek where livestock agriculture is most affective and erosive enables agencies to promote better land practices and restore riparian corridors. The Sanctuary, whose jurisdiction of the degraded downstream Tomales Bay merits its inclusion as one of these agencies, should work with the RWQCB and other Marin County land managers to rectify and restore the watershed

to stabilize sediment. Collaborative efforts should prioritize surveying along the riparian corridors of Lagunitas and Walker Creek to identify where poor land management causes sediment erosion. As much of the land in the Tomales Bay Watershed is privately held, the agencies will need to work with landowners to obtain permission to survey in these areas. Poor land practices include the lack of cattle fences or persistent grazing; without fences to contain livestock, the animals can graze along the creeks, removing riparian vegetation and destabilizing the creek's banks (Niemi and Hall, 1996). Both activities erode sediment into the water body, which eventually settles downstream in Tomales Bay. Landowners that contain cattle to one area of grazing for entire seasons or years, while preventing roaming cattle from directly entering riparian corridors, also contribute to erosion. The hillsides and pastures stripped bare from continuous grazing lack any vegetation to anchor sediment, so any storms or wind events force huge quantities of loose sediment downslope into the streams and creeks. Sites such as these require improved land management practices the Sanctuary and its partner agencies might promote: building cattle fences throughout the upper watershed and working with landowners to develop sustainable livestock practices.

In private rangelands whose property includes riparian corridors or a creek channel, the Sanctuary and its partners should work with landowners to build simple cattle fences to inhibit animals' mobility into these sensitive ecosystems. Doing so would continue the riparian zone's role as a filtration and catchment zone for sediment, nutrients, and other potential toxins from loading the creek (Laughlin, 2009; Smith et al., 2009). In regards to encouraging better rangeland practices on overused pastures, the participating agencies should determine which properties are large enough to allow livestock's alternation from one pasture to another to encourage vegetation regrowth. Outreach to those landowners to educate them on the issue of erosion and sedimentation might encourage these individuals to adjust their land practices to better protect the watershed and Tomales Bay.

The above management recommendations may require a cost analysis to identify the source of funding. The county, state, or even federal agencies may be responsible for some or all of the cost of constructing cattle fences on public lands, but this needs determination prior to proceeding. Furthermore, a determination as to the fiscal

responsibility for cattle fences on private land in the watershed is also necessary. Targeting erosion at its source in the upper Tomales Bay Watershed directly mediates sedimentation of the bay itself, and is the most effective strategy for a long-term solution to this problem.

Riparian Restoration

The watershed surveys recommended in Section 7.3.3.2 also determine where restoration of riparian corridors is necessary. To create pastures and ranges for livestock, land developers removed much of the vegetation in the upper Tomales Bay Watershed. Riparian buffer vegetation, as discussed in Section 4.3, provides invaluable ecosystem services in the form of nutrient cycling, sediment retention, and habitat provision. By removing these corridors, developers inadvertently degraded water quality. Loose soil and sediment from the upland as well as the stream banks eroded into the stream, altering the channel form and flow while also increasing the suspended particle load and water turbidity of the stream itself (Rooney and Smith, 1999). Furthermore, removing the riparian trees and shrubs along the creeks decreased the amount of shade available, thus warming water temperatures and inhibiting the survival of shade-dependent amphibians and fish species (Rooney and Smith, 1999). The significant loss of both habitat and ecosystem services that are so valuable to the health of both Tomales Bay and the Tomales Bay Watershed merits the consideration of riparian restoration projects.

To begin the restoration process, the Sanctuary and its partners should determine which riparian corridors in the Lagunitas and Walker Creek sub-watersheds could be effectively restored to a self-sustaining state. Surveys should be conducted throughout the upland and transport zones of both major creeks in the Tomales Bay Watershed to identify where riparian corridors could best catch eroding sediment and slow down sedimentation. In the upland and transport zones where rangelands and cattle significantly altered the landscape, constructing fences (as mentioned in Section 7.3.3.1) prevents livestock from entering the riparian vegetated zones along the creek banks; these now-protected areas could be first prioritized for revegetation or channel rectification. With the risk of grazing removed, riparian trees (willows or alders), shrubs and grasses could successfully reestablish and slowly recreate a riparian buffer zone. Managers could

recruit community-based volunteers and local conservation groups to assist with planting efforts, similar to the Green Gulch Creek restoration efforts as well as those in Redwood Creek (Laughlin, 2009). These projects emphasized the need for riparian restoration to improve upstream salmonid access from Tomales Bay (Laughlin, 2009), so a similar framework could be developed with Olympia oysters as the key benefactor.

In designing a riparian restoration project, the Sanctuary and its partners should collaborate with Point Blue Conservation Science (2015) and consider its “Climate-Smart Restoration Toolkit,” which includes a guide and checklist as to proceeding with revegetation (Point Blue Conservation Science, 2015). Because its jurisdiction pertains only to Tomales Bay, the Sanctuary may defer the planning and undertaking of riparian restoration to its partners or to the TAC; however, the benefits of restoration on both the bay and Olympia oysters call for the Sanctuary’s involvement. The sediment monitoring discussed in Section 7.3.3.1 is a good indicator of the degree to which revegetation is successful. Thus, a multi-agency and community-engaging approach to halting sedimentation of Tomales Bay and its watershed is most effective.

Total Maximum Daily Load (TMDL) for Sediment

Tomales Bay and one of its major tributaries, Walker Creek, are both listed as impaired water bodies for fine sediment pollutants under Section 303d of the Clean Water Act (TBWC, 2005; Laughlin, 2009). This means that fine sediment is a major pollutant significantly degrading the habitat quality and threatening biodiversity. The acute effects of and the unsuccessful attempts to curb the fine sediment suggest that legislative action and enforcement is now necessary. Violations of the Clean Water Act, of which Tomales Bay and its two major tributaries find themselves, require mitigation and cessation as soon as possible. The best tool available is a Total Maximum Daily Load, or TMDL (hereafter TMDL) (TBWC, 2005); this regulation could greatly reduce the amount of fine sediment so degrading to these water bodies and their inhabitants, including the Olympia oyster.

While long-term sediment accumulation studies in Lagunitas and Walker Creek are underway by the United States Geological Survey, little preventative action has occurred. There are several sediment-monitoring stations throughout the Lagunitas and

Walker Creek basins, which is an encouraging attempt to fill the existing data gap regarding sediment origin. However, after several years of monitoring there does not seem to be any forward mobility in TMDL development; the San Francisco Bay Regional Water Quality Control Board (RWQCB) lists Walker Creek as “under development” for sediment TMDLs, but a progress report or update on this TMDL development process cannot be found (Laughlin, 2009).

A TMDL for Walker Creek does not completely address the sedimentation issue: sediment is an offender for Walker Creek, Lagunitas Creek, and Tomales Bay, thus TMDLs are needed for each of these water bodies. Tomales Bay’s multi-agency jurisdiction, which includes the Sanctuary, could facilitate the development of a sediment regulation through direct appeal to the RWQCB. The negative effects of sediment on a federally protected estuary and its inhabitants, including Olympia oysters, merit closer investigation by the Sanctuary to determine if legal action should be taken by the Sanctuary against those parties responsible for significant volumes of this pollutant in the Watershed. However, it could be very difficult to pinpoint the sources, since mass erosion is both widespread and historical. Furthermore, the correlation between Tomales Bay’s water and habitat quality and its watershed indicate that interagency appeal and advocacy for stringent sediment TMDLs to the RWQCB is a worthy endeavor.

7.4.4 Conclusion

Fine sediment, a major pollutant of Tomales Bay and degrader of Olympia oysters, originates from large-scale events on the regional level, and this scale complicates efforts to mitigate it. However, using a location-specific focus to address sediment will facilitate its reduction and regulation. By targeting sediment in both Tomales Bay and at its source, the upland watershed region, managers can effectively recreate Olympia oyster habitat while also reestablishing lost riparian habitats upstream. Collaboration amongst those agencies with jurisdictional authority in the bay and the watershed is essential, so the Sanctuary might foster this relationship through the TAC or a subcommittee of that TAC.

Reducing fine sediment inflow into Tomales Bay ensures that future Olympia oyster restoration projects are as successful and thorough as possible. While formidable

in its spatial scale, sedimentation can be halted through interagency and community collaboration.

7.5 Recommendations for Invasive Species

7.5.1 Overview of the Issue

Two introduced, highly invasive species pose the greatest obstacle to Olympia oyster restoration in Tomales Bay. The Atlantic oyster drill and Japanese oyster drill, both of which are marine gastropods, arrived in Tomales Bay as hitchhikers; imports of Eastern and then Pacific oysters for commercial aquaculture inadvertently brought these predatory snails to Tomales Bay in the late nineteenth to early twentieth centuries (Williams, 2007). Both species of oyster drill thrived, particularly in the inner bay region, subsequently consuming any accessible sparse populations of Olympia oysters and displacing the native intermediate and top predators (Kimbrow, 2008; Jensen et al., 2007). Through predation and the interruption of trophic levels and cascades, the Atlantic and Japanese oyster drills negatively affect the abundance and fitness of Olympia oysters and the overall ecology of Tomales Bay. The oyster drills, as one of three major degrading factors, are the most acute in effect on Olympia oysters as well as the most inhibiting of restoration success. Fortunately, these invasive species are both easily identifiable and found in high concentrations in specific regions of the bay (Kimbrow et al., 2009), so addressing the issue is fairly straightforward.

There are two types of management approaches the Sanctuary and the TAC might take when addressing the invasive oyster drills: avoidance strategies or removal strategies. The first type of strategy, avoidance, is more of a mitigation measure than a permanent solution to the invasive species issue. By identifying those areas of Tomales Bay where oyster drill populations are most dense or abundant and avoiding them during restoration site selection, the Sanctuary could proceed with Olympia oyster restoration in other regions of the bay. The second type of strategy, removal, focuses on the source of the problem and aims to remove it from the bay, thus restoring Olympia oyster habitat thoroughly in both the short and long-term. Both avoidance and removal strategies could effectively lead to the reestablishment of oysters, but prioritizing removal tactics ensures more widespread and long-term success in Olympia oyster restoration.

7.5.2 Invasive Species Studies in Tomales Bay

Knowing where and in what abundance the invasive oyster drills infest Tomales Bay is essential data needed to proceed with Olympia oyster restoration. While some studies in inner Tomales Bay indicate that this region has the highest abundances of Atlantic oyster drills found in the bay, more data could support this finding and provide an opportunity to develop effective site-specific restoration plans. This data also provides the Sanctuary and TAC with the ability to choose to either avoid certain sites due to oyster drill presence, or remove them. The Tomales Bay Native Oyster Potential Restoration Sites Map and Site Evaluation Tool provide the means of obtaining accurate information about both oyster drill species in the bay.

To proceed with the survey process, the Sanctuary and the TAC should first use the Tomales Bay Native Oyster Potential Restoration Sites Map to identify and understand the general regions in the bay where physical conditions and jurisdictional boundaries most support Olympia oyster populations. This cartographic representation of the bay and its various layers are subjective, and hypothesize where more detailed population surveys and investigation into habitat quality are worthwhile. The map (and published literature) indicates that the oceanographic and biogeophysical conditions make the middle to mid-outer bay regions (that region within the first 14 km of the bay from the mouth) most ideal, so the Sanctuary and the TAC should then use the data-intensive Site Evaluation Tool to survey these regions for invasive impact on Olympia oysters in specific locations to evaluate this hypothesis.

The Site Evaluation Tool, the collaborative result of Olympia oyster conservation and restoration research lead by San Francisco National Estuarine Research Reserve and Elkhorn Slough National Estuarine Research Reserve, measures the risk of predation by oyster drills at a site (Wasson et al., 2014). In Tomales Bay, where drills are known predators of Olympia oysters but the range is uncertain (Kimbrow et al., 2009), measuring this risk provides strong support for the Sanctuary's decision to either avoid that site entirely, or remove the oyster drills to improve the habitat quality for restored oysters.

Subsequent sections examine the two approaches to address the degrading Atlantic and Japanese oyster drills: avoidance or removal. The Sanctuary and its advising committees and partners should carefully consider each approach to determine what is the

most cost-effective and time-effective method; long-term survival and recruitment by Olympia oysters, however, is the goal of any restoration work in the bay and thus should remain at the forefront when considering one approach over the other.

7.5.3 Restoration Approach: Avoidance

Similar to avoidance of sites with fine sediment or rapid sediment accumulation (discussed in Section 7.3.2.1), avoiding sites in Tomales Bay with high population abundances or densities of Atlantic or Japanese oyster drills could prove effective in restoring Olympia oysters. Studies published by Bodega Marine Lab researchers indicate that the inner bay region of Tomales Bay is highly infested with Atlantic oyster drills, and thus cannot realistically support Olympia oysters due to predation (Kimbrow et al., 2009). Therefore, the Sanctuary and TAC could identify such sites and avoid them entirely during the planning and implementation phases of oyster restoration.

To proceed, the Sanctuary and the TAC should use the Tomales Bay Native Oyster Potential Restoration Sites map to identify general regions with physical conditions and jurisdictional boundaries supportive of Olympia oyster populations. This cartographic representation of the bay and its various layers are subjective, and hypothesize where more detailed surveys and investigation into habitat quality are worthwhile. The map (and published literature) indicates that the oceanographic and biogeophysical conditions make the middle to mid-outer bay regions (that region within the first 14 km of the bay from the mouth) most ideal, so the Sanctuary and the TAC should then use the data-intensive Site Evaluation Tool to survey these regions for invasive species abundance, impact, and range. If site surveys and data indicate that the oyster drills are present, then the Sanctuary should avoid that area; the high rates of predation and absence of native top and intermediate predators render such sites inhospitable to Olympia oysters (Kimbrow and Grosholz, 2006; Kimbro et al., 2009). Avoidance enables the Sanctuary to begin restoration projects at other sites within Tomales Bay quickly.

If the Sanctuary decides to use avoidance strategies such as those discussed above, it should keep in mind that even thorough restoration projects do not always proceed as intended: Olympia oysters may settle or recruit in unpredictable patterns

despite strategic project placement. In Willapa Bay, Washington, project managers noticed that despite the addition of rocky substrate at sites with minimal invasive oyster drills, larval and juvenile oysters recruited to the freshwater areas of the bay (Trimble et al., 2009). This result could be because other physical conditions, such as water temperature, food availability, or preferred substrate attracted them more strongly to that region. If a similar reaction occurred in Tomales Bay, the Olympia oysters are at great risk of predation, as the freshwater inner bay supports a significant population of Atlantic oyster drills (Kimbrow et al., 2009). The possibility of unintended larval and juvenile settlement is one the Sanctuary and TAC should keep in mind if avoidance strategies are developed for restoration projects.

Avoiding the invasive oyster drills during restoration site selection and during the project implementation is a viable method, particularly if the Sanctuary does not have the partnerships or financial resources to facilitate oyster drills' removal. However, avoidance is a temporary solution and does not fully address one of the major degraders of Olympia oysters in Tomales Bay. Therefore it is highly recommended to target invasive species at their source and remove them to improve the success rate of projects and permanently rectify the degradation.

7.5.4 Restoration Approach: Removal

The goal of this document is to facilitate the restoration of Olympia oysters in Tomales Bay. However, other restoration efforts are necessary before the oysters can successfully retake their former role as ecosystem engineers in the bay. Those efforts include invasive species removal, an alternative to the avoidance strategies discussed in Section 7.4.3. Removing the Atlantic and Japanese drills eliminates the degrading problem at its source and thereby paves the way for more thorough oyster restoration projects as well as improves the ecological integrity of this estuary. Removal of the oyster drills includes the seasonal removal and destruction of their eggs, which is of greater priority and a more effective strategy than the removal of adult individuals (Ruesink et al., 2005). With its large volunteer network as well as its interagency partners, the Sanctuary is capable of planning and organizing the removal of the oyster drill eggs and adults through persistent seasonal efforts and monitoring. The subsequent

benefits of removing the two degrading invasive snails make such a management approach preferable due to the permanence and thoroughness of its outcome for both Olympia oysters and Tomales Bay.

There are two removal strategies the Sanctuary might undertake to reduce the populations of both oyster drill species in Tomales Bay: remove the fertilized eggs or remove individual adults. Both efforts are time-consuming, long-term projects that will require several years of collective efforts. However, removal is the most effective means of mitigating and hopefully eliminating these invasive species to create conditions more supportive of Olympia oysters. The removal process can be site-specific at those locations where restoration of oysters is planned, or as an ongoing effort throughout the bay. The TAC should advise the Sanctuary and its partners which of these options is the most viable. Because the invasive oyster drills' range in Tomales Bay is regional and not restricted to a few sites, their impacts on both Olympia oysters and the bay's food webs are widespread (Kimbrow et al., 2009). Furthermore, studies show that climate change and warming sea surface temperatures could expand the oyster drills' ranges and population sizes (Lord and Whitlatch, 2013). Therefore, bay-wide removal projects may be preferable to the Sanctuary.

The timing of removal projects depends on the reproductive cycle of female oyster drills. After spawning, female Atlantic and Japanese oyster drills lay fertilized egg capsules on rocky substrate in the spring and summer months. After one to two months, approximately 10 juvenile snails emerge from these egg capsules to feed (Cohen, 2011). The large clusters of eggs are easy to recognize by their vase-shape and leathery texture; the coloring varies from a translucent white in the Atlantic species to bright yellow in the Japanese species (Cohen, 2011; Lützen et al., 2012). Figure 8 shows these distinctive eggs as they appear after upon hard substrate.



Figure 10: The egg capsules of Atlantic oyster drills mid-development (Image courtesy of Andrew N. Cohen, Center for Research on Aquatic Bioinvasions; Cohen, 2011).

Removal efforts should target these egg capsules quickly after their deposition to minimize the possibility that juvenile snails hatch (Ruesink et al., 2005); ideally, the beginning of the egg laying season in spring. Groups of Sanctuary-organized and trained volunteers can recognize these eggs and their location (Cheng, 2014). These volunteers can then enter the rocky intertidal on foot during low tide events to remove the eggs. Those eggs located in the deeper subtidal may require the wearing of waders or possibly divers; the TAC and research partners should advise the Sanctuary as to proceeding with subtidal egg removal.

A second strategy to reduce the total number of Atlantic and Japanese oyster drills targets the adult individuals. Both species are easily recognizable and large enough for a human to pick up from exposed intertidal rocks, thus reducing numbers at a site. As with the projects targeting eggs, the removal of adult oyster drills can occur at either the individual restoration site-level or the regional level. Similarly, the same development of a Sanctuary-led volunteer team could take on this effort; it may, however, be more labor-intensive and costly than removing the seasonally present egg capsules. However, the year-round presence of adult oyster drills presents the Sanctuary with more opportunities to involve the community or partner organizations while slowly depleting the adult oyster drill population in Tomales Bay.

Total removal of the Atlantic and Japanese oyster drills will not be achieved in one or two years' worth of effort. This removal will be an ongoing process with unexpected setbacks; population explosions due to changing climate trends or limited access to infested sites are some of the possibilities that could frustrate the Sanctuary's efforts. However, persistent, long-term planning and adaptive management to keep ahead of the dynamics of invasive species removal will ultimately produce positive results.

7.5.5 Long-term Monitoring

Managing an estuarine invasive species, either through avoidance or removal, requires long-term monitoring as part of the restoration plan's framework. Long-term monitoring enables the restoration management plan to adapt and change as the physical conditions and invasive species' behavior change. Additionally, it identifies where data gaps or inexplicable events, such as the oyster drills' ranges, sudden population growth, or predation patterns, exist and require further investigation.

Currently, it is unclear why Atlantic and Japanese oyster drills settle in some regions of Tomales Bay rather than others with similar physical conditions (Kimbrow et al., 2009), so additional research needs to clarify this discrepancy. Similar clarification is needed to provide a picture of the oyster drills' range under elevated temperature or reduced pH conditions. Such research affects the reestablishment and survival of Olympia oysters and would therefore be useful to restoration managers. Both studies and Olympia oyster restoration could proceed concurrently; this pairing creates the possibility of reference and study sites and also gives the Sanctuary the opportunity to use avoidance strategies until more information is available.

Long-term monitoring is essential to gauge the success of oyster drill removal, during and after the project. Measuring the oyster drills' abundance and densities throughout the removal season as well as in the off-season gives the Sanctuary an idea of how successful its current efforts are and also provides opportunities to adjust the restoration plan (Kimbrow et al., 2009). Observing the reaction of Olympia oysters to the removal efforts is similarly useful information to have over several years.

The variability of restoration work requires flexibility from project managers, which is achievable through an adaptive restoration plan. To create and develop that

adaptive plan, long-term monitoring and data collection are necessary. In Tomales Bay, where invasive species significantly degraded both a foundation species, the Olympia oyster, as well as the ecological function of the estuary, long-term monitoring ensures that any removal or avoidance of these invaders is as successful as possible.

7.6 Recommendations Summary

The Olympia oysters of Tomales Bay endured degradation and limitation due to centuries of human activities. Therefore, it is the responsibility of humans to address and manage the degrading factors. As a federally protected estuary, Tomales Bay enjoys certain protections and restrictions against environmentally harmful activities, but violators like ocean acidification, sedimentation, and invasive species cannot be fined or cited. The only solution to their detrimental impacts is for the Sanctuary and its partners to target them at their sources.

The Sanctuary should consider these management recommendations because Tomales Bay and one of its imperiled native species are within the Sanctuary's scope of management. The Sanctuary is mandated with protecting the bay and its inhabitants; the Olympia oyster is a native foundation species whose presence improves the water quality and biodiversity of the entire ecosystem. Therefore, Olympia oyster restoration requires immediate consideration.

The general management recommendations and issue-specific recommendations require further cost analysis to determine what is possible and within what particular timeframe. However, the recommendations are realistic in their scope of work; interagency and inter-organization cooperation makes each of the efforts possible. The restoration of Olympia oysters in Tomales Bay will be a long-term process requiring frequent adaptation and reevaluation, but it is a goal that can be realized should the Sanctuary apply these recommendations to its management plan.

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Appendix A:
Tomales Bay Native Oysters
Potential Restoration Sites Map

Tomales Bay Native Oysters Potential Restoration Sites

Carolyn Gibson 2015

- Area of Interest
- Preferred Depth Range
- Preferred Substrate
- Seagrass Bed
- No-anchor Zones
- Aquaculture Leases
- NPS No-mooring Zone
- Mooring Zones
- CA Dept of Parks and Rec
- National Marine Sanctuary

