6. Responses in Marine Habitats

The study region is comprised of several habitat types (Fig. 6.1), with each affected in multiple ways by climate change – through influences on physical processes and conditions (see 3.0 Physical Effects of Climate Change), influences on biological processes (see 4.0 Responses in Biological Processes), and influences on biological populations that use a specific habitat (see 5.0 Responses in Marine Species). The following chapter synthesizes the possible changes that can manifest in each of the key marine habitats represented in the study region. While multiple environmental pathways influence each habitat, the response of a given species in this habitat occurs due to a combination of environmental change and changes in the populations with which this species interacts. However, little information is available for community-wide responses to climate change and additional research is needed in this area.

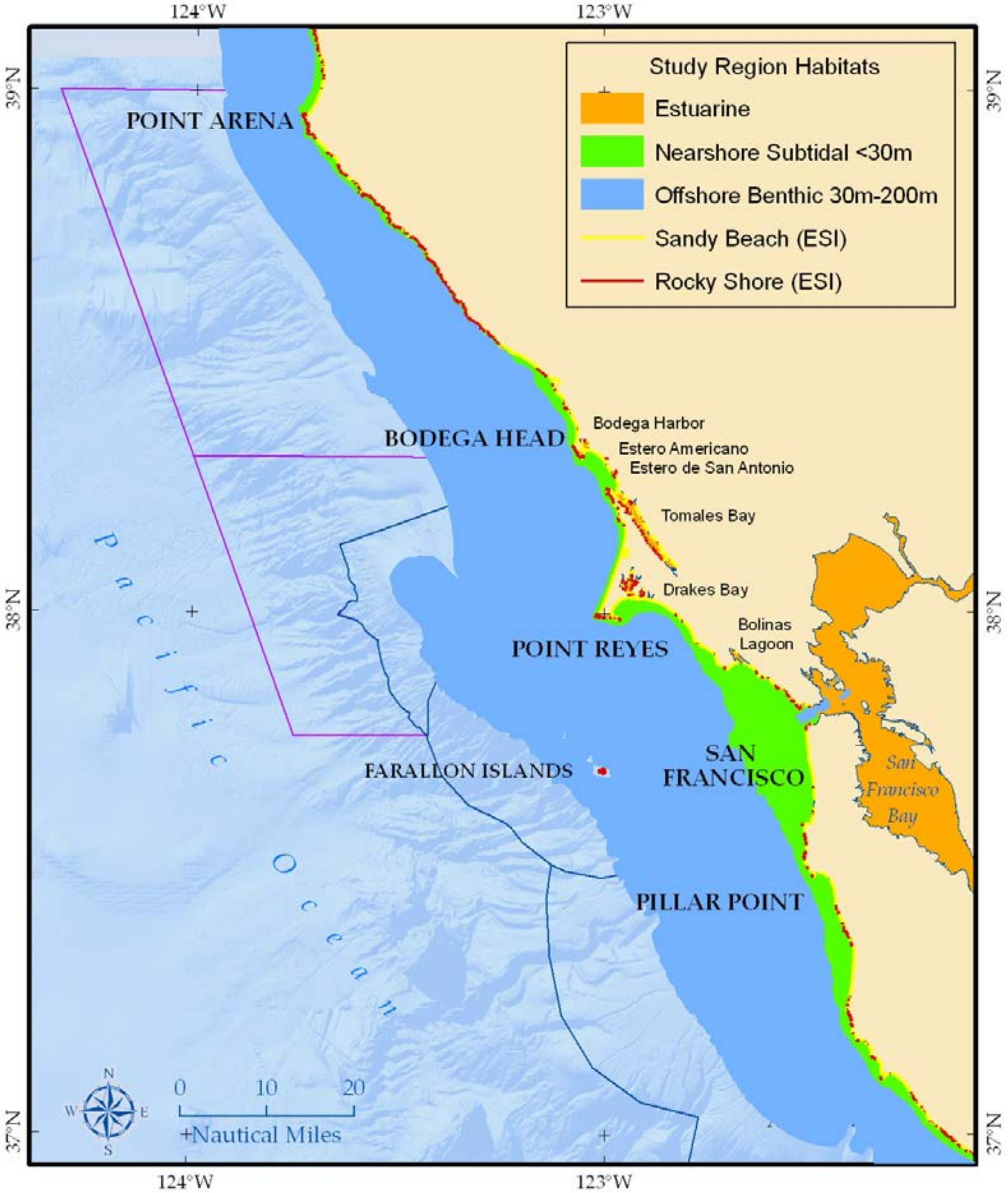

Figure 6.1. *Map of habitat types within the study region. Pelagic habitat is not shown as it overlaps the offshore benthic habitat, with "pelagic" referring to water column habitat and "benthic" referring to habitat associated with the seabed. T. Reed (2009).*

6.1 Pelagic Habitat

Pelagic habitat includes the entire water column from the sea surface to the seabed. This habitat is a highly heterogeneous and dynamic environment that results from small differences in water properties, which lead to patchiness in the distribution of primary and secondary production. The availability of nutrients and light are the main factors that determine the distribution of life in this habitat. Physical processes control the biological activity by means of a delicate balance between wind driven upwelling and stratification of the water column.

Temperature and Stratification: The global increase in ocean temperatures and the freshening of the Pacific Ocean act in the same direction and contribute to reduce mixing between the upper layer of the ocean and nutrient rich water just below the pycnocline (Bindoff et al. 2007). Although an increase in upwelling may offset the effect of surface warming over the shelf (see 3.3.3 Coastal Upwelling), an increase in stratification may also be seen in sheltered waters in bays. Increased water column stratification may lead to a major shift in phytoplankton communities in the region, as was observed in Monterey Bay between 2002 and 2004. Diatom abundance declined and dinoflagellate abundance increased concomitant with increased stratification (Pennington et al. 2007). Diatoms are generally associated with strong upwelling in the spring and summer, while dinoflagellates become more abundant during the “oceanic period” in the fall and early winter. Reduced atmospheric forcing during 2002-2004 and the presence of elevated nutrient levels in Monterey Bay (possible related to the enhanced upwelling observed along the open coast in the same years), led to a massive dinoflagellate bloom in areas with warm sea surface temperatures, highly stratified water column and shallow thermoclines. In the Bering Sea, elevated numbers of gelatinous zooplankton have been linked to warmer and more stratified waters (Brodeur and Terazaki 1999). Increased water temperatures lead to higher reproductive rates and extended growing seasons. These gelatinous organisms may become the dominant predators in altered ecosystems

Diet studies of common seabirds breeding on Southeast Farallon Island have shown major changes in the availability of juvenile rockfish. Diet studies on common murres (*Uria aalge*) have shown a decrease in juvenile rockfish (*Sebastes* spp.) during years with warm sea surface temperatures and/or warm (positive) PDO periods (Miller and Sydeman 2004). Similar findings were found for rhinoceros auklet (*Cerorhinca monocerata*) where the appearance of juvenile rockfish in the diet was higher in years with low sea surface temperatures (Thayer and Sydeman 2007). Trawl data from NOAA National Marine Fisheries Service shows similar results, particularly a sharp decline in juvenile rockfish in response to the warm-water conditions observed in the central California Current region in 2005.

Other Water Properties: Global ocean salinity in subpolar latitudes has decreased whereas in shallower parts of the tropical and subtropical ocean salinity has increased. The total inorganic carbon content of the oceans also continues to rise, resulting in more corrosive waters as shown by trends of decreasing pH over the last 20 years (Fig. 3.16). There is also evidence for decreased oxygen concentrations (see 3.6.5 Dissolved Oxygen), further lowering pH levels in the California Current (Feely et al. 2008) in addition to the reduced availability of oxygen in the water column. How these properties are chaging in the study region remains uncertain and improved observations are needed.

Upwelling: In years where alongshore winds were strong and began earlier in the spring, strong and early upwelling resulted in increased abundance of important zooplankton species (e.g., euphausiids and copepods). The increased abundance of these zooplankton species (specifically krill) during the critical breeding time of the Cassin's auklet resulted in above average breeding success of this species. The opposite of the above scenario occurs in years when alongshore winds are weak and/or delayed, which was characteristic of conditions in 2005 and 2006. Upwelling occurred later in the spring, causing reduced phytoplankton and zooplankton abundances in the region. The zooplankton community changed as well; not only did abundances of krill (adult krill, in particular) and copepods decline, but abundances of gelatinous zooplankton appeared to have increased. Due to the lack of available adult krill, Cassin's auklets abandoned nests and failed to breed in these years. The decline in adult krill in 2005 may also be related to decreased survival of Chinook salmon entering the ocean that year and low salmon returns in California in 2008. Sightings of blue whales (another krill predator) also dropped significantly from 2004 numbers (PRBO *unpublished data).* Drastic bottom-up effects in the ecosystem were observed and documented in a relatively short time period (July 2004 to August 2005), including low primary production, low krill abundance, a decline in at-sea seabird abundance, and late and reduced reproductive success in seabirds on the Farallon Islands (Jahncke et al. 2008).

6.2 Offshore Benthic Habitat


Figure 6.2 *Benthic community on Cordell Bank. Rick Starr/ CBNMS.*

Offshore benthic habitat (between 30 and 200 meters depth) encompasses a large area of the continental shelf between Point Arena and Año Nuevo and makes up the majority of the area protected by the Gulf of the Farallones and Cordell Bank sanctuaries. Benthic habitats can be grossly characterized as soft or hard bottom and each has a characteristic biological community (Fig. 6.2). Benthic communities are characterized by organisms that are attached or slow moving, and typically occupy small home ranges. This life history exposes these organisms to acute changes in physical conditions but also makes them vulnerable to changes over longer time periods as sedentary animals are unable to move out of an area as conditions change. The physical drivers that will most directly affect benthic communities offshore are changes in water properties (temperature, dissolved oxygen, ocean acidification) and regional winds (upwelling, transport). Benthic species within a community will respond to climate change in currently unknown and various ways depending on their tolerances of changes in temperature, oxygen and/or pH. Further research is needed to exaime how community structure may change depending on vulnerability levels of individual species.

Temperature: Water temperatures in this region may increase due to warming or decrease due to increased upwelling (see 3.6.1 Temperature and 3.3.3 Coastal Upwelling), perhaps increasing temperatures offshore while decreasing temperatures in upwelling centers. Benthic organisms that are unable to extend their geographic range as temperatures change will have to adapt or perish. If temperatures increase, then species with a center of distribution in higher latitudes may have a difficult time adapting as these species are at the southern end of their distribution and likely close to their thermal tolerance limits. In contrast, species that have their center of distribution to the south in warm temperate oceans will likely expand their distribution north as ocean temperatures warm. However, there are complex interactions between temperature and other physical parameters that will have synergistic and unpredictable effects on benthic communities (see 4.1 Physiology).

Dissolved Oxygen: When dissolved oxygen (DO) concentrations in coastal oceans fall to hypoxic levels, there are severe consequences for offshore benthic communities. The oxygen depleted water mass suffocates everything that cannot move out of the area resulting in a massive mortality event. Areas adjacent to upwelling centers like Point Arena are particularly susceptible to low DO levels as the upwelling process naturally delivers low oxygen water onto the continental shelf from the deep ocean. Currently the source for upwelled water is shallower than the Oxygen Minimum Zone (OMZ) (Grantham et al. 2004). An extensive OMZ exists along the continental margin of the northeast Pacific Ocean (Kamykowski and Zentara 1990). Recent work indicates that in the vicinity of Point Conception, the OMZ has shoaled by up to 90 meters (Bograd et al. 2008). Shoaling of the OMZ could lead to significant and complex ecological changes in the California Current System including direct hypoxia-related effects on benthic organisms where the OMZ contacts the continental margin (Levin 2003). If the OMZ were to migrate shallow enough to provide the source water for coastal upwelling, hypoxic events may be observed in this region and there would be severe ecological impacts (Bograd et al. 2008).

Ocean Acidification: Ocean acidification will add cumulatively to the stress of benthic organisms. Low-pH water becomes corrosive to a wide variety of marine animals including corals, sea urchins, and mollusks (Guinotte and Fabry 2008), and calcification rates are likely to decline (Gazeau et al. 2007). Decline in the biomass of plankton will also affect the deeper benthic communities but the implications to food webs are poorly understood. Shell-building pteropods and foraminiferans are key species at the base of ocean food webs that will be adversely impacted by increasing acidity (Fabry et al. 2008; Spero et al. 1997). Ocean acidification could also impact larval and juvenile stages of benthic organisms during the developmental phase of their early life history (Kurihara et al. 2007). Many species spend this part of their life in the water column as free-floating plankton.

Upwelling: Sessile benthic organisms depend on currents to deliver food. Any significant disruption to the timing or intensity of seasonal upwelling winds resulting in reduced productivity over time would have negative impacts on long term survival of benthic animals.

Transport: Many offshore benthic organisms that live in the California Current have early life histories linked to an annual production cycle driven by coastal upwelling. Most of these animals spend the first part of their lives as free-floating plankton, which facilitates dispersal, feeding and predator avoidance. If the timing or magnitude of seasonal winds driving coastal upwelling were to change significantly, it could reduce larval survival for many resident species.

6.3 Island Habitat

Anticipated changes in climate will significantly impact the physical habitat on offshore islands. Of particular concern are potential alterations to seabird and marine mammal breeding and resting habitat at the Farallon Islands, the largest seabird-breeding colony in the contiguous United States and an important breeding and haul-out area for marine mammals.

Sea Level Rise: Projected sea level rise off northern and central California has the potential to significantly alter island habitats and cause a redistribution of wildlife populations. Digital elevation models have demonstrated that a rise of 0.5 m would result in permanent flooding of 23,000 m^2 of habitat at the South Farallon Islands (PRBO *unpublished data*; Fig. 6.3). This represents approximately 5% of the island surface area and would include much of the intertidal areas where pinnipeds haul out as well as pocket beaches and gulches around the island. As a result, these areas would become inaccessible, forcing the animals to move higher up onto the marine terrace or to abandon the colony. This redistribution of pinnipeds would, in turn, impact seabird habitat by reducing the available nesting areas and causing the destruction of nest sites, particularly for burrow nesting species such as the Cassin's auklet (*Ptychoramphus aleuticus*). Furthermore, during extreme high tides and storm events, waves would be expected to extend higher still, leading to increased erosion, flooding, and loss of habitat.

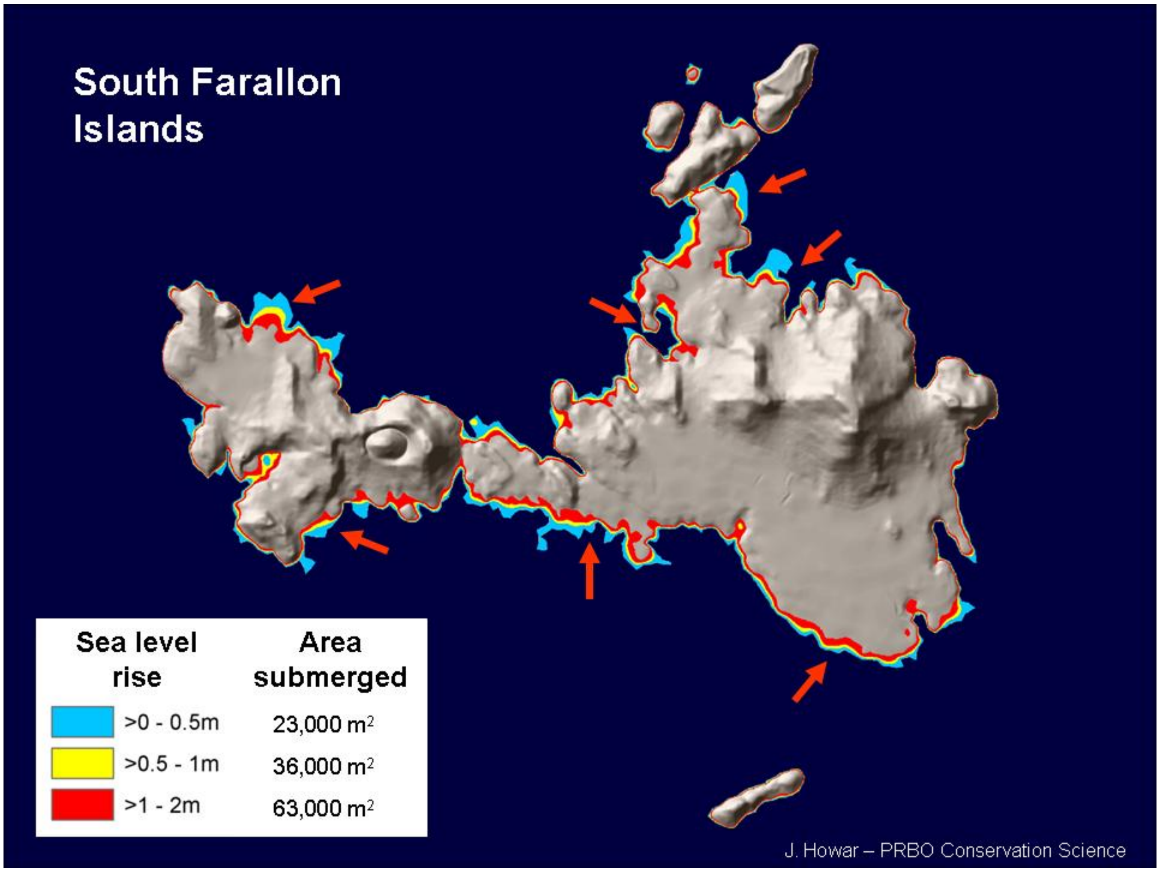

Figure 6.3. *Map of the South Farallon Islands showing the cumulative habitat area (in square meters) submerged by differing degrees of sea level rise relative to the average tide level. The arrows indicate major pinnipeds rookeries and haul out areas. J. Howar, PRBO Conservation Science.*

Examples of these changes can be seen during El Niño events when alongshore winds decrease and warm water floods into the area from the tropical Pacific, leading to higher sea level off the coast of California. During the El Niño events of 1983 and 1992, higher water and increased storm activity resulted in significant erosion of elephant seal (*Mirounga angustirostris*) breeding areas and the destruction of important beach access routes at the Farallones (Sydeman and Allen 1999). This in turn made it more difficult for them to access their primary breeding areas and led to local population declines and reduced breeding success (Sydeman and Allen 1999). The distribution of pinnipeds was also significantly altered during El Niño events, resulting in greater numbers of animals hauled out high on the marine terrace, habitat normally occupied by breeding seabirds (PRBO *unpublished data*). Similar consequences would be expected with rising oceans, particularly if coupled with more extreme weather events, which are also projected to occur as a result of climate change.

Precipitation: Intensified winter precipitation and more significant rainfall later in the season may alter physical habitat in many ways. Increased erosion of the hillsides can alter vegetation structure, increase the frequency of rockslides and degrade nesting habitat, particularly for species that rely on rock crevices such as auklets and storm petrels. Flooding of low lying areas on the marine terrace will also decrease suitable habitat for burrow nesting species and carry away the thin layer of soil in which they dig their burrows.

Air temperature: Average annual air temperature at the Farallones has exhibited an increasing trend over a 36-year period, from 1971- 2007 (PRBO *unpublished data*; Fig. 6.4). Given current predictions, PRBO scientists expect this trend to continue, leading to overall changes in the climate of the islands. While warmer temperatures would not necessarily alter the physical structure of the island, it may affect habitat by altering the vegetation structure on the island and facilitating the proliferation of more heat tolerant non-native species, such as grasses. Increasing air temperatures will also have important implications for island wildlife. Many of these species are adapted to cold and windy conditions and quickly become stressed when conditions change. During unusually warm weather, seabirds may abandon their nests, neglect dependent offspring, and die of heat stress (Warzybok and Bradley 2008). Marine mammals will spend less time hauled out and would be expected to abandon young in the rookeries if temperatures become too warm.

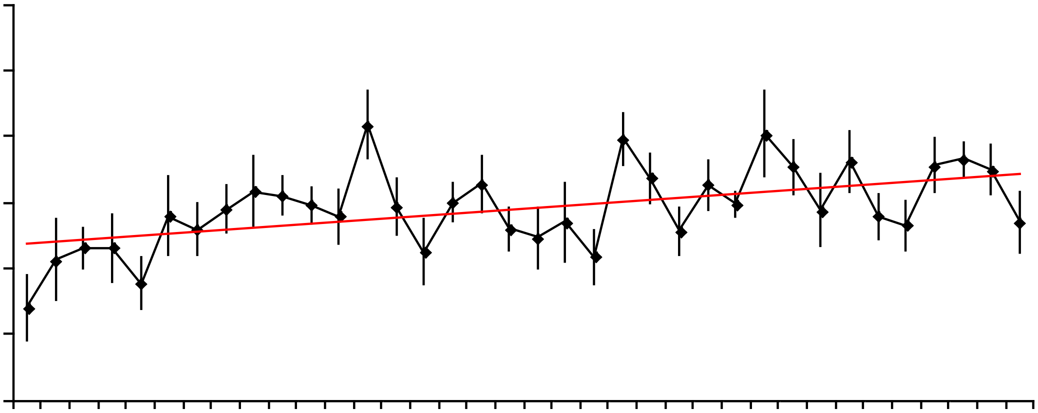

Figure 6.4. *Mean annual air temperature at the South Farallon Islands from 1971 to 2006. The red line illustrates the trend in the data. PRBO Conservation Science.*

6.4 Sandy Beach Habitat

Composed of unconsolidated sand from watersheds and coastal bluffs that is constantly shaped by wind, waves and tides, sandy beach ecosystems are strongly influenced by marine and terrestrial processes. The biodiversity and unique ecological functions and resources supported by sandy beach ecosystems are important to include along with their high socio-economic values

(Brown and McLachlan 2002; Schlacher et al. 2007). Ecosystem services and ecological values and functions of beaches and dunes in the study region include unique vegetation, rich invertebrate communities that are prey for shorebirds and fish, absorption of wave energy, the filtration of large volumes of seawater, nutrient recycling, and critical habitat for pinnipeds, declining and endangered wildlife, such as shorebirds, and a variety of threatened plants (McLachlan and Brown 2006; PWA 2008).

Figure 6.5. *Stinson Beach, CA. Golden Gate National Parks Conservancy.*

<u>Sea Level Rise and Erosion</u>: Sandy beach and dune habitats are increasingly squeezed between the impacts of human land development and manifestations of climate change at sea (Schlacher et al. 2007; Nordstrom 2000). Human alterations severely limit the ability of beach ecosystems to adjust to changes in shoreline stability (Clark 1996) as well as sea level rise and erosion caused by climate change. Sea level rise and other projected effects of climate change, including increased storminess, are expected to intensify pressures on these exposed ecosystems by increasing rates of shoreline erosion and retreat, and degrading habitat (Nordstrom 2000; Slott et al. 2006). In addition, the expected proliferation of shoreline armoring to protect upland properties can significantly degrade sandy beach habitats. Passive erosion associated with this armoring response effectively drowns beaches and shifts the sandy beach habitat zones downward on the beach profile, disproportionately affecting the mid and upper beach zones with resulting effects on biota, biodiversity and food webs (Dugan et al. 2008). Such biotic effects are projected to expand with sea level rise which will alter the position of existing armoring on the beach profile and act to increase the degree of interaction of these manmade structures with waves and tides (Dugan et al. 2008). Habitat loss, fragmentation, and alteration from sea level rise will have profound ecological implications, as beaches become narrower and steeper and as once continuous habitat in front of coastal bluffs and cliffs is converted to isolated pocket beaches. The type of responses of beach ecosystems to sea level rise and increased storminess associated with climate change are projected to be similar to episodic ENSO storm events (Revell et al. *in press*), although time scales will differ, especially where coastal land uses and development constrain retreat.

Ecological zonation on exposed sandy beaches is extremely dynamic due to the highly mobile nature of the sandy substrate, the intertidal animals and the resources on which these animals depend (McLachlan and Jaramillo 1995; McLachlan and Brown 2006). In general, three different intertidal zones inhabited by distinct groups of mobile animals are present on most exposed sandy beaches (McLachlan and Jaramillo 1995). These zones generally correspond to the: 1) relatively dry sand/substrate of the coastal strand and supra-littoral zone at and above the drift line; 2) damp sand of the middle intertidal; and 3) wet or saturated sand of the lower intertidal zone. Changes in the relative proportions and condition of these zones from the combined effects of sea level rise and coastal development can result in strong ecological responses that propagate up the food web (Dugan et al. 2008). The majority of prey biomass available for birds and fish on beaches within the study region is provided by intertidal invertebrates, such as sand crabs (*Emerita analoga*) whose populations can be strongly affected by storm-generated erosion and coastal evolution, as well as alteration of ocean currents delivering planktonic larvae. Another major prey resource on beaches in the region are the intertidal wrack consumers, such as talitrid amphipods (*Megalorchestia* spp.) and insects, whose populations and presence are strongly affected by erosion, storms and upper beach conditions as well by the availability and production of drift macroalgae from kelp forests and reefs, all of which are vulnerable to climate change effects. These invertebrates are also crucial to wrack processing and subsequent nutrient cycling on beaches (Lastra et al. 2008).

Sand Dunes: As with salt marsh and intertidal ecosystems, the supralittoral coastal sand dune vegetation communities will be affected by several climate change related processes. Sea level rise may force the landward retreat of these communities as inundation floods existing habitat (Feagin et al. 2005). Where coastal dunes are backed by development that blocks retreat, upland habitat for the colonization and persistence of dune vegetation may become increasingly limited, fragmenting this ecosystem further (Feagin et al. 2005). Changes in sediment transport dynamics may also contribute to a reduction of beach width, increased exposure of the dune to wave attack and the subsequent loss of dunes (see 3.5 Coastal Erosion). Sea level rise and reduced habitat can also disrupt the successional dynamics and coastal evolution that lead to the formation of mature coastal dune vegetation communities and biodiversity (Feagin et al. 2005). Changing climatic variables such as precipitation and salt spray may also affect the composition of these communities by modifying soil salinity, with subsequent effects on plant physiology (Williams et al. 1999; Greaver and Sternberg 2007).

Use of Habitat: Shorebird use of beaches can be high and has been positively correlated with the availability of invertebrate prey, the amount and type of macroalgae wrack, beach slope and beach width (Dugan 1999; Dugan et al. 2003; Dugan et al. 2004; Neuman et al. 2008; Revell et al. *in press*) in California, including shores in the study region. Birds of all types, including shorebirds, seabirds and gulls, have been shown to respond negatively to beach width and zone losses associated with coastal armoring (Dugan et al 2008). Threatened birds, such as the western snowy plover (*Charadrius alexandrinus nivosus*) and California least tern (*Sterna antillarum brownii*), nest in open beach and dune habitats on GFNMS shorelines (Lehman 1994, Page et al. 1995) making use of the dry sand zone, a habitat where erosive impacts from climate change will be strongly expressed.

Fish, such as the California grunion and smelt, also depend on these vulnerable uppermost intertidal zones of open sandy beaches for spawning, burying their eggs at the driftline for incubation in the region (Thompson 1918). Finally, pinnipeds, including elephant seals, sea lions, and harbor seals, pup and raise their young on sandy beaches, again using the upper beach zones within the study region, such as at Año Nuevo. Along with environmental drivers associated with climate change, evolution in beach and strand geomorphology, sediment dynamics, coastal and watershed perturbations, recreational activity and beach front development all affect these coastal ecosystems, the wildlife that depends on them, and the ecosystem function and services they provide.

6.5 Rocky Intertidal Habitat

Rocky intertidal habitat is characterized by complex environmental conditions that are driven by both aquatic and terrestrial forces (Fig 6.6). Of primary concern are possible increases in average water and air temperature as well as the prevalence of extreme conditions that can result in mass mortality of intertidal organisms. Also, the combined effects of ocean acidification and upwelling could have tremendous implications for the ability of intertidal organisms to produce shell as well as capture food. Upwelling will also affect the availability of nutrients for primary producers (plants and algae). Sea level rise and increased wave activity may also affect intertidal organisms, in some cases through interactions with other factors like elevated air temperature, although the outcomes of these processes are less certain. Three significant rocky intertidal areas within the study region are located at the Farallon Islands, Duxbury Reef, and Fitzgerald Marine Reserve.

Figure 6.6. *Rocky intertidal habitat in Gulf of the Farallones. Joe Heath.*

Temperature: Most rocky intertidal organisms are ectothermic ("cold-blooded") and are therefore sensitive to ambient temperatures. During a low tide, intertidal organisms can experience body temperatures as high as 40°C and as low as 10°C when the tide comes in (Denny and Wethey 2003). The temperature perceived by intertidal organisms is determined by apparent variables such as water and air temperature. However, temperature is also influenced by more subtle factors such as long-term tidal cycles, fog, wind speed, wave splash, and the spatial orientation of the organism in question. As such, studies evaluating the response of intertidal organisms to changes in temperature have generated complex patterns of how species will respond (Helmuth, 2002; Gilman et al. 2006). Moreover, temperature effects in the intertidal are dependent on an 18.6-year lunar cycle. For example, the emergence time for an organism in Monterey, CA can almost double depending on this lunar oscillation because the force exerted by the moon varies (Denny and Paine 1998; Helmuth et al. 2002). Working on intertidal California mussels, Gilman et al. (2006) found that body temperature was most sensitive to climate drivers at northern latitudes (including the study region) and also in those organisms living in the high intertidal zone. Increased temperature may also heighten the susceptibility of intertidal organisms to disease. Raimondi et al. (2002) found that increased warm water conditions associated with ENSO events may accelerate the development of withering foot syndrome in the black abalone, *Haliotis cracherodii.* Similar results have been found in farmed red abalone, *H. rufescens* that were raised in the lab at elevated temperatures of 18°C (Moore et al. 2000).

Many climate change studies of rocky intertidal communities have focused on the response of the California mussel *Mytilus californianus* (Fig 6.7) to climate change stressors. Mussels are a competitively dominant species that can decrease the diversity of other space competitors but also increase the diversity of organisms that live within dense mussel beds. Mussels generally appear to increase growth rates in response to increased water temperatures and increased food supply (Blanchette et al. 2007; Menge et al. 2008). Increasing temperature trends have been observed across coastal California and mussels may therefore exhibit increased growth. However, the production of phytoplankton for mussel consumption will depend on wind patterns and the transport of nutrients for phytoplankton growth.

Figure 6.7. *California mussel (Mytilus californianus). GFNMS Photo Library.*

In contrast, intertidal mussels may see population declines depending on the occurrence of extreme environmental conditions. Extreme heat waves have resulted in mass mortality events of California mussels and limpets (*Lottia scabra*) in the Bodega Marine Reserve (Harley 2008). Due to the timing of low tides, extreme heat events in the study region are most prevalent in the spring when low tides occur during the daytime when heat stress is greatest (Helmuth et al. 2002; 2006). Mussel mortality patterns are also related to predation rates by their primary predator, the ochre sea star *Pisaster ochraceus*. These sea stars set the lower limit of mussel beds in the intertidal throughout California and Oregon (Menge et al. 2004). Small changes in water temperature have been documented to greatly modify the rate of sea star predation on mussels (Sanford 1999). Cold upwelling waters decreased sea star activity whereas increased seawater temperatures increased sea star consumption. Thus, mussel susceptibility to predation will in large part depend on broad temperature trends (increasing predation) as well as upwelling conditions that can bring cool deep waters onto the rocky intertidal (decreasing predation).

<u>Ocean Acidification and Upwelling</u>: The effect of ocean acidification on the saturation state of surface waters is not fully understood (see 3.3.3 Coastal Upwelling and 3.6.2 Ocean Acidification). The effects of ocean acidification on intertidal habitats will probably be felt most intensely through upwelling events that will bring undersaturated deep waters to the surface (Feely et al. 2008). Undersaturated conditions decrease the ability of calcifying organisms to produce shells and may dissolve already existing shell structure while the organism is still alive. Upwelling will also influence the delivery of food (phytoplankton), nutrients (for algae and plants), and larvae to intertidal habitats.

Many rocky intertidal organisms produce calcium carbonate skeletons. Ocean acidification can make production of calcium carbonate structures more difficult as well as acidify internal body fluids (Doney et al. 2009). As of yet, no ocean acidification studies have been conducted on the mussels found within the study region. However, the closely related mussel *Mytilus edulis* exhibits decreased calcification rates with increasing aqueous CO_2 concentrations (Gazeau et al. 2007). Decreased abundances of mussels on rocky intertidal shores could thus create significant space for other species to attach to. Further, sea star populations may be forced to switch to other prey items in the absence of mussels, although it is not clear what species it could feed upon since other documented prey items are calcifiers as well.

Coralline algae are another dominant species within the sanctuary that will likely be affected by acidic conditions. In one of the few studies examining acidification effects on this taxonomic group, Kuffner et al. (2008) evaluated the response of crustose coralline algae, a widespread non-branching coralline alga (Fig. 6.8). Experiments revealed decreased recruitment and growth of calcifying coralline algae with increased growth of non-calcifying species. Reduced coralline algae abundance within the study region may create space for non-calcifying algal species to establish. Coralline algae dominate shallow marine habitats that have hard substrate and an abundance of herbivores (Steneck 1986).

Figure 6.8. *Crustose corraline algae (unidentified sp.). Steve Lonhart / SIMoN NOAA.*

Sea Level Rise: Intertidal organisms will respond to sea level rise by shifting their distributions to keep pace with rising sea level. It has been suggested that all but the slowest growing organisms will be able to keep pace with rising sea level (Harley et al. 2006) but few studies have thoroughly examined this phenomenon. As in soft sediment systems, the ability of intertidal organisms to migrate will depend on available upland habitat. If these communities are adjacent to steep coastal bluffs it is unclear if they will be able to colonize this habitat. Further, increased erosion and sedimentation may impede their ability to move.

Waves: Greater wave activity (see 3.3.2 Waves) suggests that intertidal and subtidal organisms may experience greater physical forces. A number of studies indicate that the strength of organisms does not always scale with their size (Denny et al. 1985; Carrington 1990; Gaylord et al. 1994; Denny and Kitzes 2005; Gaylord et al. 2008), which can lead to selective removal of larger organisms, influencing size structure and species interactions that depend on size. However, the relationship between offshore significant wave height and hydrodynamic force is not simple. Although local wave height inside the surf zone is a good predictor of wave velocity and force (Gaylord 1999, 2000), the relationship between offshore H_s and intertidal force cannot be expressed via a simple linear relationship (Helmuth and Denny 2003). In many cases (89% of sites examined), elevated offshore wave activity increased force up to a point (H_s > 2-2.5 m), after which force did not increase with wave height. Since many northern sites on the west coast of North America already experience wave heights of this magnitude, forces may not increase with increasing H_s. On the other hand, the remaining 11% of sites examined exhibited a positive relationship with H_s that did not level off (Helmuth and Denny 2003). At sites such as these, larger wave forces may accrue, as well as greater wave splash and ensuring modulated temperatures by means of chronic wetting. Also note that the above percentages reflect at least in part the spectrum of bathymetries represented in the sites examined, suggesting that a greater or lesser fraction of shores could be influenced by changes in wave height than implied in the analysis of Helmuth and Denny (2003).

Population Range Shifts: Forecasting changes in marine communities is limited because of the large number of complex interactions that can result from climate change (see 4.2 Range Shifts). Theory predicts that species will shift their ranges towards the poles in response to warming (Peters and Darling 1985). However this prediction is complicated by the fact that species not only respond to climate but they also respond to other species (e.g., predators, habitat-forming flora and fauna). For the purposes of evaluating climate change, it can therefore be useful to focus on the response of key species that have large roles in structuring marine communities. These species can form habitat for other organisms (e.g., foundation species such as mussels that provide structure and refuge for infaunal organisms, or kelp that support populations of many associated invertebrates). Alternatively, key species can be ones that have a large influence on populations of other species (consumers such as sea urchins or sea stars).

The vast majority of marine species have planktonic larval stages that may be subject to entirely different selective pressures than adults on the shore (Strathmann 1987). Correlations between adult habitat “suitability” and the abundance of adults across the range thus become complex. Many species exhibit abrupt shifts in density near range edges, raising questions about the applicability of simplistic climatic envelope models that assume that organisms are most abundant in the centers of their ranges (Sagarin et al. 2006). In this context, understanding that range boundaries can potentially be set by circulation patterns *per se*, rather than by thermal constraints or other conditions local to an intertidal habitat may become critically important (Gaylord and Gaines 2000; see 4.2 Range Shifts).

6.6 Nearshore Subtidal Habitat

The nearshore subtidal environment within the study region includes sandy continental shelf habitat as well as rocky reefs, which support kelp forest communities (Fig. 6.9). Primary climate change drivers of interest for nearshore subtidal habitats include changes in upwelling, stratification, ocean acidification, storm activity, and sea level rise.

***Figure 6.9.** Kelp forest community. Claire Fackler, NOAA/ ONMS.*

<u>Upwelling</u>: The direction of change in upwelling for the study region is uncertain, but either scenario (increases or decreases in intensity) will affect nutrient delivery to the nearshore subtidal. Increased nutrient availability in the nearshore may therefore benefit benthic macroalgae as well as phytoplankton. However, intensification of upwelling could also alter the strength of offshore transport, increasing the dispersion of larvae and spores released in the nearshore subtidal, as well as enhance turbulent mixing, thus disturbing food particle concentrations critical to larval survival (Bakun 1990; see 4.4 Population Connectivity).

<u>Stratification and Mixing</u>: Thermoclines have become stronger and deeper in offshore waters in the study region (Palacios et al. 2004; see 3.3.3 Coastal Upwelling) and a similar increase in stratification could be expected in sheltered bays (e.g., Monterey Bay; see 6.1 Pelagic Habitat). In offshore waters, stratification as a consequence of climate change has already been reported to change zooplankton communities in the California Current (Roemmich and McGowan 1995). In nearshore regions sheltered from the direct effects of upwelling, an increase in stratification would reduce nutrient delivery to surface waters and thus to subtidal habitats, as well as decrease offshore transport of larvae and spores. In Southern California, where stratification is observed during summer, nitrate availability limits kelp forest productivity (Zimmerman and Kremer 1984; 1986; Zimmerman and Robertson 1985), and if conditions in sheltered northern waters approached those found further south, it is conceivable that these important ecosystems could be significantly altered. Further, changes in horizontal mixing and transport is expected to occur with changes in upwelling and the associated mesoscale (10s-100s km) circulation, such as recirculation cells in the lee of headlands. Mesoscale features are important corridors between offshore and nearshore habitats. Climate moderates mesoscale circulation in the California Current System, thereby affecting nearshore-offshore connections (Keister and Strub 2008).

<u>Ocean Acidification</u>: The northern and central California coast is especially vulnerable to acidification because of upwelling, which transports acidified waters (under-saturated with respect to aragonite) from offshore onto the continental shelf, potentially reaching the coastal shallow subtidal (Feely et al. 2008). The acidified upwelled water may affect calcifying organisms utilizing the nearshore subtidal habitat (see 3.6.2 Ocean Acidification), although, unlike the rocky intertdal, few nearshore subtidal habitats in this region are dominated by calcifying organisms.

Storm Activity: Increasing significant wave heights will affect sediment redistribution and may change the coastal topography of the area. Increased storm activity may increase precipitation in this area, leading to greater freshwater input to the nearshore subtidal, including inputs from the San Francisco Bay outflow. An increase in terrestrial inputs as well as storm activity will lead to higher resuspension of sediment resulting in increased turbidity and light attenuation. Increased turbidity will compromise kelp growth. Increased storm activity may also move nearshore kelp forests into deeper water (Graham 1997) and create greater intra-annual variability in kelp productivity and abundance (Graham et al. 1997). Greater turbidity may compromise the growth and recruitment of some kelp species (e.g., *Macrocystis*) while promoting others (e.g., *Nereocystis*). For kelp forest communities on rocky reefs (which form a physical habitat for reef-associated species), increased storm activity may also increase dislodgement of kelp holdfasts resulting in a loss of physical habitat for kelp forest associated species (Seymour et al. 1989; Graham et al. 1997). Some of these effects may also be modulated by alterations in mean transport, perhaps tied to alterations in upwelling phenomena, through subtle interactions between waves and currents (Gaylord et al. 2003). The loss of kelp forests can have further effects due to their immense importance as subsidizing agents to other communities. Dislodged kelp biomass serves as a critical food resource both to deep-water ecosystems as well as for intertidal and (in particular) beach fauna (ZoBell 1971; Harrold et al. 1998; Vetter and Dayton 1999; Colombini and Chelazzi 2003).

Sea Level Rise: Sea level rise will affect kelp forest communities on rocky reefs in the nearshore subtidal (Graham et al. 2003, 2008). Increased sea level will decrease light availability to sessile macroalgae and cause a shoreward migration, which will depend on available rocky substrate at shallower depths. Sea level rise may also change the shape of the coastline and substrate composition (i.e., rocky vs. sandy shores; Graham 2007), and thus impact the availability and living conditions of macroalgae and their associated species.

6.7 Estuarine Habitat

The physical structure of estuarine habitat is likely to undergo significant changes in the face of changing climates. Sea level rise is among the most important climate change factors forcing changes in the physical structure of estuarine systems in the coming decades. Other factors such as increasing air and sea surface temperatures and CO_2 may interact with sea level rise to influence the physical environment of these habitats. Climate change is also projected to result in changes in oceanographic and atmospheric linkages resulting in changes in ocean currents and storm cycles that will likely influence estuarine geomorphology. Finally, the hydrological cycle, including rainfall and outflow from rivers into estuaries will also influence the transport and deposition of sediments with long-term consequences for the physical structure of California estuaries.

Figure 6.10 *Left: Bolinas Lagoon, CA. GFNMS Photo Library. Right: Tomales Bay, CA. Brad Damitz NOAA/GFNMS.*

Sea Level Rise: Despite the certainty of rising sea levels, much uncertainty surrounds the long-term effects of sea level rise on the physical habitats of estuaries. Many other factors can potentially interact with climate change to influence the rates at which tidal elevation is altered and consequently the extent to which estuarine habitat is lost. For instance, increasing inundation may be offset by increased rates of inorganic sediment deposition (Friedrichs and Perry 2001). Also, increasing CO_2 levels may also result in greater production of C_3 plants thereby increasing rates of organic deposition (Morris et al. 2002; Körner 2006). However, this increased deposition could, in turn, be offset by increased freshwater intrusion, which can increase rates of decomposition (Weston et al. 2006). In particular, estuarine habitats more dependent on organic rather than inorganic deposition may be more subject to the influences of changes in sea level (Stevenson et al. 1986). Sediment supply remains an important if not completely understood indicator of wetland and estuary resiliency.

An important factor that will influence estuarine response to sea level rise is the ability of estuaries to migrate where the upland border abuts roads, levees or other armored structure or by natural steep slopes or bluffs. This upper border may result in an accelerated loss of habitat as has been demonstrated for sandy beaches (Fletcher et al. 1997; Dugan et al. 2008). It also may severely limit the upland migration of estuarine plants and animals as rising sea levels inundate lower tidal elevations (Dugan et al. 2008). Areas where estuarine upland borders are partly or entirely surrounded by armored structures or by bluffs and slopes are therefore significantly at risk of habitat loss.

Coastal lagoon habitat types, such as those occurring in Bolinas Lagoon (Fig. 6.10), have been modeled in detail (PWA 2006). Each estuarine habitat type will respond differently based on the overall response of the individual systems. Brackish and salt marsh estuarine habitats are likely to be exposed to salt water more frequently and at higher elevations. This expansion of subtidal wetlands will increase the area for wind wave formation potentially accelerating erosion along the marsh edges. Along estuaries with unarmored barrier spits (e.g., Drakes Estero) overwash events will be more frequent, depositing sediment on the inland side of the spit. These overwash deposits generally form small deltas, which over time can result in a “rollover” of the spit, or landward migration of the entire spit toward the mainland. This “rollover” may reduce the tidal prism and flushing characteristics of the lagoon and potentially lead to changes in frequency and duration of breaching events. In estuaries unconstrained by development, infrastructure, and landscapes, the wetland habitats will likely migrate inland and upward to remain in balance. However, in locations where development, infrastructure, and landscapes constrain or border wetlands, intertidal wetlands habitats may be lost as indicated above.

Among the most sensitive species to sea level rise in estuarine habitats are shorebirds, because of their dependence on exposed intertidal mudflat habitats for foraging. Studies of restoration planning efforts have shown the importance of tidal elevation for maintaining populations of foraging shorebirds (Stralberg et al. 2008; Goss-Custard and Stillman 2008). Other studies have indicated that sea level rise may have negative effects on foraging budgets of individual shorebirds and influence choice of foraging habitats, such as movement from bays to outer coast areas (Durell et al. 2006, Goss-Custard and Stillman 2008). Sea level rise is also likely to strongly influence the plant and animal communities of the nearshore benthos (Scavia et al. 2002).

Freshwater Input: Estuaries with regular and substantial inputs of freshwater may be influenced by changes in watershed outflow (Kimmerer 2002). Predictions for much of California suggest that the amount of water entering estuaries will have increased interannual variation (Cayan 2008). However, equally influenced may be estuaries where the outflow and connection to coastal marine waters may be seasonal or intermittent (Largier and Taljaard 1991). These 'bar-built' estuaries, which include Estero Americano and Estero de San Antonio in GFNMS, are strongly influenced by the creation of sandbars that are in turn affected by changes in the magnitude and variability of runoff (Kensch 1999).

Changing patterns of precipitation and consequently outflow may have significant affects on the biota of estuaries as well (Kimmerer 2002). Predictions for much of California suggest increasingly interannual variability in rainfall and outflow patterns (Cayan et al. 2008). Current predictions suggest that these increasingly variable flows may favor the invasion of coastal estuaries by invasive species. These changing patterns of outflow will mean that there will also be increasing changes in the salinity gradient with substantial consequences for estuarine biota. Increasing storm activity will also potentially alter estuarine geomorphology due to greater transport of sediments into estuaries from both ocean and watershed sources (Hoyos et al. 2006; Day et al. 2008). Storm activity will interact with other cyclic phenomena, such as the El Niño-Southern Oscillation and the Pacific Decadal Oscillation, to influence estuaries in complex ways (Day et al. 2008).

Temperature: Increasing water and air temperatures are magnified in estuaries relative to the outer coast and are important drivers of community and ecosystem responses in estuaries. Increasing water temperatures can result in the range expansion of both native and non-native species into new areas (Williams and Grosholz 2008), and can have significant demographic effects as well. For instance, temperature increases have been responsible for the disappearance of the marine bivalve, *Macoma balthica,* in Northern Spain. Common in study region mud flats from San Francisco Bay north, the Baltic clam experienced elevated temperatures in Northern Spain, (> 30^0C) increasing metabolic rates and resulting in eventual starvation. M. *bathica* disappeared from the northern Spanish coast because of increasing summer maxima during past decades (Jansen et al. 2007). The impacts of increasing water temperature on intertidal plants can affect desiccation stress and may interact with nutrient dynamics, tolerance to soil conditions and recruitment from seed vs. vegetative growth (Levine et al. 1998). Increasing temperatures may also alter interactions between marine plants and their herbivores (O'Connor 2009). In addition, increased temperatures may generally put greater stress on plants and animals and magnify problems with parasites and pathogens. For instance, Poulin and Mouritsen (2006) found increasing evidence that parasites such as trematodes are extremely sensitive to temperature increases of less than four degrees Celsius, causing amphipod population crashes. Relatively small perturbations may translate into large alterations of mud flat communities.

Ocean Acidification: Ocean acidification may adversely affect estuaries because they are subject to freshwater input that lowers buffering capacity as well as intrusion of upwelled waters from the adjacent coastal ocean. Increasing atmospheric CO_2 will also disproportionately influence C_3 plants (Mayor and Hicks 2009). Current studies from experimental CO_2 enrichment arrays show that increasing levels of CO_2 can influence the relative above and below ground growth of plants and favor C_3 plants relative to C_4 plants. Long-term studies have not found that these effects continue without the expected effects of nitrogen limitation. In addition, the additional production may increase the role of estuarine plants as a carbon sink with implications for the future carbon budgets (Mayor and Hicks 2009).

Ocean acidification will likely cause serious and unknown effects in mud flat community structure. Alvarado-Alvarez et al. (1996) found at a pH of < 8.5 the Pismo Clam (*Tivela stultorum*) had decreased fertilization and embryo development rates. Similarly, Green et al. (2004) found that the clam *Mercenaria mercenaria* showed juvenile shell dissolution leading to increased mortality at aragonite saturation states of 0.3 (Ω_{arag}). The authors found that the removal of the surface layer would expose the reduced organic rich deposits to oxidation resulting in reduced pH and carbonate undersaturation. Shell dissolution is a recognized source of mortality for juvenile bivalves and has serious implications as populations can be modified by thermodynamic conditions encountered by juveniles (Gosselin and Qian 1997). Freshwater inundation could also lower the pH of estuaries by reducing the buffering capacity of estuaries with lower salinities, higher organic inflows and more acidic freshwater. These are conditions found in Tomales Bay (Smith and Hollibaugh 1997; Marshall et al. 2008).

Transport: Finally, climate change is likely to alter linkages between atmospheric and oceanographic forces resulting in changes in upwelling, coastal advection and variety of processes influencing the transport of organisms within and between estuaries (Gawarkiewicz et al. 2007). These changes in coastal ocean transport processes are likely to result in changes in the frequency or magnitude of delivery of plankton and various larval and adult dispersal stages among estuaries (Harley et al. 2006). Therefore, the degree of connectivity among populations and communities, both from a population genetic and a population dynamic perspective, are likely to be altered with unknown consequences.

Figure 6.11 *Mudflats in Tomales Bay, CA. Dan Howard.*

Mudflats: Estuarine mud flats, in contrast to other intertidal soft sediment habitats such as sandy beaches, cannot develop in the presence of wave action and need a source of fine grain sediments (Lenihan and Micheli 2001). Mud flats are located in partially protected bays, lagoons and harbors. Examples within the study region include: Pillar Point Harbor, Bolinas Lagoon, Esteros Americano and de San Antonio, Tomales Bay (Fig. 6.11) and Bodega Bay. Mud flats will be threatened by sea level rise, ocean acidification, organic loading and sea surface temperature change. Low lying muddy shores are most vulnerable to sea level rise with accompanying stronger tidal currents, wave action and changes in salinity. This will result in sediment starvation, erosion and the eventual loss of this coastal ecosystem (de la Vega-Leinert and Nicholls 2008; Lebbe et al. 2008; Callaway et al. 1997). Mud flats with hypsometric characteristics (an extensive intertidal area and a restricted inlet) will be particularly sensitive to sea level rise (French 2008). Deteriorating sediment conditions are thought to be responsible for declining recruitment success in Wadden Sea cockles (Beukema and Dekker 2005). Salt water inundation will cause vegetation changes as more saline water replaces brackish and fresh water (Callaway et al. 2007). For example, at Pillar Point, this would impact the upstream brackish water cattail (*Typha* spp.) and freshwater willow (*Salix* spp.) marshes.

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Cover

1) Wave breaking at Maverick’s, Half Moon Bay, CA. Josh Pederson / SIMoN NOAA; 2) Krill: *Euphausia pacifica*. Matt Wilson/Jay Clark, NOAA NMFS AFSC; 3) Bottlenose Dolphins: *Tursiops truncatus*. NMFS Southwest Fisheries Science Center.

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