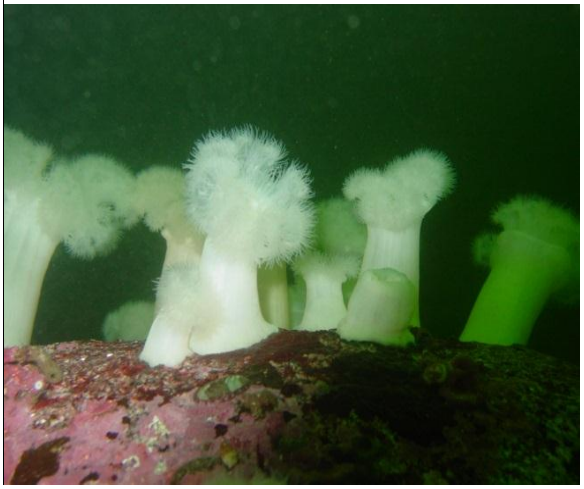
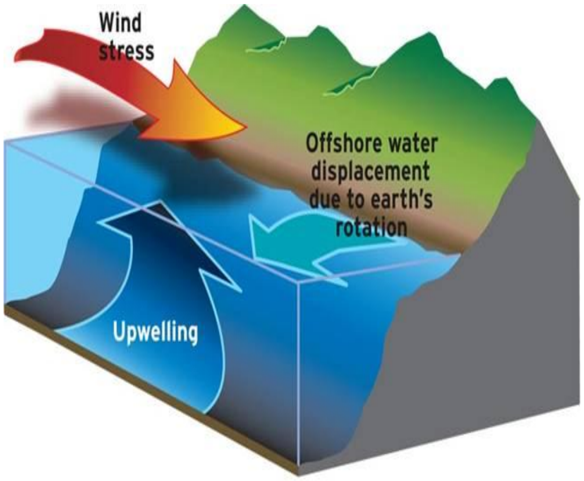
CONCEPTUAL MODELS AND INDICATOR SELECTION PROCESS FOR WASHINGTON STATE'S MARINE SPATIAL PLANNING PROCESS





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CHAPTER 1. CONCEPTUAL MODEL OF WASHINGTON STATE'S MARINE ECOSYSTEM

CONCEPTUAL MODEL FRAMEWORK

In March 2010, the Washington State legislature enacted a new state law on marine spatial planning (MSP; Substitute Senate Bill 6350). One of the primary objectives of this law was to develop a comprehensive marine management plan for the state's marine waters. The law stipulated that the "plan must include an ecosystem assessment that analyzes the health and status of Washington marine waters including key social, economic, and ecological characteristics. This assessment should seek to identify key threats to plan goals, analyze risk and management scenarios, and develop key ecosystem indicators."

In support of Washington State's MSP process, this chapter develops a conceptual model that describes the important ecological components, oceanographic drivers, and human pressures in Washington State waters. For the purposes of this report, "Washington State waters" refers to waters and habitats that will be included within Washington's marine spatial planning boundary, not the 3-mile state territorial sea boundary. The conceptual model will serve as the basic framework for the development of ecosystem indicators and assessing the health and status of Washington marine waters. In this report, we focused on non-human ecological components, oceanographic drivers and human pressures. Future research will focus on integrating social, economic and cultural characteristics into the conceptual model.

We organized the conceptual model of Washington State waters according to major types of habitat found along and off the coast. These habitats were derived primarily from the Washington Department of Fish & Wildlife's (WDFW) "State of the Washington Coast" and the Olympic Coast National Marine Sanctuary's (OCNMS) "Condition Report". The WDFW categorizes the Washington coast into four major physical habitats: estuaries (Grays Harbor and Willapa Bay), sandy beaches, mixed substrates, and rocky shores. On the outer coast 210 km consist of sediment flats or beaches, 118 km consist of mixed substrates such as cliffs or platforms with gravel or sand beaches, 60 km are rocky shores (all in the northern reaches of the Coast), and 5 km are man-made. The OCNMS categorizes habitat within the sanctuary into five habitat types: intertidal zone, kelp forests, rocky reefs, open ocean, and the seafloor.

For this report, we developed conceptual models based on five habitat categories (Table 1): rocky intertidal shores, sandy beaches, kelp forests, seafloor, and the pelagic zone. Due to time limitations, we did not include the coastal estuaries, the Strait of Juan de Fuca, or Puget Sound. A conceptual model of coastal estuaries (e.g., Willapa Bay, Grays Harbor, and the Columbia River estuary) will be developed at a later date. Conceptual models and indicator development for the Puget Sound ecosystem and the Strait of Juan de Fuca has been the subject of much research by the Puget Sound Partnership and should be incorporated into Washington's marine spatial planning process.

Table 1. General characteristics of habitat types used to develop a conceptual model of Washington State marine waters.

Habitat type	**General extent of habitat**	**Definition**
Rocky intertidal shores	Outer coast north of Point Grenville	Rocky or mixed intertidal shorelines.
Sandy beaches	Outer coast south of Point Grenville	Sandy intertidal shorelines.
Kelp forests	Outer coast along the north	Kelp forest habitats and rocky reefs <60m deep.
Seafloor	Seafloor habitats throughout Washington State waters.	Benthic communities >60m.
Pelagic zone	Water column habitat throughout Washington State waters.	Pelagic offshore waters.

For each habitat type, we created a conceptual model of the important ecological components, oceanographic drivers, and human pressures. These models describe the key food web connections and drivers and pressures responsible for the general dynamics of each ecosystem. We begin with a general overview of the oceanography that affects the Washington Coast and is generally applicable to all habitat types. We then go through each habitat and describe the components in each conceptual model.

GENERAL OCEANOGRAPHY AND PHYSICAL DRIVERS OF WASHINGTON STATE WATERS

CURRENTS

The waters off Washington's coast are located near the northern edge of the California Current Large Marine Ecosystem (CCLME). The Washington Coast is subject to the complex and seasonally variable current patterns of the California Current System (Hickey and Banas 2003). Circulation patterns are dominated by strong alongshore winds and the narrow continental shelf. West of the continental shelf break, a southward current (the California Current) dominates year round (Fig. 1). The California Undercurrent flows northward over the continental slope and supplies most of the nutrient-rich water that

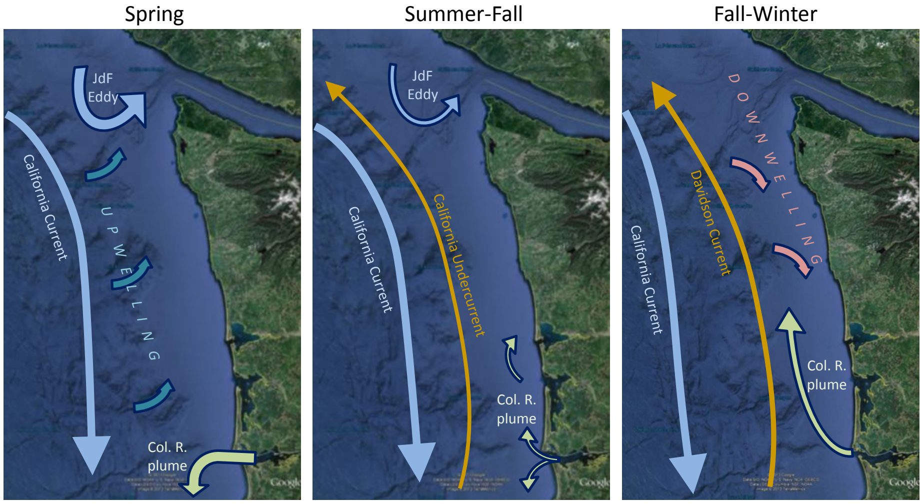

Figure 1. Prevailing currents off the Washington Coast and the influence of the Juan de Fuca eddy and Columbia River plume.

reaches the waters over the shelf during summer upwelling conditions. In fall and winter the Davidson Current flows northward over the continental shelf and slope, along with a southward undercurrent.

UPWELLING

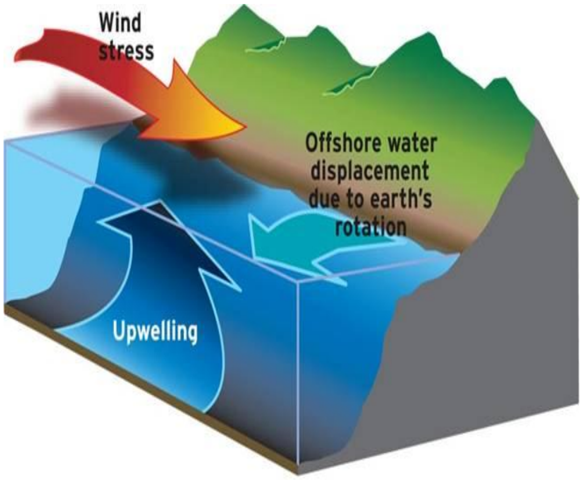

Figure 2. Schematic of upwelling forces (Northwest Fisheries Science Center).

The California Current is an eastern boundary current system largely driven by upwelling forces. A rapid change from northward-dominated winter currents to southward-dominated summer currents, known as the spring transition, signals the onset of the summer upwelling season. In the spring and summer, winds generally accelerate surface currents southward and offshore, bringing cold, salty, nutrient-rich water to the surface and spreading fresher water from coastal estuaries away from shore and towards the south (Fig. 2). The nutrients brought up into the photic zone (the upper portion of the water column where sunlight penetrates) nourish the planktonic base of the coastal food web. However, during storms or other periods of northward winds the currents (especially those closer to shore) are generally reversed, the system switches into downwelling, and plumes of fresh water tend to be pushed back towards the shore. Consequently, phytoplankton blooms form during upwelling events, but are pushed back towards shore during storms. In summer, local sea levels and currents are also strongly affected by coastal-trapped waves (water movements resulting from a complex interaction of shelf slope, wind, and the water's angular momentum) generated as far away as central California (Skewgar and Pearson 2011).

Upwelling is critically important to productivity and ecosystem health in the CCLME (Huyer 1983) and this link occurs on seasonal, annual, and interannual scales (Chavez et al. 2003). Upwelling in the central-northern CCLME occurs in two distinct seasonal modes (winter and summer), with certain biological processes being more sensitive to one or the other (Black et al. 2011, Thompson et al. 2012). The strength and duration of upwelling in the CCLME is highly variable, and is forced by large-scale atmospheric pressure systems. More specifically, the pressure gradient between the oceanic North Pacific High and continental Low situated over the southwestern United States drives upwelling-favorable northerly winds. The interaction (friction and Coriolis force) of the northerly winds and the water surface moves water offshore in the surface layer, and this water is replaced by water upwelled from depths of greater than 50 - 100 m. The upwelled water is cooler, saltier and higher in nutrient concentrations than the surface water it replaces. The onset and duration of the upwelling season varies latitudinally, starting earlier and lasting longer in the southern CCLME (Bograd et al. 2009).

EDDIES AND PLUMES

Ecologically important mesoscale (10-500 km) features such as eddies or plumes are formed by interactions between currents and coastal headlands and submarine canyons, or by intrusion of fresh water. The changes in flow patterns that occur with such features can greatly affect upwelling of nutrients, with correspondingly large effects on phytoplankton and zooplankton retention and growth rates.

The Juan de Fuca Eddy (Fig. 1), located off the coasts of northern Washington and southern Vancouver Island, British Columbia has been identified as a site of high phytoplankton biomass (Trainer et al. 2002), elevated primary productivity (Marchetti et al. 2004), and enhanced higher trophic level biomass (McFarlane et al. 1997). This eddy forms in spring and dissipates in fall, shows up in satellite imagery as a consistent area of low sea surface temperature (MacFadyen and Hickey 2010), indicating sustained upwelling. Nutrients are high in the eddy, due to wind- and topography-driven upwelling from submarine canyons, and water from the eddy periodically moves to the Washington Coast, sometimes carrying toxic algae (MacFadyen et al. 2005, Trainer et al. 2009, Skewgar and Pearson 2011).

The Columbia River plume is a major oceanographic feature that brings buoyant freshwater to the Washington Coast, along with sediment, nutrients, carbon, and particulate organic matter that fuel productivity along the outer coast. The Columbia River plume also modifies coastal currents, affecting residence times and transport along the shelf, with biologically important consequences for plankton and larval fish (Simenstad et al. 1990). As well-defined fronts develop between the plume and oceanic surface waters, increased zooplankton biomass provides valuable foraging grounds for planktivorous fishes, including juvenile salmonids as they transition from freshwater to the ocean (Morgan et al. 2005). The plume is frequently over the Washington shelf in both summer and winter when prevailing winds slacken or reverse (Fig. 1), and although terrestrial nutrients are usually depleted in the estuary in summer, mixing during upwelling provides nutrients to the photic zone (Hickey et al. 2005). At times, a strong front along the seaward side of the plume can inhibit the shoreward movement of patches of toxic algae, preventing accumulation of harmful biotoxin levels in razor clams and other harvested species. The combination of mesoscale features and coastal trapped waves on the Washington coast create mixing and upwelling and make primary productivity higher than would be expected from local wind stress values (Hickey and Banas 2008).

At a smaller scale, counter currents and eddies shape water movements that are much harder to predict and model. These smaller features, however, might prove particularly important in the case of an oil spill, determining whether or not the spill reaches vulnerable biological resources.

CLIMATE CHANGE

Increases in atmospheric CO_2 continue to put pressure on marine ecosystems through warming of the oceans and increasing the acidity of ocean waters. These changes alter the large-scale atmospheric forcing patterns creating more variable weather patterns across the globe. We briefly describe general impacts below in terms of changes in sea surface temperature and ocean acidification. Each of these drivers/pressures will affect the communities of each habitat in Washington State waters to various degrees.

SEA SURFACE TEMPERATURE

Temperatures in the CCLME vary at multiple time scales: seasonally due in large part to upwelling, inter-annually due to broad scale forcing, and at the broadest scales due to anthropogenic climate change. Upwelling timing and strength greatly influences the CCLME through productivity and temperature changes, and many species are thermally limited directly (Song et al. 2012) or indirectly through trophic interactions (Wells et al. 2008). ENSO events and climatic forcing has the greatest influence on interannual temperatures resulting in changes in species composition and biodiversity in the CCLME. At the broadest scales, temperatures in the world's oceans are predicted to warm up to 6 degrees Celsius by 2100 (IPCC 2007). The effects of ocean warming on marine ecosystems are being examined more in recent years, and multiple studies have observed or predicted range shifts in marine over the next century (Hazen et al. 2012, Sunday et al. 2012), spatial changes in productivity and diversity (Rijnsdorp et al. 2009), and changes in timing of migration for oceanic and riverine fish (Spence and Hall 2010). Long term warming in the CCLME may be buffered by upwelling, but changes in source waters and stratification may limit any buffering effect.

OCEAN ACIDIFICATION

Anthropogenic ocean acidification (OA), a component of global climate change, occurs as human-generated carbon dioxide (CO_2) in the atmosphere is taken up by the oceans. As CO_2 dissolves into seawater, it lowers ocean pH and reduces the availability of carbonate (CO_3^{2-}) and lowers the saturation state of calcium carbonate ($CaCO_3$), a mineral whose various forms—particularly magnesium calcites, aragonite and calcite—are used in shell and exoskeleton formation for many marine species (Feely et al. 2004). It is thus widely held that OA will have direct negative impacts on calcifying marine organisms (Feely et al. 2004, Kleypas et al. 2006, Fabry et al. 2008, Doney et al. 2009). The deep, nutrient-rich upwelled water that fuels spring and summer production along the US West Coast tends to be inherently low in pH, due to the extensive time the water mass spends below the euphotic zone, where respiration processes dominate (Feely et al. 2008). However, anthropogenic CO_2 emissions will exacerbate the undersaturated state of upwelled water, and the timing and extent of undersaturation events may change or interact with other aspects of global climate change.

The biological consequences of OA on marine organisms will not only affect calcifying organisms, but the rest of the food web that rely on these organisms as food; however, these population and ecosystem responses are not well understood yet. Available evidence suggests broad-scale changes in the distribution of organisms will occur, especially for shelled planktonic species that undergo diel vertical migrations or for species with low metabolic rates (Fabry et al. 2008). Predators that feed on OA susceptible prey would be able to switch to other prey types, increasing predation risk for other species, or alter their distribution, thus changing trophic structure and food-web dynamics of the region.

HUMAN PRESSURES RELEVANT TO ALL WASHINGTON STATE WATERS

FISHERY REMOVALS

Fishing provides important services to society, including production of food, employment, livelihood and recreation. At the same time, fisheries have potential to adversely affect the ecosystem that supports them. Impacts of fisheries on ecosystems have been extensively discussed in the literature (Dayton et al. 1995, Kaiser and Spencer 1996, Goni 1998, Agardy 2000, Garcia et al. 2003, Gislason 2003, Pauly and Watson 2009) with major effects associated with fishery removals and destruction of habitats in which fishing occurs.

Fishery removals directly impact target resources by reducing their abundance. When poorly managed, fisheries can develop excessive pressure on fishery stocks, leading to overfishing, and causing major ecological, economic and social consequences. Fisheries for the Pacific ocean perch and widow rockfish are among the most notable examples of overexploitation in the CCLME. Fishery targeting Pacific ocean perch developed in the Northern California Current Ecosystem in the 1950s, and catches quickly grew from just over 1000 metric tons in 1951 to almost 19,000 metric tons in 1966, reducing the stock below the overfished threshold of 25% of unfished biomass, established by the Pacific Fishery Management Council, in 1980 (Hamel and Ono 2011). Fisheries targeting widow rockfish developed in the late 1970s, after it was discovered that the species forms aggregations in the pelagic waters at night. Widow rockfish catches sharply increased from 1,107 tons in 1978 to 28,419 tons in 1981 and started to drop, indicating reduction in the resource, so that severe catch limits were imposed in 1982 (Love et al. 2002).

Fisheries are rarely selective enough to remove only the desired targets (Garcia et al. 2003), and they often take other species incidentally, along with targets. Even though incidentally taken fish (often referred to as bycatch) are routinely discarded, discard mortality can be quite high, especially for deep-water species. Therefore, fisheries can significantly reduce abundance of bycatch species associated with removals of targeted resources as well. Unintended removals can be also be facilitated by lost (or dumped) fishing gear, particularly pots, traps and gillnets, which may cause entanglement of fish, marine mammals, turtles and sea birds. The extent of such “ghost” fishing in the CCLME is unknown, but studies conducted elsewhere suggest that the impact might be non-trivial (Fowler 1987, Goni 1998, Garcia et al. 2003).

Fisheries typically target larger individuals. By removing particular size groups from a population, fisheries can alter size and age structure of targeted and bycatch stocks, their sex ratios (especially when organisms in a population exhibit sexual dimorphism in growth or distribution), spawning potential, and life history parameters related to growth, sexual maturity and other traits.

Extensive fishery removals may also affect large scale ecosystem processes and cause changes in species composition and biodiversity. These can occur with gradual decrease in the average trophic level of the food web, caused by reduction in larger, high trophic level (and high value) fish and increase in harvest of smaller, lower trophic level species, a process described as “fishing down the food chain” (Pauly et al.

1998, Pauly and Watson 2009). The extensive removal of forage fish species, mid trophic level components, can also modify interactions within a trophic web, alter the flows of biomass and energy through the ecosystem, and make systems less resilient to environmental fluctuations through a reduction of the number of prey species available to top predators (Garcia et al. 2003, Pauly and Watson 2009).

POLLUTANTS

Pollution of the marine environment occurs in several forms broadly categorized into land-based and ocean-based pollution. Land-based pollution includes pollution from inorganic and organic sources which can be transported via runoff or atmospheric circulation, as well as the input of excess nutrients from predominantly agricultural practices. Ocean-based pollution derives from ocean-based industries such as the activity of commercial shipping operations and sea-ports. Input of pollutants from coastal cities is not a huge concern, but input from runoff of these pollutants into streams and rivers provide a pathway for distant pollutants to enter Washington waters. Moreover, the intrusion of the Columbia River plume into Washington waters increases the potential of land-based pollutants affecting Washington ecosystems. We describe these various types of pollutants below.

INORGANIC POLLUTION

Inorganic pollution includes chemicals used by industries and businesses for the production of goods which our society depends. Many of the chemicals used in the manufacturing and production of these goods are toxic at some level to humans and other organisms and some are inevitably released into the environment. The production, use and release of various toxic chemicals have changed over time depending on economic indices, management methods (recycling and treatment of chemicals), and environmental regulations (USEPA 2010). The pathway of these chemicals to estuarine and marine environments can be direct (e.g., wastewater discharge into coastal waters or rivers) or diffuse (e.g., atmospheric deposition or urban runoff). Over the past 40 years, direct discharges have been greatly reduced; however, the input of pollutants to the marine environment from more diffuse pathways such as runoff from land-based activities is still a major concern (Boesch et al. 2001).

While all pollutants can become toxic at high enough levels, there are a number of compounds that are toxic even at relatively low levels (Johnson et al. 2008). The US Environmental Protection Agency (USEPA) has identified and designated more than 126 analytes as “priority pollutants.” According to the USEPA, “priority pollutants” of particular concern for aquatic systems include: (1) dichlorodiphenyl trichloroethane (DDT) and its metabolites; (2) chlorinated pesticides other than DDT (e.g., chlordane and dieldrin); (3) polychlorinated biphenyl (PCB) congeners; (4) metals (e.g., cadmium, copper, chromium, lead, mercury); (5) polycyclic aromatic hydrocarbons (PAHs); (6) dissolved gases (e.g., chlorine and ammonium); (7) anions (e.g., cyanides, fluorides, and sulfides); and (8) acids and alkalis (Kennish 1998, USEPA 2003). While acute exposure to these substances produce adverse effects on aquatic biota and habitats, chronic exposure to low concentrations probably is a more significant issue for fish population structure and may result in multiple substances acting in “an additive, synergistic or antagonistic manner” that may render impacts relatively difficult to discern (Thurberg and Gould 2005).

Coastal and estuarine pollution can affect all life stages of fish, but fish can be particularly sensitive to toxic contaminants during the first year of life (Rosenthal and Alderdice 1976). Over time, organisms will accumulate contaminants from water, sediments or food in their tissues, which then transfers to offspring through reproduction and throughout the food web via trophic interactions. One of the most widely recognized effects of inorganic pollution was the decline of bald eagles and brown pelicans during the 1960’s and 1970’s. These birds accumulated DDT in their tissues which changed their ability to metabolize calcium, which resulted in birds producing abnormally thin eggshells which led to reproductive failure (Hickey and Anderson 1968, Blus et al. 1971). Negative impacts of pollution on commercial fish stocks have generally not been demonstrated, largely due to the fact that only drastic changes in marine ecosystems are detectable and the difficulty in distinguishing pollution-induced changes from those due to other causes (Sindermann 1994). Normally, chronic and sublethal changes take place very slowly and it is impossible to separate natural fluctuations from anthropogenic causes. Furthermore, fish populations themselves are estimated only imprecisely, so the ability to detect and partition contaminant effects is made even more difficult. However, measurements of marine biodiversity have shown that species richness and evenness are reduced in areas of anthropogenic pollution (Johnston and Roberts 2009).

ORGANIC POLLUTION

Organic pollution encompass numerous classes of chemicals including pesticides, polycyclic aromatic hydrocarbons (PAHs) and other persistent organic pollutants (POPs) and is introduced to the marine environment via runoff to rivers, streams and groundwater, poor-disposal practices and the discharge of industrial wastewater. Pesticides can affect the health and productivity of biological populations in three basic ways: (1) direct toxicological impact on the health or performance of exposed individuals; (2) indirect impairment of the productivity of the ecosystem; and (3) loss or degradation of vegetation that provides physical structure for fish and invertebrates (Hanson et al. 2003, Johnson et al. 2008). For many marine organisms, the majority of effects from pesticide exposures are sublethal, meaning that the exposure does not directly lead to the mortality of individuals. Sublethal effects can be of concern, as they impair the physiological or behavioral performance of individual animals in ways that decrease their growth or survival, alter migratory behavior, or reduce reproductive success (Hanson et al. 2003, Johnson et al. 2008), but in general the sublethal impacts of pesticides on fish health are poorly understood. Early development and growth of organisms involve important physiological processes and include the endocrine, immune, nervous, and reproductive systems. Many pesticides have been shown to impair one or more of these physiological processes in fish (Gould et al. 1994, Moore and Waring 2001). The direct and indirect effects that pesticides have on fish and other aquatic organisms can be a key factor in determining the impacts on the structure and function of ecosystems (Preston 2002).

Petroleum products, including PAHs, consist of thousands of chemical compounds which can be particularly damaging to marine biota because of their extreme toxicity, rapid uptake, and persistence in the environment (Johnson et al. 2008). PAHs have been found to be significantly higher in urbanized watersheds when compared to non-urbanized watersheds. Low-level chronic exposure to petroleum components and byproducts (i.e., polycyclic aromatic hydrocarbons [PAH]) have been shown in Atlantic salmon *Salmo salar* to increase embryo mortality, reduce growth (Heintz et al. 2000), and lower the return rates of adults returning to natal streams (Wertheimer et al. 2000). Effects of exposure to PAH in benthic species of fish include liver lesions, inhibited gonadal growth, inhibited spawning, reduced egg viability and reduced growth (Johnson et al. 2002). In general, the early life history stages of most species are most sensitive, juveniles are less sensitive, and adults least so.

Municipal wastewater treatment facilities have made great advances in treatment practices to eliminate pollutants prior to discharge, but any discharges will undoubtedly affect the quality of habitat in estuarine environments (Diaz and Rosenberg 1995, Kam et al. 2004). Several studies have shown that many benthic species increase in abundance and biomass in response to increased organic loading (Weston 1990, Savage et al. 2002, Alves et al. 2012). However, excessive nutrient enrichment can lead to hypoxia and potentially anoxic conditions, consequently leading to declines or shifts in biomass and diversity in the benthic community (Ysebaert et al. 1998, Essington and Paulsen 2010). Species richness among benthic communities has been shown to increase in relation to both temporal and spatial distance from organic loading sources (Savage et al. 2002, Wear and Tanner 2007). In addition to municipal wastewater treatment facilities, widely-distributed poorly-maintained septic systems contaminate shorelines in many places (Macdonald et al. 2002).

NUTRIENT INPUT

Elevated nutrient concentrations are a leading cause of contamination in streams, lakes, wetlands, estuaries, and ground water of the United States (USEPA 2002). Nutrients (primarily nitrogen and phosphorus) are chemical elements that are essential to plant and animal nutrition; in marine waters, either phosphorus of nitrogen can limit plant growth. However, in high concentrations they can be considered water contaminants (USEPA 1999).

Excess nutrients in a body of water can have many detrimental effects on drinking water supplies, recreational use, aquatic life use, and fisheries, and there are multiple indirect effects of nutrient enrichment of surface waters on human health. However, excessive nutrients are more often a cause of concern because of their role in accelerating eutrophication, which produces a wide range of other impacts on aquatic ecosystems and fisheries. Severely eutrophic conditions may adversely affect aquatic systems in a number of ways, including: algae blooms; declines in submerged aquatic vegetation (SAV) populations through reduced light transmittance, epiphytic growth, and increased disease susceptibility; mass mortality of fish and invertebrates through poor water quality (e.g., via oxygen depletion and elevated ammonia levels); and alterations in long-term natural community dynamics (Dubrovsky et al. 2010). Algal toxins harmful to animal and human health can be produced from blooms of some cyanobacteria species. High algal biomass also is associated with hypoxia (low dissolved-oxygen concentrations), which can contribute to the release of toxic metals from bed sediments, increased availability of toxic substances like ammonia and hydrogen sulfide, and fish kills. In recent years, nitrate and other nutrients discharged from the Mississippi River Basin have been linked to a large zone of hypoxia in the Gulf of Mexico along the Louisiana-Texas coast (Sprague et al. 2009).

Nonpoint sources of nutrients which affect stream and groundwater concentrations include fertilizer use, livestock manure, and atmospheric deposition (Ruddy et al. 2006). Within some coastal regions of the U.S. (e.g., mid-Atlantic states), much of the excess nutrients originates from point sources, such as sewage treatment plants, whereas failing septic systems often contribute to non-point source pollution and are a negative consequence of urban development (Johnson et al. 2008). However, nutrient loading can be a complex indicator to interpret, as a variety of hydro-geomorphic features (basin slope, basin area, mean annual precipitation, stream flow, and soil type) may also interact with possible nutrient sources to complicate estimates of nutrient concentration and loading. As well, there often are multiple and possibly counteracting anthropogenic factors influencing nutrient source and transport in a watershed, and without detailed knowledge of all important factors in each watershed, it may be difficult to discern the specific cause(s) of a trend in concentration (Sprague et al. 2009). Best land-use practices are known to reduce nutrient loading. Protocols for establishing total maximum daily load (TMDL) values of nutrients have been developed for specific bodies of water throughout the country (USEPA 1999); however, we uncovered few examples in the literature of TMDLs for marine systems on the Pacific coast of the US.

OCEAN-BASED POLLUTION

The impact of ocean-based pollution is wide-spread as we include pollution from sea-going vessels and activity within ports. Marine ports are major industrial centers providing jobs and steady revenue streams yet contributing significantly to pollution. Ships with huge engines running on bunker fuel without emission controls, thousands of diesel trucks per day, diesel locomotives, and other polluting equipment and activities at modern seaports cause an array of environmental impacts that can seriously affect local communities and marine and land-based ecosystems throughout a region (Bailey and Solomon 2004). As vessels transit within ports, along the coast, and along international shipping lanes, there are inevitable discharges of waste, leaks of oil and gas, loss of cargo during rough seas, and increased risk of oil spills from oil shipping vessels. Beaches close in proximity to oil shipping lanes have been observed to have high tar content related to the degree of oil pollution in the sea (Golik 1982).

The effects of oil pollution on ecological components are both direct and indirect. Because seabirds and marine mammals require direct contact with the sea surface, these taxa experience high risk from floating oil (Loughlin 1994). Oiled seabirds and marine mammals lose the insulating capacity of their feathers and fur which can lead to death from hypothermia (Peterson et al. 2003). Chronic exposure to partially weathered oil is toxic to eggs of pink salmon *Oncorhynchus gorbuscha* and herring *Clupea pallasii* (Marty et al. 1997, Heintz et al. 2000). Many effects of exposure to oil and the associated polycyclic aromatic hydrocarbons (PAHs) are sublethal and have lasting effects on individual survival which may scale up to population-level responses. For example, embryos of zebrafish *Danio rerio* exposed to PAHs showed delayed changes in heart shape and reduced cardiac output (Hicken et al. 2011). Strandings of oiled seabirds have been used as an indicator of chronic oil pollution along heavily used shipping lanes in the North Sea and recent studies show declining oil-rates reflecting reduced oil spills (Camphuysen 1998, Camphuysen 2010).

In addition to the potential for pollution, other common impacts of vessel activities include vessel wake generation, anchor chain and propeller scour, vessel groundings, the introduction of invasive or nonnative species, and the discharge of contaminants and debris.

CONCEPTUAL MODEL FOR EACH HABITAT TYPE

The conceptual models described below were primarily developed using information from peer-reviewed journal articles and state and federal agency reports. In addition, these conceptual models were presented at the "Ecosystem Indicators on Washington's Pacific Coast" workshop on May 13, 2013. Scientists, resource managers, and other stakeholders from the region contributed comments and suggestions that have been incorporated into the final models presented in this report.

ROCKY INTERTIDAL SHORES

Rocky shorelines are important features of the Washington outer coast from roughly Point Grenville to Cape Flattery (Fig. 3), although sites vary considerably from isolated headlands to mixed substrate areas to boulder fields to rocky cliffs and bedrock platforms. Developing a single conceptual model for this variety of rocky habitats thus presents a challenge. The conceptual model outlined below (Fig. 4) represents an attempt to capture the dominant drivers and ecological interactions that characterize rocky intertidal habitats, particularly those of the Washington coast or adjacent areas in the northeast Pacific, but finer-scale refinement may be necessary for marine spatial planning related to specific

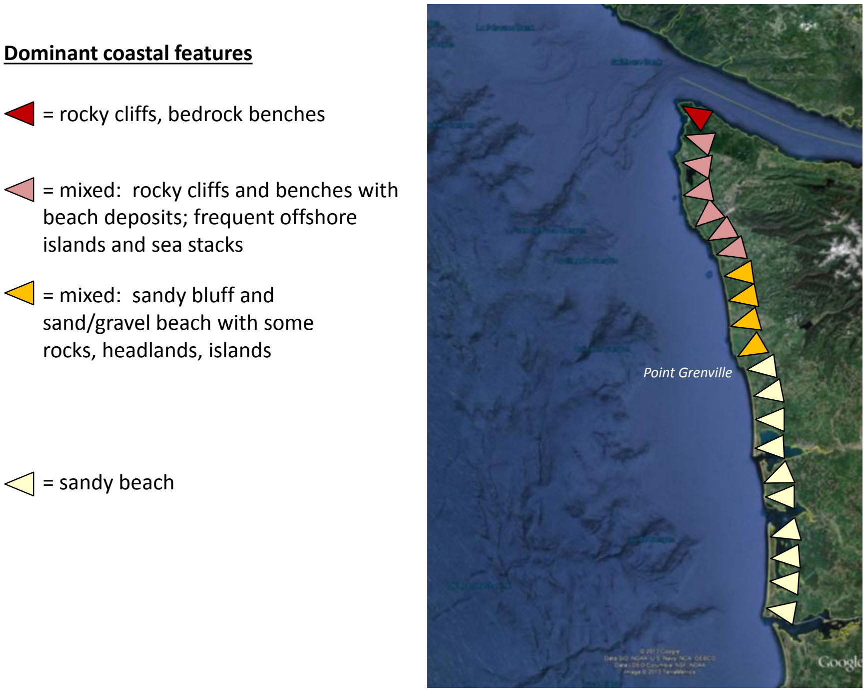

Figure 3. Schematic of habitat features along the outer coast of Washington. Derived by the authors from Skewgar and Pearson (2011), Rau (1973), and unpublished sources.

sections of rocky coastline.

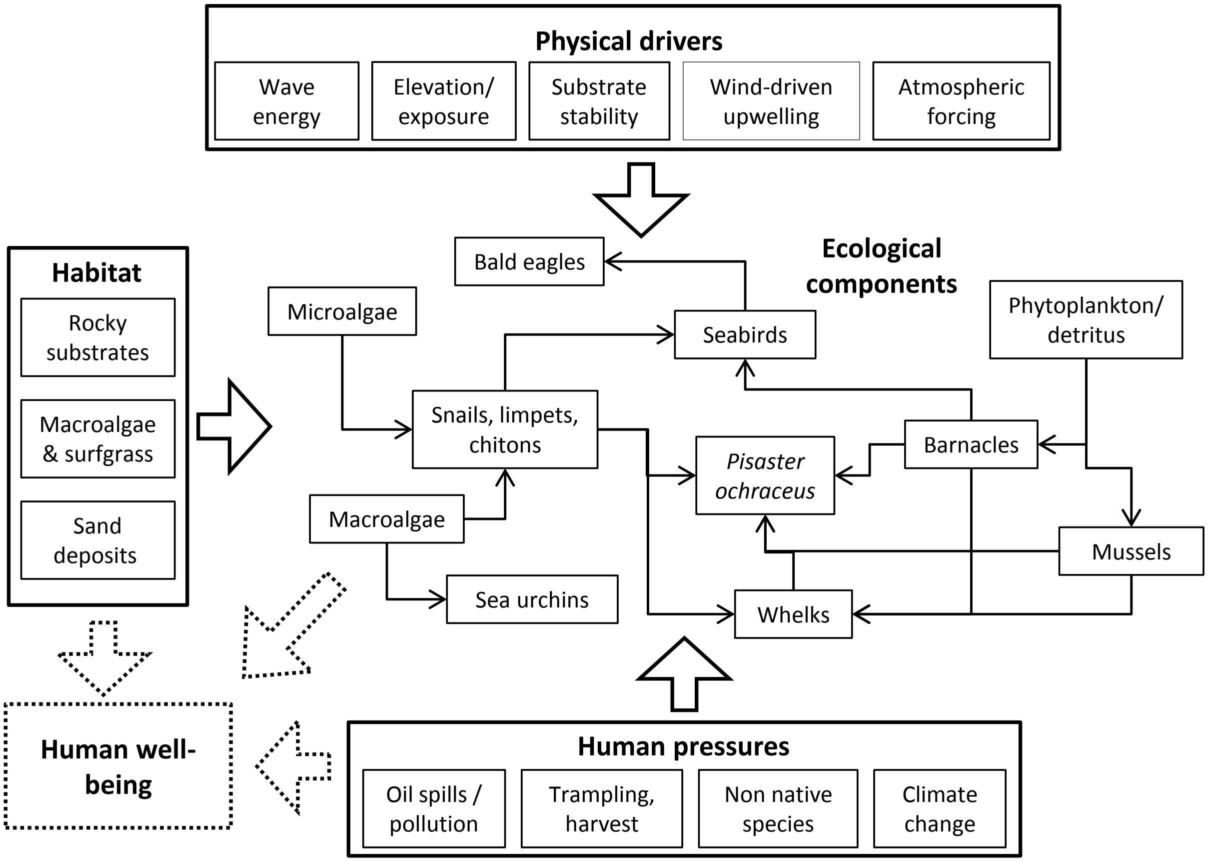

Figure 4. Conceptual model of important habitat, ecological components, physical drivers and human pressures for the rocky intertidal habitat.

HABITAT

SUBSTRATES

Rocky substrates along the Washington coast range from exposed bedrock to boulder fields to cobble and gravel. The composition of the substrate fundamentally shapes the ecological dynamics of the local intertidal community.

Bedrock is highly stable substrate, and depressions in bedrock may retain water on descending tides, creating tide pools that support many organisms; the composition of tide pool communities depends on factors such as depth, shape, volume, and tidal elevation—pools in the upper intertidal experience greater exposure and tend to face much more variable environmental conditions than pools in the lower intertidal (Knox 2000).

When present, boulders have many different effects, as a function of their size and location in the intertidal (summarized in Knox 2000). The size of boulders affects their mobility, with smaller boulders more likely to be displaced by wave energy, which can severely impact any attached biota. Larger boulders are more stable and may entrain greater amounts of sediment as well. The tops of large boulders are out of the water longer during a tidal cycle than small boulders in the same tidal elevation zone, subjecting biota to different exposure gradients. Large boulders may have a lee, protected from direct wave impact and thus more likely to support wave-intolerant species. Boulder size is also a determinant of the volume and stability of interstitial space between and beneath boulders, which greatly influences community composition. Interactions among the above factors are important; for example, some sites have positive correlations between boulder size and algal cover but the greatest algal diversity on less-stable, medium-sized boulders that experience an intermediate disturbance level, which prevents dominance of climax species (Sousa 1979). However, grazer populations are likely also influenced by boulder size and stability, and thus top-down grazer effects may further complicate the relationship between boulder size and algal cover and diversity (Knox 2000).

Many rocky areas have large sandy deposits or are bounded to the north and/or south by several kilometers of sandy beaches. Proximity to sand can have important effects on community composition of flora and fauna due to disturbances such as burial or scour (Knox 2000). Thus the presence of sand can lead to a greater abundance or persistence of sand-tolerant (psammophilic) biota in rocky areas.

MACROPHYTES

Rocky substrates along Washington's northern outer shoreline support a wide diversity of intertidal macrophytes (macroalgae, surfgrass, etc.). For example, Dethier (1988) estimated that ~120 macrophyte species occur within rocky habitats of the Olympic Coast National Marine Sanctuary, and more recent surveys found 104 intertidal algal species at just three sites in the region (Klinger et al. 2007). The diversity of macrophyte cover present is emblematic of several defining, interacting features of rocky intertidal habitats (Schoch and Dethier 1996, Knox 2000, Menge and Branch 2001). First, these habitats have solid substrates that range in size, stability, elevation, aspect and roughness, which produces a diverse range of surface conditions for macrophyte attachment and growth. Second, the primary productivity of this area is very high, due in part to upwelled nutrients and extensive late spring/early summer daylight, thus promoting extensive and rapid growth. Third, the tidal elevation gradient results in a range of immersion/emersion and wave exposure conditions, which increases diversity by supporting small, desiccation-tolerant species in the upper intertidal; larger, canopy-forming species in the lower intertidal where emersion only occurs on very low tides; and still other species in the intermediate zones where wave exposure is most variable. Fourth, disturbances, such as climate or weather events, overturning of rocks, smothering or scouring by sand, impact of logs or other heavy debris borne by the surf, and changes in grazing rates facilitate the persistence of some species that might otherwise be outcompeted (e.g., Dayton 1971, Sousa 1979, Paine 2002).

As a general rule, the overall biomass and coverage of macrophytes increases as one moves lower in the intertidal and the physiological stresses of emersion weaken. In addition to that gradient, the diversity of features outlined in the previous paragraph influences the occurrence, persistence and relative importance of different macrophytes across and within rocky intertidal sites. Dethier (1991, as summarized by Klinger et al. 2007) listed several common macrophytes in rocky intertidal zones of Washington, delineated by substrate size and wave exposure:

- Bedrock: Intertidal bedrock exposed to strong wave action is typified the long-bladed brown algae *Laminaria* and *Lessoniopsis*; sites with exceptional wave exposure may have sea palm *Postelsia palmaeformis.* On moderately exposed bedrock, representatives include the brown alga *Hedophyllum sessile* and the surfgrass *Phyllospadix scouler*. Protected bedrock often has brown rockweed *Fucus gardneri* and the red algae *Porphyra* spp. and *Mastocarpus papillatus*.
- Boulder habitat: Intertidal boulder habitat commonly contains the red algae *Plocamium cartilagineum* and *Prionitis* spp.
- Hardpan: Intertidal hardpan (consolidated clays firm enough to support epibenthos) commonly has the bubble-like red alga *Halosaccion glandiforme*, commonly called the “sea sac.”
- Mixed/coarse substrates protected from wave exposure commonly have *Fucus gardneri*.

Schoch and Dethier (1996) surveyed biota at low, intermediate and high elevations in rocky intertidal sites along the Washington coast. According to their surveys (Schoch and Dethier 1996, Web Appendix 1), 23 macrophyte species or species complexes occurred at ≥50% of sites. Of these 23, some were fairly ubiquitous across all elevation zones (e.g., coralline and crustose red algae; the red algal genus *Polysiphonia*; the green algal genus *Ulva*). Some were most common at lower elevations (e.g., surfgrass *Phyllospadix*; red algae such as *Prionitis* spp., *Plocamium* spp., *Cryptopleura* spp., and *Mazzaella splendens*). Others increased in frequency at higher elevations (e.g., the red algae *Mastocarpus* spp., *Endocladia* spp.; the green alga *Cladophora* sp.; the brown alga *Fucus* spp.). Still others peaked at intermediate heights (e.g., the red algae *Porphyra* spp., *Callithamnion* sp., and *Halosaccion glandiforme*). Findings such as those of Dethier (1991) and Schoch and Dethier (1996) may help elucidate macrophytes that are good indicators of intertidal drivers such as stability, wave exposure and sea level height.

ECOLOGICAL COMPONENTS

SUSPENSION-FEEDING INVERTEBRATES

With their solid substrates and exposure to productive, turbulent waters, rocky shores of Washington support large biomasses of sessile, suspension-feeding benthic invertebrates. The dominant suspension feeders at higher tide elevations are small barnacles (Kozloff 1983, Schoch and Dethier 1996). *Balanus glandula*, *Semibalanus cariosus*, and *Chthalamus* sp. are the most common species. Their upper distributional limits are determined by factors such as desiccation and thermal stress, while predation by snails and seastars and competition for space can affect their lower elevation limits.

While dozens of suspension feeding species are present (Schoch and Dethier 1996), the most conspicuous are mussels (particularly *Mytilus californianus*) and goose barnacles *Pollicipes polymerus*. The upper and lower elevation limits for mussels appear to be set by desiccation stress and predation, respectively (Knox 2000). Goose barnacle distribution is affected by a complex of factors such as space competition with *Mytilus*, the morphology of the rock, the volume of wave backwash, and predation by gulls (e.g., Kozloff 1983, Wootton 1992, Meese 1993).

Schoch and Dethier (1996, Web Appendix 1) found that most of the other common suspension feeders (sponges, tubeworms, tunicates, bryozoans, etc.) in Washington's rocky intertidal communities were more abundant at lower tidal elevations. If upper limits of intertidal organisms are mainly set by physical factors (Connell 1961), then these other suspension feeders are likely less resistant to factors such as desiccation and thermal stress compared to mussels and barnacles.

The primary food resources for suspension feeders in rocky intertidal habitats are phytoplankton and detritus, and thus oceanographic processes (e.g., upwelling) that affect productivity in adjacent shelf and slope waters may affect growth and productivity of intertidal suspension feeders. However, the processes that drive seasonal growth of mussels and barnacles in this region are not fully understood; for example, mussels and barnacles in some sites on the Oregon coast grew substantially during winter months when phytoplankton production was low (Menge 2000).

Suspension feeders serve other ecological functions. For example, Suchanek (1992) cataloged over 300 species living within the interstices of *M. californianus* beds in Washington; these taxa represented three divisions of macroalgae, 12 invertebrate phyla, and three fish species that use mussel beds as habitat. In addition, mussel beds can affect phytoplankton and nutrient concentrations and ratios in intertidal waters, trap large amounts of sediment and organic matter, and provide food for predators including humans (Knox 2000).

GRAZERS

Dozens of grazing invertebrates occur along rocky shores of Washington's outer coast, most notably snails, limpets, chitons, and small crustaceans. Two genera were ubiquitous at sites surveyed by Schoch and Dethier (1996, Web Appendix 1): the snail *Littorina*, abundant throughout but particularly at higher elevations; and the limpet *Lottia*, common at all elevations. Chitons (e.g., *Lepidochitona dentiens*, *Tonicella lineata*, *Katharina tunicata*) and herbivorous amphipods and isopods were common at middle and lower tidal elevations. In the lower intertidal, the chiton genus *Mopalia* and the purple sea urchin *Strongylocentrotus purpuratus* were also common. In addition to these species, a conspicuous grazer is the black turban snail *Tegula funebralis*, particularly on boulder habitats (Dethier 1991).

The feeding ecology of grazers varies. At high intertidal elevations, where macrophyte biomass is low, snails and limpets primarily feed on benthic microalgae. At middle and lower tidal heights, limpets, snails, chitons and crustacean herbivores graze on benthic microalgae as well as coralline algae and macroalgae or algal detritus (Kozloff 1983, Paine 1992). The sea urchin *S. purpuratus* feeds on macroalgae, mainly drifting fragments as well as direct grazing on attached algae when necessary.

PREDATORY INVERTEBRATES

The ochre seastar *Pisaster ochraceus* is the most noteworthy predator on Washington's rocky coastline. It is a keystone predator, a consumer with disproportionately large effects on community composition. In a series of foundational papers on experiments conducted in Washington coastal waters, Paine (e.g., 1966, 1974, 1980) demonstrated that *Pisaster* predation enhanced and maintained biodiversity of the benthic invertebrate community; when *Pisaster* was excluded, dominant space competitors, particularly *Mytilus californianus*, were released from *Pisaster* predation and came to occupy most of the habitat, resulting in sharp declines in the number of species present.

Pisaster ochraceus itself has few predators. *Pisaster* in this region may be subject to disease outbreaks, such as wasting disease, which could be exacerbated by climate change (Bates et al. 2009).

Other predatory invertebrates in rocky habitats include several whelks found throughout the intertidal zones; the most common species at Washington sites was *Nucella canaliculata* (Schoch and Dethier 1996), a key predator on barnacles and small mussels (especially *Mytilus trossulus*; Wootton 2002). *Nucella lamellosa* is more characteristic of protected rocky habitats (Dethier 1991). Two predatory sea anemones, *Anthopleura elegantissima* and *A. xanthogrammica*, are common in tide pools. *A. elegantissima* is smaller-bodied and often occurs in crevices as well; it can be found at somewhat higher tidal elevations than *A. xanthogrammica*, which is most common in middle and lower elevations. Predatory nemertean and nereid worms and several omnivorous crabs (hermit crabs *Pagurus* spp., spider crabs *Pugettia* spp.) are common as well, particular and mid and lower elevations (Kozloff 1983, Schoch and Dethier 1996).

VERTEBRATES

Many fishes inhabit rocky intertidal zones, moving in and out with the tide or remaining in tide pools at low tides. Common representatives include demersal fishes such as small sculpins (family Cottidae) and gunnels (family Pholidae). Numerous fishes likely inhabit the subtidal waters (see, e.g., Appendix F in Klinger et al. 2007). Little work to date has examined the ecological roles of fishes in these habitats.

A number of bird species are associated with Washington's rocky coast. Many seabirds, shorebirds, raptors, and avian generalists forage in these habitats; some birds, such as crows, gulls and oystercatchers, have been shown to influence intertidal community composition and ecology (Skewgar and Pearson 2011; see "Key Interactions" below). The numerous offshore rocky islands and sea stacks are isolated from terrestrial predators and provide extensive nesting habitats for colonial seabirds (Klinger et al. 2007). Major populations include various petrels, cormorants, gulls, and alcids.

Harbor seals *Phoca vitulina*, the most numerous pinnipeds in Washington waters, are common in rocky intertidal habitats along the outer coast, particularly around offshore rocks, reefs and islands (Jeffries et al. 2000). Harbor seals are year-round residents of these waters. Peak abundances at haul-out sites occur in the summer, when seals pup (May-July) and molt (August-September). Many rocks, reefs and islands are also used as haul-outs for migratory Steller sea lions *Eumetopias jubatus* and California sea lions *Zalophus californianus*, with peaks of both in the fall and winter. Northern elephant seals *Mirounga angustirostris* are seen occasionally at some rocky islands along the outer coast.

Numerous species of terrestrial mammals, such as raccoons, mustelids, and deer, forage opportunistically in mainland rocky intertidal habitats (Skewgar and Pearson 2011).

KEY INTERACTIONS

MACROPHYTES AS FOOD AND HABITAT

Macrophytes provide food for numerous grazers and detritivores within the rocky intertidal community, and leak dissolved organic carbon that is utilized by microbes. Detached algal drift provides valuable organic matter subsidies to nearby sand or gravel beaches, where macrophytes cannot grow due to the unstable substrates. Macrophytes also provide microhabitats for fauna, reducing their exposure to stressors such as wave energy during high tides and light, temperature changes, and desiccation during low tides. The diversity and productivity of rocky intertidal macrophytes across intertidal zones and conditions thus serves to support a tremendous diversity of fauna (Dethier 1988, PISCO 2002).

SPACE COMPETITION

Space is often a limiting resource for the largely sessile or slow-moving organisms within the zones of rocky intertidal systems. Algal species compete for space with other algae, possibly by outgrowing them in the presence (or absence) of grazers (Paine 2002). Some algae take advantage of disturbances that denude rocks, becoming established and preempting other algal sporelings from settling. Some species "whiplash" and damage other algae in the turbulence of wave action. Macroalgae also compete with benthic invertebrates by crowding them, growing on their shells and thus displacing them by increasing drag, or by whiplashing them; these effects may also release other invertebrates from space competition (Dayton 1971). Others such as the sea palm *Postelsia palmaeformis* are outcompeted for space by invertebrates like the mussel *Mytilus californianus* unless mussels are frequently dislodged by disturbance in high-energy areas (Paine 1988).

The invertebrate space competitors that have received the most study in this system are *Mytilus californianus* and the goose barnacle *Pollicipes polymerus*. These species are found in large patches at intermediate tidal elevations (Kozloff 1983). *Mytilus* is generally recognized as the superior competitor through its ability to overgrow barnacles (e.g., Paine 1974), although mechanical disturbance or predation can remove mussels and facilitate the persistence of the barnacles. Limpets may compete with small barnacles and other invertebrates for space as well: as limpets move about the intertidal, they often dislodge ("bulldoze") small barnacles (Dayton 1971).

PISASTER PREDATION ON MUSSELS

As outlined above, predation by *Pisaster ochraceus* on *Mytilus californianus* is a major community structuring force, due to *Mytilus*' ability to outcompete many other sessile benthic invertebrates as well as some forms of macroalgae for space at middle intertidal elevations. Not only does this top-down interaction affect the biodiversity of conspicuous species (Paine 1966), it likely also affects other ecosystem functions performed by *Mytilus*, such as retention of detritus (Knox 2000) and provision of habitat (Suchanek 1992).

The keystone predator effects of *Pisaster* can be influenced by a variety of factors. Sanford (1999) showed that coastal upwelling introduced cooler water and slowed *Pisaster* predation, whileGooding et al. (2009) found that *Pisaster* growth feeding and growth accelerated at warmer temperatures. If *Pisaster* is absent from an area for an extended period of time due to disturbance, disease, poor recruitment, demographic effects, etc., then some prey may grow to sizes too large for *Pisaster* to prey upon (Paine and Trimble 2004).

GRAZER CONTROL OF MACROALGAE

Field experiments indicate that some grazers are capable of controlling the macroalgal community in Washington rocky intertidal zones. Paine (1992) found that grazer densities controlled the density of brown algae recruits. Two grazers, the chiton *Katharina tunicata* and the sea urchin *Strongylocentrotus purpuratus*, had particularly strong negative effects on algal sporeling density, while another, the limpet *Acmaea mitra*, had a positive effect on algal sporeling density, possibly because its foraging activity improves the habitat quality for brown algae establishment (Paine 1992). *Acmaea* feeds preferentially on coralline algae (Kozloff 1983), and thus makes habitat available to brown algae sporelings by removing coralline algae. The effects of grazers on algae likely track the distributions of the grazers (e.g., highly aggregated, as with *S. purpuratus*, or more haphazard, as with *Katharina*); moreover, the effects are likely not additive because these grazers tend to exclude one another from patches of habitat.

Wootton (1992) demonstrated that another group of limpets (*Lottia* spp.) can control algal biomass in Washington rocky intertidal habitats. In plots where avian predators were excluded and limpets were able to graze, total algal cover was more than an order of magnitude lower than in control plots where avian predators were present.

A long-term grazer manipulation in Washington rocky intertidal habitat showed that grazers can influence the species composition of macroalgae. Paine (2002) reduced or excluded grazers from lower intertidal plots for seven years, the composition of macroalgae in the plots shifted strongly relative to control plots; highly productive, annual brown algal species such as *Alaria marginata* and *Nereocystis* became dominant in manipulated plots, while perennials such as *Hedophyllum* and *Laminaria* were more common in control plots. Despite the change in algal composition, total primary production was not different in control and treatment conditions (Paine 2002).

SEABIRD PREDATION

Several predatory interactions involving seabirds may be influential in community and ecosystem dynamics around rocky shores. For example, changes in predation by gulls on goose barnacles *Pollicipes polymerus* can influence the rate at which *Mytilus californianus* reestablishes in bare patches following a disturbance (Wootton 1993); further, by reducing *Pollicipes* cover, gull predation may release the smaller barnacle *Semibalanus* from space competition, which then leads to increases in the predatory whelk *Nucella* (Wootton 1994). These experiments point to numerous direct and indirect effects of gulls on species that are central to the diversity and functions of this habitat.

The American black oystercatcher *Haematopus bachmani* is a predator of interest because of its abundance at some rocky intertidal sites and the high individual consumption rates on its preferred prey, particularly limpets (Wootton 1997). There is evidence that black oystercatchers are capable of altering abundance and habitat use of intertidal limpet communities, which may in turn affect the composition of algae through alteration of grazing pressure (e.g., Frank 1982, Sorensen and Lindberg 1991, Wootton 1992, Lindberg et al. 1998).

Recent evidence indicates that the recovery of bald eagles *Haliaeetus leucocephalus* has led to increased direct and indirect mortality on seabird colonies located on Washington's rocky coast. Bald eagles prey directly upon adults, chicks or eggs at colonies, or may simply flush the adults by their presence, which leaves nests vulnerable to other avian predators such as gulls or crows. These eagle-driven effects have likely contributed to population declines in common murres *Uria aalge* and Glaucous-winged gulls *Larus glaurescens* in coastal Washington (Parrish et al. 2001, Hayward et al. 2010). The extent to which eagle effects cascade to lower trophic levels such as forage fish in coastal waters is presently unknown, and is a topic worthy of field study or ecosystem modeling (Harvey et al. 2012).

IMPORTANT PHYSICAL DRIVERS

TIDE HEIGHT

Zonation by elevation is a defining physical feature of rocky intertidal systems, and is related to the incursions and excursions of tides on daily, monthly, and annual cycles. The extent of the tidal incursion/excursion determines the extent to which zones of the intertidal system are exposed to air, and the related stressors of emersion: temperature changes relative to seawater; desiccation; light and ultraviolet radiation; weather events that may include freshwater inputs such as rain or snow; and terrestrial species. Sessile organisms found at higher tidal elevations must therefore be tolerant of such stressors, and in fact the upper limit of a species' distribution in an intertidal habitat is often determined by its tolerance to physical extremes (Menge and Branch 2001). In fact, tide height and other factors such as substrate size and stability (see above, "Habitat") are important predictors of the assemblage of species present in rocky intertidal habitats (Knox 2000).

WAVE ENERGY

Rocky intertidal organisms are subjected to the force of waves breaking upon the rocky substrates on or around which they dwell. This fact imposes upon all species the need for morphology or behavior that enables them to maintain position, and likely accounts for the prevalence of species with sizes, profiles and shapes that minimize drag (Denny 1988). The force of waves is determined by several key factors. The profile of the coast is important, as wave energy tends to be focused on headlands and dissipate in bays, although the Washington outer coast does not have as many major headlands as the coastline to the south in Oregon and California. The slope of the surf zone influences how energy builds as a wave nears the shore, and also how much of the wave's energy is reflected forcefully (steeper slopes) or dissipated gradually (shallower slopes) when it meets the shore. The aspect of the shoreline also plays a role due to large-scale currents that move along the coast. For example, the poleward-flowing Davidson Current in winter would tend to exacerbate wave energy breaking on a south-facing rocky coastline. Wave energy is increased by winds and during storms, particularly the strong winter storms that hit the Washington coast; especially strong waves may dislodge individual or patches of intertidal organisms, especially if waves crash floating logs into the substrate or cause boulders to turn over. On the other hand, offshore structures such as islands, reefs, or sea stacks may lessen the wave energy that reaches the mainland. Nearshore kelp forests may have a similar dissipative effect.

While wave energy creates physical stresses, Leigh et al. (1987) postulated that it also facilitates the high productivity of rocky intertidal systems in this area. Waves that directly dislodge biota open habitat for other, less competitive biota, and some predators avoid areas where wave energy is too high. Waves also replenish nutrient-deprived boundary layer water with nutrient-rich water from offshore. Waves may enhance light uptake by algae, particularly understory species that might otherwise be overgrown and shaded. Waves may also convey competitive advantages, such as for algae that can whiplash competitors. Waves also help to supply intertidal habitats with larvae, spores and other propagules (Underwood and Keough 2001).

UPWELLING

Upwelling-derived plankton and detritus provide food for rocky intertidal suspension feeders in this region, particularly in Oregon and Northern California where upwelling is most intense (Menge 2000). Upwelled waters are also relatively cool and therefore may lower metabolic rates and energy demands for fishes and invertebrates (Sanford 1999).

Upwelling may also be involved in recruitment dynamics in rocky intertidal habitats along the West Coast. Upwelling timing, intensity, and relaxation may affect larval supply and growing conditions (temperature, productivity) in coastal habitats, and there may be interspecific or interguild differences in recruitment as well (e.g., Barth et al. 2007). However, there is some debate as to whether upwelling is a causal mechanism for regional patterns of recruitment variability (e.g., Menge 2000, Connolly et al. 2001, Morgan et al. 2009, Shanks and Shearman 2009).

WEATHER AND CLIMATE

As noted above, intertidal biota are exposed at low tide to local weather conditions, which can range from full sunlight and relatively warm temperatures in the summer to freezing conditions or storms and heavy rains in the winter. Storms or strong winds can intensify wave size and frequency, resulting in greater exposure to wave energy. Intertidal organisms have differing degrees of tolerance to weather-related variables such as temperature, UV light exposure, desiccation, wave energy, and salinity. While many of these variables have a strong seasonal component, they can vary interannually due to large-scale climate anomalies, such as El Niño or La Niña events, or interdecadally due to large-scale climate regime shifts. In addition, long-term global climate change is expected to affect regional weather variables on both annual and seasonal time scales in the coming decades (e.g., Mote and Salathe 2010, Salathe et al. 2010; also see the Climate Change discussions at the beginning of this chapter and below under "Important Human Pressures").

IMPORTANT HUMAN PRESSURES

The human pressures that face communities at the land-sea interface differ somewhat from the general human pressures common to all marine habitats (see above, “Human Pressures Relevant to All Washington State Waters”), due to greater proximity to human activity. Although many human practices affect Washington’s rocky shores, we focus here on pressures explicitly cited in recent status reports as substantial current or pending threats (Klinger et al. 2007, ONMS 2008, Skewgar and Pearson 2011). According to monitoring done by the Olympic Coast National Marine Sanctuary, rocky habitats within the Sanctuary (i.e., the 217 km of coast from the Copalis River north to near Cape Flattery) appear to be healthy and to have experienced relatively low human impact (ONMS 2008), although threats remain present as human populations continue to grow and activities continue to expand.

SHIPPING AND OIL SPILLS

Due to the large volume of shipping that moves through the Strait of Juan de Fuca, the number of non-cargo vessels moving along the coast, and the volume of petroleum that is refined in Washington state each year, the threat of oil spills is significant in coastal waters (ONMS 2008, Skewgar and Pearson 2011). Two large petroleum spills in the late 20th Century (the *Nestucca*, 231,000 gallons of fuel oil near Grays Harbor in 1988; the *Tenyo Maru*, 100,000 gallons of diesel fuel offshore of the Makah Reservation in 1991) caused short-term and long-term impacts along the Washington coast. Rocky and mixed substrates experienced many effects, ranging from direct lethality, to longer-term sublethal effects, to impacts of oil removal (Skewgar and Pearson 2011).

Rocky shores can be especially vulnerable to large oil spills because oil can be trapped in tide pools, on bedrock benches, in spaces between rocks, or within sediments, mussel beds, and other microhabitats, thereby continually re-exposing organisms to oil toxicity (Skewgar and Pearson 2011). Thus, the physical features described above for rocky habitats are important to how impacted and/or resilient a site might be to an oil spill. The two large spills also caused considerable mortality among seabirds that brood on rocky islands, including thousands of common murres *Uria aalge*, and recovery times of bird populations are very slow (ONMS 2008).

ONMS (2008a) considered oil spills “the most serious threat to local populations of marine organisms,” and “a low-probability but high-impact threat.” This threat has resulted in changes in shipping policy and oil spill response readiness on the Washington Coast, including a voluntary “Area-to-be-Avoided” established in 2002 that guides larger vessels up to 25 nautical miles (46.3 km) offshore of sensitive coastal areas (ONMS 2008). Shipping accidents still pose a threat to Washington coastlines depending on the type of oil or fuel spilled and the direction and strength of winds and currents.

POLLUTION AND MARINE DEBRIS

In their recent status report, the ONMS (2008a) concluded that intertidal habitats within the Olympic Coast National Marine Sanctuary have not been substantially affected by human-derived chemical pollutants, rating overall water quality as “Good” or “Good/Fair” and trends as generally stable. This is in part a function of the small human population and low number of point and non-point sources along Washington’s outer coast. Pollutants from nearby systems (e.g., Grays Harbor or industrial discharges in the Strait of Juan de Fuca) could reach outer coast rocky habitats through oceanographic mixing processes, but the impacts of such pollutants are expected to be small except in the case of large accidental spills (Klinger et al. 2007).

Marine debris poses threats to some rocky shoreline inhabitants (e.g., marine mammals and seabirds) due to ingestion or entanglement. Tons of debris are continuously deposited on the Washington coast each year, mostly from non-local sources (Klinger et al. 2007). The annual Washington Coast Cleanup coinciding with Earth Day has removed on average over 24 tons of debris from beaches every year since 2000 (www.coastsavers.org). The ONMS (2008a) cited little evidence of ecological impacts of marine debris on rocky habitats along the Washington coast, although the annual cleanup events show no temporal trend in total debris removed (www.coastsavers.org), which implies that debris would likely accumulate without the cleanup efforts (Klinger et al. 2007). Marine debris may become more of a problem in future years because marine debris loading is increasing globally, although declines in activities such as nearshore commercial fishing may reduce debris incidence in Washington waters.

NON-INDIGENOUS SPECIES

Non-indigenous and potentially invasive species have been observed in rocky intertidal habitats of the Washington outer coast, although so far their abundance and extent appear to be limited (deRivera et al. 2005, Skewgar and Pearson 2011). The brown alga *Sargassum muticum* is considered a potential threat (ONMS 2008). Potentially invasive in more protected waters, *Sargassum* is found at some rocky sites on the outer coast, but its interactions with native algae and fauna have not been investigated extensively (Skewgar and Pearson 2011). Restrictive ballast water exchange policies, which force both domestic and, in particular, foreign vessels to exchange ballast far from shore, may help reduce spread of non-indigenous species, although ballast remains a concern due to the high volume of shipping through the Strait of Juan de Fuca (Klinger et al. 2007). Non-native species spread by other vectors as well, such as vessel hulls, aquaculture activities, floating debris, or natural dispersal from other established populations. Climate change may facilitate establishment of non-indigenous species as well.

TRAMPLING

Rocky intertidal flora and fauna risk being trampled or dislodged by human visitors causing unstable rocks to shift or walking directly on biota, which is particularly damaging to biota on rocky platforms (Klinger et al. 2007). The ONMS (2008a) reported that Olympic National Park visitation levels have been stable in recent years, and also concluded that impacts of human trampling were not substantial. However, a contemporary report for the National Park Service (Klinger et al. 2007) highlighted research in the Park and the nearby San Juan Islands in which trampling caused measurable impacts to barnacles and to the common brown alga *Fucus*. Skewgar and Pearson (2011) concluded that trampling effects can be important and persistent at areas where human visitation is focused.

HARVEST

Rocky habitats of the outer Washington coast experience some harvest of marine resources, such as removal of invertebrates for fishing bait; collection of marine animals by souvenir hunters; tribal treaty and subsistence harvest of intertidal organisms, including macroalgae; and limited recreational harvests as stipulated by the Washington Department of Fish and Wildlife and the Olympic Coast National Marine Sanctuary (Klinger et al. 2007, ONMS 2008, Skewgar and Pearson 2011). There is no clear evidence of widespread human harvest impacts in these habitats. Erickson and Wullschleger (1999) concluded that recreational harvest of most intertidal marine species in this area was low. However, this broad area is difficult to monitor and regulations are challenging to enforce (Klinger et al. 2007). The practice of scraping and denuding a rock for goose barnacles, mussels, or bait species obviously represents a small-scale disturbance, the recovery time from which is poorly studied (ONMS 2008, Skewgar and Pearson 2011). ONMS (unpublished report, cited in ONMS 2008) estimated that goose barnacles may need up to three years to recover from being scraped from a high energy rocky intertidal site.

CLIMATE CHANGE

The effects of anthropogenic global climate change were viewed by Halpern et al. (2009) as the top threat to West Coast ecosystems; in particular, many experts conclude that climate change poses a greater threat to rocky intertidal habitats than to any other coastal ecosystem in the California Current (Teck et al. 2010). There are many potential impacts of climate change on rocky intertidal sites:

- Climate change will affect the averages and extremes of local weather (warmer temperatures, drier summers, wetter winters, changes in cloud cover), which will impact some species' metabolic demands and/or distributional ranges.
- Changes in the seasonality and amount of rain will affect the seasonality of sedimentation via runoff (Klinger et al. 2007).

- Storm intensity is increasing, resulting in greater wave height and wave energy, higher wave incursion, and vulnerability to erosion (Allan and Komar 2006).
- Climate change is expected to cause an increase in sea level, which may cause erosion or accretion along the coast, elevate the distribution of wave energy, and may partly immerse some habitats, particularly gently sloped shoreline (Klinger et al. 2007).
- Air and water temperature increases may promote establishment or expansion of non-native species and alter community composition (Klinger et al. 2007, ONMS 2008).
- Climate change may cause circulation changes related to ocean winds and stratification, which may affect the intensity and timing of processes such as upwelling and bloom development. This, in turn, may affect organic matter availability and productivity in rocky intertidal habitats.
- If climate change affects the biomass or coverage of large nearshore kelp beds, it may alter the buffering of wave energy that kelp beds provide to adjacent rocky shoreline.
- Climate change may also cause human population relocation to areas such as the Pacific Northwest that are expected to be impacted less by climate change than other parts of the continental U.S. This acceleration in the region's population growth will likely lead to greater human use of rocky shoreline.
- Ocean acidification (OA) effects have been observed in water chemistry and biota at Tatoosh Island (Pfister et al. 2011, Wootton and Pfister 2012). Experiments indicate OA effects on key rocky intertidal species such as *Pisaster ochraceus* (increased growth rates; Gooding et al. 2009), *Nucella lamellosa* (shell dissolution; Nienhuis et al. 2010), and *Strongylocentrotus purpuratus* (reduced larval growth and metabolism; Matson et al. 2012, Padilla-Gamino et al. 2013).

SANDY BEACHES

Sand flats and beaches (henceforth "sandy beaches") of the Washington coast have received less attention among ecological researchers than other nearshore communities (rocky intertidal, kelp forest), despite the fact that sandy habitats make up roughly half of Washington's outer coastline (Skewgar and Pearson 2011). Thus, the conceptual model outlined below (Fig. 5) relies somewhat more on generalizations from the literature than other habitats considered in this chapter.

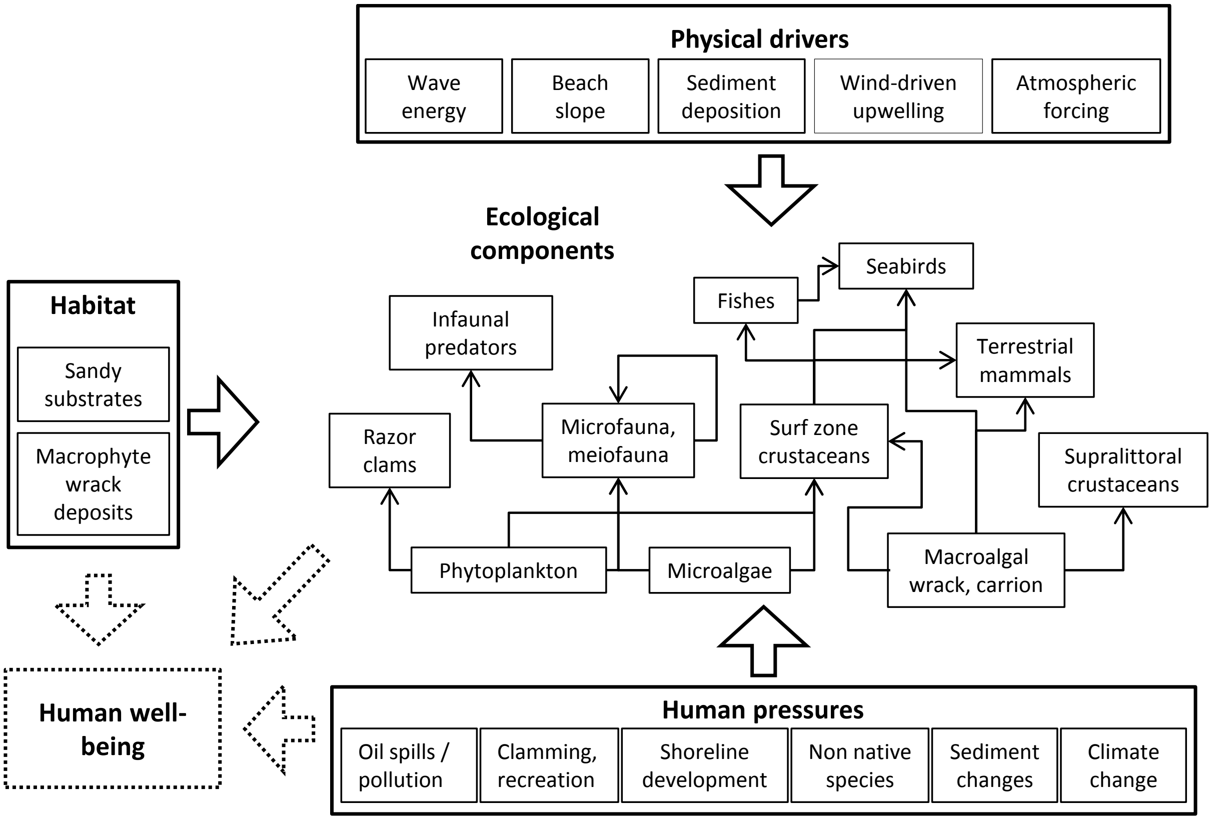

Figure 5. Conceptual model of important habitat, ecological components, physical drivers and human pressures for the sandy beach habitat.

HABITAT

INTRODUCTION

More than most marine ecosystems, physical controls are central to the ecology and functioning of sandy beaches (McLachlan 1990, Defeo and McLachlan 2005), and in large part physical forces appear to shape sandy beach community composition much more so than biological interactions (Defeo and McLachlan 2005). Even so, significant relationships between potential physical controls and biological metrics have proven difficult to find beyond some broad, general patterns (McLachlan et al. 1993), and much work remains to be done to understand physical forcing on Washington coastal sandy beaches. Below are some general findings about the structuring of sandy beaches.

WAVE ENERGY, ZONATION, AND GRAIN SIZE

Wave energy, the size of sand grains, and the elevation gradient interact to shape sandy beach systems. Sandy beaches are globally divided into three general morphodynamic categories: reflective, intermediate, and dissipative (McLachlan 1990). Reflective beaches tend to have steep slopes, coarse sand, low wave energy, small tide ranges, and no surf zones; most wave energy is reflected directly back into the sea. In contrast, dissipative beaches are relatively flat, have finer sand, high wave energy, large tide ranges, and broad surf zones; wave energy is thus dissipated across a long distance. Intermediate beaches fall between the extremes outlined above, and often feature sand bars, channels, and rip currents within their surf zones. Washington coast beaches are generally regarded as dissipative, particularly south of Point Grenville (e.g., Gelfenbaum and Kaminsky 2010, Skewgar and Pearson 2011).

Zonation by elevation is a defining physical feature of sandy beaches, and is related to the incursions and excursions of tides on daily, monthly, and annual cycles. McLachlan (1990) summarized general zonation categories as: a subterrestrial fringe (or supralittoral) zone at the upper tidal elevations, which receives little water from tidal input and is populated mainly by air-breathing fauna; a midlittoral zone that is rewetted with each tidal cycle, but drains substantially when emersed and retains only capillary water; a sublittoral zone that lies over the groundwater table on low tides; and a zone at the bottom of the shore that remains saturated and experiences little groundwater circulation. The exact boundaries between zones are fuzzy and spatiotemporally dynamic within and across beaches because beaches change constantly with daily and monthly tidal cycles, storms, and other physical forces (McLachlan and Jaramillo 1995, Knox 2000).

As noted elsewhere in relation to rocky shoreline, wave energy is influenced by several other factors. The profile of the coast is important, as wave energy tends to be focused on headlands and dissipate in bays. The aspect of the shoreline plays a role due to large-scale currents that move along the coast. For example, the poleward-flowing Davidson Current in winter would tend to exacerbate wave energy breaking on a south-facing rocky coastline. Wave energy is increased by winds and during storms, particularly the strong winter storms of our region. Offshore structures such as islands, reefs, or sea stacks may deflect wave energy.

ECOLOGICAL COMPONENTS

PRIMARY PRODUCERS

Local primary production on sandy beaches comes from surf zone phytoplankton, benthic diatoms and other small autotrophs (Knox 2000). Benthic production tends to be highest on fine-grained sand flats; sandy areas highly exposed to wave action have essentially no benthic carbon fixation. Surf zone phytoplankton can be highly productive in patches, again mostly on dissipative flat beaches (Defeo and McLachlan 2005), such as those south of Point Grenville. Total production on sandy beaches is heavily subsidized by organic matter input from adjacent ecosystems (see below, "Key Interactions").

INVERTEBRATE MACROFAUNA

The species most commonly associated with Washington sandy beaches is the razor clam *Siliqua patula*, a suspension feeder most abundant in the lower portions of flat, wave-swept beaches. Razor clams are highly sought by people for food as well as the recreational value of clam digging. Thousands of people participate in clam seasons each year on beaches along the southern coast of Washington, bringing great economic benefit to the region. Razor clams may also perform important ecological functions; for example, they can recycle sufficient ammonium into the nearshore water column to promote primary production of surf zone diatoms at Copalis Beach (Lewin et al. 1979).

Kozloff (1983) and Dethier (1991) note many other macroinvertebrates common to exposed sandy beaches on the Washington coast. Examples include several crustacean suspension and deposit feeders, such as opossum shrimp (mysids, e.g., *Archaeomysis grebnitzkii*) and amphipods (families Phoxocephalidae and Haustoriidae); burrowing shrimp of the genus *Crangon*; numerous burrowing polychaetes that are deposit feeders or predators; the burrowing purple olive snail *Olivella biplicata*, a carrion scavenger; another carrion scavenger, the isopod *Excirolana kincaidi*, known for painful bites; and ephemeral populations of mole crab *Emerita analoga*, which strain particulates from back-flowing waves. Most of these species are found at middle or lower tidal elevations; higher on the beach, often near the drift line, are crustacean scavengers such as beach hoppers (amphipods, family Talitridae) and isopods, as well as terrestrial arthropods.

INVERTEBRATE MEIOFAUNA AND MICROFAUNA

The meio- and microfaunal invertebrate communities that inhabit surface and interstitial habitats are important components of sandy beach ecosystem function (Knox 2000). However, they have received very little attention in sandy beaches of the Washington coast. Meiofaunal communities generally include small worms, crustaceans, mollusks, and cnidarians, while microfaunal communities mostly consist of unicellular heterotrophs. Studies on other sandy shores have suggested that most invertebrate standing biomass is far and away macrofauna, but that meiofauna outnumber macrofauna by an order of magnitude and microfauna outnumber meiofauna by several orders of magnitude (Knox 2000). These groups have high diversity in temperate beaches, process significant amounts of organic matter, and support higher trophic levels (e.g., macroinvertebrates, juvenile fishes), though their overall roles in the function of Washington coastal beaches have not been quantified.

VERTEBRATES

Dozens of species of small-bodied fishes and juveniles of larger fishes inhabit the subtidal waters along sandy beaches in our region (Klinger et al. 2007, ONMS 2008, Skewgar and Pearson 2011), and some (e.g., surf smelt *Hypomesus pretiosus*) spawn in intertidal sand substrate (ONMS 2008). Common fishes are sculpins (family Cottidae), sand lance (*Ammodytes hexapterus*), surfperches (family Embiotocidae), juvenile tomcod (*Microgadus proximus*), and flatfishes (mainly family Pleuronectidae).

Beside humans, the most influential and conspicuous vertebrates on sandy beaches are birds. Many species of gulls, diving birds, wading birds, shorebirds and crows forage on sandy beaches at high and low tides (Skewgar and Pearson 2011). Sandy beaches are also visited by foraging terrestrial mammals.

The dependence of vertebrate populations on these beaches has not been quantified to any great extent, nor has the role that they play in beach ecosystem function.

KEY INTERACTIONS

THE INFLUENCE OF BEACH STRUCTURE ON BIOMASS AND BIODIVERSITY

The interacting physical forces that structure beach zonation, grain size, moisture content (see above, "Habitat") have strong influence on sandy beach community composition. In theory, reflective beaches should have lower biomass and biodiversity than dissipative beaches (Eleftheriou and Nicholson 1975, McLachlan et al. 1981), and this expectation holds up for dissipative, species-rich sandy beaches in nearby Oregon relative to less-diverse, less-productive reflective and intermediate beaches from the Southern Hemisphere (McLachlan 1990). One possible mechanism is that dissipative beaches allow sand-dwelling consumers longer periods of time between swashes of tide, enabling more time for feeding and movement and thus supporting a greater diversity of microhabitats, niches, body sizes, and modes of locomotion (McLachlan 1990, McLachlan et al. 1993). Defeo and McLachlan (2005) hypothesized that dissipative beaches were the most likely to achieve high enough levels of species abundance and diversity that biotic interactions (e.g., competition, predation, density dependence) would become important parts of community regulation.

Elevation changes and moisture gradients seem to track community structure on sandy beaches. McLachlan (1990) and McLachlan and Jaramillo (1995) noted the consistency of zonation categories (supralittoral, midlittoral and sublittoral) with shifts in community composition and niche function in sandy beach habitats. Jarrin and Shanks (2011) found that tidal height influenced the benthic invertebrate assemblage on a dissipative Oregon sandy beach, but not the swimming assemblage moving in and out with the tides.

IMPORT OF PHYTOPLANKTON, DETRITUS AND MACROPHYTES

The substrate size, instability and wave exposure of sandy beaches on the outer coast precludes the presence of substantial macrophytes; most endogenous primary production is due to surf zone phytoplankton, benthic diatoms and other single-cell autotrophs (Knox 2000). Wave-borne phytoplankton and particulate organic matter from the offshore pelagic ecosystem provide valuable subsidies of organic materials for suspension and deposit feeders on sandy beaches; in fact, Knox (2000) reported that particulate organic matter concentrations on sandy beaches are typically much higher and more temporally consistent than endogenous microalgae. Detached macrophytes from nearby kelp bed or rocky intertidal ecosystems further provide organic matter for scavengers, but also produce microhabitats for surf zone fish in the water or for invertebrates once deposited on the beach (e.g., Knox 2000, Jarrin and Shanks 2011). Rafts of kelp or algae often have abundant invertebrates as well, and thus provide food for larger consumers. Jarrin and Shanks (2011) found that the presence of detached macrophytes explained variation in sandy beach community diversity and abundance of certain species.

IMPORTANT PHYSICAL DRIVERS

SEDIMENT DEPOSITION

Sandy beaches of coastal Washington receive most of their sand from the Columbia River (reviewed in Gelfenbaum and Kaminsky 2010). Generally, sand export from the Columbia moves to the north and is deposited on the continental shelf in the winter, when the Columbia River plume is moving north and strong waves, storms, and high sea levels transport sediments offshore; later, during the milder weather of the spring and summer, the sand deposited on the shelf during the winter is transported onshore by swells and waves (Ruggiero et al. 2005). The timing and extent of onshore transport and beach accretion are functions of distance from the mouth of the Columbia River and of longshore transport processes, and predictive models of beach growth/retreat within the Columbia River littoral cell are improving in their data content, performance, and application (Gelfenbaum and Kaminsky 2010).

UPWELLING

Upwelling-derived plankton and detritus provide a principal food source for lower trophic levels on Washington sandy beaches, as well as nutrients for benthic microalgae. Upwelled waters are also relatively cool and therefore may lower metabolic rates and energy demands for fishes and invertebrates (Sanford 1999).

Upwelling may also be involved in recruitment dynamics on sandy beaches. Upwelling timing, intensity, and relaxation may affect larval supply and growing conditions (temperature, productivity) in coastal habitats, and there may be interspecific or interguild differences in recruitment as well (e.g., Barth et al. 2007). However, there is some debate as to whether upwelling is a causal mechanism for regional patterns of recruitment variability (e.g., Menge 2000, Connolly et al. 2001, Morgan et al. 2009, Shanks and Shearman 2009).

WEATHER AND CLIMATE

Sandy beach organisms, particularly those that spend at least some time above the tide level, are subject to local weather conditions that range from full sunlight and relatively warm temperatures in the summer to freezing conditions or heavy rains in the winter. Intertidal organisms have differing degrees of tolerance to weather-related variables such as temperature, UV light exposure, desiccation, wave energy, and salinity. Unlike the rocky intertidal habitats, however, sandy beach invertebrates tend to be mobile, and behaviors like burrowing, moving with the tide, or nocturnal habits can buffer sandy beach invertebrates from weather stresses (Kozloff 1983, Knox 2000). Seasonal storms or winds can intensify wave size and frequency, resulting in greater exposure to wave energy and causing sand to shift (Kozloff 1983). Rainfall can affect sand saturation and groundwater table height (McLachlan 1990) as well as local salinity. While these variables have a strong seasonal component, they can vary interannually due to large-scale climate anomalies, such as El Niño or La Niña events, or interdecadally due to large-scale climate regime shifts. In addition, long-term global climate change is expected to affect regional weather variables on both annual and seasonal time scales in the coming decades (e.g., Mote and Salathe 2010, Salathe et al. 2010; also see the Climate Change discussions at the beginning of this chapter and below under "Important Human Pressures").

Empirical and modeling studies have shown that interannual climate anomalies also affect sandy beach formation and ecology. El Niño events, for example, transport sand to the north along the Washington coast due to changes in wave direction and higher sea levels, which causes shoreline retreat along the southerly part of the coast (Gelfenbaum and Kaminsky 2010, Ruggiero et al. 2010). El Niño conditions may also promote growth of a prokaryotic parasite that causes high episodic mortality in razor clams (Elston 1986, Klinger et al. 2007).

HUMAN PRESSURES

Although many human practices affect (or have the potential to affect) Washington's sandy shores, we will focus here on pressures that have been explicitly cited in recent status reports as substantial current or pending threats (Klinger et al. 2007, ONMS 2008, Skewgar and Pearson 2011). Many but not all (e.g., Shoreline Development, Harvest) of these pressures and threats are similar to those described for intertidal rocky habitats elsewhere in this report.

SHIPPING AND OIL SPILLS

Due to the large volume of shipping that moves through the Strait of Juan de Fuca, the number of non-cargo vessels moving along the coast, and the volume of petroleum that is refined in Washington state, the threat of oil spills is significant in coastal waters (ONMS 2008, Skewgar and Pearson 2011). Two large spills in the late 20th Century (the *Nestucca*, 231,000 gallons of fuel oil near Grays Harbor in 1988; the *Tenyo Maru*, 100,000 gallons of diesel fuel offshore of the Makah Reservation in 1991) caused short-term and long-term impacts along the Washington coast, although the overall long-term effects of the *Nestucca* spill on many intertidal sites were judged to be minor (Dethier 1991, Klinger et al. 2007).

ONMS (2008a) considered oil spills to be "the most serious threat to local populations of marine organisms," and "a low-probability but high-impact threat." This threat has resulted in changes in shipping policy and oil spill response readiness, including a voluntary "Area-to-be-Avoided" established in 2002 that guides larger vessels up to 25 nautical miles (46.3 km) offshore of sensitive areas of the Washington coast (ONMS 2008). Shipping accidents still pose a threat to Washington coastlines depending on the type of oil or fuel spilled and the direction and strength of winds and currents.

In a recent review,Defeo et al. (2009) described oil spills as a major destructive threat to sandy beaches, and characterized the susceptibility of beaches to oil spill impacts. Coarse-sand, reflective beaches (i.e., the type more typical in northern areas of the outer coast of Washington) allow for rapid and deep penetration of oil, perhaps to the groundwater table. However, dissipative, fine-sand beaches (more typical of the southern areas of the outer Washington coast) may be more sensitive due to the lower rates of wave flushing; these are also the beaches that tend to have the greatest biodiversity (McLachlan

1990, Defeo and McLachlan 2005). Oil breakdown is a function of physical factors (grain size, wave energy, temperature, microbial responses, etc.).

POLLUTION AND MARINE DEBRIS

According to their recent status report, the ONMS (2008a) concluded that intertidal habitats within the Olympic Coast National Marine Sanctuary have not been substantially affected by human-derived chemical pollutants, rating overall water quality as “Good” or “Good/Fair” and trends as generally stable. This is in part a function of the small human population and low number of point and non-point sources along Washington’s outer coast. Pollutants from nearby systems (e.g., Grays Harbor) likely reach coastal sandy beach habitats, but the impacts of such pollutants are assumed to be small except in the case of large accidental spills (Klinger et al. 2007).

Marine debris poses threats to some sandy beach inhabitants (e.g., shorebirds and seabirds) due to ingestion or entanglement. Tons of debris are continuously deposited on the Washington coast each year, mostly from non-local sources (Klinger et al. 2007). The annual Washington Coast Cleanup coinciding with Earth Day has removed on average over 24 tons of debris from beaches every year since 2000 (www.coastsavers.org). The ONMS (2008a) cited little evidence of ecological impacts of marine debris on habitats along the Washington coast, although the annual cleanup events show no temporal trend in total debris removed (www.coastsavers.org), which implies that debris would likely accumulate without the cleanup efforts (Klinger et al. 2007). Marine debris may become more of a problem in future years because marine debris loading is increasing globally, although declines in activities such as nearshore commercial fishing may reduce debris incidence in Washington waters.

NON-INDIGENOUS SPECIES

Of the potential stressors of sandy beach habitats in the California Current, surveyed experts rated invasive species the greatest threat by far (Teck et al. 2010). Most of the rapid assessment sites for non-indigenous species in the Olympic Coast National Marine Sanctuary in 2001-2002 had rocky substrate (deRivera et al. 2005), so this is a data gap for Washington coastal sandy beaches. However, the abundance and extent of non-indigenous and potentially invasive species appear to be rather limited along the outer coast of Washington to date (deRivera et al. 2005, Skewgar and Pearson 2011). Restrictive ballast water exchange policies, which force domestic and, in particular, foreign vessels to exchange ballast far from shore, may help reduce spread of non-indigenous species, although ballast remains a concern due to the high volume of shipping through the Strait of Juan de Fuca (Klinger et al. 2007). Non-native species spread by other vectors as well, such as vessel hulls, aquaculture activities, floating debris, or natural dispersal from other established populations. Climate change may facilitate establishment of non-indigenous species as well.

SEDIMENTATION

The core processes that control Columbia River sand export and deposition along the Washington coast are millennial in scale. However, contemporary anthropogenic activities have had significant effects on both deposition and erosion of sand over the past century (Gelfenbaum and Kaminsky 2010). The three major activities that have contributed to beach erosion are jetty construction, dredging, and the construction of >200 dams in the Columbia River drainage. Jetty construction at the mouths of the Columbia River and Grays Harbor once promoted strong progradation of beaches for decades. More recently, the modification of shoreline orientation has diverted sand transport, leading to localize shoreline retreat. Furthermore, dredging sand from the mouth of the Columbia and dumping it over the continental shelf results in the permanent export of ~1.5 million m^3 of sand each year from the littoral zone, while dams reduced annual sand transport down the Columbia River by three-fold over the last century, from 4.3 million m^3/year to 1.4 million m^3/year (Gelfenbaum and Kaminsky 2010).

SHORELINE DEVELOPMENT

Development adjacent to sandy beach ecosystems of coastal Washington is low, thanks to the remoteness of the region, the low human population, the restricted use of tribal lands, and the extensive protections provided by park or sanctuary designation (ONMS 2008). However, there are growing population centers along the southern portion of the coast, and U.S. Highway 101 has increased access to many points along the coast (Klinger et al. 2007). Human development activities such as land conversion, road building, timber harvest, and light and noise pollution thus are growing threats, although these are offset somewhat by stricter regulations designed to minimize impacts of these activities (ONMS 2008).

HUMAN VISITATION AND RECREATION

Human visitation and activity on sandy beaches for purposes such as beachcombing, clam digging, surfing, and other recreation was not regarded as a serious impact in recent status updates (Klinger et al. 2007, ONMS 2008, Skewgar and Pearson 2011). This may be related to seasonal human use patterns, coupled with the high degree of natural disturbance and turnover that these habitats experience (e.g., Defeo et al. 2009). The most vulnerable species to human presence on or near sandy beaches may be birds. Birds can be flushed or harmed by human activities, noises, motor vehicles, the presence of dogs, or other activities; these disturbances can result in nest destruction or abandonment (ONMS 2008, Skewgar and Pearson 2011).

HARVEST

Most harvest effort on Washington sandy beaches is directed at razor clams, mainly in tribal and recreational fisheries (Klinger et al. 2007, ONMS 2008, Skewgar and Pearson 2011). The fishery is jointly managed by the Washington Department of Fish and Wildlife (WDFW), the Hoh and Quinault tribes, and the National Park Service, in conjunction with seafood safety monitoring conducted by the Washington State Department of Health. These agencies jointly determine harvest limits each year, based in part on population surveys conducted by the WDFW; maximum harvest rates are set at a percentage of the total clams on a beach above a size limit (~7.5 cm), with percentages ranging from 25.4% to 50% depending on beach location and fishery type (recreational, tribal, or both; for more information, see wdfw.wa.gov/fishing/shellfish/razor clams). Most clam digging occurs in the southern portion of the coast (Klinger et al. 2007).

Recreational harvest of other species generally appears to be fairly low (Klinger et al. 2007). Although macrophyte harvest is prohibited along much of the coast (e.g., within the boundaries of Olympic National Park and Washington State Parks), enforcement is difficult and some harvest likely occurs (Klinger et al. 2007). This is a potential threat because of the value of macrophyte wrack as habitat and a food subsidy for sandy beach ecosystems (Defeo et al. 2009)

CLIMATE CHANGE

The effects of anthropogenic global climate change were viewed by Halpern et al. (2009) as the top threat to West Coast ecosystems. Climate change may influence regional weather patterns as well as oceanographic variables, with ramifications for Washington coastal sandy beaches that include:

- Climate change will affect the averages and extremes of local weather (warmer temperatures, drier summers, wetter winters, changes in cloud cover), which will impact some species' metabolic demands and/or distributional ranges.
- Changes in the seasonality and amount of rain and storms will affect the seasonality of sedimentation via runoff (Klinger et al. 2007).
- Storm intensity is increasing, resulting in greater wave height and wave energy, higher wave incursion, and vulnerability to erosion (Allan and Komar 2006); however, Ruggiero et al. (2010) predict that El Niño effects on sand transport will be greater than projected changes caused by increased storm-driven wave height. Thus, the effect of climate change on El Niño frequency may be a more important determinant of coastal sand budgets.
- Climate change is expected to cause an increase in sea level, which may exacerbate erosion or accretion along the coast, elevate the distribution of wave energy, and may partly immerse some habitats, particularly gently sloped shoreline (Klinger et al. 2007).
- Air and water temperature increases may promote establishment or expansion of non-native species and alter community composition (Klinger et al. 2007, ONMS 2008).
- Climate change may cause circulation changes related to ocean winds and stratification, which may affect the intensity and timing of processes such as upwelling and bloom development. This, in turn, may affect organic matter availability and productivity in sandy beach habitats.
- Climate change impacts on nearby kelp beds or macrophyte production in adjacent rocky intertidal habitats could affect the supply of drifting kelp or macrophyte detritus that subsidizes sandy beach production.
- Climate change is believed to be exacerbating the frequency, size intensity and toxicity of harmful algal blooms (HABs) for species such as *Pseudo-nitzschia* and *Alexandrium* (Moore et al.

2008, Fu et al. 2012), which would negatively affect human health, harvests of razor clams and other shellfish, and coastal economies and way of life.

- Climate change may cause human population relocation to areas such as the Pacific Northwest that are expected to be impacted less by climate change than other parts of the continental U.S. This acceleration in the region's population growth will likely lead to greater human use of sandy beaches.
- Ocean acidification (OA) could affect populations of calcifying sandy beach organisms (crustaceans, mollusks, echinoderms).

KELP FORESTS

We include two general types of habitat in our definition of kelp forests for the Washington Coast: 1) habitats that consist of floating kelp canopies of bull kelp *Nereocystis leutkeana* or giant kelp *Macrocystis pyrifera* and, 2) rocky reefs that occur at depths <30m. We considered rocky reefs in this category also because many of the species that inhabit kelp forests also inhabit shallow rocky reefs without kelp. We used 30m as a cut-off point from seafloor habitat because this is often cited as the depth that most local kelps and other structure-forming algae do not grow below due to light limitations (Springer et al. 2006, Mumford 2007). The conceptual model outlined below (Fig. 6) represents an attempt to capture the dominant drivers and ecological interactions that characterize kelp forest habitats, particularly those of the Washington coast.

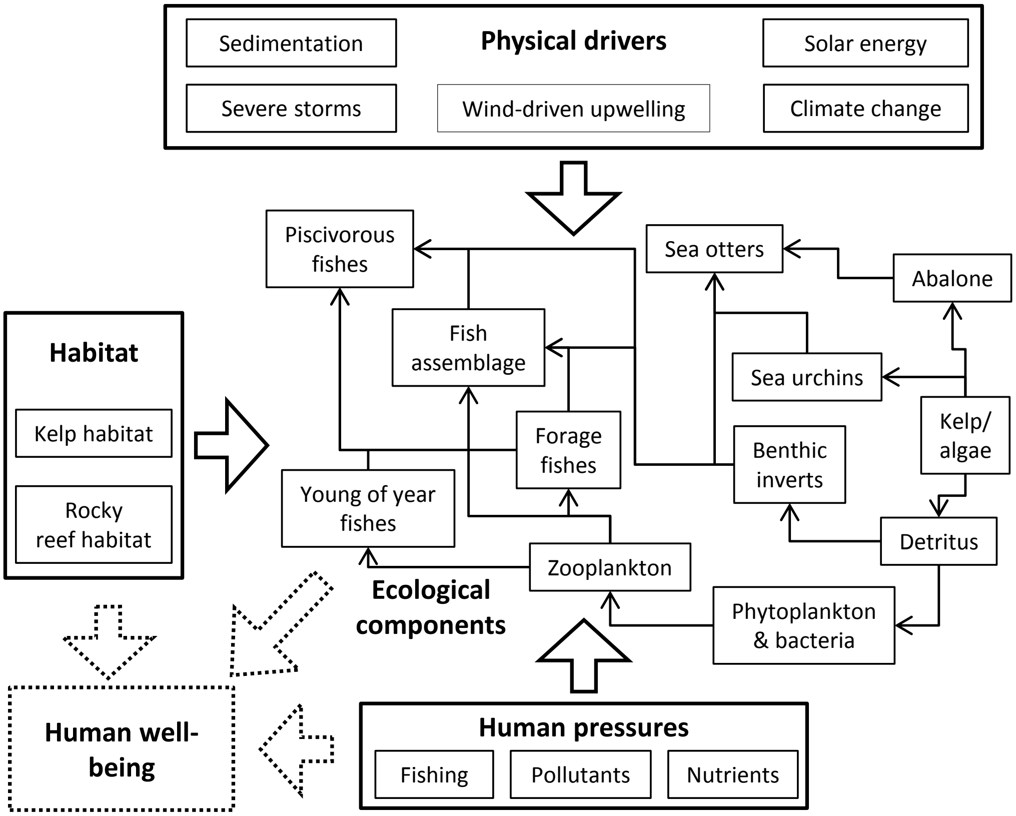

Figure 6. Conceptual model of important habitat, ecological components, physical drivers and human pressures for kelp forest habitat.

HABITAT

Kelp forests form diverse communities tied directly to the production of energy from the kelp (Dayton 1985, Graham 2004); however, most kelp forests only exist in waters less than 60 m deep. Changes in kelp forest coverage affect recruitment of invertebrates and other species (rockfish in particular); such that kelp forest coverage could anticipate recruitment of older life stages into bottom trawl surveys or local fisheries. Indexes of kelp biomass using satellite imagery exist, so cost should be limited to data mining.

Two canopy-forming kelp species inhabit Washington waters: giant kelp *Macrocystis pyrifera* and bull kelp *Nereocystis leutkeana*. The annual bull kelp grows at depths between the extreme low tide line and 10-30 m, whereas the perennial giant kelp prefers shallower depths from the low intertidal to 4 m (Mumford 2007). The ShoreZone database (Washington Department of Natural Resources) lists floating kelp as absent, patchy, or continuous along each segment of shoreline. On the outer coast, this survey recorded 55 km of linear shoreline with patchy or continuous kelp. According to analysis of aerial photographs from 1989-2004, kelp canopy increased on the northern outer coast and in the western Strait of Juan de Fuca, with higher variance in bull kelp than giant kelp canopy cover (Berry et al. 2005).

These primary producers provide habitat by serving as surface area for sessile organisms and refuges for young fish (Carr 1991). This complex structural component serves as a nursery and foraging area for a variety of fishes, especially rockfishes, sculpins, greenling, lingcod, perch, juvenile salmon, and others, including many fish on Washington's list of Species of Concern. Herring spawn on kelps, invertebrates such as octopi and snails use these large algae as habitat, and sea urchins feed on them. Some smaller algae live preferentially under the canopy provided by the forest-forming kelp species. Kelp beds are the preferred habitat of the northern abalone (*Haliotis kamtschatkana*), a Species of Concern in the state. This habitat provisioning role is therefore important for structuring the food web within the ecosystem. Both the total extent of surface canopy, as well as the characteristics, particularly area and density, of the kelp beds affects the species assemblages found in this habitat. Trends in kelp bed characteristics thus provide insight into ecosystem condition and also provide important information to interpret trends in fish and invertebrate populations. Kelp populations fluctuate seasonally and inter-annually depending on oceanographic conditions as well as herbivore pressure. Interpretation of trends in kelp cover will therefore consider additional information about physical drivers of this system, including temperature and swell heights (Skewgar and Pearson 2011).

Floating kelp also provides a surface habitat where wind waves are dampened, and this semi-protected surface is used as foraging habitat by scoters, loons, grebes, goldeneyes, buffleheads, and harbor seals. Sea otters feed primarily in kelp-dominated habitat, and preferentially rest in nearshore areas among floating kelp beds (Laidre et al. 2009). Sea otter distributions and sea urchin harvest may influence kelp abundance (Berry et al. 2005; Laidre et al. 2006). Large kelp beds are also thought to physically affect adjacent shoreline communities by damping wave energy and thereby providing some protection for otherwise-exposed coastlines (Eckman et al. 1989). Kelp beds have been shown to indirectly affect nearby intertidal communities by harboring the predators of the larvae of intertidal invertebrates (Gaines and Roughgarden 1987).

Kelp forests and other macroalgae also play a key role in producing detritus (Duggins and Eckman 1994). Approximately 500 species of green, brown, and red algae have been documented on the coast (Waaland 1997). Sections or entire plants break loose during storms and wash up on beaches, where they are scavenged by small crustaceans, insects, and other scavengers. Decomposing kelp supplies dissolved organic matter and particulate organic matter to the nearshore waters (Mumford 2007). Erosion of growing kelp leaves also supplies particulate and dissolved organic matter to the water column, fueling bacterial growth which supplies zooplankton and benthic filter-feeders. Kelp-derived carbon outstrips the contribution of phytoplankton in nearshore food webs where it is present (Duggins et al. 1989).

During the 1997 El Niño event, total kelp canopy in Washington decreased by 32%. Bull kelp populations along the outer coast were reduced by 75% (compared to only 8% reductions for Macrocystis). While mortality associated with strong storm events and wave action also have the potential to reduce the size of Nereocystis beds, the weedy nature of bull kelp might allow the species to rapidly recolonize impacted areas following the removal of more competitively dominant species of algae such as *Macrocystis*. In 1998, following the reductions in bull kelp abundance in Washington described above, *Nereocystis* populations rebounded dramatically, increasing by 423% (Berry et al. 2001). This may be evidence of a positive effect of storms on bull kelp abundance arising from temporary release from competition with other algal species for light, nutrients, or primary space. The timing and intensity of storms, and the identity and abundance of competing species of sympatric algae are probably important in determining the nature of strong storm and wave disturbance on bull kelp (Skewgar and Pearson 2011).

ECOLOGICAL COMPONENTS

PHYTOPLANKTON AND BACTERIA

Phytoplankton and bacteria are essential to all habitats as the base of the food web. The growth of phytoplankton and bacteria is dependent on solar irradiance and nutrients. Coastal upwelling provides nutrients to the Washington Coast. In kelp forest habitat, kelps erode and decompose into particulate and dissolved organic matter (Mumford 2007), which supports a strong bacterial community that fuels phytoplankton and benthic filter-feeder growth in the nearshore environment (Duggins et al. 1989). Zooplankton communities, including larvae of commercially-important fishes and invertebrates, prey on the phytoplankton community and support the rest of the food web.

DETRITUS

As kelps grow and senesce, they erode, fragment, become dislodged and release particulate and dissolved organic matter which is a significant source of organic carbon for nearshore and intertidal communities (Duggins et al. 1989). Detritus settles within kelp forests and is exported to neighboring habitats, including sandy beaches, rocky intertidal shores, subtidal areas, as well as the deep sea. Exported kelp detritus can provide a significant resource subsidy and enhance secondary production in these communities ranging from tens of meters to hundreds of kilometers from the source of production (Krumhansl and Scheibling 2012). Drift kelp is widespread in deep-subtidal environments in the San Juan Islands, WA and common grazers of drift material were seen to be associated with depths and habitats where drift kelp was most abundant (Britton-Simmons et al. 2012).

ZOOPLANKTON

Zooplankton in the kelp forest often consist of invertebrate larvae from nearshore intertidal communities (Gaines and Roughgarden 1987). This prey base is essential for young-of-year, juvenile, and planktivorous adult fishes and invertebrates. Characterizing the zooplankton community is often indicative of how productive higher trophic levels will be. Zooplankton species vary considerably in their lipid content and communities with higher lipid-content often support higher levels of growth and survival in their predators (e.g., Peterson 2009).

SEA URCHINS

There are three common sea urchin species in Washington: red *Strongylocentrotus franciscanus*, purple *Strongylocentrotus purpuratus* and green *Strongylocentrotus droebachiensis*. Sea urchin grazing is the primary cause of kelp deforestation, creating what is commonly known as urchin barrens (e.g., Chapman 1981, Dayton et al. 1984, Harrold and Reed 1985). Most kelp forest habitats have, at some time in their history been deforested to barrens by sea urchins (Steneck et al. 2002). The loss of kelp forest habitat has cascading effects throughout the ecosystem and thus, the abundance of sea urchins is an important indicator of the stability of kelp forest habitats.

The abundance of sea urchins is notably controlled by predation. The most commonly described mechanism of sea urchin population increases and resulting kelp deforestation occurred when predators of urchins were removed due to fishing pressure (as reviewed by Steneck et al. 2002). Sea otters and crabs are the most notable predator on sea urchins in the North Pacific, but the trophic effects of the sea otter-sea urchin interaction have not been quantified in Washington.

PINTO (NORTHERN) ABALONE

The Pinto or Northern abalone *Haliotis kamtschatkana* is a federally listed Species of Concern and is the only abalone species found in inland waters of Washington State. It ranges from Sitka, Alaska, to Pt. Conception, California, in patchy distribution but is predominantly found in Washington, British Columbia, and Alaska, but distribution is patchy (Abalone Recovery Team 2004, NOAA 2004). Northern abalone occur in a wide range of habitats from fairly sheltered bays to exposed coastlines, but the populations with the highest densities are found in areas with the highest wave exposure (Lessard and Campbell 2007). Habitat is predominantly kelp beds along outer well-exposed coasts; typically low intertidal to 30 feet depth, but ranges to 100 m depth (Abalone Recovery Team 2004, NOAA 2004). Within the nearshore, exposed or semi-exposed coastal waters, northern abalone play the role of herbivore and are prey of many species. Young northern abalone feed on diatoms and micro-algae. Food for juveniles and adult abalone includes macroalgae and kelp.

Dramatic declines have occurred throughout their range, with no indication of recovery despite commercial fishery closures in 1990 in British Columbia and 1995 in Alaska. The species is highly susceptible to overexploitation due to patchy distribution, short larval period, slow growth, low sporadic recruitment, and aggregation of adults during spawning. Recovery of northern abalone may be related to the abundance and health of kelp forests in certain areas. Northern abalone compete with other species (e.g., red sea urchins, *Strongylocentrotus franciscanus*) for food, and interactions with these species are considered in the recovery strategy as well as the combined effects of legal recreational/subsistence harvest and suspected illegal harvest, low recruitment levels due to the Allee effect, and predation caused by reintroduction and recovery of sea otters (Abalone Recovery Team 2004, NOAA 2004).

FISH ASSEMBLAGE

There are several important components of the fish assemblage in kelp forests. First, young-of-year (YOY) fishes take advantage of refuge and abundant food supplies in kelp forest habitats. For many species, particularly rockfishes, individuals settle out of the plankton into kelp habitats, grow, and then move to offshore waters; thus, kelp forests are often thought of as source populations for the next generation or sources for fishes that eventually recruit into local or offshore fisheries. Juvenile salmon also appear to preferentially use kelp bed habitats over unvegetated habitats along the Washington Coast (Shaffer 2004).

Forage fishes, such as sand lance *Ammodytes hexapterus* and surf smelt *Hypomesus pretiosus*, are common components of shallow rocky reefs and kelp habitats and provide a prey base for the rest of the fish assemblage. Sand lance and herring species were the dominant prey items of juvenile (10-50 cm) lingcod in the San Juan Islands (Beaudreau and Essington 2007).

Conspicuous members of the rest of the fish assemblage include several rockfish species (e.g., black *Sebastes melanops*, copper *S. caurinus*, quillback *S. maliger*, yellowtail *S. flavidus*), greenlings (*Hexagrammus decagrammus* and *H. lagocephalus*), perches (*Rhacochilus vacca* and *Cymatogaster aggregata*), and lingcod *Ophiodon elongatus*. Many species in the fish assemblage are opportunistic predators, feeding on a wide variety of zooplankton, benthic invertebrates, forage fishes, and other piscivorous fishes depending on abundance of preferred prey items.

Lingcod are generally the top fish predator in kelp forests or shallow rocky reefs. Population estimates of lingcod along the Washington and Oregon coast declined rapidly in the 1980's and early 1990's. Greatly reduced harvest levels began to be implemented in 1994 (Jagielo and Wallace 2005) and lingcod populations have rebounded to levels of ~60% of virgin biomass (Hamel et al. 2009).

SEA OTTERS

Sea otters inhabit nearshore waters up to 20 fathoms deep and seldom venture more than 1-2 km from land. They typically inhabit rocky habitats with kelp beds, but also occur at lower densities in soft-sediment areas without kelp. Kelp is generally considered an important part of habitat and is used for foraging and resting. Sea otters capture prey from the sea bottom, and then carry it to the surface for handling and feeding. A variety of prey is eaten, especially in areas inhabited for long periods. In Washington, prey includes urchins, abalone, clams, mussels, crabs, snails, and chitons (Bowlby et al. 1988, Laidre and Jameson 2006). Predation on urchins gives sea otters a fundamental role in maintaining the structure of nearshore marine ecosystems in many areas (Estes and Duggins 1995, Kvitek et al. 1998). Removal of urchins promotes the growth of kelp and kelp-associated communities.

The species once lived along most of the North Pacific coast from California to Japan, but was extirpated from most of its range by the early 1900s because of the fur trade (Kenyon 1969). In Washington, sea otters historically occurred in estuarine and sandy habitats from the Columbia River to Pt. Grenville, along the rocky outer Olympic Peninsula coast, and into the Strait of Juan de Fuca, but with few reaching the San Juan Islands and Discovery Bay, and none present in Puget Sound (Scheffer 1940, Kenyon 1969). The species was extirpated from the state by about 1910 (Scheffer 1940, Kenyon 1969). Sea otters were reintroduced to Washington in 1969 and 1970, when 59 animals were translocated from Amchitka Island, Alaska (Lance et al. 2004). The population has grown steadily at 7.9% per year since 1989 to 1,154 animals in 2011 (Jameson and Jeffries 2011). However, overall population growth has slowed since 2008 and the northern population segment may be reaching carrying capacity. At present, otters occur primarily in rocky habitats along the Olympic Peninsula coast from Destruction Island northward to Tatoosh Island. Colonization of the western Strait of Juan de Fuca has not yet occurred despite the presence of groups of animals using the area during fall and winter months until 2000 (Laidre et al. 2009). A state recovery plan for the otter was written in 2004 (Lance et al. 2004).Sea otters in Washington face a number of potential threats (Lance et al. 2004). These include oil spills, contaminants, disease, marine biotoxins, entanglement in fishing nets, loss of kelp habitat, and reduced genetic diversity.

KEY INTERACTIONS

SEA OTTER/SEA URCHIN/KELP TROPHIC CASCADE

The trophic cascade that occurs when sea otters are removed from kelp forest habitats has been well documented in the Pacific Ocean (Duggins 1980, Ebeling and Laur 1988. , Estes and Duggins 1995, Estes et al. 1998). Although direct effects of the sea otter-sea urchin interaction have not been quantified in Washington waters, correlative studies have shown decreases in urchins and increases in foliose algae in areas that became inhabited by sea otters between 1987 and 1995 (Kvitek et al. 1998). Trophic interactions are not limited to this single pathway, however. Barnacles and mussels grow three to four times faster in kelp forests with sea otters than in otter-free urchin barrens (Duggins et al. 1989); rock greenling are approximately ten times more abundant in kelp forests with sea otters than in otter-free urchin barrens (Reisewitz et al. 2006); the diets of glaucous winged gulls contain about 90 percent fish in kelp forests with otters and about 90 percent intertidal invertebrates in otter-free urchin barrens (Irons et al. 1986); and bald eagles shift their diet from an even mix of fish, marine mammals, and seabirds to one dominated by seabirds (~80 percent by number of prey consumed) when otters are absent (Anthony et al. 2008). Many of these patterns are caused by the loss of kelp, which provides highly-productive three-dimensional habitat capable of providing structurally-complex refuge, concentrating plankton, and modifying wave heights and current velocity.

IMPORTANT PHYSICAL DRIVERS

There are numerous physical drivers that affect the marine environment simultaneously. In addition to the drivers acting upon the entire Washington Coast (described above), we briefly describe the major physical drivers acting upon kelp forest habitats below.

CLIMATE CHANGE

Large-scale atmospheric forcing of the oceans provides the backdrop for the potential productivity of kelp forests, with cool-water regimes being more productive than warm-water regimes. Kelp forest habitats are particularly influenced by El Niño events, in which large storm-driven waves and nutrient-poor waters result in the decimation of kelp forests, or La Niña events, in which cold, nutrient-rich waters allow for extraordinary growth conditions (Dayton and Tegner 1984, Tegner and Dayton 1987, Tegner et al. 1997). During the 1997 El Nino event, total kelp canopy in Washington decreased by 32%: bull kelp *Nereocystis leutkeana* populations declined by 75%, while giant kelp *Macrocystis pyrifera* declined by 8% (Berry et al. 2001). Determining whether the frequency, duration, and strength of El Nino events is changing is a topic of considerable research (Collins et al. 2010, Vecchi and Wittenberg 2010). Any changes, particularly increases, in these metrics will have direct effects on the vulnerability of kelp forests in the future.

UPWELLING

Upwelling of cold, nutrient-rich waters provides the necessary environment for kelps and other structural-forming algae to grow and reproduce at high rates. Suppression of upwelling reduces the amount of cold, nutrient-rich water brought into shallow subtidal areas and can lead to warming of surface waters by up to 4°C for extended periods (McPhaden 1999). This is particularly relevant to Washington waters because the dominant species, bull kelp, is sensitive to increases in water temperature and the availability of nutrients (Schiel et al. 2004).

STORMS

As mentioned above, storm-driven waves have the potential to dislodge kelp plants. Under normal conditions, this natural process opens up habitat and allows for further recruitment of kelp or other understory algae. The natural abrasion of kelp fronds from waves and storms contributes detritus and particulate and dissolved organic matter to the nearshore environment, fueling bacterial growth and plankton productivity. Under El Nino conditions, storms can severely decrease the extent and density of kelp plants.

LIGHT PENETRATION

For *Nereocystis* the availability of light is critical for the growth and sexual maturation of adults and the successful recruitment of sporophytes (Springer et al. 2006). Numerous processes on the outer coast increase water turbidity that could reduce light penetration. Municipal water discharge and nutrient runoff leads to plankton blooms that can reduce water clarity. Sediment runoff from shorelines, dredging activities, or storm-driven waves on the beach all contribute to the suspension of sediments in the water column and reduce light penetration. Moreover, the growth of other algae or benthic invertebrates can overshadow and limit recruitment success of young sporophytes. Reduced densities of bull kelp adults and sporophytes have been observed in areas of landslides (Shaffer and Parks 1994, Konar and Roberts 1996) and exceptionally heavy rains (Burge and Schultz 1973). Prolonged exposure to freshwater has also been shown to cause deterioration in bull kelp tissues (Brown 1915) and cause sporophytes to develop blisters and wilt (Hurd 1916). Thus, processes such as sedimentation or freshwater incursion that limit light penetration to the bottom are important for the sustainability of kelp forest habitats.

IMPORTANT HUMAN PRESSURES

Numerous anthropogenic pressures are acting on the marine environment simultaneously, and it is extremely difficult to determine the contribution of each pressure to the response of ecological components. Here, we treat each pressure individually and briefly describe the major human pressures acting on kelp forest habitats in Washington State waters.

RECREATIONAL FISHING

Recreational fishing is generally the most influential type of fishing in kelp forests or shallow rocky reefs; although, nearshore seining for salmon and forage fishes may also be a potential pressure. Nearshore recreational fishing includes hook-and-line fishing for rockfishes, lingcod, and other groundfishes, along with pot-fishing for crabs and shrimp. Spearfishing for lingcod, rockfish, and other groundfish is also allowed during specific fishing seasons and in specific marine areas. See 'Human Pressures Relevant to All Washington State Waters: Fishing' for ecosystem effects of fishing.

POLLUTANTS

The input of pollutants into nearshore waters where kelp habitats exist impacts the kelp and the communities that reside within these kelp and rocky reef habitats. There is very little known about the direct effects of toxic chemicals on bull kelp, but severe tissue necrosis was observed on kelp exposed to diesel and crude oil (Antrim et al. 1995), but no differences in kelp biomass or percent cover was observed between oiled and control sites following the Exxon Valdez oil spill (CEQA 2001). See 'Human Pressures Relevant to All Washington State Waters: Pollutants' for ecosystem effects of pollutants.

NUTRIENT INPUT

The input of terrestrial-based nutrients may have both positive and negative effects on kelp forest communities. Nitrogen and phosphorus can be a limiting factor in kelp growth during certain times of the year or during periods of low upwelling. The addition of terrestrial-based nutrients may compensate kelp growth during these low-nutrient periods. Excess nutrients, however, can result in plankton blooms which can limit light penetration to the bottom for sporophyte growth. As plankton blooms die, bacteria decompose them and consume large quantities of dissolved oxygen. This can potentially lead to areas of hypoxia. In nearshore habitats, this is not a likely scenario due to circulation patterns and the replenishment of water.

SEAFLOOR HABITAT

The seafloor habitat type represents all bottom habitats below 30 m depth in Washington State waters. The conceptual model outlined below (Fig. 7) represents an attempt to capture the dominant drivers and ecological interactions that characterize seafloor habitats, particularly those within Washington State waters.

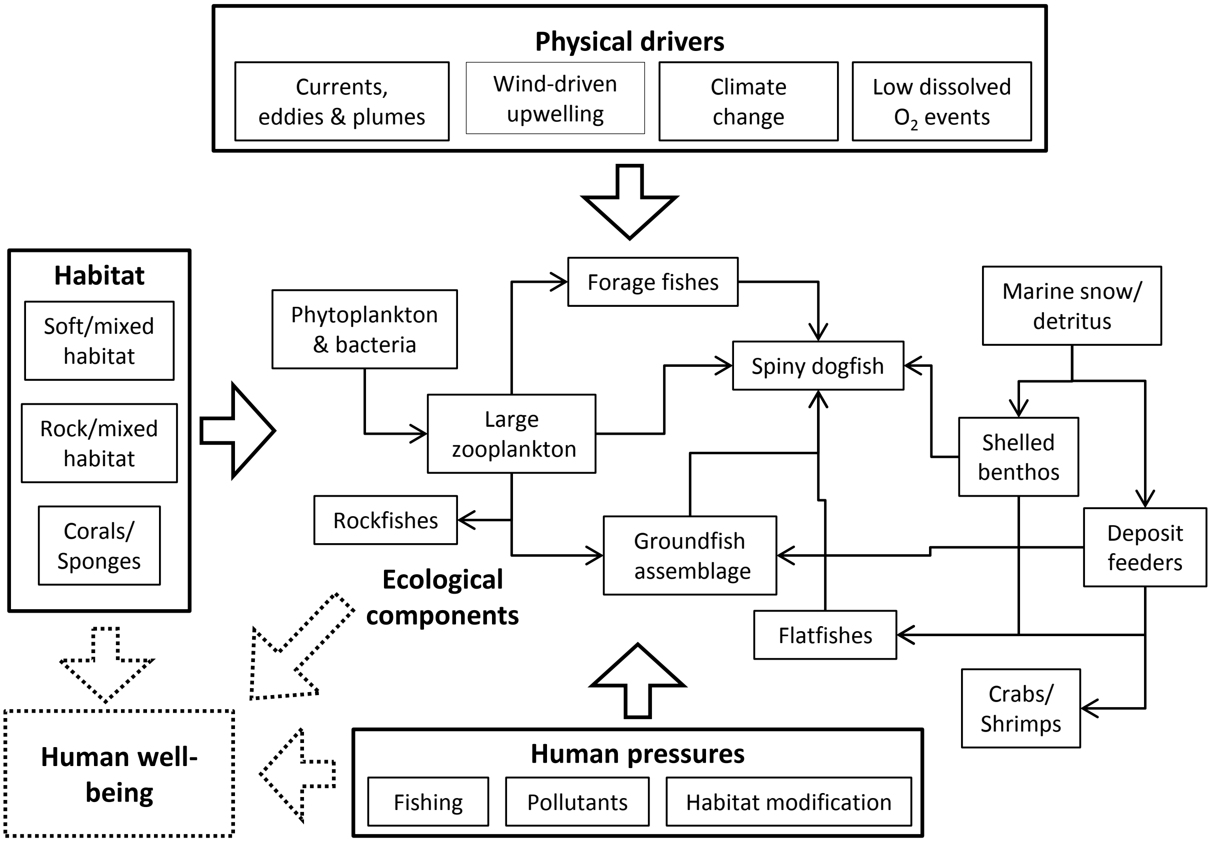

Figure 7. Conceptual model of important habitat, ecological components, physical drivers and human pressures for the seafloor habitat.

HABITAT

BIOGENIC HABITAT

Structure-forming organisms, such as deep-sea corals and other invertebrates (e.g., sponges and anemones), have been recognized as areas where fishes and invertebrates congregate, particularly young-of-year fishes or structure-associated species (Heifetz 2002, Krieger and Wing 2002, Etnoyer and Morgan 2005). In Washington State waters, the highest density of observed biogenic habitat occurs in the northernmost region in the Juan de Fuca Canyon area (Fig. 8). These are only locations of observed corals and sponges entered into NOAA's Deep Sea Coral National Geodatabase. Other areas of biogenic habitat likely occur and potentially suitable habitat for deep-sea corals has been modeled by Guinotte and Davies (2012).

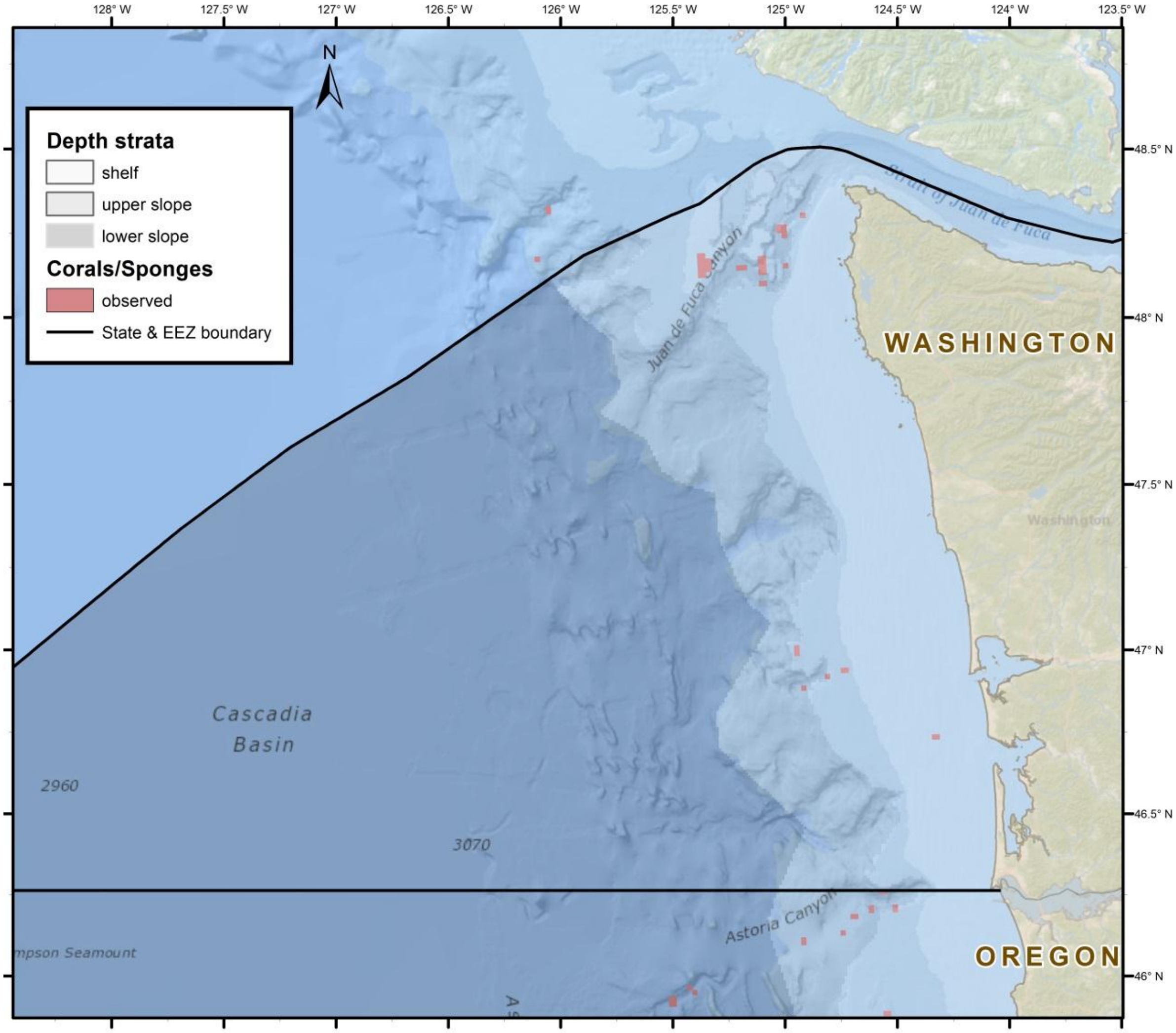

Figure 8. Location of corals and sponges observed in Washington State. Data from NOAA's Deep Sea Coral Research and Technology Program. Deep Sea Coral National Geodatabase.

PHYSICAL HABITAT

The seafloor off Washington's coast is predominantly made up of soft sediments (Fig. 9). The majority of rocky and mixed habitats occur in the Juan de Fuca Canyon system at the northern boundary with Canada and in nearshore areas within the Olympic National Marine Sanctuary. Habitat maps such as this can be used in efforts to determine essential fish habitat or to establish specific spatial management boundaries (NMFS 2013).

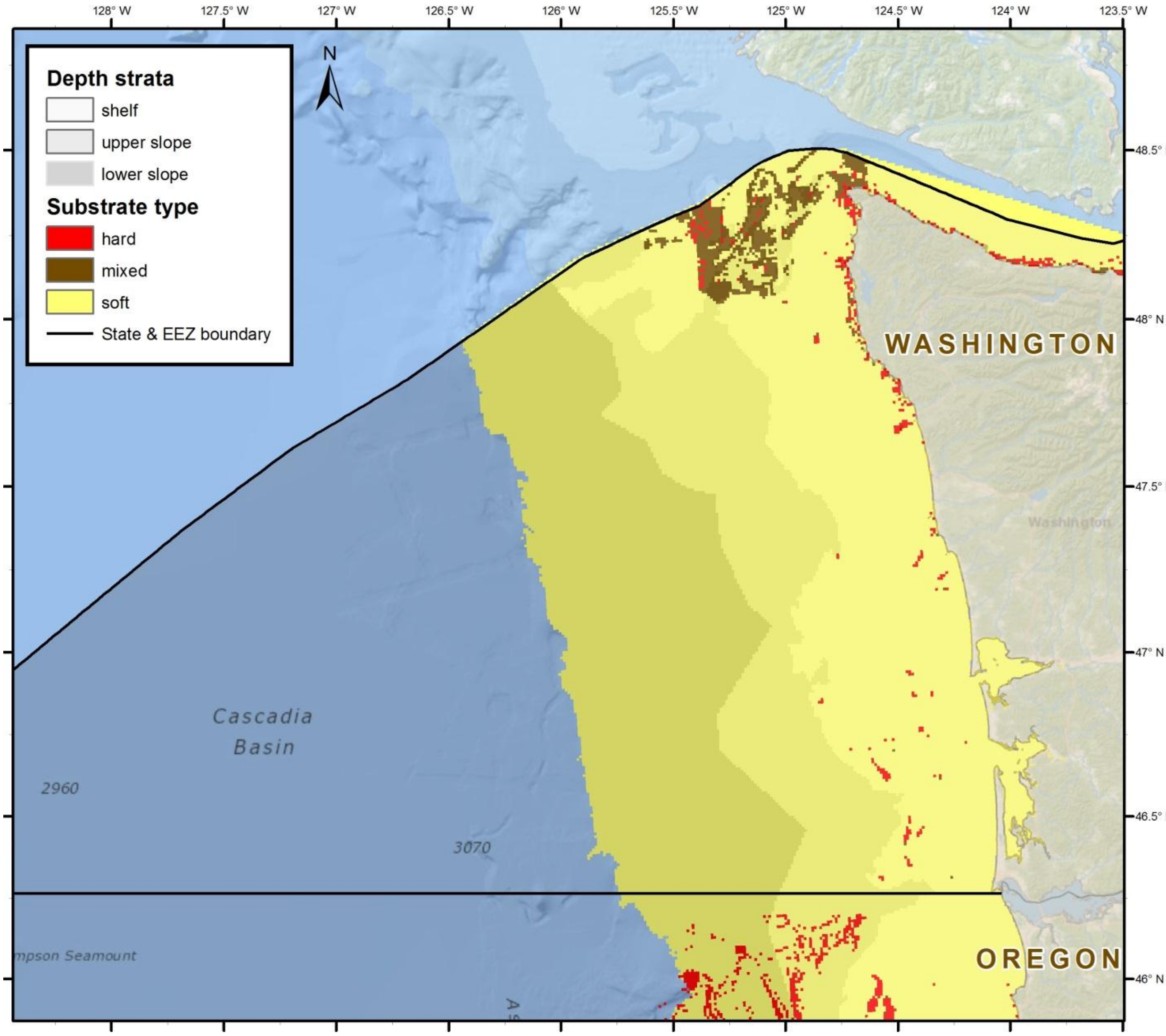

Figure 9. Physical habitat off Washington's coast showing depth strata and substrate type. Data from NMFS (2013).

ECOLOGICAL COMPONENTS

PHYTOPLANKTON COMMUNITY

The phytoplankton community is the base of the food web for the entire marine community and thus the health and community structure of this community is important to understand. Vertical migration of zooplankton from the seafloor to the surface in order to feed on the phytoplankton community connects the seafloor community to the phytoplankton community near the ocean's surface.

The taxonomic structure of phytoplankton communities is an important determinant of ecosystem function, with far-reaching implications for the cycling of energy and matter in the marine environment

(GoeRicke 2011). Phytoplankton community composition changes with forcings such as nutrient, light and temperature and can influence primary production (Smith et al. 1983) and even influence carbon fixation (Lohrenz et al. 1994). Across the broad California Current ecosystem, the phytoplankton community changes predictably as total chlorophyll a (TChl a) increases in the system, a pattern driven by increasing nutrient loading or nutrient content. Variability of autotroph biomass is primarily due to blooms of dinoflagellates and to some extent diatoms, i.e., the larger autotrophs that contributed 81% to the variability of TChl a over time (GoeRicke 2011). Some noted limitations in our understanding of the controls of phytoplankton community: data sets from southern California suggest that nearshore communities may differ fundamentally from coastal oceanic communities, and temperature may exert important secondary effects on phytoplankton community structure based on cyanobacteria distributions.

Knowing the dominant taxa of a community can be indicative of the stage of "upwelling" or "relaxation" of a system (Tilstone et al. 2000). Detailed taxonomic information is most useful, but general classifications such as diatom- vs. dinoflagellate-dominated communities still hold useful information. For example, copepod egg production seems to be favored by dinoflagellate dominance(Vehmaa et al. 2011), but hatching success and survival are more dependent on the specific diatom of dinoflagellate species involved (Vehmaa et al. 2012).

The phytoplankton community off the Washington Coast is highly productive due to strong upwelling of nutrient-rich waters and the influence of the Juan de Fuca Eddy, the Fraser River, and the Columbia River plume (Thomas and Strub 2001, Ware and Thomson 2005). Frame and Lessard (2009) observed a relatively homogeneous phytoplankton community across Washington and Oregon in the spring and summer from 2004 to 2006. Diatoms accounted for over 65% of the total photosynthetic biomass with the majority of diatoms represented by the following genera: *Thalassiosira, Chaetoceros, Guinardia, Leptocylindrus, Skeletonema, Pseudo-nitzschia, Asterionellopsis, Ditylum, Eucampia, Rhizosolenia, Cylindrotheca, and Tropidoneis*. Large dinoflagellates, such as *Prorocentrum gracile* and *Ceratium spp*., an unidentified raphidophyte, and cyanobacteria were the next dominate taxa during different sampling cruises in the spring and summer of 2004-2006.

MARINE SNOW

Marine snow is a macroscopic aggregate of organic and inorganic particles including bacteria, phytoplankton, detritus, fecal pellets, feeding structures, trapped living organisms, and bio-minerals. The feeding structures of larvaceans are a common component aggregating other particles together (Alldredge and Silver 1988). These aggregations contributes the majority of the downward transport of surface-derived matter to the seafloor (Alldredge and Silver 1988). Peaks in marine snow production are commonly observed following large diatom blooms (e.g., Passow et al. 1994). The downward transport of these organic and inorganic globules provides highly nutritional food sources (Robison et al. 2005) for fishes, invertebrates, and marine mammals in the pelagic zone. As the snow reaches the bottom, it is preyed upon by detritus-feeding invertebrates or becomes buried and a source of organic-rich matter for deposit feeders. This detrital food-web provides a secondary pathway of production, in addition to primary production from the phytoplankton food web, for communities on the seafloor.

In addition to sources of organic-rich material for organisms, the sinking of this surface-derived carbon to the deep-ocean floor provides a critical 'sink' to the Earth's carbon cycle (Pilskaln et al. 2005)

LARGE ZOOPLANKTON

Large zooplankton, such as *Euphausiids*, are a large portion of the diet for many groundfishes that inhabit the seafloor off Washington (Dufault et al. 2009), and are thus an important component in any assessment of the health of Washington State waters. For example, *Euphausiids* make up 40% of the diet for yellowtail rockfish *Sebastes flavidus*, 50% for spiny dogfish *Squalus suckleyi*, 90% for canary rockfish *S. pinniger*, and 80% of Pacific hake *Merluccius productus* diet (Dufault et al. 2009). These represent the most abundant species (dogfish) and the two most abundant rockfish species collected in bottom-trawl surveys in Washington State waters (see Table 2 in 'Groundfish assemblage' below) as well as the most abundant groundfish species on the U.S. West Coast (Pacific hake).

The predominant species in offshore waters is generally *Euphausia pacifica*, while *Thysanoessa spinifera* is dominant in inshore waters (Field 2004). The abundance of these species has been observed to be much higher during high upwelling conditions than low upwelling conditions (Brodeur and Pearcy 1992). Euphausiids feed on a wide variety of large phytoplankton and zooplankton, mesozooplankton, microzooplankton, and gelatinous zooplankton (Dufault et al. 2009). Thus, the effects of climate change will certainly affect the abundance and distribution of this critical prey species.

DEPOSIT FEEDERS

Deposit feeders include several benthic invertebrates including amphipods, isopods, small crustacean, snails, *Thalassinidea* shrimp, sea cucumbers, worms, polychaetes, sea slugs, barnacles, and hermit crabs (Dufault et al. 2009). These taxa feed primarily on detritus in the sediment of the seafloor. This provides a secondary pathway of production on the seafloor bottom as organic matter and nutrients are recycled from the sediment and introduced back into the food web. Deposit feeders make up a large proportion of the diet of several commercially or recreationally valuable species, including English sole *Parophrys vetulus* (70%), Longspine thornyhead *Sebastolobus altivelis* (24%), and Pacific halibut *Hippoglossus stenolepis* (20%) (Dufault et al. 2009). The recycling capabilities and their importance to valuable fish species make deposit feeders a relatively important component of the seafloor habitat.

SHELLED BENTHOS

The shelled benthos generally include benthic filter feeder groups, (e.g., bivalves and corals), benthic herbivorous grazers (e.g., sea urchins), and deep macrozoobenthos (e.g., sea stars). These species compose up to 35% of the diets of some flatfish and rockfish groups (Buckley et al. 1999). The importance in monitoring this group of organisms is related to the potential effects of ocean acidification. As aragonite saturation states decrease, the ability of some species to produce shells will be compromised (e.g., Feely et al. 2004). If shelled benthos on the Washington seafloor are affected, species that prey on shelled benthos will either need to switch to unaffected prey (which may difficult for some flatfish species) or these species may incur decreased growth and/or survival(Kaplan et al. 2010).

CRAB AND SHRIMP

One of the most important commercial fisheries in Washington is Dungeness crab *Cancer magister*, with average ex-vessel values of roughly $20 million (WSOPWG 2006). For this reason alone, monitoring the status and trends of Dungeness crab should be included in an assessment of Washington's ecosystem. The recruitment of Dungeness crab has been shown to be directly related to the subsequent commercial catch across much of the California Current ecosystem (Shanks and Roegner 2007). The recruitment of Dungeness crab varies with atmospheric forcing patterns: crab megalopae return in higher densities 1) when the spring transition is earlier in the year (Shanks and Roegner 2007), 2) during cooler phases of the Pacific Decadal Oscillation (Shanks et al. 2010), and 3) when upwelling is greater (Shanks 2013). These crabs primarily prey upon deposit feeders (amphipods, isopods, etc.) and other benthic filter feeders (e.g., bivalves), while they are primarily preyed upon by octopus, small demersal sharks, and some large rockfish species (Dufault et al. 2009).

Spot prawns *Pandalus platyceros*, coonstripe shrimp *P. danae* and *P. hypsinotus* and pink shrimp *P. eous and P. jordani* are commercially harvested off the Washington Coast. Spot prawns recruit to shallow waters and then migrate to deeper waters after maturing. High densities of spot prawn have been observed near Juan de Fuca and Gray's Canyons (Lowry 2007). The recruitment of shrimp appears to be similar to Dungeness crab: recruitment corresponds with the spring transition and warm-water phases tend to result in less recruitment (Hannah 1993). Little information is known about the abundance of these species off the coast of Washington, but they are all considered 'stable' by the Washington Department of Fish & Wildlife. The diet of spot prawns consists mostly of crustaceans, polychaetes, and siliceous sponges, but they also scavenge dead fish, mollusks and crustaceans (Butler 1970). Predators of these shrimp most likely include lingcod, spiny dogfish, pacific cod, and octopus; and pacific hake has been shown to impact the stock of pink shrimp off Oregon (Hannah 1995).

In addition to effects from large-scale atmospheric forcing and climate change, crabs and shrimp accumulate toxins from harmful algal blooms which can lead to fisheries closures and loss of revenue to coastal and tribal communities.

GROUNDFISH ASSEMBLAGE

The groundfish assemblage off the coast of Washington provides one of the primary fisheries for Washington coastal communities; thus, making it one of the most important ecological components to monitor. The Pacific Fisheries Management Council is responsible for the management of this assemblage along the entire U.S. West Coast in federal waters. NOAA's Northwest Fisheries Science Center supports the management of these species by performing an annual groundfish bottom-trawl survey along the entire coast.

In Washington State waters, the most abundant and most variable member of the groundfish community is the spiny dogfish *Squalus suckleyi* (Table 2). Spiny dogfish is a demersal shark that is most frequently observed in relatively shallow waters (55-184 m) off the northern Washington coast. Dogfish exhibit migratory behavior in which they can move hundreds of kilometers to the north through the spring and summer and then move back south during the fall and winter (Taylor et al. 2009). This behavior is also seen in Puget Sound, in which dogfish enter Puget Sound in late spring/early summer, spend the rest of the summer and fall in Puget Sound and then exit Puget Sound in the late fall/early winter and migrate to the outer coast (Andrews and Harvey 2013). This species is particularly interesting because its diet consistently consists of prey from both pelagic and benthic taxa (Brodeur et al. 2009, Dufault et al. 2009).

Table 2. Top ten species collected in waters extending off the coast of Washington (i.e. north of latitude 46.26°N to the Canadian border) by NOAA's Northwest Fisheries Science Center groundfish bottom-trawl survey (2003 – 2011). Mean CPUE values are kilograms per square kilometer towed (kg^{-km2}).

Species name	Common name	Mean CPUE ± SD
Squalus suckleyi	Spiny dogfish	387,049 ± 590,562
Microstomus pacificus	Dover sole	290,201 ± 63,822
Atheresthes stomias	Arrowtooth flounder	191,895 ± 65,737
Merluccius productus	Pacific hake (whiting)	142,191 ± 159,972
Sebastes flavidus	Yellowtail rockfish	128,458 ± 55,731
Sebastes pinniger	Canary rockfish	89,563 ± 149,408
Anoplopoma fimbria	Sablefish (black cod)	87,075 ± 89,452
Raja rhina	Big skate	77,142 ± 23,534
Sebastolobus altivelis	Longspine thornyhead	67,838 ± 24,661
Glyptocephalus zachirus	Rex sole	63,719 ± 15,898

The rockfish assemblage consists of numerous species. Thirty of the fifty-four rockfish species identified in NOAA's groundfish bottom-trawl survey have been collected in Washington State waters during the past ten years. The most abundant rockfish species are the yellowtail and canary rockfish (Table 2). There is a vast array of life-history types in this assemblage and there are species strongly associated with rocky habitats, other species associated with sandy, muddy bottoms and other that are found in all substrate types (Love et al. 2002). Due to this variation in life-history and habitat preferences, the diet of rockfishes varies greatly. Species that move up off the bottom, such as yellowtail and canary, prey heavily on Euphausiids, while species that reside almost completely on the substrate (e.g., yelloweye rockfish) have diets that vary in amounts deposit feeders, benthic herbivorous grazers, small flatfish, and small planktivorous fishes (Dufault et al. 2009). Many rockfish species are long-lived, slow-growing, and late-maturing species which make them particularly susceptible to overfishing.

The flatfish assemblage also consists of numerous species. In Washington State waters, dover sole *Microstomus pacificus,* arrowtooth flounder *Atheresthes stomias*, and rex sole *Glyptocephalus zachirus* are the most abundant in bottom-trawl surveys (Table 2). Small flatfish (e.g., dover and rex sole) primarily feed on deposit feeders, sea stars, brittle stars, and polychaetes, while large flatfish (e.g., arrowtooth flounder and petrale sole *Eopsetta jordani*) prey considerably on Pacific hake, small flatfish, and small planktivorous fish. Predators of small flatfish include spiny dogfish, skates and rays, large flatfish and yelloweye rockfish, while predators of large flatfish are generally other large flatfish or pelagic sharks (Dufault et al. 2009).

IMPORTANT PHYSICAL DRIVERS

The important physical drivers on the seafloor habitat are generally consistent with those described above in the 'General Oceanography and Physical Drivers…' section. Upwelling of deep-nutrient rich waters, based on large-scale atmospheric forcing patterns, fuels the base of the food web that supports the groundfish and invertebrate assemblages of the seafloor.

CLIMATE CHANGE

The seafloor habitat will be affected by large-scale atmospheric forcing patterns associated with climate change. As regime phases change, the seafloor communities will be exposed to the effects of changes in sea-surface temperature, upwelling conditions, and source waters. See 'General Oceanography and Physical Drivers of Washington State Waters' for further details.

As ocean waters become more acidic from increases in atmospheric CO_2, shelled benthos are predicted to have higher mortality and/or reduced growth (Hall-Spencer et al. 2008), while large zooplankton (pteropods; Feely et al. 2004, Orr et al. 2005), and small phytoplankton (coccolithophores; Riebesell et al. 2000, foraminifera; Fabry et al. 2008) are expected to show decreases in calcification rates, resulting in increased mortality. Using ecosystem model simulations, the notable impacts of ocean acidification on higher trophic-level species was a large decrease in English sole *Parophrys vetulus* (the 17th most abundant species in bottom-trawl surveys in Washington State waters), modest decreases in spiny dogfish, skates and rays and a slight increase in canary rockfish (Kaplan et al. 2010).

DISSOLVED OXYGEN

Low dissolved oxygen concentrations in coastal and shelf waters off Washington State is a relatively recent issue (Grantham et al. 2004, Bograd et al. 2008). When dissolved oxygen concentrations fall below 1.4 ml L^{-1}, the waters are considered to be 'hypoxic'. Dissolved oxygen (DO) concentrations in the ocean are dependent on a number of physical and biological processes, including circulation, ventilation, air-sea exchange, production and respiration. In Oregon, upwelling transports hypoxic waters onto productive continental shelves, where respiration can reduce water-column DO and thus subject coastal ecosystems to hypoxic or anoxic conditions. Off southern California, the boundary between oxygenated and hypoxic waters has shoaled in recent years. Some nutrients are supplied from rivers and surface runoff, but these sources are minor inputs to the coastal and shelf ecosystem when compared to upwelling in contrast to the Gulf of Mexico and Chesapeake Bay. For the northern California Current, upwelling primarily occurs during the summer months (May – Sept.) when the seasonal winds blow from the north. Towards the south, upwelling occurs throughout the year (Bograd et al. 2009). The deep, nutrient-rich waters that are brought up onto the shelf are often low in oxygen, but are rarely 'hypoxic'

(Hales et al. 2006). Biochemical respiration in the water column and within the sediments draws the oxygen level down further, sometimes to hypoxic or anoxic levels (Connolly et al. 2010). The areas most vulnerable to hypoxia tend to be banks and wider shelf regions where water may be retained for extended periods of time with minimal ventilation from horizontal and vertical mixing (Grantham et al. 2004). There is evidence that the frequency, duration and spatial coverage of hypoxic events has been increasing over the last 20 years (Diaz and Rosenberg 2008), potentially due to increased stratification (reduced vertical mixing) and a decrease in the oxygen concentration of upwelled waters.

The impact of hypoxia on organisms is poorly understood (Keller et al. 2010). Severe events have been shown to kill sessile and slow-moving benthic invertebrates and displace demersal fish species (Grantham et al. 2004, McClatchie et al. 2010). Studies from coastal regions of the Gulf of Mexico and Eastern United States indicate that a range of trophic levels, from plankton to fish, show behavioral changes, may be displaced or killed, or have negative impacts on early life history growth when exposed to low oxygen for extended periods (Rabalais and Turner 2001, Kidwell et al. 2009).

UPWELLING

See ‘General Oceanography and Physical Drivers of Washington State Waters’.

CURRENTS, EDDIES AND PLUMES

See ‘General Oceanography and Physical Drivers of Washington State Waters’.

IMPORTANT HUMAN PRESSURES

COMMERCIAL FISHING

Commercial fishing is the predominant pressure on the seafloor habitat in Washington State waters. The relative cumulative effort of the bottom-trawl, longline, and pot fisheries fleets has several ‘hotspots’ within Washington waters, mostly in the northern region along the edges of the Juan de Fuca Canyon system (Fig. 10). Several groundfish species that occur in Washington State waters have been overfished and currently have rebuilding plans (e.g., yelloweye rockfish *Sebastes ruberrimus*, canary rockfish *S. pinniger*, and Pacific ocean perch *S. alutus* (NOAA 2012). The largest fishery in Washington State waters is for Pacific hake *Merluccius productus*, with 161 thousand metric tons landed coastwide in 2010 (Stewart et al. 2011). This fishery uses mid-water trawling gear, so it doesn’t trawl along the seafloor, but the capture of Pacific hake certainly affects groundfish community dynamics since Pacific hake represents a relatively large proportion of total biomass and is an important predator in the system. See ‘Human Pressures Relevant to All Washington State Waters: Fishing’ for ecosystem effects of fishing.

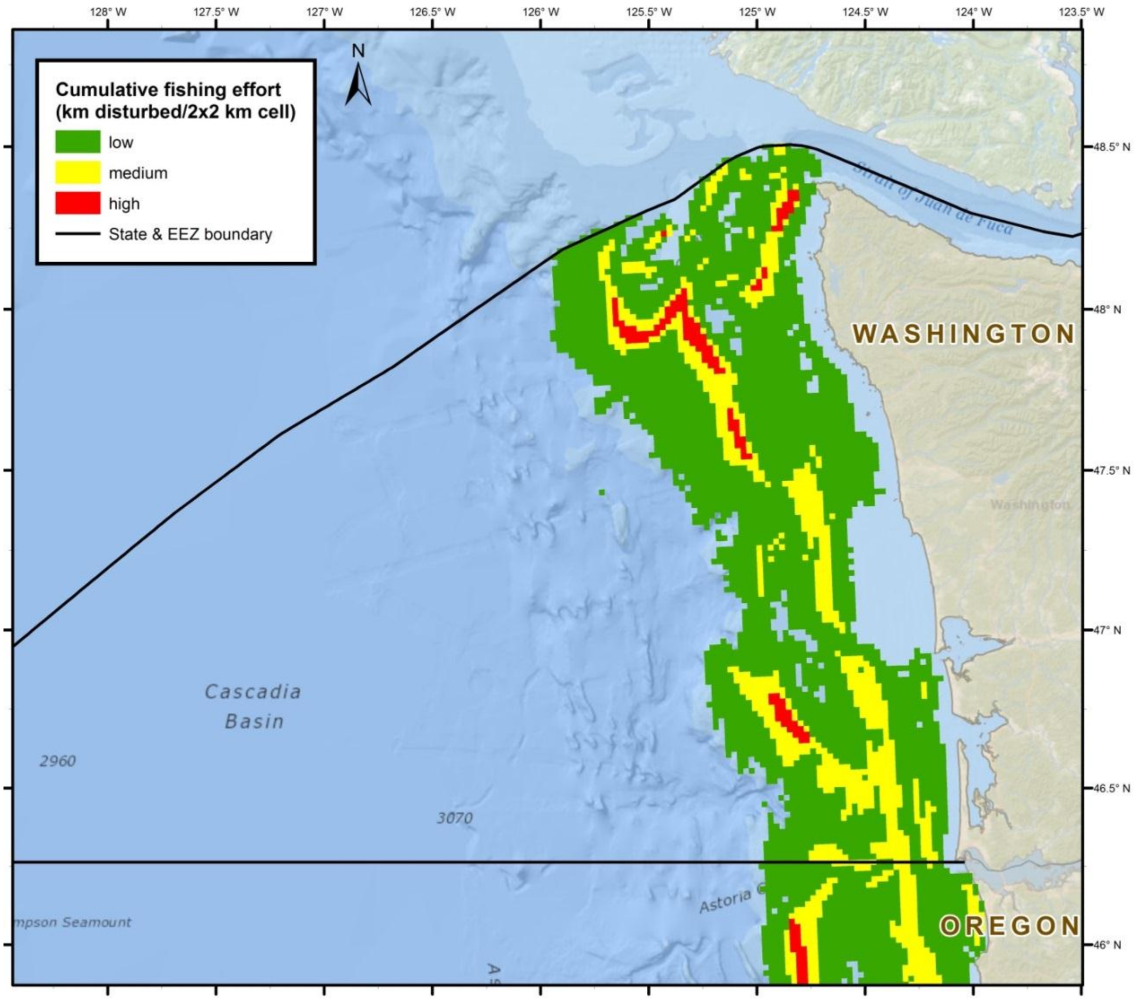

Figure 10. Cumulative fishing pressure from trawling, longline, and pot gears in Washington waters.

HABITAT MODIFICATION

Fishing can alter benthic habitats by disturbing and destroying bottom topography and associated communities, from the intense use of trawls and other bottom gear (Kaiser and Spencer 1996, Hiddink et al. 2006). Habitat destruction, in turn, can lead to extirpation of vulnerable benthic species and disruption of food web processes (Hall 1999, Hiddink et al. 2006). The effect is particularly dramatic when those gears are used in sensitive environments with sea grass, algal beds, and coral reefs, and is less evident on soft bottoms (Garcia et al. 2003). However, fisheries often tend to operate within certain areas more than others (Kaiser et al. 1998), and long-term impacts of trawling may cause negative changes in biomass and the production of benthic communities in any habitat type, to various degrees (Hiddink et al. 2006).

In Washington State waters, essential fish habitat, areas necessary for fish spawning, breeding, feeding, or growth to maturity, and marine protected areas, in combination with gear regulation measures, have been used to reduce adverse impact of fisheries on vulnerable habitats. Also, the introduction of rockfish conservation areas as management measures to prevent overfishing makes additional areas along the coast inaccessible to fishing during some or all of the year.

POLLUTANTS

Pollutants to the seafloor occur as pollutants sink to the bottom or are brought in with prevailing currents. Atmospheric deposition is a source of pollutants that is particularly high off the coast of Washington (Halpern et al. 2009); however, there is little research on the concentration of these pollutants in the sediments of deep, offshore habitats, or whether there are any effects of these deposited pollutants. However, the Washington coast, particularly in the north, has relatively few inputs of other pollutants due to limited development of the coast. See 'Human Pressures Relevant to All Washington State Waters: Pollutants' for potential ecosystem effects of pollutants.

PELAGIC ZONE

The pelagic zone represents all water column habitat from the surface to near-bottom in Washington State waters. The conceptual model outlined below (Fig. 11) represents an attempt to capture the dominant drivers and ecological interactions that characterize the pelagic zone, particularly those waters within the Washington State marine spatial planning boundary.

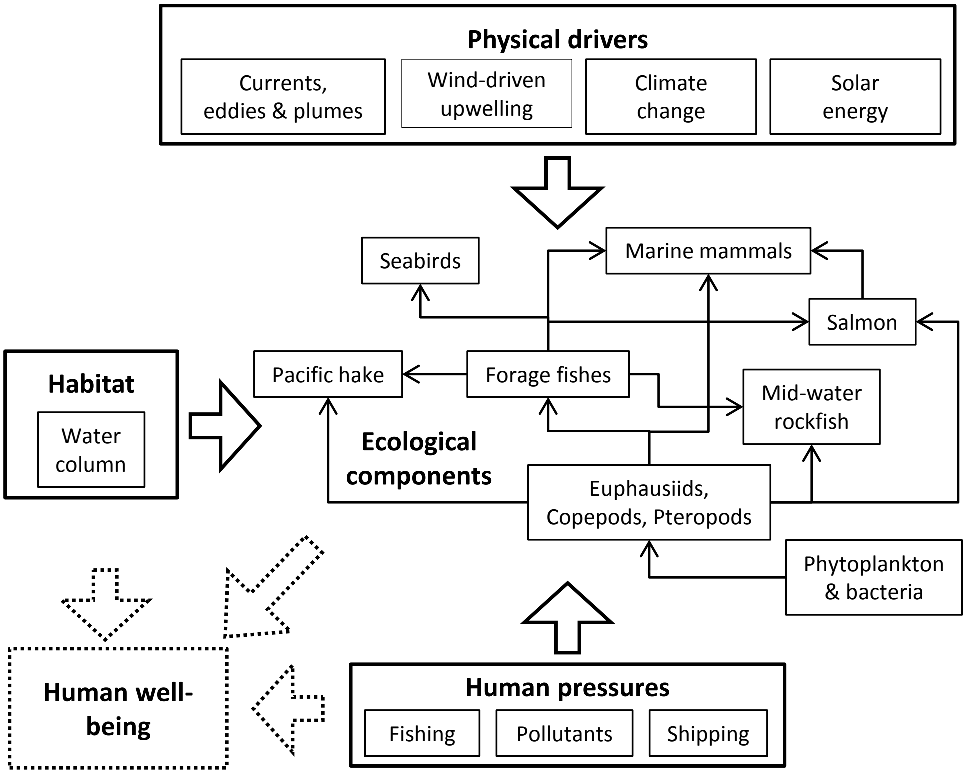

Figure 11. Conceptual model of important habitat, ecological components, physical drivers and human pressures for the pelagic habitat.

HABITAT

The habitat of the pelagic zone consists of the water column from the surface to near-bottom. Species in the pelagic zone will alter their distribution patterns according to the physical characteristics of the water column, particularly with respect to temperature, salinity, and the location of the pycnocline.

ECOLOGICAL COMPONENTS

PHYTOPLANKTON COMMUNITY

The phytoplankton community is the base of the food web for the entire marine community and thus the health and community structure of this community is important to understand. Vertical migration of zooplankton from the seafloor to the surface in order to feed on the phytoplankton community connects the seafloor community to the phytoplankton community near the ocean’s surface.

The taxonomic structure of phytoplankton communities is an important determinant of ecosystem function, with far-reaching implications for the cycling of energy and matter in the marine environment (GoeRicke 2011). Phytoplankton community composition changes with forcings such as nutrient, light and temperature and can influence primary production (Smith et al. 1983) and even influence carbon fixation (Lohrenz et al. 1994). Across the broad California Current ecosystem, the phytoplankton community changes predictably as total chlorophyll a (TChl a) increases in the system, a pattern driven by increasing nutrient loading or nutrient content. Variability of autotroph biomass is primarily due to blooms of dinoflagellates and to some extent diatoms, i.e., the larger autotrophs that contributed 81% to the variability of TChl a over time (GoeRicke 2011). Some noted limitations in our understanding of the controls of phytoplankton community: data sets from southern California suggest that nearshore communities may differ fundamentally from coastal oceanic communities, and temperature may exert important secondary effects on phytoplankton community structure based on cyanobacteria distributions.

Knowing the dominant taxa of a community can be indicative of the stage of "upwelling" or "relaxation" of a system (Tilstone et al. 2000). Detailed taxonomic information is most useful, but general classifications such as diatom- vs. dinoflagellate-dominated communities still hold useful information. For example, copepod egg production seems to be favored by dinoflagellate dominance(Vehmaa et al. 2011), but hatching success and survival are more dependent on the specific diatom of dinoflagellate species involved (Vehmaa et al. 2012).

The phytoplankton community off the Washington Coast is highly productive due to strong upwelling of nutrient-rich waters and the influence of the Juan de Fuca Eddy, the Fraser River, and the Columbia River plume (Thomas and Strub 2001, Ware and Thomson 2005). Frame and Lessard (2009) observed a relatively homogeneous phytoplankton community across Washington and Oregon in the spring and summer from 2004 to 2006. Diatoms accounted for over 65% of the total photosynthetic biomass with the majority of diatoms represented by the following genera: *Thalassiosira, Chaetoceros, Guinardia,* *Leptocylindrus, Skeletonema, Pseudo-nitzschia, Asterionellopsis, Ditylum, Eucampia, Rhizosolenia, Cylindrotheca, and Tropidoneis*. Large dinoflagellates, such as *Prorocentrum gracile* and *Ceratium spp*., an unidentified raphidophyte, and cyanobacteria were the next dominate taxa during different sampling cruises in the spring and summer of 2004-2006.

ZOOPLANKTON COMMUNITY

Zooplankton time series provide some of the best opportunities to understand marine ecosystem responses to climate change because zooplankton are the foundation of the ocean food web, linking oceanographic conditions and primary production to upper trophic levels and fueling the delivery of ocean ecosystem services. Zooplankton life cycles are short (on the order of weeks to a year) and populations have the potential to respond to and reflect event-scale and seasonal changes in environmental conditions (Hooff and Peterson 2006). Moreover, many zooplankton taxa are known to be indicator species whose presence or absence may represent the relative influence of different water types on ecosystem structure. Thus zooplankton may serve as sentinel taxa that reflect changes in marine ecosystems by providing early indications of a biological response to climate variability and are often used as an indicator to detect climate change or regime shifts (Hooff and Peterson 2006, Mackas et al. 2006, Peterson 2009). Finally, zooplankton are abundant and can be quantified by relatively simple and comparable sampling methods and, because few are fished, most population changes can be attributed to environmental causes (Mackas and Beaugrand 2010). As such, they may prove useful as a leading indicator of what may happen to regional commercial fish stocks several years later (Mackas et al. 2007, Peterson et al. unpubl. manuscr.).

All along the California Current, anomalies in zooplankton species composition shifts have been correlated with regional climate patterns (Mackas et al. 2006). For example, off the Oregon coast zooplankton indices have been developed based on the affinities of copepods for different water types: those with cold water and those with warm water affinities (Peterson et al. unpubl. manuscr.). The cold water group usually dominates the coastal zooplankton community during the summer (typically May through September) upwelling season, whereas the warm water group usually dominates during winter, although this pattern is altered during summers with El Niño events or when the Pacific Decadal Oscillation (PDO) is in a positive (warm) phase. Perhaps the most significant aspect of the copepod index is that two of the cold water species, *Calanus marshallae* and *Pseudocalanus mimus*, are lipid-rich species. Therefore, an estimate of northern copepod biomass may also index the amount of wax esters and fatty acids being fixed in the food chain, compounds which appear to be essential for many pelagic fishes if they are to grow and survive through the winter successfully.

Several long-term zooplankton monitoring programs, representing seven subregions spanning the entire CCLME from Baja California to Vancouver Island, now provide zooplankton time series of various lengths from 1969 to the present. Although differences in processing and sampling zooplankton time series introduce a variety of biases that often prevent comparisons between data sets, many major questions can still be answered because an individual data set can be presented and analyzed as a time series of log-scale anomalies relative to the local long-term-average seasonal climatology. Anomalies are primarily used to separate interannual variability from the often large annual seasonal cycle of zooplankton stock size (Mackas and Beaugrand 2010). The specific species associated with these anomalies vary regionally, but can generally be classified as resident versus nonresident species. Regional anomalies can be combined into a single index using multivariate techniques (e.g., principal component analysis) in similar fashion to the calculation of regional climate indices, such as the Multivariate El Niño Southern Oscillation (ENSO) Index (Wolter and Timlin 1993). This index can then be tested for use as a leading indicator of regional climate signals, such as ENSO or PDO, using existing time series from the last 20 years, during which time the California Current saw at least two major climate regime shifts.

FORAGE FISH COMMUNITY

Forage fish species support important commercial fisheries as well as a number of higher trophic level species including those that are commercially exploited (e.g., rockfish, salmon) and/or legally protected (e.g., salmon, marine mammals, seabirds). In Washington State waters, there are four primary forage fish species: whitebait smelt *Allosmerus elongates,* Pacific herring *Clupea pallasii*, northern anchovy *Engraulis mordax*, and Pacific sardine *Sardinops sagax (McClatchie et al. 2013)*. These species all have similar characteristics that make them a ‘forage fish’ species: 1) they are often present in high abundance, 2) feed on plankton for a portion of their life cycle, and 3) form dense schools or aggregations. Other species that are often included as forage fish species along the rest of U.S. West Coast include sardines, jack mackerel, mackerel, as well as invertebrate species such as squid and krill. Such species are often the principal means of transferring production from primary and secondary tropic levels (typically phytoplankton and zooplankton) to larger predatory fish, marine mammals and seabirds. Recent work suggests negative effects on the ecosystem caused by reductions in abundance of lower trophic level species (Smith et al. 2011).

Recent efforts to determine the status and trends of the forage fish community has shown that cooler ocean conditions since 2010 have resulted in decreased abundance or survival of sardines, but an increased abundance of whitebait smelt and a general positive trend for all forage fish combined (McClatchie et al. 2013).

SALMON

Salmon are a defining species in Pacific Northwest communities, both in economic and cultural value (Quinn 2011). There are six salmon species that inhabit Washington State waters: Chinook, coho, chum, pink, sockeye and steelhead. Each species has unique characteristics and describing each of them is beyond the scope of this report. For the purposes of an ecosystem assessment, we must determine how to characterize these populations as concisely as possible. NOAA’s California Current Integrated Ecosystem Assessment includes Chinook and Coho salmon as indicators of all populations along the U.S. West Coast primarily because they are the most abundant and have the most data.

Here, we suggest the use of Chinook salmon as an indicator of salmon populations in Washington State waters. Five stocks of Chinook salmon that enter Washington State waters are listed as either ‘Threatened’ (Lower Columbia, Puget Sound, Snake River Fall, Snake River Spring/Summer) or

‘Endangered’ (Upper Columbia Spring) by the Endangered Species Act. These listings dictate management at federal and state levels and are good reasons to include Chinook salmon in an assessment of the overall ecosystem of Washington State waters.

Chinook salmon feed directly upon euphausiids (Brodeur 1990), particularly during their initial time at sea, as well as forage fish such as Pacific herring (Brodeur and Pearcy 1992). For Chinook off central California, body condition of juveniles is positively related to the abundance of adult euphausiids in the previous year. Subsequently, the condition of juveniles was correlated to the abundance of mature adults returning the following year (Wells et al. 2012). Several ecosystem indicators have been used to forecast the returns of Chinook and coho salmon in the Northeast Pacific (Burke et al. 2013). These indicators include the Pacific Decadal Oscillation, sea surface temperature anomalies, coastal upwelling, spring transition date, and copepod diversity and anomalies (Peterson et al. 2012).

MID-WATER ROCKFISH

Mid-water rockfish generally include species that spend a large portion of their time above the substrate of the seafloor, including adult widow *S. entomelas*, Pacific ocean perch *S. alutus*, yellowtail *S. flavidus*, and black rockfish *S. melanops* (Dufault et al. 2009). Widow rockfish was a heavily fished species in the 1980’s and 1990’s, was declared overfished in 2000 (Williams et al. 2000), and has been rebuilt to 51% of virgin biomass since then (He et al. 2011). Pacific ocean perch are currently overfished and have a rebuilding plan (Hamel and Ono 2011).

Mid-water rockfish primarily prey on large zooplankton (e.g., *Euphausiids*), gelatinous zooplankton (e.g., salps, jellyfish & ctenophores) and small planktivorous fishes (e.g., northern anchovy, Pacific sardine, and Pacific herring). Seabirds and Chinook salmon *Oncorhynchus tshawytscha* prey on juveniles of mid-water rockfish, while deep, large rockfish prey on both adults and juveniles (Dufault et al. 2009). These species are of ecological interest because they undergo vertical migrations in the water column. This behavior helps couple the pelagic and benthic food webs.

PACIFIC HAKE

Pacific hake *Merluccius productus* is a semi-pelagic schooling species and is currently the most abundant groundfish species in the California Current ecosystem. Hake migrate long distances along the North American coastline, spawning in the winter offshore south-central California, moving onshore and to the north in the spring to feed along the continental shelf and slope from northern California to Vancouver Island, BC (Stewart et al. 2011). During warm-water years, larger proportions of the population migrate further north (Dorn 1995, Agostini et al. 2006). If waters of the North Pacific continue to warm as predicted or warmer water phases increase in duration or frequency, waters off Washington State can expect larger populations of hake in the future.

Hake are voracious predators of euphausiids, shrimp, herring, and other forage fish and have been implicated as potential predators of juvenile salmon (Emmett and Brodeur 2000, Field 2004). All of these prey items are also prey of salmon, rockfish and other groundfish species. With the potential for larger populations of hake in Washington State waters in the future, competition among these species for these prey items will dramatically increase.

SEABIRDS

Seabirds are relatively numerous, conspicuous, and forage across multiple habitat types and trophic levels. For these reasons, they are often considered indicators of ocean conditions, and the status of their populations provides insight into ecosystem health (Parrish and Zador 2003, Piatt et al. 2007). In general, both surface and migrating seabirds prey heavily on small planktivorous fishes, but also on juvenile rockfishes, cephalopods and large zooplankton (Dufault et al. 2009)

Five species of marine birds that breed off the coast of Washington are on federal or state species of concern lists: common murre *Uria aalge*, marbled murrelet *Brachyramphus marmoratus*, tufted puffin *Fratercula cirrhata*, Cassin's Auklet *Ptychoramphus aleuticus*, and Brandt's cormorant *Phalacrocorax penicillatus* (ONMS 2008). The murre population declined dramatically in 1982 and 1983, coinciding with a severe El Niño-Southern Oscillation (ENSO) event and has not recovered to pre-1983 levels since that time (Warheit and Thompson 2003). In Washington State waters, the breeding population of mures declined from approximately 53,000 birds to <10,000 between 1979 and 1995 (Manuwal et al. 2001). Aside from other ENSO events, it has been suggested that the population has not recovered due to a combination of oil spills, disturbance at breeding colonies (e.g., historic Naval bombing practices), and gillnet mortality (Warheit and Thompson 2003). At the breeding colony on Tatoosh Island, common murre populations have also been affected by an influx of avian predators, including bald eagles, peregrine falcons and nest-depredating glaucous-winged gulls (Parrish et al. 2001). The multiple stressors affecting the sluggish recovery of common murres may be indicative of the challenges facing the long-term recovery of other seabirds (ONMS 2008).

MARINE MAMMALS

There are at least 29 species of marine mammals that inhabit or transit through Washington State waters at some point in their life. Similar to salmon, marine mammals represent a taxa group that people have strong feelings about. Ecologically, they're interesting because they are top predators at different trophic levels of the food web. Transient killer whales prey on other marine mammals, while southern resident killer whales prey on Chinook salmon and are thought to be at risk from multiple human activities (Krahn et al. 2004). Humpback whales primarily feed on large zooplankton and forage fishes, while gray whales forage for benthic invertebrates in nearshore sediments. Pinnipeds prey on a wide array of fishes, including Pacific salmon, but much of their diet consists of skates and rays.

The California Current is an important, seasonal feeding area for humpback and blue whales (Calambokidis et al. 2001, Calambokidis et al. 2009). Fin whales are present in the California Current throughout the year, but have higher abundances during the summer (Forney et al. 1995). Gray whales use coastal waters of the California Current as migratory pathways and are exposed to various pressures including ship strikes and fisheries entanglements during these travels (International Whaling Commission. 2011).

California sea lions of all age/sex classes are accessible on land, making them an easy target for monitoring. There is a long history demonstrating linkages between population parameters for California sea lions and El Niño events, including pup and yearling survival (DeLong et al. *In prep.*), natality (Melin et al. *In press*), and pup production (Lowry and Maravilla-Chavez 2005). Melin et al. (2010) also demonstrated linkages between upwelling and pup mortality during the 2009 oceanographic event in Central California. Studies have also explored the diets of California sea lions and linked diet to abundances of their prey (Lowry 1999), which include several commercial species: Pacific hake, market squid, Pacific sardine, northern anchovy, shortbelly rockfish, Pacific mackerel, and jack mackerel. Finally, studies have also shown a relationship between *Leptospirosis* disease and male survival (DeLong et al. *In prep.*) and impacts of man-made pollution on populations (Ylitalo et al. 2005).

The status and trends of marine mammal populations are difficult to determine due to short time series and large amounts of variation in estimates (Carretta et al. 2011). Nonetheless, Forney (2000) has shown that the abundance of Dall’s porpoise along the U.S. West Coast is likely related to patterns in sea surface temperature. Gray whale abundance and condition as they migrate through Washington waters is largely determined by environmental variability on the Arctic feeding (Moore 2008). Off the coast of southern Washington, harbor porpoise were the most sighted marine mammals in nearshore waters during small-boat surveys in 2008 and 2009, whereas Dall’s porpoise were the most frequently-sighted species offshore (Oleson and Hildebrand 2012). In the 2008 Olympic Coast National Marine Sanctuary cetacean survey, humpback whales were the most frequently-sighted species followed by Dall’s porpoise (Oleson and Hildebrand 2012).

KEY INTERACTIONS

One of the most important links in the food web off the coast of Washington is the strength of interaction between Pacific hake and the rest of the food web. During particularly strong years when Pacific hake is most abundant, there are numerous competitive and predatory interactions that are altered from years when Pacific hake are less abundant (Field 2004). As hake migrate further north during warm-water years, their effects on the pelagic food web within Washington State waters will vary with environmental conditions.

IMPORTANT PHYSICAL DRIVERS

The important physical drivers in the pelagic zone are generally consistent with those described above in the ‘General Oceanography and Physical Drivers…’ section. Upwelling of deep nutrient-rich waters, based on large-scale atmospheric forcing patterns, fuels the base of the food web that supports the forage fish assemblage, as well as mid-water species such as rockfish and Pacific hake.

CLIMATE CHANGE

The pelagic zone will be affected by large-scale atmospheric forcing patterns associated with climate change. As regime phases change, pelagic communities will be exposed to the effects of changes in sea-surface temperature, upwelling conditions, and source waters. One predominant measure of these conditions is the change in copepod community structure (Peterson et al. 2012). See 'Zooplankton Community' and 'General Oceanography and Physical Drivers of Washington State Waters' for further details.

UPWELLING

See 'General Oceanography and Physical Drivers of Washington State Waters'.

CURRENTS, EDDIES, AND PLUMES

See 'General Oceanography and Physical Drivers of Washington State Waters'.

IMPORTANT HUMAN PRESSURES

FISHING

The predominant source of fishing pressure in the pelagic zone off the coast of Washington is from the Pacific hake fishery. This fishery occurs from northern California to British Columbia primarily from June to November and is conducted with mid-water trawls. Across the fishery, over 200,000 metric tons were landed in 2012 (Hicks et al. 2013). In Washington, there are also two coastal pelagic fisheries (limited entry sardine fishery and anchovy fisheries), but these fisheries have total landings in the range of 12,000 metric tons. The sardine fishery typically occurs in the months of June, July and September. There is also a Washington fishery for widow rockfish. This fishery removed 62 metric tons of widow rockfish in 2010 (He et al. 2011). The bottom-trawl fishery exists throughout Washington State waters and as this fishing gear is set, it moves through the water column and has the potential to capture or trap pelagic species on the way up or down. See 'Human Pressures Relevant to All Washington State Waters: Fishing' for ecosystem effects of fishing.

POLLUTANTS

Similar to the seafloor habitat, the pelagic zone of Washington State waters is exposed to relatively high levels of pollution from atmospheric deposition (Halpern et al. 2009). It is unclear what effects, if any, these pollutants have on organisms in the pelagic zone. However, the Washington coast, particularly in the north, has relatively few inputs of other pollutants due to limited development of the coast. See 'Human Pressures Relevant to All Washington State Waters: Pollutants' for potential ecosystem effects of pollutants.

COMMERCIAL SHIPPING ACTIVITIES

Approximately 90% of world trade is carried by the international shipping industry and the volume of cargo moved through U.S. ports is expected to double (as compared to 2001 volume) by 2020 (AAPA 2012) due to the economic efficiencies of transporting goods via ocean waterways. The impacts of commercial shipping activity are numerous, including the potential risk of ship strikes of large animals, noise pollution and the risk of habitat modification due to propeller scouring, sediment resuspension, shoreline erosion, and ship groundings or sinkings (similar definition as Halpern et. al. (2008)). Vessel activity in coastal waters is generally proportional to the degree of urbanization and port and harbor development within a particular area (Johnson et al. 2008). Benthic, shoreline, and pelagic habitats may be disturbed or altered by vessel use, resulting in a cascade of cumulative impacts in heavy traffic areas. The severity of boating-induced impacts on coastal habitats may depend on the geomorphology of the impacted area (e.g., water depth, width of channel or tidal creek), the current velocity, the sediment composition, the vegetation type and extent of vegetative cover, as well as the type, intensity, and timing of boat traffic (Johnson et al. 2008).

Ship strikes have been identified as a threat to endangered blue, humpback and fin whales (NMFS 1991, 1998, 2006), and this is of particular concern within the Olympic National Marine Sanctuary where 29 species of marine mammals reside or migrate through. In addition to direct mortality from ship strikes, shipping vessels increase noise levels in the ocean which could interfere with normal communication and echolocation practices of marine mammals. When background noise levels increase, many marine mammals amplify or modify their vocalizations which may increase energetic costs or alter activity budgets when communication is disrupted among individuals (Holt et al. 2009, Dunlop et al. 2010). Underwater noise levels associated with commercial shipping activity increased by approximately 3.3 dB/decade between 1950 and 2007 (Frisk 2012).

The effects of commercial shipping activity on fish populations is not very well understood, but some data suggest responses will be behavioral in nature (e.g. Rostad et al. 2006) and related to loss of habitat (Uhrin and Holmquist 2003, Eriksson et al. 2004) or noise pollution (Slabbekoorn et al. 2010). Some fish species may be attracted to vessels, rather than being repelled by them and are not bothered by noisy, passing ships (Rostad et al. 2006). However, frequently traveled routes such as those traveled by ferries and other transportation vessels may impact fish spawning, migration, communicative, and recruitment behaviors through noise and direct disturbance of the water column (Barr 1993, Codarin et al. 2009).

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CHAPTER 2. SELECTING AND EVALUATING POTENTIAL INDICATORS FOR WASHINGTON STATE'S MARINE SPATIAL PLANNING PROCESS

SELECTING ECOSYSTEM INDICATORS FOR WASHINGTON STATE

In March 2010, the Washington State legislature enacted a new state law on marine spatial planning (MSP; Substitute Senate Bill 6350). One of the primary objectives of this law was to develop a comprehensive marine management plan for the state's marine waters. The law stipulated that the "plan must include an ecosystem assessment that analyzes the health and status of Washington marine waters including key social, economic, and ecological characteristics. This assessment should seek to identify key threats to plan goals, analyze risk and management scenarios, *and develop key ecosystem indicators*."

In support of Washington State's MSP process, this Chapter describes a process for addressing the last objective mentioned above: developing key ecosystem indicators. Much of this work was based on previous efforts to develop ecosystem indicators for NOAA's California Current Integrated Ecosystem Assessment (IEA) which includes Washington State waters. The first step for Washington State waters focused on non-human biological components, oceanographic drivers and anthropogenic pressures. Future research will focus on the development of indicators for socioeconomic and cultural characteristics of the ecosystem.

WHAT IS AN ECOSYSTEM INDICATOR?

Ecosystem indicators are quantitative biological, chemical, physical, social, or economic measurements that serve as proxies of the conditions of attributes of natural and socioeconomic systems (Landres et al. 1988, Kurtz et al. 2001, EPA 2008, Fleishman and Murphy 2009). Ecosystem attributes are characteristics that define the structure, composition, and function of the ecosystem that are of scientific or management importance but insufficiently specific or logistically challenging to measure directly (Landres et al. 1988, Kurtz et al. 2001, EPA 2008, Fleishman and Murphy 2009). Thus, indicators provide a practical means to judge changes in ecosystem attributes related to the achievement of management objectives. They can also be used for predicting ecosystem change and assessing risk.

Ecosystem indicators are often cast in the Driver-Pressure-State-Impact-Response (DPSIR) framework—an approach that has been broadly applied in environmental assessments of both terrestrial and aquatic ecosystems, including NOAA's Integrated Ecosystem Assessment (Levin et al. 2009). Drivers are factors that result in pressures that cause changes in the system. Both natural and anthropogenic forcing factors are considered; an example of the former is climate conditions while the latter include human population size in the coastal zone and associated coastal development, the desire for recreational opportunities, etc. In principle, human driving forces can be assessed and controlled. Natural environmental changes cannot be controlled but must be accounted for in management.

Pressures are factors that cause changes in state or condition. They can be mapped to specific drivers. Examples include coastal pollution, habitat loss and degradation, and fishing. Coastal development results in increased coastal armoring and the degradation of associated nearshore habitat. State variables describe the condition of the ecosystem (including physical, chemical, and biotic factors). Impacts comprise measures of the effect of change in these state variables such as loss of biodiversity, declines in productivity and yield, etc. Impacts are measured with respect to management objectives and the risks associated with exceeding or returning to below these targets and limits.

Responses are the actions (regulatory and otherwise) taken in response to predicted impacts. Forcing factors under human control trigger management responses when target values are not met as indicated by risk assessments. Natural drivers may require adaptational response to minimize risk. For example, changes in climate conditions that in turn affect the basic productivity characteristics of a system may require changes in ecosystem reference points that reflect the shifting environmental states.

Ideally, indicators should be identified for each step of the DPSIR framework such that the full portfolio of indicators can be used to assess ecosystem condition as well as the processes and mechanisms that drive ecosystem health. State and impact indicators are preferable for identifying the seriousness of an environmental problem, but pressure and response indicators are needed to know how best to control the problem (Niemeijer and de Groot 2008). For this report, we focused primarily on indicators of ecological components, oceanographic drivers, and anthropogenic pressures for the outer coast of Washington State. Future work should address and evaluate indicators for the major estuaries (Columbia River estuary) and bays (Willapa Bay and Grays Harbor) along Washington’s coast, as well as state and pressure indicators for socioeconomic and cultural characteristics. Ultimately, the final portfolio of indicators should be used as measurement endpoints for examining alternative management scenarios in ecosystem models or in emerging analyses to predict or anticipate regime shifts.

SPECIFIC GOALS WILL DETERMINE THE SUITE OF INDICATORS

It is a significant challenge to select a suite of indicators that accurately characterizes the ecosystem while also being relevant to policy concerns. A straightforward approach to overcoming this challenge is to employ a framework that explicitly links indicators to policy goals (Harwell et al. 1999, EPA 2002). This type of framework organizes indicators in logical and meaningful ways in order to assess progress towards policy goals. Development of specific policy goals for Washington State was a parallel process being conducted by the Marine Spatial Planning Team, so we did not have specific goals and objectives to build a specific framework for this analysis. Thus, we developed a basic framework that uses ideas from other indicator selection frameworks (National Research Council 2000, EPA 2002, Heinz Center 2008, Levin and Schwing 2011) to define general goals that would be of interest to the Marine Spatial Planning Team. This framework can be easily adjusted to take into account final decisions made on goals and objectives of the MSP process.

CONCEPTUAL FRAMEWORK FOR INDICATOR SELECTION

The development of indicators for Washington State begins with the set of five habitat types described by the conceptual models in Chapter 1: sandy beaches, rocky intertidal, kelp forests, seafloor habitat, and the pelagic zone. These habitat types represent the region's primary ecosystems and serve as the basis for assessing the condition of Washington State ecosystems ('estuaries' will be an additional habitat type in future indicator selection work). For each habitat type, three structural elements define the principle components of interest in any ecosystem assessment: ecological components, physical drivers, and human pressures (Fig. 1). Indicators of physical drivers and human pressures are tied directly to the specific driver or pressure, but indicators of the ecological components need to be linked with specific policy goals as mentioned above. The ecological components represent discrete segments of the ecosystem (biological, physical, or human-dimension related) that reflect societal goals or values and should be relevant to the policy goals of Washington State. Each of these goals is then characterized by key attributes, which describe fundamental aspects of each goal (Fig. 1); and, finally, we map indicators onto each key attribute. For this analysis, we defined three major goals that any ecosystem assessment will be interested in: habitat, ecosystem health, and focal species. Goals and indicators related to socioeconomic or cultural values will eventually be included into the framework here.

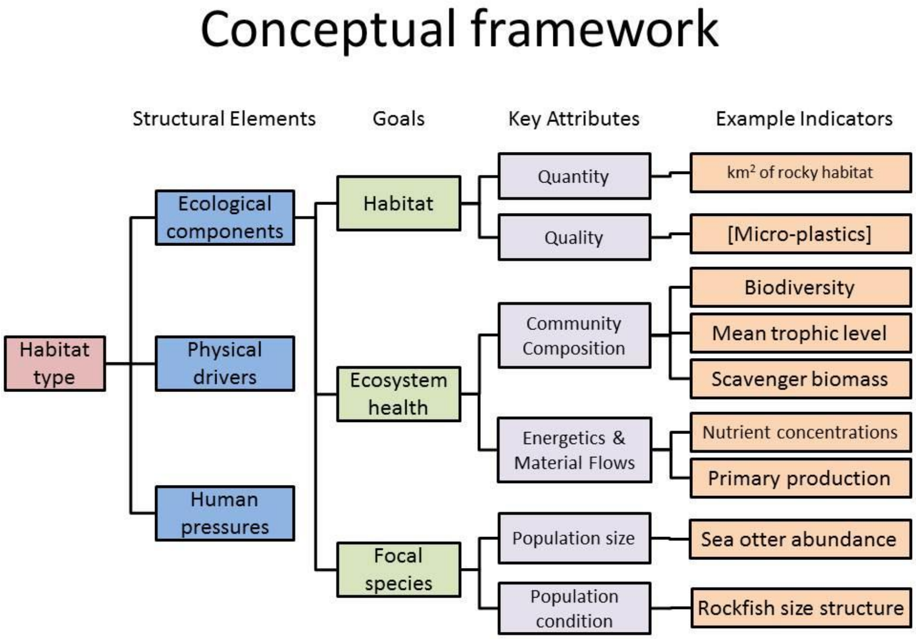

Figure 1. Conceptual framework for the development of indicators for ecological goals relevant to Washington State's marine spatial planning process.

HABITAT

Habitat is often the focus of management efforts because natural resources or ecosystem services are generally associated with specific types of habitat (e.g., designations of essential fish habitat or critical habitat). Conservation or restoration efforts for many species is often focused on necessary habitats needed to support specific life-history stages and is thus a critical component of ecosystem assessments.

FOCAL SPECIES

The goal of focal species incorporates various species that are of interest to managers, policy makers and the general public for a variety of reasons. Thus, depending on the specific goals and objectives for Washington State, this goal may incorporate a variety of indicators at the species level. For example, species listed under the Endangered Species Act (Chinook salmon) or Species of Concern (e.g., northern abalone) could be accounted for within this framework here. Species that exert strong influence over community structure and function (i.e. keystone species such as sea otters and *Pisaster* sea stars) may also be important indicators for specific habitat types and can be accounted for under this goal.

ECOSYSTEM HEALTH

Rapport et al. (1985) suggested that the responses of stressed ecosystems were analogous to the behavior of individual organisms. Just as the task of a physician is to assess and maintain the health of an individual, resource managers are charged with assessing and, when necessary, restoring ecosystem health. This analogy is rooted in the organismic theory of ecology advocated by F. E. Clements more than 100 years ago, and is centered on the notion that ecosystems are homeostatic and stable, with unique equilibria (De Leo and Levin 1997). In reality, however, disturbances, catastrophes, and large-scale abiotic forcing create situations where ecosystems are seldom near equilibrium. Indeed, ecosystems are not “superorganisms”—they are open and dynamic with loosely defined assemblages of species (Levin 1992). Consequently, simplistic analogies to human health break down in the face of the complexities of the nonequilibrial dynamics of many ecological systems (Orians and Policansky 2009). Even so, the term “ecosystem health” has become part of the ecosystem-based management lexicon and resonates with stakeholders and the general public (Orians and Policansky 2009). In addition, ecosystem health is peppered throughout the literature on ecosystem indicators. Thus, while we acknowledge the flaws and limitations of the term, we use it here because it is familiar and salient in the policy arena. Ecosystem health is defined specifically by the key attributes described below.

KEY ATTRIBUTES OF ECOLOGICAL COMPONENTS

Key attributes are ecological characteristics that specifically describe some relevant aspect of each ecological component. They are characteristic of the health and functioning of each ecological component, and they provide a clear and direct link between the indicators and goals. We identified two key attributes for each goal (Table 1; Levin and Schwing 2011): Habitat: 1) Quantity and 2) Quality; Focal Species: 1) Population size and 2) Population condition; and Ecosystem Health: 1) Community Composition, and 2) Energetics and material flows.

Table 1. Selected key attributes for each goal. Relevant measures describe what each attribute means (e.g., population size is represented by the number of individuals in a population or the total biomass).

Goal	**Key attribute**	**Relevant measures**
Habitat	Quantity	Areal coverage of specific physical or biogenic habitats.
	Quality	Measures that describe the condition of specific habitat.
Focal Species	Population size	Number of individuals or total biomass, population dynamics
	Population condition	Measures of population or organism condition including: age structure, population structure, phenotypic diversity, genetic diversity, organism condition
Ecosystem Health	Community composition	Ecosystem structure: species diversity, trophic diversity, functional redundancy, response diversity
	Energetics and Material Flows	Ecosystem function: primary production, nutrient flow/cycling

HABITAT

1. Quantity: Understanding the distribution and/or abundance of specific types of physical or biogenic habitat is important for management actions. Habitat characteristics are often used to delineate spatial management boundaries that regulate specific activities. For example, rockfish conservation areas (RCAs) designate areas that prohibit bottom trawl fishing. These closure areas are primarily located along the continental shelf break because several rockfish species are associated with this type of habitat.

2. Quality: The quality of habitat available has been shown to influence demographic rates of many marine organisms. Indicators related to these underlying population processes are often important for identifying mechanisms responsible for changes in population size and condition of focal species or changes in ecosystem health.

FOCAL SPECIES

1. Population size: Monitoring population size in terms of total number or total biomass is important for management and societal interests. For example, abundance estimates are used to track the status of threatened and endangered species and help determine whether a species is recovering or declining. Accurate population biomass estimates of targeted fisheries species are used to assess stock viability and determine the number of fish that can be sustainably harvested from a region. While population size can be used to assess population viability, more accurate predictions of viability can be obtained by including the mechanisms responsible for the dynamics of the population. Population dynamics thus provide a predictive framework to evaluate the combined effect of multiple mechanisms of population regulation (e.g., birth and death rates, immigration, and emigration) to evaluate changes in abundance through time.

2. Population condition: Whereas the preceding attribute is concerned with measures of population size, there are instances when the health of the population may be of interest. For example, monitoring changes in population condition may presage an effect on population size or provide insight into long-term population viability. The dynamics of many populations are better understood through knowledge of population conditions such as organism condition, age structure, genetic diversity, phenotypic diversity, and population structure. Impaired condition of any or all of these subcategories indicates biological resources at risk. In addition, monitoring changes in population condition can be used to infer changes in environmental conditions.

ECOSYSTEM HEALTH

1. Community composition: This attribute represents the structure of the ecosystem, describing the individual components and the relative extent of their potential interactions. Our definition of community composition includes species diversity, trophic level diversity, functional group redundancy, and response diversity. Species diversity encompasses species richness or the number of species in the ecosystem, and species evenness or how individuals or biomass are distributed among species within the ecosystem (Pimm 1984). Trophic diversity refers to the relative abundance or biomass of different primary producers and consumers within the ecosystem (EPA 2002). Consumers include herbivores, carnivores or predators, omnivores, and scavengers. Functional redundancy refers to the number of species characterized by traits that contribute to a specific ecosystem function, whereas response diversity describes how functionally similar species respond differently to disturbance (Laliberte and Legendre 2010). For example, an ecosystem containing several species of herbivores would be considered to have high functional redundancy with respect to the ecosystem function of grazing, but only if those herbivorous species responded differently to the same perturbation (e.g., trawling) would the food web be considered to have high response diversity.

2. Energetics and material flows: This attribute represents ecosystem function and includes ecological processes such as primary production and nutrient cycling, in addition to flows of organic and inorganic matter throughout an ecosystem. Primary productivity is the capture and conversion of energy from sunlight into organic matter by autotrophs, and provides the fuel fundamental to all other trophic transfers throughout the ecosystem. Material flows, or the cycling of organic matter and inorganic nutrients (e.g., nitrogen, phosphorus), describe the efficiency with which an ecosystem maintains its structure and function.

EVALUATING POTENTIAL INDICATORS FOR WASHINGTON STATE

INITIAL SELECTION OF INDICATORS

There are numerous publications that cite indicators of species and ecosystem health in marine systems. For this report, we relied heavily on NOAA's California Current IEA (Levin and Schwing 2011), which itself relied on several core references from the literature (Jennings and Kaiser 1998, Link et al. 2002, Rochet and Trenkel 2003, Fulton et al. 2005, Jennings 2005, Jennings and Dulvy 2005, Link 2005, Shin et al. 2005, Samhouri et al. 2009, Sydeman and Thompson 2010) to develop an initial list of potential indicators for each of the key attributes for the ecological components. In many cases, indicators identified in the literature were chosen by the authors based on expert opinion or based on the context of the researchers' expertise. For example, many reviews of marine ecosystem indicators are put into the context of fisheries (e.g., Fulton et al. 2005, Link 2005); which indicators reflect changes in the population as a result of fishing pressure? The approach we describe throughout this section to select and evaluate indicators for ecosystem health and focal species could be applied to the any other goals and key attributes identified as important by the Marine Spatial Planning Team.

During reviews of the literature, we identified 110 indicators for the key attributes for the habitat, focal species, and ecosystem health goals. Indicators of habitat quantity include the measurement and spatial mapping of various physical and biogenic habitats or population size of algae, corals, sponges and other biogenic habitats. Habitat quality indicators vary widely with measurements of water quality, structural complexity, and food availability. Indicators of population size are rather obvious, including estimates of abundance in numbers or biomass and estimates of population growth rate. Indicators of population condition vary widely in the literature and are generally dependent on the taxa of interest. Physiological measurements, such as cortisol and vitellogenin levels, and measurements of body growth and size/age structure are often related to the condition of populations via size-related fecundity processes, while measurements of genetic diversity and spatial structure of a population are often cited as measures of resilience in populations against perturbations such as fishing pressure or climate change. Indicators of community composition include community level metrics such as taxonomic diversity and ratios between different foraging guilds. Community composition indicators also include population level trends and conditions across a wide variety of taxa such as marine mammals, seabirds, and zooplankton. Indicators of energetics and material flows primarily examine the base of the food web and the cycling of nutrients that supply the basis for phytoplankton growth.

EVALUATION FRAMEWORK

We follow the evaluation framework established by Kershner et al. (2011) and Levin & Schwing (2011). We divide indicator criteria into three categories: primary considerations, data considerations, and other considerations. Ecosystem indicators should do more than simply document the decline or recovery of species or ecosystem health; they must also provide information that is meaningful to resource managers and policy makers (Orians and Policansky 2009). Because indicators serve as the primary vehicle for communicating ecosystem status to stakeholders, resource managers, and policy makers, they may be critical to the policy success of EBM efforts, where policy success can be measured by the relevance of laws, regulations, and governance institutions to ecosystem goals (Olsen 2003). Advances in public policy and improvements in management outcomes are most likely if indicators carry significant ecological information and resonate with the public (Levin et al. 2010).

For the purposes of this report, we only evaluated indicators for Washington State using the ‘Primary Considerations’ criteria. The Marine Spatial Planning Team was eliciting comments from stakeholder groups about the appropriateness of using the ‘Data’ and ‘Other considerations” criteria at the time this report was written. Once final criteria have been determined, the evaluation of indicators can be completed. We describe all criteria below.

PRIMARY CONSIDERATIONS

Primary considerations are essential criteria that should be fulfilled by an indicator in order for it to provide scientifically useful information about the status of the ecosystem in relation to the key attribute of the defined goals. They are:

1. Theoretically sound: Scientific, peer-reviewed findings should demonstrate that indicators can act as reliable surrogates for ecosystem attributes.
2. Relevant to management concerns: Indicators should provide information related to specific management goals and strategies.
3. Predictably responsive and sufficiently sensitive to changes in specific ecosystem attributes: Indicators should respond unambiguously to variation in the ecosystem attribute(s) they are intended to measure, in a theoretically expected or empirically expected direction.
4. Predictably responsive and sufficiently sensitive to changes in specific management actions or pressures: Management actions or other human-induced pressures should cause detectable changes in the indicators, in a theoretically expected or empirically expected direction, and it should be possible to distinguish the effects of other factors on the response.
5. Linkable to scientifically defined reference points and progress targets: It should be possible to link indicator values to quantitative or qualitative reference points and target reference points, which imply positive progress toward ecosystem goals.

DATA CONSIDERATIONS

Data considerations relate to the actual measurement of the indicator. Data considerations criteria are listed separately to highlight ecosystem indicators that meet all or most of the primary considerations, but for which data are currently unavailable. They are:

1. Concrete and numerical: Indicators should be directly measureable. Quantitative measurements are preferred over qualitative, categorical measurements, which in turn are preferred over expert opinions and professional judgments.

2. Historical data or information available: Indicators should be supported by existing data to facilitate current status evaluation (relative to historic levels) and interpretation of future trends.
3. Operationally simple: The methods for sampling, measuring, processing, and analyzing the indicator data should be technically feasible.
4. Broad spatial coverage: Ideally, data for each indicator should be available across a broad range of the California Current.
5. Continuous time series: Indicators should have been sampled on multiple occasions, preferably without substantial time gaps between sampling.
6. Spatial and temporal variation understood: Diel, seasonal, annual, and decadal variability in the indicators should ideally be understood, as should spatial heterogeneity and patchiness in indicator values.
7. High signal-to-noise ratio: It should be possible to estimate measurement and process uncertainty associated with each indicator, and to ensure that variability in indicator values does not prevent detection of significant changes.

OTHER CONSIDERATIONS

Other considerations criteria may be important but not essential for indicator performance. Other considerations are meant to incorporate nonscientific information into the indicator evaluation process. They are:

1. Understood by the public and policy makers: Indicators should be simple to interpret, easy to communicate, and public understanding should be consistent with technical definitions.
2. Historically reported: Indicators already perceived by the public and policy makers as reliable and meaningful should be preferred over novel indicators.
3. Cost-effective: Sampling, measuring, processing, and analyzing the indicator data should make effective use of limited financial resources.
4. Anticipatory or leading indicator: A subset of indicators should signal changes in ecosystem attributes before they occur, and ideally with sufficient lead-time to allow for a management response.
5. Lagging indicator: Reveals evidence of a failure in or to the attribute.
6. Regionally, nationally, and internationally compatible: Indicators should be comparable to those used in other geographic locations, in order to contextualize ecosystem status and changes in status.

SCORING INDICATORS

As mentioned above, each indicator was evaluated independently according to the five 'Primary Considerations' evaluation criteria by reviewing peer-reviewed publications and reports. The result is a matrix of indicators and criteria that contains specific references and notes in each cell, which summarize the literature support for each indicator against the criteria. This matrix can be easily re-evaluated and updated as new information becomes available or if criteria are added or removed.

The matrix of ecosystem indicators and indicator evaluation criteria provides the basis for scoring the relative support in the literature for each indicator (Kershner et al. 2011, Levin and Schwing 2011). For each cell in the evaluation matrix, we assigned a literature-support value of 1.0, 0.5, or 0.0 depending on whether there was support in the literature for the indicator, whether the literature was ambiguous, or whether there was no support in the literature for the indicator, respectively. The sum of values across the five criteria provided the final score for each indicator.

For each key attribute of each ecological component goal, we then calculated the quartiles for the distribution of scores for each indicator. Indicators that scored in the top quartile (top 25%) for each attribute of each goal were considered to have good support in the literature as an indicator of the attribute they were evaluated against.

RESULTS OF INDICATOR EVALUATIONS

The results of our evaluation of indicators for each ecological component goal are summarized in the tables below. Following the framework outlined above, we organized the results of the evaluation by ecological component goal (i.e., habitat, focal species, and ecosystem health). The sum-of-scores across the five evaluation criteria are provided along with a brief summary of why the indicator is important and how it evaluated. Indicators that ranked highly (i.e. in the top quartile for each goal) are identified in the tables by their sum-of-scores values. These highly-ranked indicators provide a working directory of indicators that can be used to assess the important components identified in each of the conceptual models in Chapter 1. Detailed matrices of the evaluations are available as electronic files upon request.

EVALUATION OF HABITAT INDICATORS

1. Quantity – Indicators of habitat quantity are similar to indicators of population size for focal species (see *Focal Species: Population size* below) in that we are simply interested in how much habitat is there. The initial selection of indicators for quantity was rather obvious and all of these indicators scored highly in the evaluation (Table 2). Indicators of quantity of biogenic habitat will vary depending on habitat type (e.g., kelp and algae in kelp forests or corals and sponges in seafloor habitat). Indicators of physical habitat will most likely be in the form of habitat maps (Fig. 2; NMFS 2013).

Table 2. Summary of habitat quantity indicator evaluations. The numerical value that appears under each of the considerations represents the sum of scores across the five ‘Primary considerations’ evaluation criteria. Indicators with a sum-of-scores value ≥ 5 scored in the upper quartile.

Indicator	**Sum of scores**	**Summary comments**
Areal coverage of biogenic species	5	Estimates of the areal coverage of biogenic species will provide specific estimates of the quantity of habitat available.
Density of biogenic species	5	Density estimates of biogenic species will provide specific estimates of the quantity of habitat available.
Areal coverage of physical habitat	4.5	Estimates of the areal coverage of physical habitat (i.e., rocky, sandy, muddy, mixed) will provide specific estimates of the quantity of habitat available. Categorization of habitat types should be clearly defined.

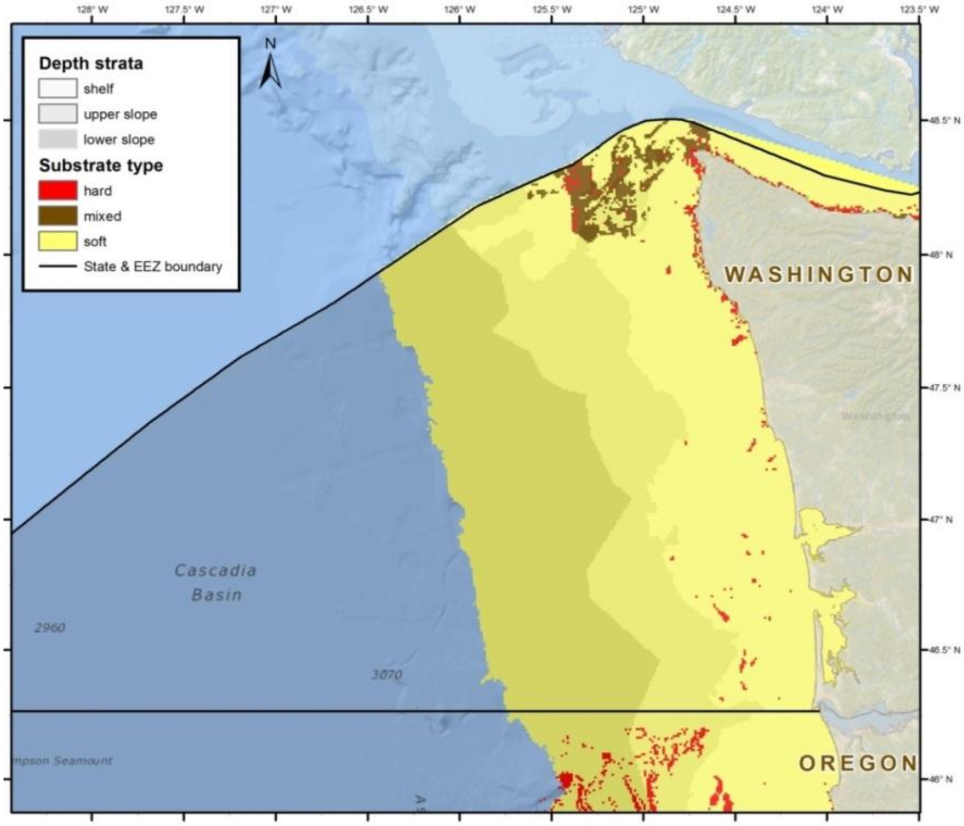

Figure 2. Spatial distribution of three major seabed substrate types and depth strata off the coast of Washington State (data from the National Marine Fisheries Service’s 2013 Groundfish Essential Fish Habitat Synthesis Report).

2. Quality – Indicators of habitat quality are akin to indicators of population condition for focal species (see *Focal Species: Population condition* below). These indicators measure specific characteristics that make good habitat for marine species, including the spatial distribution of habitat (i.e. connectivity/fragmentation), water quality, sediment quality, and population dynamics or health of biogenic habitats. Indicators of water quality and sediment quality ranked highest in our evaluation of primary considerations (Table 3).

Table 3. Summary of habitat quality indicator evaluations. The numerical value that appears under each of the considerations represents the sum of scores across the five 'Primary considerations' evaluation criteria. Indicators with a sum-of-scores value ≥ 5 scored in the upper quartile.

Indicator	**Sum of scores**	**Summary comments**
Water quality index	5	This indicator should include or integrate specific measurements relevant to each habitat type related to pollutants, nutrients, dissolved oxygen, pH (pCO_2), salinity, and temperature. Estimates of human-derived characteristics, such as pollutants, should respond to management actions while large-scale oceanographic characteristics, such as dissolved oxygen and pH, may only respond to large-scale environmental changes.
Sediment quality index	5	Similar to water quality, this indicator should include or integrate measurements related to the chemical and physical makeup of the sediment, including sediment grain size and concentrations of pollutants, organic matter, and dissolved oxygen.
Rugosity of substrate	4.5	Rugosity is used as a proxy for habitat complexity which tends to explain a large amount of variation in species richness, biomass, and abundance. Management actions such as spatial closures may allow biogenic habitat to recruit and grow, creating more structurally complex habitats of higher quality. Reference points have only been used relative to different sites (e.g., sites in MPAs had higher rugosity than non-MPA sites).
Habitat connectivity/fragmentation	3.5	The connectivity or fragmentation of habitat types relates to the community structure, source/sink dynamics, and predator/prey dynamics of these locations and may have implications for dispersal duration and larval size. However, there are numerous interacting factors behind recruitment of biogenic habitats that make it difficult to determine mechanisms of response. Nearest neighbor measurements have been used to quantify connectivity.
Growth of biogenic habitat	3	The growth of biogenic habitat such as kelps, algae, corals, and sponges is important for species taking refuge within these habitats; however, good growth conditions for the habitat may not translate to high quality conditions for the ecological component of interest if other processes are more important.

EVALUATION OF FOCAL SPECIES INDICATORS

We evaluated a total of 29 indicators of the two key attributes: population size and population condition. In general, the indicators that were evaluated scored well against the primary considerations criteria; however, when indicators performed poorly, it was generally because data collected by fisheries-dependent methods have several biases or because indicators do not necessarily respond predictably to specific environmental pressures or management actions.

1. <u>Population size</u> – We first evaluated three primary indicators which are obvious and well-established—numbers of individuals, total biomass of the population, and population growth rate (Table 4). These indicators performed well across all three evaluation criteria categories and are supported as indicators of population size by all of our primary literature resources (e.g., Fulton et al. 2005, Link 2005). However, the ability of scientists and managers to measure the

abundance or growth rate of any population over time relies on surveys that are performed to collect data.

In general, fishery-independent surveys based on the life-history characteristics of each focal species evaluated highly, while indicators related to fishery-dependent data (e.g., commercial landings numbers, total harvest biomass) did not perform well against the primary considerations evaluation criteria. For example, recreational landings data are generally collected at docks and only include individuals and species that are kept by fishers. Thus these data are highly biased by fisher behavior both in what species are targeted and what species or individuals they retain. Interestingly, "local ecological knowledge" scored well in the primary considerations categories, but these interviews of people's memories simply do not exist for most of Washington State. One attempt in Puget Sound, WA by Beaudreau et al. (2011) has shown a correlation between abundance trends of marine species derived from interviews with fishers and divers and scientifically collected survey data.

Table 4. Summary of focal species population size indicator evaluations. The numerical value that appears under each of the considerations represents the sum of scores across the five 'Primary considerations' evaluation criteria. Indicators with a sum-of-scores value ≥ 4.125 scored in the upper quartile.

Indicator	Sum of scores	Summary comments
Population biomass (using best method)	5	Biomass for each species is an obvious indicator for individual focal species, but changes in biomass/individual over time may lead to misinterpretation – use in conjunction with "Population numbers" below.
Population numbers (using best method)	5	Similar comment as "biomass" above.
Population growth rate	4.5	Theoretically sound and can be calculated at numerous spatial and temporal scales as datasets can be integrated.
Local ecological knowledge	4	Theoretically sound, but the link to reference points is questionable.
Number of groups below management thresholds	4	Good snapshot of species trends over time, but only a few species are assessed.
Egg/larvae abundance	3.5	Stock/recruit/egg relationships may be independent when stock or spawning biomass is at high levels and if recruitment is mostly affected by environmental drivers.
Commercial landings biomass	2	Fishery-dependent data biased toward fisher behavior, fleet dynamics and management restrictions. Only economically valuable species.
Commercial landings numbers	2	Similar comments as above.
Recreational landings biomass	2	Similar comments as above.
Recreational landings numbers	2	Similar comments as above.
Total harvest biomass, catch per unit effort	2	Similar comments as above.
Bycatch abundance	0	Levels of bycatch are heavily influenced by fisher behavior and management restrictions.

2. Population condition – We identified and evaluated 17 potential indicators (Table 5) for population condition. Similar to population size, we chose to only evaluate population condition indicators with the 'Primary Considerations' criteria because 'Data and Other Considerations' criteria will vary widely among focal species. Indicators related to age structure, fecundity, or spatial structure of populations generally scored well in the primary considerations categories. Looking forward, these types of indicators are generally not as well understood as indicators of population size and surveys collecting 'condition' data are generally more limited.

Table 5. Summary of focal species population condition indicator evaluations. The numerical value that appears under each of the considerations represents the sum of scores across the five 'Primary considerations' evaluation criteria. Indicators with a sum-of-scores value ≥ 5 scored in the upper quartile.

Indicator	Sum of scores	Summary comments
Age structure of populations	5	Strongly supported by the literature in most criteria.
Age at maturity	5	Strongly supported by the literature in most criteria.
Fecundity	5	Strongly supported by the literature in most criteria.
Spatial structure of population	5	Strongly supported by the literature in most criteria, but difficult to interpret without time series.
Mean length of species	5	Strongly supported by the literature in most criteria, but mostly relevant to fish species.
Genetic diversity of populations	5	Strongly supported by the literature in most criteria.
Size at maturity	4	Similar comments as above.
Condition factor (K)	4	Theoretically sound as condition of fish is directly related to growth and fecundity.
Rebuilding timeline	4	Only available for assessed and overfished species.
Larval abundance	3.5	Abundance of larvae most likely driven by oceanographic conditions and not reflective of the condition of specific populations.
Parasitic load	3.5	Theoretically sound but not relevant to management actions or reference points.
Center of distribution (latitudinal or depth)	3	Distributional shifts tend to suggest a pressure is acting on the population (i.e., fishing or climate).
Body growth	3	Body growth rates could signify size-selective pressures in which slower growing individuals are more fit and escape pressure (i.e. fishing), but variation in body growth to environmental changes or management actions is not likely.
Size structure of populations	2.5	Size structure is generally biased by gear selectivity and catchability of survey methods.
Cortisol/vitellogenin	2	May be related to condition, but changes in the attribute are not likely to vary with this indicator at any scale but the very smallest.
Disease	2	Similar comments as above.
Diet of groundfish	0	Not supported for any criteria.

EVALUATION OF ECOSYSTEM HEALTH INDICATORS

We evaluated indicators of the two key attributes: 1) community composition and 2) energetics and material flows. The support in the literature for these indicators varied widely and support for many of these indicators comes from ecosystem modeling studies. Ecosystem health indicators will often integrate across more than one of the ecosystem components of a habitat type described in the conceptual models in Chapter 1.

1. <u>Community composition</u> – We identified and evaluated 66 potential indicators of ecosystem health related to community composition across a wide variety of taxa and foraging guilds (Table 6). Indicators that scored well under primary considerations generally included species or foraging guild trends and abundance. Many functional group ratios have been identified by modeling exercises as good indicators of diversity and total biomass in the system. A common theme for many indicators was that they performed poorly for the criteria “responds predictably and is sufficiently sensitive to changes in a specific ecosystem attribute.” This is because changes in species’ or foraging guilds’ trends and abundance will influence community composition and ecosystem structure, but changes in community composition may not be reflected in any one species or foraging guild. Moreover, it is conceivable that many of the foraging guild ratio indicators (e.g., piscivorous to zooplanktivorous fish ratio) could have scientifically defined reference points and progress targets, but these ratios may not be easily understood by the public and policy makers for establishing management targets. These evaluations suggest that multivariate indicators may be more indicative of changes in ecosystem structure. Changes in many of these community-level metrics cannot be observed in short-term monitoring sets and may be more useful at longer management time scales (Nicholson and Jennings 2004).

   Population trends of large-bodied, long-lived, or high trophic–level vertebrates (e.g., cetaceans, pinnipeds, sea turtles, or seabirds) were consistently considered poor indicators of ecosystem condition because of the inherent low variability of their life history characteristics, which limited their ability to serve as an early warning (i.e., leading indicator) of impacts, as well as the associated difficulty in attributing change to particular causes or interpreting the spatial extent of trends (Hilty and Merenlender 2000, Holmes et al. 2007). Indicators related to fishery removal (e.g., total catch or total harvested biomass) also performed poorly because landings were often poorly correlated with marine population trends due to fleet behavior and dynamics, targeting and behavior of the fishermen, and bias from misreporting (Hilborn and Walters 1992, Watson and Pauly 2001, Rochet and Trenkel 2003, de Mutsert et al. 2008).

Table 6. Summary of Ecosystem Health Community Composition indicator evaluations. The numerical value that appears under each of the considerations represents the sum of scores across the five 'Primary considerations' evaluation criteria. Indicators with a sum-of-scores value ≥ 4 scored in the upper quartile.

Guild	**Indicator**	**Primary considerations (5)**	**Summary comments**
Marine mammals	Pinniped annual reproductive performance	4	Strong link to nutritional stress, contaminants, and disease
	Cetacean species status and trends	3	Theoretically sound sentinel species, but low sample size and high variability in data makes it difficult to link to changes in attribute and management actions; slow population response rate.
	Pinniped abundance and population trends	3	See above, although surveys at breeding grounds and haul-out sites facilitate population estimates.
	Pinniped biomass	3	See above.
	Pinniped contaminant load	3	Theoretically sound, but problems due to high migratory patterns.
	Pinniped diet (fatty acids, stable isotopes)	2	Reflects broad status of food supply, variety of methods can discern variable scales of feeding, high sampling replication and effort required.
	Pinniped disease, death, mortality, bycatch	2	Theoretically valid and increasingly well-studied; often difficult to attribute cause to changes in pinniped mortalities.
	Integrative marine mammal index (multivariate)	2	Can be used to show predictable responses to stressors, type of data in the index affect interpretability, unlikely to correlate specific cause with effect.
	Pinniped stress hormones	0	Integrative measure of stress, but difficult to differentiate cause and effect; baseline information needed to discern normal variation.
Key fish groups	Forage fish biomass; species status and trends	3	Changes in a single group may or may not be indicative of entire community.
	Groundfish status and trends	3	Similar to comments.
	Flatfish biomass	3	Changes in a single group may or may not be indicative of the entire community.
	Zooplanktivorous fish biomass	3	Identified as the best indicator of total biomass in marine systems during modeling exercises.
	Piscivorous fish biomass	3	Changes in a single group may or may not be indicative of the entire community.
	Roundfish biomass	3	Identified as a significant indicator for nine ecosystem attributes in modeling exercises.
	Demersal fish biomass	3	Changes in a single group may or may not be indicative of the entire community.
	Pelagic fish biomass	3	Changes may indicate predatory release of prey populations or insufficient forage base, but changes in a single group may not be indicative of the entire community.
	Rockfish biomass	3	Changes in a single group may or may not be indicative of the entire community.

Guild	Indicator	Primary	Summary comments
Key fish groups (cont.)	Juvenile rockfish index	3	Can be useful in forecasting year-class strength and reflect trends in adult biomass, used frequently in stock recruitment models.
	Juvenile hake abundance	3	See juvenile rockfish abundance above.
Salmon	Salmon smolt-to-adult survival rate	5	Related to dominant ocean conditions acting over the region with extensive historical records.
	Salmon adult escapement	3	Highly influenced by ocean conditions, but difficult to discern cause and effect.
Seabirds	Seabird annual reproductive performance	4	Strong correlation between breeding success, food availability, and large scale indices of ocean climate.
	Seabird diet (fatty acids, stable isotopes)	4	See pinniped diet above.
	Marine seabird species status and trends	2	Easily enumerated top consumers, difficult to attribute change to particular causes, often respond to environmental change or management actions, better indicator at years to decades.
	Seabird biomass	2	Primarily used in food web models, not highly sensitive, changes likely occur at same rate as populations.
	Seabird disease, death, mortality, bycatch	2	See pinniped disease, death, mortality, bycatch above.
	Integrative seabird index (multivariate)	2	See integrative marine mammal index above.
	Marine shorebird species status and trends	2	Provide information on coastal and shoreline habitat; often slow to respond to environmental change or management actions, but difficult to attribute cause and effect.
	Seabird contaminant load	0	See pinniped contaminant load above.
	Seabird stress hormones	0	See pinniped stress hormones above.
Reptiles	Sea turtle status and trends	2	Widely dispersed, non-prominent member; difficult to monitor population trends, except adult females during nesting events; slow to respond to environmental change or management actions, and attribute cause and effect.
Shellfish and invertebrates	Jellyfish biomass, status and trends	4	Indicator of trophic energy transfer and pelagic community composition, abundance can be linked to human activities, no existing reference condition.
	Crustaceans: catch and survey trends; larval surveys	4	Attributed to climate induced changes in water column temperature and fishing; indicative of community regime shift (high trophic level groundfish to low trophic level crustaceans); zooplankton data sets provide good record of larval abundance for estimating spawning stocks.
	Benthic invertebrate biomass	4	Correlates well with ecosystem health and responds to fishing pressure; gradual change should show major community reorganization.

Guild	Indicator	Primary	Summary comments
	Squid, Humboldt	1	Range expansion correlated with reduction in top predators; possibly indicates shifts in climate regimes, ocean circulation, and ecosystem-wide food webs.
Zooplankton	Copepod species ratio (cold vs. warm) or zooplankton species biomass anomalies)	5	Reflect modifications in water masses, currents, or atmospheric forcing; respond rapidly to climate variability; some taxa reflect influence of different water types on ecosystem structure.
	Euphausiid biomass and richness	5	Indicator of plankton biomass changes, critical link in marine food web, low counts and high patchiness in samples may increase variability.
	Zooplankton abundance and biomass	4	Base of food web; fundamental component correlated with regime shift and climate change, can be used to estimate thresholds.
Diversity indices	Biodiversity index (Hurlbert's Delta)	4	Reflects taxonomic evenness; calculated from abundance estimates; change detectable with latitude and depth at large scales; natural and baseline levels of evenness may vary; significance of certain types of change not known.
	Slope of log (biomass) vs. trophic level–Simpson Diversity Index	4	Theoretically sound, calculated from abundance estimates; difficulty linking diversity indices to targets or reference points.
	Marine mammal diversity – Shannon Diversity	4	Measures taxonomic richness and evenness; community stability related to higher diversity; difficulty linking diversity indices to targets or reference points.
	Adult sablefish biomass – Shannon Diversity	4	Theoretically correlated with community diversity in British Columbia ecosystem during modeling exercises.
	Detritivore biomass – Shannon Diversity	4	Similar to comments above.
	Number of threatened species (IUCN A1 criteria as modified by Dulvy et al. 2006)	4	Composite indicator based on weighted average of species threat, criteria somewhat arbitrary, linking index to targets or reference points is difficult.
	Taxonomic distinctness (average and variation in)	3	Uses species lists, not abundance data; minimal data requirements allows integration of data sets, use of historical data, and data of varying quality.
Functional groups	Top predator biomass (trophic level > 4.0)	5	Top predator removal typically results in trophic cascades.
	Scavenger biomass	4	Some evidence that disturbances, such as fishing activities, induce chronic increases in scavenger populations, plus comments above.
	Detritivore biomass	3	Similar comments as above.
	Herbivore biomass	3	Similar comments as above.
	Invertivore biomass	2	Correlated with several measures of diversity and total biomass in modeling exercises, but variation in community composition may not be detected by variation in this functional group alone.

Guild	Indicator	Primary	Summary comments
Functional group ratios	Forage fish and jellyfish biomass ratio	3	Highly correlated with diversity measures and mean trophic level in modeling exercises.
	Piscivorous and Zooplanktivorous fish biomass ratio	3	Highly correlated with diversity measures in modeling exercises.
	Pelagic and demersal fish biomass ratio	3	Appears to be a proxy for differential impact of nutrients on the pelagic and benthic food webs based on modeling exercises.
	Invertivore and herbivore biomass ratio	3	Similar to comments above.
	Finfish and crustacean biomass ratio	3	Indicative of community regime shift in several systems from high trophic level groundfish to a low trophic level, crustacean-dominated system.
	Zooplankton and phytoplankton biomass ratio	2	Highly correlated with measures of diversity and mean trophic level in modeling exercises.
	Rockfish and flatfish biomass ratio	2	Highly correlated with measures of diversity and total biomass in modeling exercises.
Fishery catch	Proportion noncommercial species (unfished groups)	5	Modeling results show response to variation in fishing pressure and correlation with ecosystem attributes; one of the more sensitive indicators of changes in species composition.
	Mean length, all species	4	Useful and simple indicator to evaluate effects of fishery removals, but may not be observable over short-term monitoring data sets.
	Trophic level of catch (mean biomass)	2	Shortcomings associated with typical catch-based data; size-based indicators are better because they do not require diet data, are less error prone, and more easily collected.
	Total fishery removals of all species	2	See comments above.
	Slope size spectrum, all species	2	Good indicator of fishing effects, models show change is predictable and consistent, unclear what attributes it would act as an indicator for besides general ecosystem health, thresholds unclear, size data sparse for some species.
	Total catch and landings of target species	1	Good indicator of fishing effects but poor indicator of marine ecosystem performance, primarily a function of fishing effort and a poor approximation of production, landings can be misleading in assessments ecosystems.

2. Energetics and material flows – We identified and evaluated 10 potential indicators of ecosystem health related to energetics and material flows (Table 7). The highest ranking indicator was number of cycles, which is generally not something easily measured, but is an output of most ecosystem models. Inorganic nutrient levels and proxies for primary productivity such as Chlorophyll-a concentration and plankton biomass also ranked highly and are most likely to be available within Washington State waters. Remote-sensing data are a valuable source of this information, though other, labor-intensive approaches are available for obtaining spatially explicit and finely resolved understanding of primary productivity as well (e.g., plankton tows). Biogeochemical approaches for measuring carbon cycling rates are well developed and theoretically sound, but such data are not widely available and can be quite expensive to obtain. Modeling efforts (e.g., Ecopath with Ecosim) currently provide a useful tool for estimating the magnitude of secondary production and pathways of energy flows and carbon cycling throughout the food web, but more detailed data collection is needed to validate many of the inherent model assumptions. Making up for this deficiency will require detailed, broad-scale studies of how different species interact with the physical and chemical oceanography to affect processes such as nitrogen fixation, carbon sequestration, and microbial decomposition. Nevertheless, we suggest the evaluation of additional indicators of energy and material flows in the future

Table 7. Summary of ecosystem health: Energetics and material flows indicator evaluations. The numerical value that appears under each of the considerations represents the sum of scores across the five 'Primary considerations' evaluation criteria. Indicators with a sum-of-scores value ≥ 4.5 scored in the upper quartile.

Indicator	**Sum of scores**	**Summary comments**
Number of cycles (carbon)	5	Carbon cycling decreases as ecosystem stress increases; can be estimated using mass balance models.
Phytoplankton biomass	4.5	Good indicator of pelagic ecosystems and hydro-climatic forcing.
Chlorophyll a	4.5	Good indicator of phytoplankton biomass and amount of energy fueling the ecosystem, satellite remotely sensed chlorophyll concentration data available.
Inorganic nutrient levels: dissolved inorganic nitrogen, silicate, phosphate, iron	4.5	Strongly linked to upwelling events, which drive system productivity and control production; poorly characterized in space and time, except intensive sampling at individual regions.
Respiration rate	3	Captures the overall state or maturity of an ecosystem, although too few samples collected worldwide to determine spatial and temporal variability; methods have precision limitations.
Microbial decomposition/ respiration rate	2.5	Good indicator of ecosystem stress.
Nitrogen fixation rate, nitrification/denitrification rate, ^{15}N ratios	2	May indicate vigor or resilience of an ecosystem, although Washington State is in an upwelling system characterized by nutrient limitation; scientific understanding of ocean N fixation lacking.
Stratification: temperature, salinity; thermocline depth	0.5	Thought to limit nutrient exchange and be source of decadal regime shift, little evidence in scientific literature that it acts as good indicator.
Oxidation rate	0	Little evidence in scientific literature that oxidation rates act as good ecosystem indicator.
Particulate organic matter, dissolved organic carbon	0	Little evidence in scientific literature that POM acts as good ecosystem indicator; however, high POM usually linked to hypoxia and dead zones.

OCEANOGRAPHIC DRIVERS

INDICATORS OF OCEANOGRAPHIC DRIVERS/PRESSURES

The majority of the oceanographic drivers/pressures described below was developed specifically for the 2012 California Current Integrate Ecosystem Assessment (Table 8; Hazen et al. 2013), but are nonetheless relevant for Washington State. Evaluations of indicators using the 'Primary considerations' criteria are also applicable to Washington State. In addition, two oceanographic drivers specific to Washington State were added to the list: Columbia River plume and the Juan de Fuca eddy. Indicators of each of these drivers were subjected to the same evaluation framework and scored according to support from the literature. Summaries of the evaluation are provided in Table 8, but an electronic file of the evaluation matrix is available upon request.

Similar to the ecological component indicators, these indicators should be further subjected to evaluation criteria related to data availability and other considerations before they are fully incorporated into an ecosystem assessment for Washington State.

Table 8. Summary of oceanographic drivers' indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, Pacific decadal oscillation as an indicator of sea surface temperature has peer-reviewed literature supporting four out of five primary considerations criteria. Data (except for Juan de Fuca eddy and Columbia River plume) from Hazen et al. (2013).

Driver/Pressure	Indicator	Sum of scores	Summary comments
Sea level	Coastal sea level / sea level height	4	Sea level rise is due to the thermal expansion of seawater and increased freshwater input from melting polar and glacial ice. Sea level height is a common measurement but long time series are necessary to distinguish sea-level rise from naturally occurring low-frequency signals derived from atmospheric and oceanic forcing.
Sea surface temperature	Pacific decadal oscillation	3.5	The Pacific decadal oscillation (PDO) show low frequency changes in seas surface temperature (SST) over the north Pacific. Positive PDO values represent warmer SST and negative values represent colder, more productive, SST. The PDO does not accurately represent variability in SST in the coastal zone – broad-scale measurement.
Sea surface temperature	Sea surface temperature	4	SST measured by coastal and offshore hydrographic buoys will accurately reflect SST.
Sea surface temperature	MEI	4	The Multivariate ENSO index (MEI) describes ocean-atmosphere coupling. Positive values are associated with warmer SST and weaker upwelling winds while negative values are associated with colder SST. Broad-scale measurement.
Sea surface temperature	NOI	4	The Northern Oscillation Index (NOI) describes the strength of atmospheric forcing between equatorial Pacific and the North Pacific – positive values associated with colder SST, negative values with warmer SST.
Source water	NPGO	3.5	Broad-scale differences in nutrients and hypoxia are related to the source waters moving through Washington State waters. Positive values of the North Pacific Gyre Oscillation are associated with increased surface salinities, nutrients and Chlorophyll-a values as the source water comes more from subarctic waters, while negative values suggest source waters from tropical regions with decreased surface salinities, nutrients, and Chlorophyll-a.
Transport currents	EKE	3	Eddy Kinetic Energy (EKE) measures mesoscale activity (strength and presence of eddies and fronts).
Columbia River plume	Salinity contours	4	Sea-surface temperature and salinity values will describe intrusion of the plume into oceanic waters. Well defined fronts develop at the leading edge of the plume and concentrate zooplankton which may increase prey availability to planktivorous fish.

Driver/Pressure	Indicator	Sum of scores	Summary comments
Columbia River plume	River discharge	3	The strength of the plume has been shown to be correlated with Columbia river discharge when measured with multispectral satellite data, but the location (how far it intrudes into oceanic waters) and strength will also be determined by winds and prevailing currents.
Columbia River plume	Sea surface temperature contours	4	Sea-surface temperature and salinity values will describe intrusion of the plume into oceanic waters.
Columbia River plume	Seasonal winds	2.5	Seasonal wind patterns drive the spatial location of the plume, but the magnitude of intrusion may not be captured by winds alone and winds observed may not reflect whether the plume is present.
Dissolved Oxygen/Hypoxic events	Dissolved oxygen	4	Dissolved oxygen concentrations are dependent on a number of physical and biological processes, including circulation, ventilation, air-sea exchange, production and respiration, but measurements are rather common for most oceanographic sampling now.
Juan de Fuca eddy	Salinity contours	4	Sea-surface temperature and salinity values will describe waters upwelled from deep canyons below the Juan de Fuca eddy into Washington State waters. Salinities of 31.5 psu represent a threshold that marks the edge of the Juan de Fuca eddy outflow as well as the edge of the Columbia River Plume. However, recognizing this boundary requires a large-scale model.
Juan de Fuca eddy	Sea surface temperature contours	4	Sea-surface temperature and salinity values will describe waters upwelled from deep canyons below the Juan de Fuca eddy into Washington State waters. The Juan de Fuca eddy can be identified as a cold-water mass in satellite data or as a cold and salty water mass at ~35m with ~33.2 ppt salinity at location near 48.6N, 124.4W.
Juan de Fuca eddy	Radius of eddy	4	The strength of the Juan de Fuca eddy can be approximated by the size of the water mass (based on sea-surface temperature and salinity values) influenced by the eddy.
Ocean acidification	pH/pCO2	4	Decreases in the acidity of seawater will impact organisms that rely on calcium carbonate for structural and protective anatomical components. Measurements of pH and pCO2 can provide general measurements of acidity, but the level at which shells
Ocean acidification	Aragonite saturation	4	Aragonite and calcite are the most common forms of calcium carbonate used by marine organisms for structural components. The saturation state of these minerals changes with pH, temperature, and pressure and as ocean waters become more acidic they tend toward undersaturation and protective shells and structural components more readily dissolve. The saturation level of these minerals is much more informative than measurements of pH or pCO2.
El Nino events	MEI	4	The Multivariate El Nino/Southern Oscillation Index (MEI) describes ocean-atmosphere coupling in the equatorial Pacific. Positive values represent El Nino conditions (warmer waters, weaker upwelling) while negative values represent La Nina conditions.

Driver/Pressure	Indicator	Sum of scores	Summary comments
El Nino events	NOI	4	The Northern Oscillation Index (NOI) describes the strength of atmospheric forcing between equatorial Pacific and the North Pacific – positive values associated with La Nina conditions, negative values with El Nino conditions.
Upwelling	UI	4	Upwelling brings cold, salty, nutrient-rich waters from deep waters onto the continental shelf which are all important for productivity and ecosystem health along the Washington coast. The Upwelling Index (UI) provides a measure of the magnitude of upwelled waters.
Upwelling	Meridional winds	4	Northerly winds result in offshore transport and upwelling of cold, nutrient rich water into the photic zone.
Upwelling	STI	4	The Spring Transition Index (STI) indicates roughly the start of the upwelling season.
Upwelling	LUSI	3.5	The Length of the Upwelling Season Index (LUSI) provides information on the duration of upwelling during the year.
Upwelling	TUMI	3.5	The Total Upwelling Magnitude Index (TUMI) measures the ultimate amount of upwelling – the sum of the UI over the duration of the upwelling season.
Water column structure	Pycnocline depth	3.5	The pycnocline represents the separation between warmer nutrient poor surface waters and cooler nutrient rich deep waters. When the pycnocline is shallow, more nutrients are available to the photic zone. Upwelling can be constrained if the pycnocline depth is deep and the strength of stratification is strong.
Water column structure	Pycnocline strength	3.5	The strength of the pycnocline can be measured by the Brunt-Väisälä frequency. The stronger the pycnocline, the less mixing of nutrients occurs across the pycnocline. Upwelling can be constrained if the pycnocline depth is deep and the strength of stratification is strong.

ANTHROPOGENIC PRESSURES

As human population size and demand for seafood increases globally and within Washington State waters, numerous human activities in the ocean (e.g., fishing and shipping activity) and on land (e.g., pollutants and runoff from agricultural activities) need to be recognized and incorporated into management of aquatic resources. We identified 23 anthropogenic pressures, primarily relying on previous work by Halpern et al. (2008, 2009) and Teck et al. (2010). These pressures included fisheries and non-fisheries related pressures and ranged in scope from land-based pressures such as inorganic pollution and nutrient input to at-sea pressures such as fisheries removals, commercial shipping, and ocean-based pollution. Ultimately, we evaluated 44 different indicators using the indicator selection framework described above. These pressures will affect the five habitat types identified in the conceptual models (Chapter 1 of this report) in different ways, both directly and indirectly. For detailed descriptions of each pressure see Andrews et al. (2013).

Similar to the ecological components' and oceanographic drivers' indicators, these indicators should be further subjected to evaluation criteria related to data availability and other considerations before they are fully incorporated into an ecosystem assessment for Washington State.

Table 9. Summary of anthropogenic pressures' indicator evaluations. The numerical value that appears under each of the considerations represents the number of evaluation criteria supported by peer-reviewed literature. For example, finfish production as an indicator of finfish aquaculture has peer-reviewed literature supporting three out of five primary considerations criteria.

Pressure	Indicator	Sum of scores	Summary comments
Aquaculture (finfish)	Finfish production	3	Production will correlate with certain aspects of the pressures (e.g., escapement, disease, nutrient input, waste, fishmeal) on the ecosystem, but specific impacts may not increase/decrease with production as new technology is used to mitigate impacts on water quality or interactions with wild stocks.
Aquaculture (finfish)	Acres of habitat used	2.5	The amount of habitat used is relevant to determine impacts on the ecosystem. However, this metric may not account for advances in technology or growing capabilities.
Aquaculture (finfish)	Wild fish used to feed aquaculture	1.5	Increases in feed will impact wild-caught fisheries as well as contribute to effluent and waste effects on the local environment. Fishmeal increases with increased production of carnivorous species, but that may change with new sources of protein. Data are not readily available due to proprietary information.
Aquaculture (shellfish)	U.S. Shellfish production	3	Shellfish production has positive (e.g., filtering, removal of nutrients) and negative effects (e.g. habitat modification, invasive species) but the cumulative effects are unknown and these effects may change over time with advances in technology or growing capabilities. Washington state produces the greatest quantity of shellfish in the US but does not have reliable estimates, so total US shellfish production should reflect the current status and trends of shellfish production in Washington State.
Aquaculture (shellfish)	Acres of habitat used	2.5	The amount of habitat used for aquaculture is relevant to determining the effects of aquaculture activities on various elements of the ecosystem. However, this metric may not account for advances in technology that allow more production per acre.
Atmospheric pollution	Concentration of deposited sulfate	5	The concentration of sulfate deposition measured by the National Atmospheric Deposition Program is a proxy for all chemicals deposited across the landscape. This dataset has been used in multiple publications as an indicator for atmospheric pollution.
Coastal engineering	% modified shoreline	3	Coastal engineering structures destroy the habitat directly under them and can significantly modify surrounding ecosystems through changes in circulation patterns and sediment transport. The proportion of the shoreline modified is a useful proxy for proportion of nearshore habitat affected by coastal development.

Pressure	Indicator	Sum of scores	Summary comments
Coastal engineering	Coastal population	3.5	The rate of shoreline armoring has been shown to correspond with the rate of population growth in coastal areas, and in the absence of good time-series of geospatial data for hardened shorelines, coastal population data (US Census) for the west coast of the United States provide a good proxy for this stressor.
Commercial shipping activity	Tons of cargo moved	1.5	The size of vessels plays an important role in determining how well “activity” compares to cargo moved. This pressure is primarily used to describe the probability of striking marine organisms, ground strikes, etc.; this metric is not as good as an indicator including “number of trips” or “volume of water disturbed during transit”.
Commercial shipping activity	# of trips	4	Correlated with shipping activity; perhaps this indicator could be improved if size of vessel and transit mileage was added to quantify the vessel's footprint and pathway. Otherwise, the number of trips doesn’t tell us anything about the extent of areas affected by these trips.
Commercial shipping activity	Volume of water disturbed	4.5	This indicator has not been used before, but it is similar to indicators that measure habitat modification caused by bottom-trawl fishing gear. Using the actual draft and breadth of each vessel times the distance travelled each trip provides a better estimate of the risk associated with the movement of shipping vessels.
Direct human impact	Beach attendance	4	Beach attendance has been used as a proxy for direct human impacts (e.g., trampling, collection, disturbance) to the intertidal and nearshore ecosystems.
Disease/ pathogens	% of scientific articles	1.5	The percentage of scientific articles reporting disease in marine taxa is a worldwide measure, so there may be significant differences in this trend and what is occurring in Washington State. This indicator does not account for the severity of the disease outbreak, a very large outbreak counts the same as a relatively small outbreak. Overall, not very useful.
Dredging	Dredge volumes	3	The amount of material dredged from Washington State waterways is a concrete, spatially explicit indicator that concisely tracks the magnitude of this human activity.
Dredging	Dredge dump volumes	2.5	Annual offshore dump volumes are not summarized and reported separately, but can be determined with some data manipulation. Most dredging-associated material disposal on the US West coast occurs in open water or is integrated into beach nourishment programs.
Fisheries removals	Landings	4	Commercial landings represent the majority of removals for most species. This metric does not include discarded catch. Landings records from 1981 forward are available via http://pacfin.psmfc.org.
Fisheries removals	Total mortality	5	Total fishing mortality estimates are generated by the West Coast Groundfish Observer Program. These estimates are for groundfish only. The data are available from 2005 forward.

Pressure	Indicator	Sum of scores	Summary comments
Freshwater retention	Runoff magnitude	4	Discharge trends for many rivers mostly reflect changes in precipitation, primarily in response to short- and longer-term atmospheric-oceanic signals, and it is difficult to distinguish signal from noise in rivers with widely variable interannual discharge. Stream discharge data are accessible from a variety of gauged streams; incomplete gauging records or unmonitored streamflow can be simulated by a comprehensive land surface model.
Freshwater retention	Impoundment volume	3	Data series associated with parameters of consumption and storage likely provide some of the best indicators of human impacts to freshwater input. For most normal rivers, reservoirs can affect the timing of discharge, but appear to have little effect on annual discharge. Freshwater storage data are available from state agency databases, which include information on construction date and impoundment area/volume for all dams.
Habitat modification	Distance trawled	2.5	Distance trawled relates to the amount of habitat disturbed and trawled areas have been shown to have different community characteristics (e.g., species assemblage structure). However, the magnitude of modification will vary with specific gear types and the specific habitat trawling occurs in.
Inorganic pollution	Total inorganic pollutants	3.5	Measures of total inorganic pollutants disposed or released on site or in water will provide a relative measure over time of what gets into Washington State waters. However, variation in other variables (e.g., precipitation and specific pollutants released) will de-couple these measurements from observations as well as the impact on organisms.
Inorganic pollution	Total inorganic pollutants * toxicity	4	Adding a measure of toxicity to the amount of pollutants released will provide better context to the severity and potential impacts of pollutants released. However, variation in other variables will still limit the correlation between these land-based pollutants and observations in Washington State waters.
Inorganic pollution	Total inorganic pollutants * toxicity* impervious surface areas	5	Including ISA helps to account for other variables and more closely links how much land-based pollutants reach Washington State waters.
Invasive species	# of invasive species	5	A quantitative global assessment scored and ranked invasive species impacts based on the severity of the impact on the viability and integrity of native species and natural biodiversity (http://conserveonline.org/workspaces/global.invasive.assessment/). This database is pooled by region, serves as a baseline for invasion, but has not been updated since its creation.

Pressure	Indicator	Sum of scores	Summary comments
Invasive species	# of shipping ports	3	Shipping is considered one of the key invasion pathways; 'number of shipping ports' was significantly correlated with harmful species introductions in most regions globally. Simple indicator, but perhaps less informative due to lack of time-series data.
Invasive species	Shipping cargo volume	3.5	Shipping is considered one of the key invasion pathways; 'shipping cargo volume' was significantly correlated with harmful species introductions in most regions globally.
Light pollution	Nighttime stable lights	4	Light pollution has considerable effects on some organisms' nocturnal behaviors, predator/prey relationships, bioenergetics, nesting and migratory patterns. Average nighttime lights data is available from the National Geophysical Data Center.
Marine debris	National Marine Debris Program coastal trash	3.5	Standardized sampling programs of measuring marine debris will be better than community groups, but it is unknown whether coastal measurements correlate with ocean measurements.
Marine debris	Coastal trash cleanup programs	3.5	Community group clean-ups are great, but they are not standardized and data will vary with sampling effort, not necessarily with abundance of marine debris. Coastal measurements may not correlate with ocean measurements.
Marine debris	Ocean-based measurement	3	Ocean-based surveys have not used consistent methods and have been performed sporadically at small spatial scales. Estimates are likely lagging indicators of debris currently going into the ecosystem.
Nutrient input	Nutrient loading	4	Nutrient loading from surface waters can be estimated using publicly available data on nutrient concentrations and flow rates from various watersheds sampled by the USGS and various state and local agencies. Flow adjusted trends in concentration can be complex, as there often are multiple and possibly counteracting anthropogenic factors influencing nutrient source and transport in a watershed.
Nutrient input	Fertilizer loading	4	Models can predict the probability of nitrate contamination in ground waters based on fertilizer loading and other factors; it is unclear how this relates to coastal systems, however. County-level estimates are available of nutrient inputs (kg/km^2) to the land surface based on fertilizer use, livestock manure, and atmospheric deposition.
Ocean-based pollution	Shipping activity and port volume	4	Ocean-based pollution, including oil spills, was assumed to be primarily driven by vessel activities and port volume. This indicator evaluated well in most criteria and is a combination of the indicators for commercial shipping activity and invasive species.

Pressure	**Indicator**	**Sum of scores**	**Summary comments**
Ocean mining	Unknown	.	This pressure has not been evaluated to date.
Organic pollution	Toxicity-weighted pesticide concentration	5	This indicator is well supported for use as a measure of organic pollution. Data are collected as part of the U.S. Geological Survey's National Water-Quality Assessment Program, so data will continue to be collected using standardized methods that will be useful for temporal and spatial analyses in the future.
Power, desalination plants	Water withdrawal volumes	3.5	Coastal power plants draw in huge amounts of marine water for cooling purposes, creating an area around the intake pipes where larvae and small plants are entrained. The USGS has conducted water-use compilations in the US by state every 5 years since 1950, and thermoelectric power has represented the largest total category of water withdrawals in every compilation since 1960. This could be a pressure in the future for Washington State.
Power, desalination plants	Entrainment mortality	4	Models for estimating organism entrainment mortality rely on estimates of power plant entrainment and source water larval populations; however, a variety of other considerations may play a more important role in determining entrainment impacts. This could be a pressure in the future for Washington State.
Seafood demand	Total consumption	5	Total consumption of edible and non-edible fisheries products is well supported as an indicator of seafood demand. Data are available at national levels, which is likely the right scale as products are used all over the nation as well as internationally, and over long temporal scales.
Seafood demand	Per capita consumption	3	Per capita consumption of edible and non-edible fisheries products may not be the best indicator if thinking about total impact, but it is important because if this indicator rises, as recommended by the U.S. Dept. of Agriculture (DGAC 2010), then increases in total consumption may increase dramatically.
Sediment input	Impoundment volume	4.5	Historically, decreases in sediment input have been the result of river damming or diversions, which directly influence the rate of coastal retreat.
Sediment input	Suspended sediment loading	4.5	Sediment loading from surface waters can be estimated using publicly available data on suspended sediment concentrations and flow rates from various US watersheds sampled by the USGS and various state and local agencies. Flow adjusted trends in concentration can be complex, as there often are multiple and possibly counteracting anthropogenic factors influencing sediment source and transport in a particular watershed.
Tourism	Gross Domestic Product of Tourism & Recreation	4	Coastal tourism is generally a driver of coastal development.

MAPPING OF INDICATORS TO CONCEPTUAL MODELS

The final step in the development of ecosystem indicators for Washington State will be to map highly-ranked indicators back onto the conceptual models for each habitat type. If important components of the conceptual models do not have indicators, then further research should be performed to determine whether that component should be in the conceptual model or whether new indicators need to be evaluated to assess missing components. We provide one example below from the conceptual models in Chapter 1 as to how these indicators could be mapped.

EXAMPLE: PELAGIC HABITAT

The pelagic habitat was described in terms of important interacting ecological components, key physical drivers, and relevant human pressures (Chapter 1; Fig. 3). In order to assess the condition of the pelagic ecosystem, there should be corresponding indicators for each of the identified components of this conceptual model. Using highly-ranked indicators from the evaluation tables described above, we can substitute indicators for each component into this conceptual model (Fig. 4). For the pelagic habitat, highly-ranked indicators were mapped to all identified components with the exception of the physical driver “solar energy”. The solar energy component should be re-examined to determine why it was identified as important and if indicators need to be developed or whether there are other complementary indicators, such as chlorophyll a concentrations, that may serve the purpose.

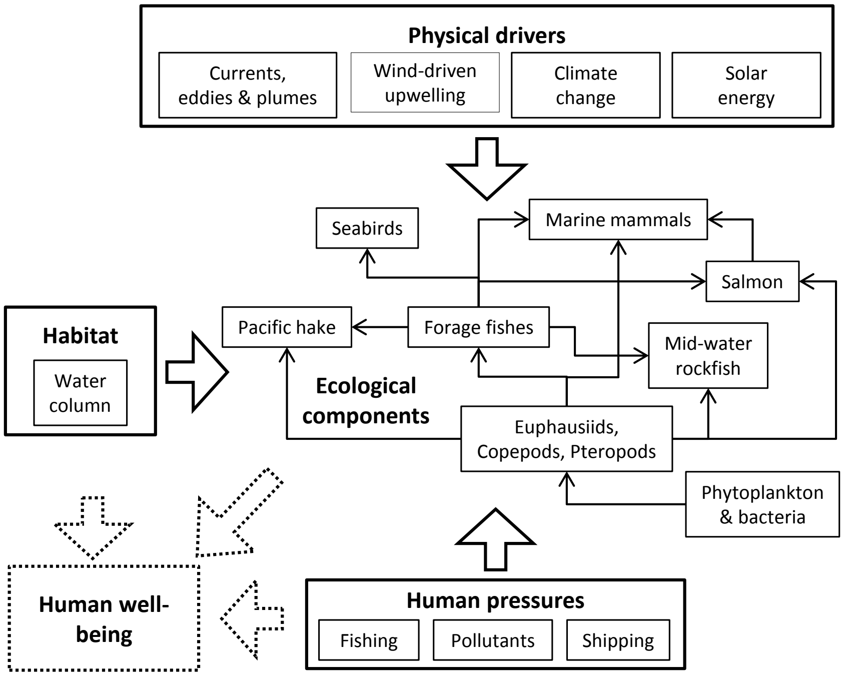

Figure 3. Conceptual model of important habitat, ecological components, physical drivers and human pressures for the pelagic habitat.

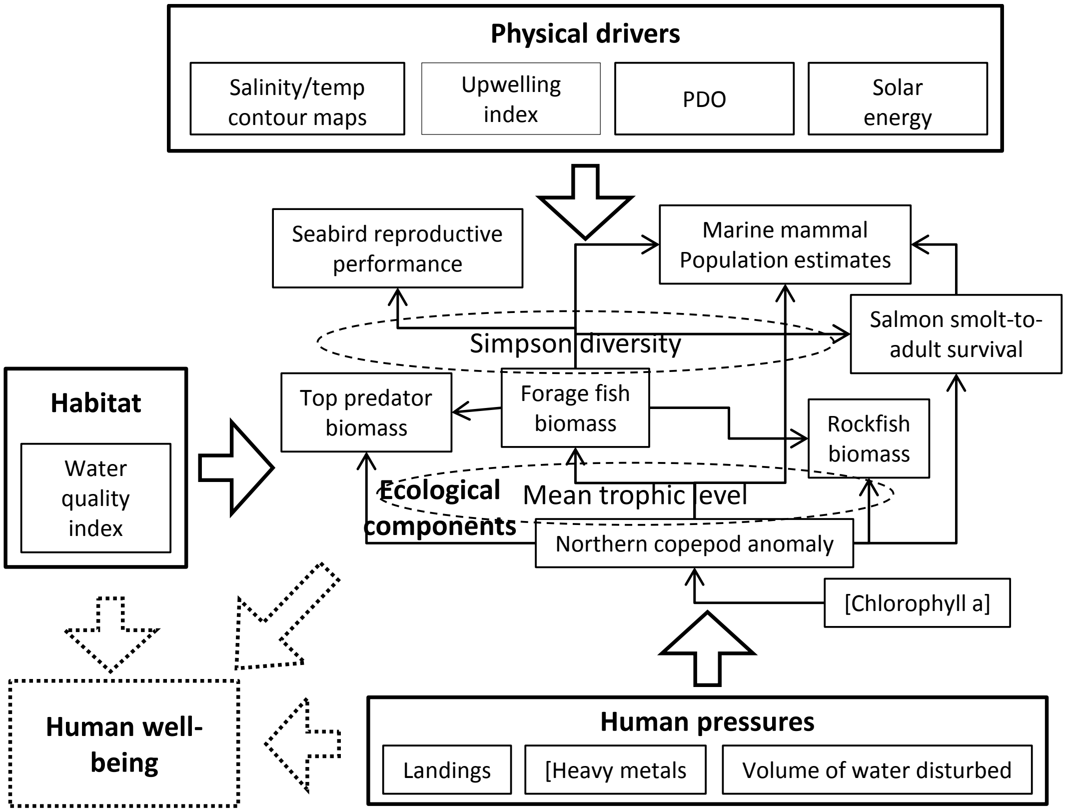

Figure 4. Conceptual model using indicators for important habitat, ecological components, physical drivers and human pressures for the pelagic habitat.

The results of this mapping exercise provide a potential portfolio of indicators that could serve to make an assessment of the pelagic ecosystem for Washington State. In this example, we have labeled only one indicator in each box for simplicity, but a full assessment will likely have more than one indicator for certain components and indicators of ecosystem health will cross over multiple components depending on the availability of appropriate data as shown by the inclusion of 'Simpson diversity' and 'Mean trophic level' in Figure 4.

FUTURE RESEARCH

ADDITIONAL HABITAT TYPES

This report focused on five habitat types along the outer coast of Washington State: sandy beaches, rocky intertidal, kelp forests, seafloor habitat, and the pelagic zone. In order to capture the entire range of ecosystems in Washington, we can foresee additional habitat types being added to this framework. First, coastal estuaries along the outer coast must be added. This habitat type would bring in Willapa Bay, Grays Harbor and the Columbia River estuary. These coastal estuaries have unique biological communities, environmental pressures and socio-economic characteristics that require additional sets of indicators. Other habitat types, such as deep-water canyons and offshore islands, may also be of interest and need included separately in this framework.

It should also be discussed how Puget Sound will fit into this framework in relation to marine spatial planning. The Puget Sound Partnership has developed a set of ecosystem indicators, known as the Puget Sound Vital Signs, which could be incorporated into the marine spatial planning framework.

SELECTION AND EVALUATION OF INDICATORS

EVALUATION CRITERIA

In addition to the primary considerations criteria used to evaluate indicators for this report, further criteria related to data availability and other considerations needs to be added into the evaluation framework. Currently, we only know what indicators are theoretically useful, but we do not know whether data is available for these indicators. Once additional criteria have been chosen by the Washington Marine Spatial Planning Team, the list of indicators should be evaluated with these criteria and ranked. It will be useful to compare highly-ranked indicators using only the primary considerations and the list using all the criteria in order to identify data gaps. For example, one indicator may be theoretically best to use, but there is little or no data to be useful in an ecosystem assessment and ranked lower than other data-rich indicators in the final evaluation. This process can identify where limited resources can get the best return on investments in monitoring.

WEIGHTING OF CRITERIA

Scoring indicators also requires careful consideration of the relative importance of evaluation criteria. The importance of the criteria will certainly vary depending on the context within which the indicators are used and the people using them. Thus, scoring requires that managers, scientists, and stakeholders work together to weight criteria. Failure to weight criteria is, of course, a decision to weight all criteria equally.

The weighting of evaluation criteria can be done in various ways, but it should incorporate the expertise of managers, scientists, and other stakeholders in the region. For example, a mixed science-policy group decided on the relative importance of criteria in a workshop setting for indicators in the Puget Sound (Kershner et al. 2011), whereas regional resource managers, policy analysts, and scientists were surveyed and asked to rate how important each of the evaluation criteria was to them for the California Current IEA (Levin and Schwing 2011). A similar weighting method should be developed based on the expertise of managers, scientists, and other stakeholders in Washington State.

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