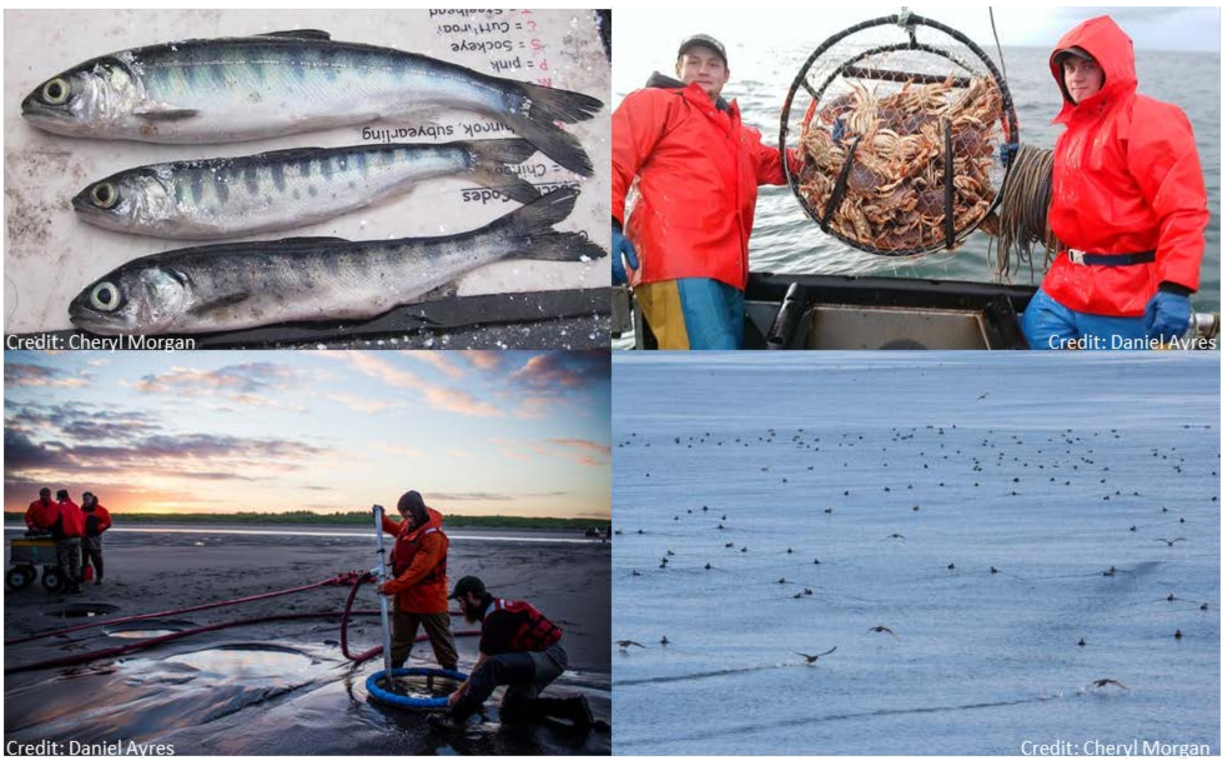
Ecological indicators for Washington State’s outer coastal waters.



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OVERVIEW

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 (WAMSP) process, this report has three main objectives:

1) **Develop conceptual models of the key ecological components, physical drivers, and human activities of the major habitat types within Washington State MSP waters.**

2) **Evaluate and select a portfolio of indicators for the key components within the conceptual models.**

3) **Quantify the status and trends of indicators for the key components within the conceptual models.**

We first developed conceptual models that described the important ecological components, physical drivers, and human activities that are important to ecosystems within WAMSP waters (see Appendix 1). For the purposes of this report, "WAMSP waters" refers to waters and habitats that will be included within Washington's marine spatial planning boundary, which includes waters and habitats beyond the 3-mile state territorial sea boundary. The conceptual models serve as the basic framework for identifying ecosystem indicators and assessing the status and trends of key components of WAMSP habitats. Next, we evaluated and selected indicators that could best assess the status of these key components. Finally, where data were available, we developed time series to quantify the status and trends of indicators for the key components in WAMSP habitats. Future research will need to be done to analyze risk, test management scenarios, and integrate social, economic and cultural characteristics into the conceptual model, as called for by the WAMSP law.

HABITATS WITHIN WASHINGTON STATE MSP BOUNDARIES

The conceptual models of Washington State waters were organized according to major types of habitat found along and off the outer 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 (Figure 1). 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. We combined these two sets of habitat categorizations into six primary habitat types within WAMSP waters (Table 1).

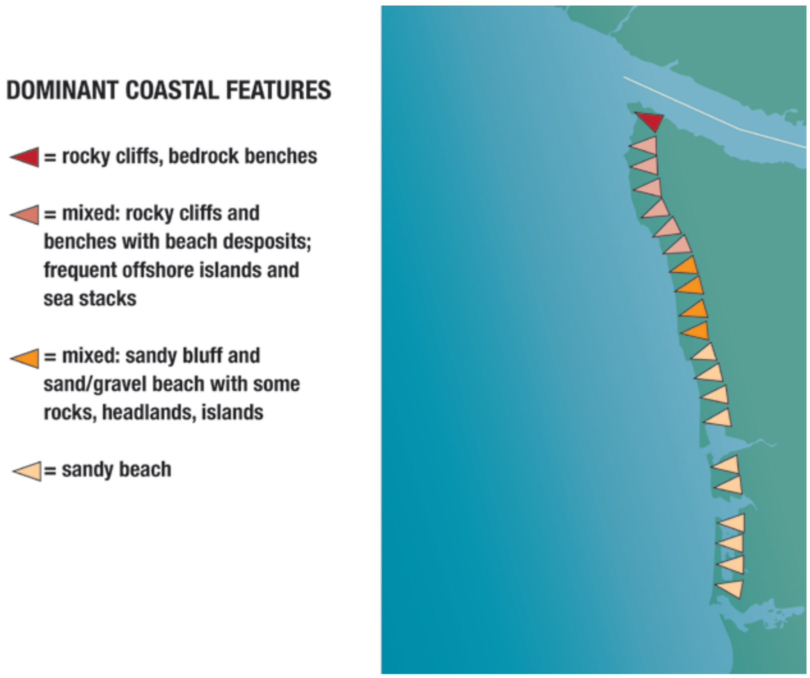

Figure 1. Dominant coastal habitats of the outer Washington coastline.

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

Habitat type	General extent of habitat	General definition
Large coastal estuaries	Grays Harbor and Willapa Bay.	Semi-enclosed, brackish inland water bodies.
Rocky 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 northern coast.	Kelp forest habitats and rocky reefs <30m deep.
Seafloor	Seafloor habitats throughout Washington State MSP waters.	Benthic communities >30m.
Pelagic zone	Water column habitat throughout Washington State MSP waters.	Pelagic offshore waters.

For each of these six habitats, we first developed a conceptual model of the most important ecological components, physical drivers, and human activities (Figure 2). These models depict the key food web connections and drivers and pressures responsible for the general dynamics of each ecosystem. Next, we used these conceptual models as a framework to develop indicators for each of the key components in each habitat. Finally, we analyzed time series for each indicator to quantify the status and trends of each component of the conceptual model.

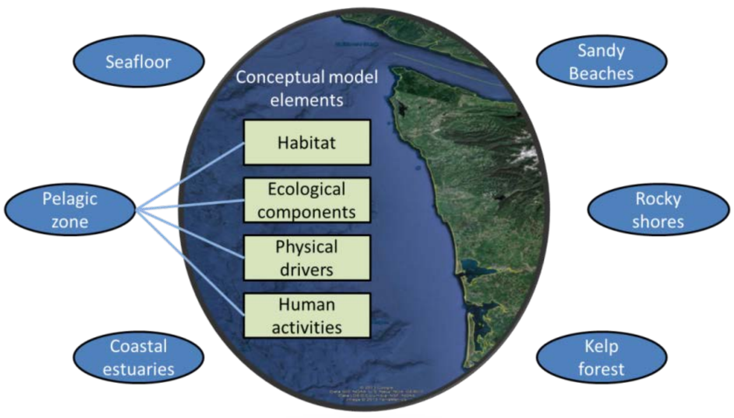

Figure 2. Habitat types and conceptual model elements used to develop ecological indicators for Washington marine spatial planning waters.

The following section describes the methodology used to evaluate and select the indicators for each of the habitat types. We then follow with an executive summary of the selected indicators and status and trends (where data was available) for each habitat type. These executive summaries will be updated with detailed chapters for each habitat as appendices. In each habitat appendix, we present the conceptual model, a description of the key components, the evaluation and selection of indicators, and figures showing the status and trends of indicators of the key components.

EVALUATION AND SELECTION OF ECOSYSTEM INDICATORS

WHAT IS AN ECOSYSTEM INDICATOR?

Ecosystem indicators are quantitative biological, chemical, physical, social, or economic measurements that serve as proxies for 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. 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 forcing 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 drivers 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 falling 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 adaptive responses 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, physical drivers (oceanographic and climatic), and human activities for the outer coast of Washington State. Parallel research is being done to evaluate and select state and pressure indicators for socioeconomic and cultural characteristics. Ultimately, the final portfolio of indicators will be available for use in subsequent risk analyses and as measurement endpoints for examining alternative management scenarios in ecosystem models or in emerging analyses to predict or anticipate regime shifts in the physical environment.

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 is 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, a basic framework that uses ideas from other indicator selection frameworks (National Research Council 2000, EPA 2002, The Heinz Center 2008, Levin and Schwing 2011) to define general goals that would be of interest to the Marine Spatial Planning Team was developed. This framework relied heavily on the development of conceptual models (see Appendix 1). The conceptual models were developed with the assistance of participants in two Marine Spatial Planning workshops in 2013 and a webinar dedicated to the coastal estuaries habitat in 2014. These conceptual models present the important ecological components, physical drivers and human activities in each of the six habitats. 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 began with the set of six habitat types: large coastal estuaries, sandy beaches, rocky shores, kelp forests, seafloor habitat, and the open pelagic zone. These habitat types represent the region's primary ecosystems and serve as the basis for assessing the condition of Washington State coastal ecosystems. For each habitat type, four "goals" define the principal elements of interest in any marine ecosystem assessment: habitat, ecological components, physical drivers, and human activities (**Error! Reference source not found.**). Indicators of physical drivers and human activities are tied directly to the specific driver or pressure, but indicators of habitat and the ecological components need to be linked with specific policy goals as mentioned above. The habitat and 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. Finally, we map indicators onto each key attribute. For this analysis, we defined three sub-goals for the ecological components goal that any marine ecosystem assessment should be interested in: fisheries taxa, focal taxa and overall ecosystem health. Goals and indicators related to human dimensions (e.g., socioeconomic and cultural values) will eventually need to be merged with this framework to form a single socio-ecological framework.

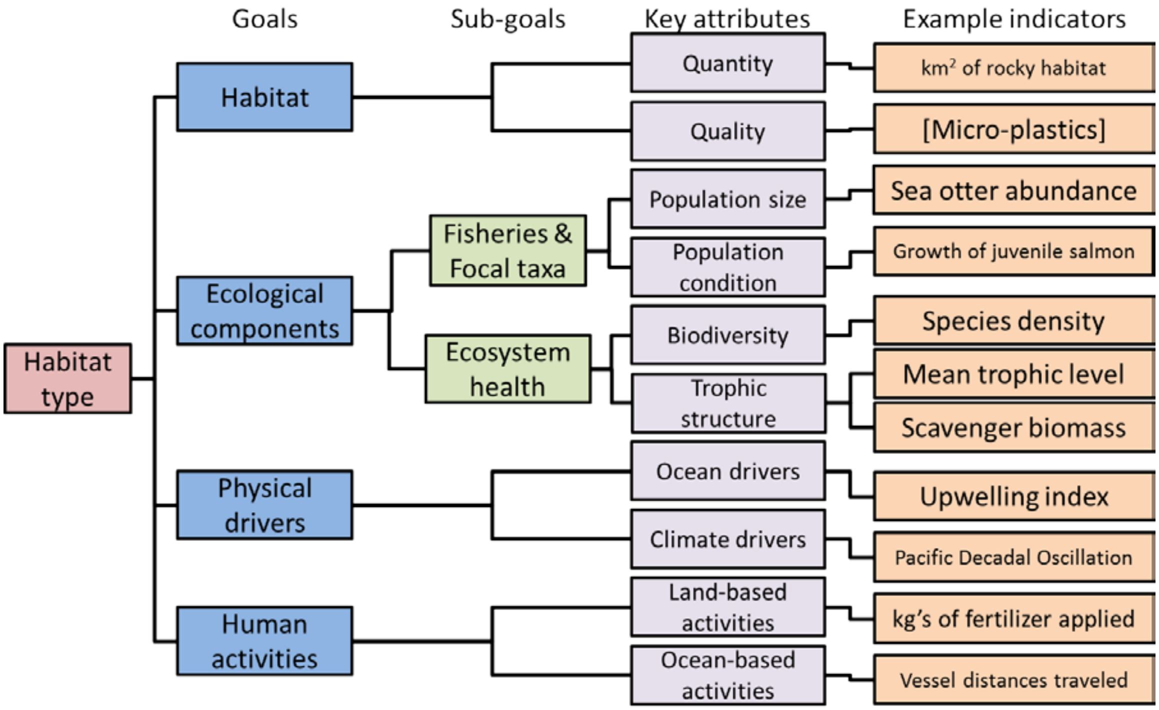

Figure 3. Conceptual framework for the development of indicators for ecological goals relevant to Washington State's marine spatial planning process.

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 often focus on habitats necessary in supporting specific life-history stages. Thus habitat is a critical component of ecosystem assessments.

FISHERIES AND FOCAL TAXA

The goal for fisheries and focal taxa is to incorporate various taxa that are of both specific and general 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 or complexes of species that are valuable fisheries resources could be included under this goal. Species listed under the Endangered Species Act (e.g., Chinook salmon *Oncorhynchus tshawytscha* and Southern Resident Killer Whales *Orcinus orca*) or Species of Concern (e.g., northern abalone *Haliotis kamtschatkana*) could be accounted for within this goal as well. Moreover, species that exert strong influence over community structure and function (i.e. keystone species such as sea otters and *Pisaster* sea stars) may be important indicators for specific habitat types and therefore may be included 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 non-equilibrial 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 CONCEPTUAL FRAMEWORK GOALS

Key attributes are characteristics that specifically describe some relevant aspect of each goal. They are general characteristics of the health and functioning of ecological goals or specific types of drivers/pressures for physical drivers and human activities. Key attributes provide a clear and direct link between the indicators and goals. We identified key attributes for each goal or sub-goal (Table 2).

PHYSICAL DRIVERS

1. Oceanographic drivers: This attribute represents oceanographic processes or characteristics that drive the conditions required for primary and secondary productivity. This would include oceanic forcings that drive temperature, salinity and the stratification of the water column, current patterns, upwelling and downwelling events, and mesoscale features such eddies and plumes. Ocean acidification is also included in this attribute.

2. Climatic drivers: This attribute represents atmospheric forcings that drive large-scale changes in weather and climate patterns. These drivers are typically the result of global patterns that cause changes in atmospheric circulation patterns resulting in the constriction and relaxation of high and low pressure regions. Changes in sea surface temperature as a result of climate change are also included in this attribute.

Table 2. 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 or sub-goal	Key attribute	Relevant measures
Physical drivers	Climatic drivers	Measures of key climatic drivers on the system.
	Oceanographic drivers	Measures of key oceanographic processes or characteristics.
Habitat	Quantity	Areal coverage of specific physical or biogenic habitats.
	Quality	Measures that describe the condition of specific habitat.
Fisheries and 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	Biodiversity	Measures of species diversity, trophic diversity, functional redundancy, response diversity.
	Trophic structure	Measures of food web interactions.
Human activities	Biological extractions	Measures of fisheries removals.
	Land-based activities	Measures of land-based activities that affect marine ecosystems: industrial, municipal, and agricultural activities.
	Ocean-based activities	Measures of ocean-based activities that affect marine ecosystems: shipping, energy exploration, habitat disturbance.

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 heavily fished 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.

FISHERIES AND FOCAL TAXA

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. Biodiversity: This attribute is meant to represent diversity and functional redundancy within the community. Species diversity encompasses species richness (the number of species in the ecosystem) and species evenness (how individuals or biomass are distributed among species within the ecosystem (Pimm 1984)).

2. Trophic structure: This attribute represents food web dynamics of the ecosystem, describing the individual components and the relative extent of their potential interactions. Trophic structure is meant to convey 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.

HUMAN ACTIVITIES

1. Land-based activities: This attribute is meant to reflect measures of human activities that occur on land, yet have some downstream effect on various marine habitats and associated flora and fauna. Types of activities include industrial, municipal and agricultural practices that result in pollutants, wastewater, excess nutrients, or garbage running off from the land, streams or groundwater into coastal habitats. These activities can introduce substances to the marine environment that increase the proliferation of plankton blooms, eutrophic conditions, ingestion of toxic substances and entanglement concerns.

2. Ocean- or estuary-based activities: This attribute represents activities that occur on or in water and affect proximate and neighboring marine habitats and associated flora and fauna. Types of activities include bottom-contact fishing practices, commercial shipping activities, port development and shoreline practices. These activities have far-ranging effects related to habitat disturbance, underwater noise, ship strikes, transport of non-indigenous species and physical processes such as sediment transport and erosion control.

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 followed the approach of NOAA's California Current Integrated Ecosystem Assessment (IEA) (Levin and Schwing 2011), a project led by the Northwest Fisheries Science Center (NWFSC) and Southwest Fisheries Science Center (SWFSC). The California Current IEA approach to indicator selection relied on several core references (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) during the process of developing 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), where the indicators which reflect changes in a population as a result of fishing pressure were identified. The approach we describe throughout this section to select and evaluate indicators for ecosystem health and fisheries and focal species could be applied to 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, fisheries and focal taxa, 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 structure include community level metrics such as taxonomic diversity and ratios among different foraging guilds. Community structure indicators also include population level trends and conditions across a wide variety of taxa such as marine mammals, seabirds, and zooplankton.

EVALUATION FRAMEWORK

To identify the most appropriate and defensible indicators from the initial list, we followed the evaluation framework established by Kershner et al. (2011) and Kershner et al. (2011), Levin and Schwing (2011). We divided indicator criteria into three categories: primary considerations, other considerations and data 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).

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.

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. 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.

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 and/or other 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 WAMSP habitat being considered.
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.

SCORING INDICATORS

We evaluated each of the indicators for each key attribute against the "primary" and "other" considerations evaluation criteria by reviewing peer-reviewed publications and reports. The result is a matrix of indicators and criteria that contain specific references and notes in each cell, which summarize the literature support for each indicator against the criteria (see Appendix 2). This matrix can be easily re-evaluated and updated as new information becomes available or if criteria are added or removed.

The matrix of 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 for indicators that were clearly supported by the literature; 0.5 for indicators with ambiguous support in the literature; or 0.0 for indicators with no support in the literature. The sum of values across the five primary and five other evaluation criteria provided the initial score for each indicator.

However, 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 and scientists work together to weight criteria. Failure to weight criteria is, of course, a decision to weight all criteria equally.

To determine the weightings for each of the evaluation criteria, we asked 35 resource managers, policy analysts, and scientists familiar with Washington State marine ecosystems to rate how important each of the evaluation criteria was to them. We asked each person to rank whether the criterion was highly important, moderately important, neutral, less important, or not important when scoring indicators for use in the Washington Marine Spatial Planning process. Each rating was assigned a value between 0 and 1, where not important equals 0, less important equals 0.25, neutral equals 0.5, moderately important equals 0.75, and highly important equals 1.0. We then calculated the percentage of responses for each rating for each criterion. The percentages were multiplied by the assigned value for each rating and then summed across each criterion and divided by 100. This provided an average weighting for each criterion (Table 3). We used the distribution of average weightings and calculated the quartiles for this distribution. We then assigned each criterion to the quartile into which its average fell. For example, the average weighting for "historically reported" (under the other considerations category) was 0.46 and that value was in the lowest quartile of the distribution so this criterion received a weighting of 0.25.

For each cell in the indicator evaluation matrix (Appendix 2), the literature support value (1.0, 0.5, or 0) was multiplied by the weighting for the respective criterion. We then summed these values for the "primary" and "other" considerations criteria across each indicator. This score was used as the first score in the selection of highly-ranked indicators. For each key attribute, we then calculated the quartiles for the distribution of scores for each indicator. Indicators that scored in the top quartile (top 25%) for each key attribute of each goal were considered to have good support in the literature as an indicator of the attribute they were evaluated against.

Finally, these highly-ranked indicators were then scored against the "data considerations" criteria following the same scoring methodology (i.e. literature support value × criterion weighting value summed across each indicator). The data considerations score was then added to the primary and other considerations score to complete the scoring of highly-ranked indicators. We then selected indicators that ranked within the top 3 indicators for each key attribute (if fewer than three indicators ranked highly, fewer indicators were selected). These indicators are highlighted in the final column of Appendix 2 and form the final set of indicators from which to quantify status and trends.

Table 3. Assignment of weightings to each criterion, based on inputs from 35 regional experts who were asked to rate each criterion from "Not important" (weighting score = 0) to "Highly important" (weighting score = 1). Values under the "Importance" categories reflect the percent of regional experts who gave the criterion that importance weighting.

Evaluation criteria	Importance					Average weighting	Quartile of average weightings
	Not important	Less important	Neutral	Moderately important	Highly important		
Theoretically sound	0.0	0.0	11.4	28.6	60.0	0.87	1.00
Relevant to management concerns	0.0	2.9	14.3	37.1	45.7	0.81	1.00
Predictably responsive to changes in specific ecosystem attributes	0.0	5.7	5.7	37.1	51.4	0.84	1.00
Predictably responsive to changes in specific management actions or pressures	0.0	8.6	14.3	37.1	40.0	0.77	0.75
Linkable to scientifically defined reference points	0.0	11.4	2.9	40.0	45.7	0.80	0.75
Concrete and numerical	0.0	2.9	5.7	40.0	51.4	0.85	1.00
Historical data or information available	0.0	8.6	11.4	51.4	28.6	0.75	0.50
Operationally simple	0.0	2.9	8.6	37.1	51.4	0.84	1.00
Broad spatial coverage	2.9	11.4	22.9	42.9	20.0	0.66	0.25
Continuous time series	0.0	14.3	22.9	48.6	14.3	0.66	0.25
Spatial and temporal variation understood	0.0	11.4	8.6	40.0	40.0	0.77	0.75
High signal-to-noise ratio	0.0	5.9	14.7	47.1	32.4	0.76	0.50
Understood by the public and policy makers	2.9	8.6	20.0	31.4	37.1	0.73	0.50
Historically reported	11.4	34.3	17.1	31.4	5.7	0.46	0.25
Cost-effective	0.0	5.7	14.3	40.0	40.0	0.79	0.75
Anticipatory or leading indicator	5.7	8.6	28.6	25.7	31.4	0.67	0.50
Regionally, nationally, and internationally compatible	8.8	26.5	26.5	20.6	17.6	0.53	0.25

STATUS AND TRENDS: DATA ANALYSIS AND PRESENTATION

In each of the subsequent habitat sections, we describe the key components of each habitat's conceptual model, the indicators selected, and create time series that quantify the status and trends of each indicator for each of the key attributes of each goal. The rationale for selection of each indicator is presented in subsequent detailed Appendices for each habitat.

The 'trend' and 'status' of each indicator was measured on a short-term basis (increasing, decreasing or no significant change over the last five years) and measured relative to the historic average of the dataset (higher than, lower than or similar to historic levels) (see Box 1 for methods). The historical status of each indicator should be placed in context with the amount of data available for each time series. For example, some indicator time series may consist of only a few years while the time series for other indicators consists of data across several decades. For shorter time series, the mean of the last five years (current status) was not likely different from the mean of the entire time series; thus, the relative status for indicators with short time series is more related to the availability of data and not actual historic trends. However, many of these indicators were chosen because they were the most fundamentally sound datasets and will continue to be measured over time, providing meaningful historic comparisons in the future.

BOX 1: DATA ANALYSIS AND PRESENTATION

We calculated two summary statistics for each indicator's time series: recent short-term trend and current status relative to the long-term mean—reported as "recent trend" and "current status," respectively.

Recent trend. An indicator was considered to have changed in the short-term if the trend over the last five years of the time series showed an increase or decrease of more than 1.0 standard deviation (SD) of the mean of the entire time series.

Current status. An indicator was considered to be above or below historical norms if the mean of the last five years of the time series differs from the mean of the full time series by more than 1.0 SD of the full time series.

Time series figures. Time series are plotted in a standard format. Dark green horizontal lines show the mean (dotted) and ± 1.0 SD (solid line) of the full time series. The shaded green area is the last five years of the time series, which is analyzed to produce the symbols to the right of the plot. The upper symbol indicates whether the modeled trend over the last 5 years increased (↗) or decreased (↘) by more than 1.0 SD, or was within 1.0 SD (↔) of the long-term trend. The lower symbol indicates whether the mean of the last five years was greater than (+), less than (-), or within (⍰) ±1.0 SD of the long-term mean.

Shading in figures. When available, we included measures of sampling error in the time series as gray shading around the data.

SUMMARY: PELAGIC HABITAT

CONCEPTUAL MODEL OF THE PELAGIC ZONE

The pelagic zone represents all water column habitats from the surface to near-bottom in WAMSP waters. The conceptual model outlined below (Figure 4) and in graphical form in Appendix 1 represents the dominant physical drivers, ecological components and interactions and human activities that characterize the pelagic zone of WAMSP waters. Suites of physical drivers and human activities affect the ecological components (i.e., the pelagic food web) and the surrounding water column within which the ecological components dwell. Humans derive wellbeing from many components and processes within the ecosystem, as well as the human activities that the pelagic system facilitates.

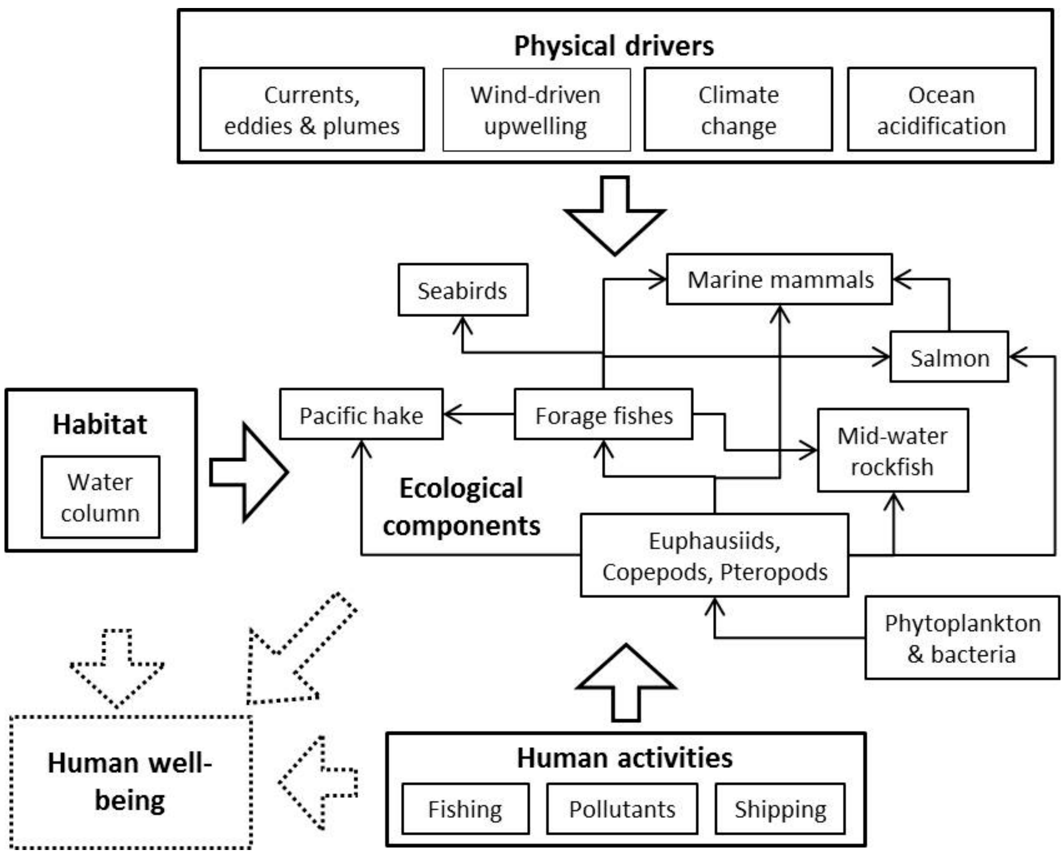

Figure 4. Conceptual model of important physical drivers, habitat, ecological components, and human activities for the pelagic habitat.

In the following sections, we briefly describe the importance and report on the status and trends (when data were available) of each indicator selected for the components shown in the conceptual model above.

Table 4. Summary of indicators and times series duration for each component's key attributes for WAMSP pelagic habitat. † indicates data are presently being analyzed.

Component	Attribute	Indicator	Time period of available data
Physical drivers			
Climatic	Water temperature	Sea surface temperature	2006 – 2012
		Pacific Decadal Oscillation	1900 – 2015
	El Niño events	Multivariate El Niño Index	1950 – 2015
		Northern Oscillation Index	1948 – 2014
	Source waters	North Pacific Gyre Oscillation index	1950 – 2015
		Northern copepod anomaly	1996 – 2015
Oceanographic	Upwelling	Upwelling index	1967 – 2014
		Spring transition index	1967 – 2015
	Currents, eddies, plumes	Columbia River plume volume	1999 – 2014
	Ocean acidification	pCO2	2006 - 2015
		Aragonite saturation	1998 - 2014
Habitat			
Physical habitat	Quantity	Thermocline depth	1998 - 2014
		Pycnocline depth	1998 - 2014
	Quality	Nitrogen: phosphorus ratio	1998 – 2014
		Sea surface temperature	2006 – 2012
Ecological components			
Phytoplankton	Population size	Chlorophyll-a quantities	2003 – 2014
	Population condition	Diatom: dinoflagellate ratio	NA†
Zooplankton	Population size	Prey field index	1999 - 2014
	Population condition	Northern copepod anomaly	1996 - 2015
Forage fish	Population size	Aggregate abundance	1999 - 2011
	Population condition	Mean age of Pacific sardines	2001 - 2013
Salmon	Population size	Escapement Juvenile abundance	1977 – 2013 1998 - 2013
	Population condition	Coastal fall Chinook age structure Juvenile Coho body growth	1975 – 2014 2000 - 2014
Pacific hake	Population size	Abundance index	1995 – 2013
	Population condition	Mean age of population	1967 - 2015
		Condition factor (K)	1995 - 2015
Marine mammals	Population size	California sea lion pup production	1997 - 2014
	Population condition	Growth of California sea lion pups	1998 - 2014
Ecosystem health	Biodiversity	Simpson's diversity	NA
		Species richness	NA
	Trophic structure	Mean trophic level	NA
		Gelatinous zooplankton	1998 - 2012

Component	Attribute	Indicator	Time period of available data
Human activities			
Biological extractions	Fishing	Fisheries landings	1982 – 2014
Land –based activities	Pollution	Atmospheric pollution	1994 – 2014
		Organic pollution	1993 – 2010
		Inorganic pollution	1988 – 2013
		Marine debris	1999 – 2007
Ocean-based activities	Commercial shipping	Volume of disturbed waters	2001 – 2013†
	Ocean-based pollution	Shipping + port volume	2001 – 2013†
	Seafood demand	Seafood consumption	1962– 2013

PHYSICAL DRIVERS

CLIMATE VARIABILITY

Climate variability represents broad spatial scale, long-term natural variability; short-term, event-driven variability; and an anthropogenic global warming signal. Increases in atmospheric CO_2 continue to put pressure on marine ecosystems through warming of the oceans, but separating anthropogenic from natural processes is difficult. The pelagic zone will be affected by large-scale atmospheric forcing patterns associated with climate change. As basin-scale climate regime phases change, pelagic communities will be exposed to the effects of changes in sea-surface temperature, the timing and frequency of El Nino events, source waters and transport currents.

OCEAN TEMPERATURE

Temperature is one of the most important drivers in the ocean. Ocean temperature regulates the rate of metabolism for most organisms and regulates the base of the food web. In WAMSP waters, cooler temperatures generally result in a prey base that contains energy-rich northern species, which promote high growth in consumers, whereas warmer temperatures generally promote southern species that are of much lower nutritional quality (Hooff and Peterson 2006, Peterson 2009). Based on the screening and weighting process, we chose two indicators of ocean temperatures in WAMSP waters: sea-surface temperature (SST) from stationary buoys and satellite-derived data and the Pacific Decadal Oscillation (PDO), which tracks low-frequency changes in SST throughout the North Pacific. We used National Data Buoy Center buoy stationed offshore from Cape Elizabeth to calculate seasonal mean SST values. PDO data was downloaded from the University of Washington's Joint Institute for the Study of the Atmosphere and Ocean. Over the last five years, SST values increased during the winter but remained relatively unchanged in the summer (Figure 5). The increasing trend in SST in the winter was due to the extremely high SST values observed in 2015. Similarly, the PDO increased rapidly over the last five years (Figure 5).

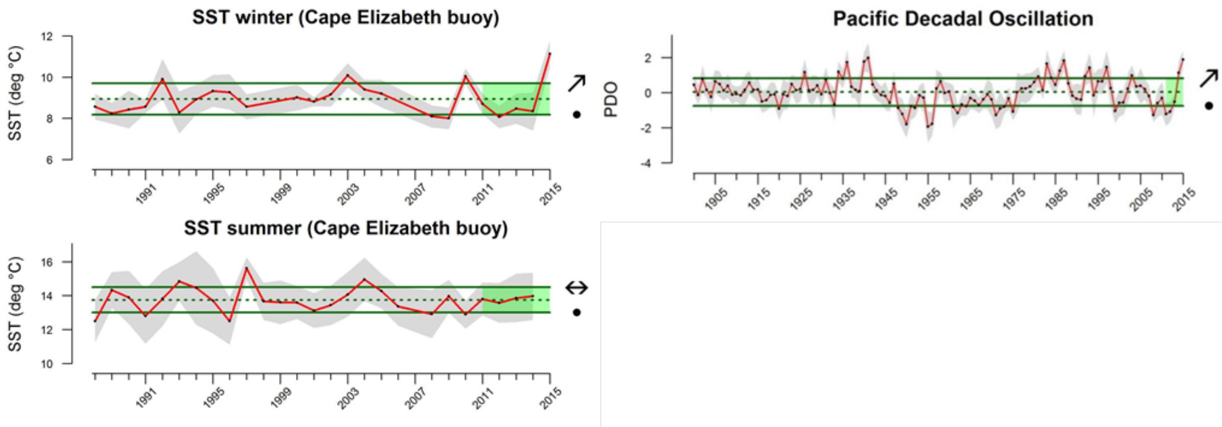

Figure 5. Indicators of ocean temperatures in WAMSP waters. Sea surface temperature (SST) data from National Data Buoy Center's buoy located at 47.353°N 124.731°W off Cape Elizabeth, WA and annual mean Pacific Decadal Oscillation index. The gray shaded region in each plot represents ±1 s.d. of the mean.

Sea-surface temperatures from satellites showed extremely warm anomalies in the winter of 2015 (Figure 6 top left). SST values at every location were >1 s.d. above the long-term average (gray dots plus x's) with most cells > 2°C above long-term averages. Approximately half of the cells had their highest winter SST values of the entire time series during winter 2015 (x's in Figure 6, top left). The 5-year means of all cells were within historical averages (Figure 6 top center), but every cell showed an increasing trend over the last five years (gray dots in Figure 6 top right). In summer 2014, locations in the southern half of WAMSP waters were > 1 s.d. above the long-term average (gray dots in Figure 6 bottom left). All cells' 5-year means were within historical averages (Figure 6 bottom center), but every cell showed an increasing trend over the last five years (gray dots in Figure 6 bottom right).

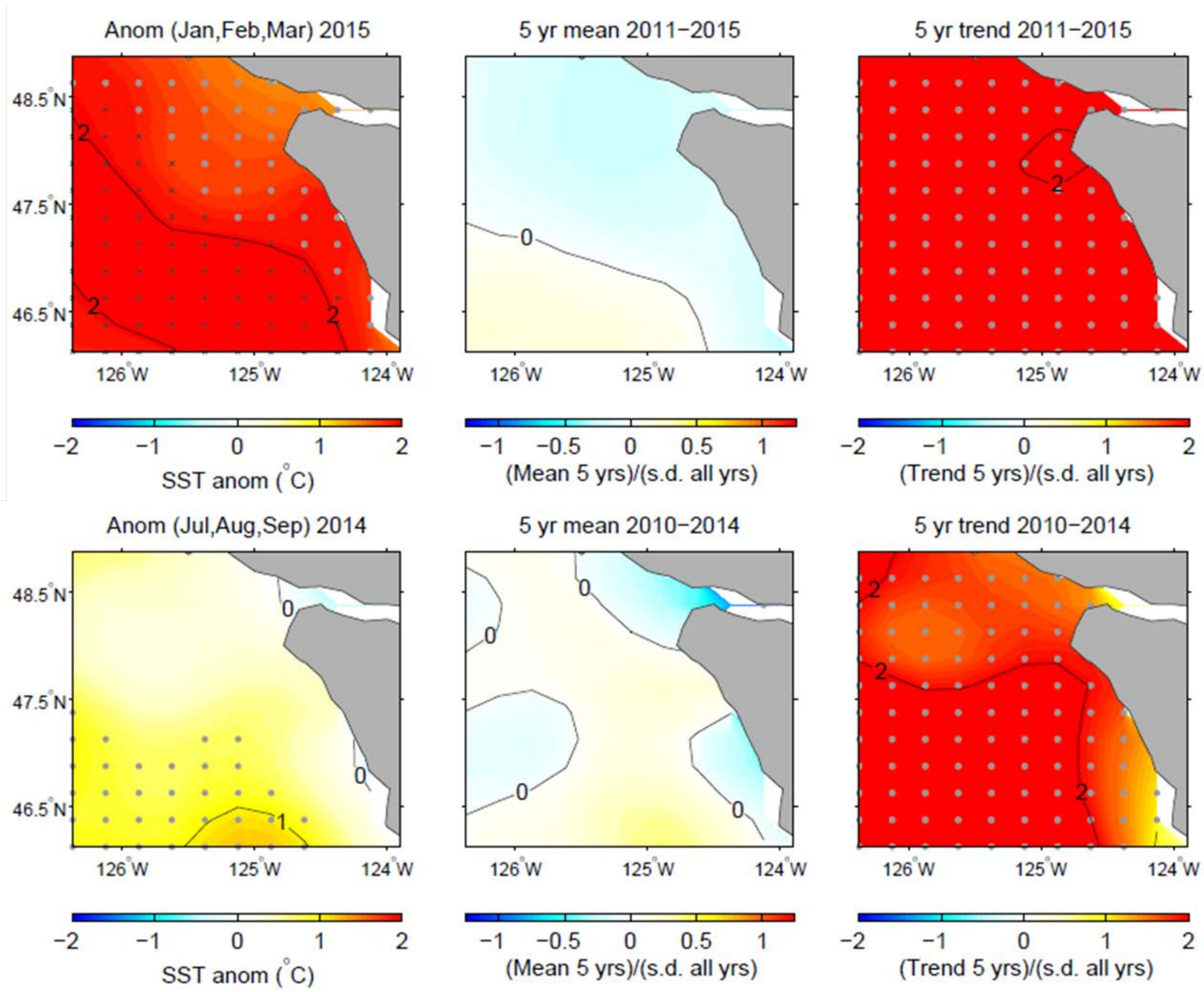

Figure 6. Sea surface temperature (SST) anomalies (left column), 5-year means (center column) and 5-year trends (right column) for winter (top row) and summer (bottom row) from blended satellite observations. Gray dots represent a location where the SST anomaly or the 5-year trend value >1 s.d. of the long-term mean (using data from 1982-2013). X's represent locations where the highest SST value for that location across the entire time series occurred in 2015. The value of each grid cell in the 5-year mean and trend maps has been normalized by the long-term standard deviation of the time series at that grid cell. Figure courtesy of Isaac Schroeder, SWFSC.

TIMING AND FREQUENCY OF EL NIÑO EVENTS

El Niño Southern Oscillation (ENSO) events result from variations in sea level pressure, winds and sea surface temperatures between the eastern and western tropical Pacific. Patterns in the tropics have wide-reaching consequences on the physical attributes in WAMSP waters. El Niño events result in ecosystem-wide effects from changes in species composition to lack of prey availability and breeding failure in top predators, while La Niña events can increase productivity in the system (Chavez 2002). El Niño conditions in WAMSP waters are associated with warmer surface water, weaker upwelling winds and lower nutrient availability at the surface; however, the effects of any given ENSO event are highly variable. As indicators of the timing and frequency of El Niño events in WAMSP waters, we selected the

Multivariate El Niño Index (MEI) and the Northern Oscillation Index (NOI). The MEI represents patterns in six main observed variables over the tropical Pacific to identify the status of ENSO. The NOI measures large-scale atmospheric teleconnections, specifically the difference between sea level pressure at the climatological location of the North Pacific High (NPH) and at Darwin, Australia. Positive NOI values correspond to more coastal upwelling, while during an El Niño the influence of the NPH is diminished and the NOI has large negative values. While NOI tracks interannual changes of atmospheric forcing that are relevant to WAMSP waters, it is still a very broad index when evaluating changes in SST.

The MEI has increased over the last five years, while the NOI has shown no trend (Figure 7).

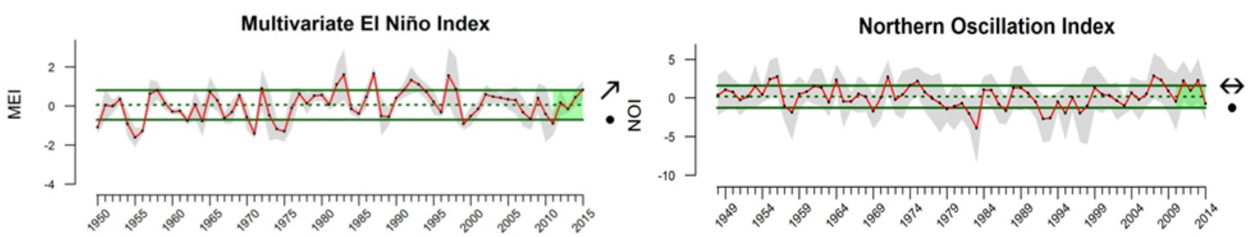

Figure 7. Indicators of changes in the timing and frequency of El Niño events in the North Pacific. The gray shaded region in each plot represents ±1 s.d. of the mean.

SOURCE WATERS

Subarctic and tropical waters are important contributors of source waters to WAMSP waters (Bograd et al. 2008). Source water changes may lead to large-scale changes in nutrients and hypoxia in the broader California Current (Bograd et al. 2008). Increases in subarctic source waters can result in changes in the food web by supplying larger, lipid-rich northern copepods and other plankton, compared to the smaller, often lipid-poor warm water copepods occurring in subtropical waters. We selected the North Pacific Gyre Oscillation (NPGO) and the northern copepod biomass anomaly as indicators of changes in source waters for WAMSP waters. The NPGO, which describes changes in salinity, nutrients and chlorophyll-a in the California Current ecosystem, has decreased significantly over the last five years (Figure 8). The northern copepod anomaly showed no overall trend over the last five years, but there has been a significant decrease beginning in 2014. This suggests a shift in the sources of WAMSP waters, from cooler, productive sub-arctic water to warmer, less productive subtropical water (Figure 8).

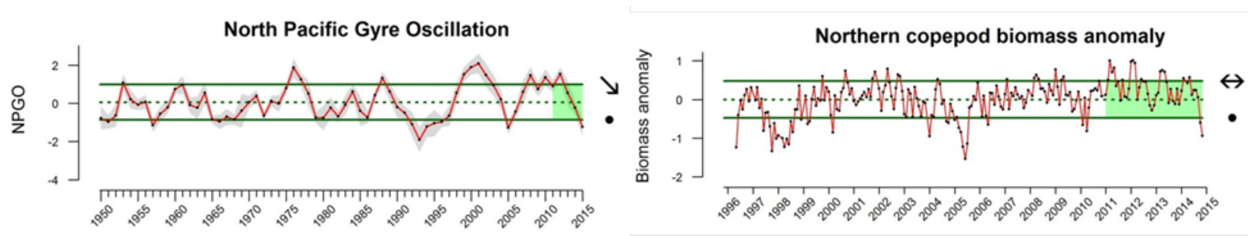

Figure 8. Indicators of changes in source waters to WAMSP waters. Left: the North Pacific Gyre Oscillation. The gray shaded region represents ±1 s.d. of the mean (data Emanuele Di Lorenzo, http://www.o3d.org/npgo/). Right: the northern copepod biomass anomaly, showing the change in the copepod community from northern species (positive values) to southern species (negative values) within years and during oceanographic regime changes (data courtesy of Bill Peterson, NWFSC).

UPWELLING

WAMSP waters reside within the broader California Current ecosystem, an eastern boundary current system largely driven by upwelling forces that bring deep, cold, nutrient-rich waters to the surface. 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 (Bograd et al. 2009). 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. Upwelling in WAMSP waters generally 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). We selected the Upwelling Index (UI) calculated off La Push, WA in the winter and summer and the Spring Transition Index (STI) as indicators of upwelling in WAMSP waters. We downloaded monthly mean values of the UI from NOAA's Pacific Fisheries Environmental Laboratory website (http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/upwelling.html) and calculated winter (Jan – Mar) and summer (Jun – Aug) averages. The STI is the day of the year in which upwelling is at its minimum value and is calculated directly from the UI. The winter upwelling index increased while the more relevant summer upwelling index remained unchanged over the last five years (Figure 9, top). The spring transition index has been widely variable over the last five years with no significant trend (Figure 9, bottom).

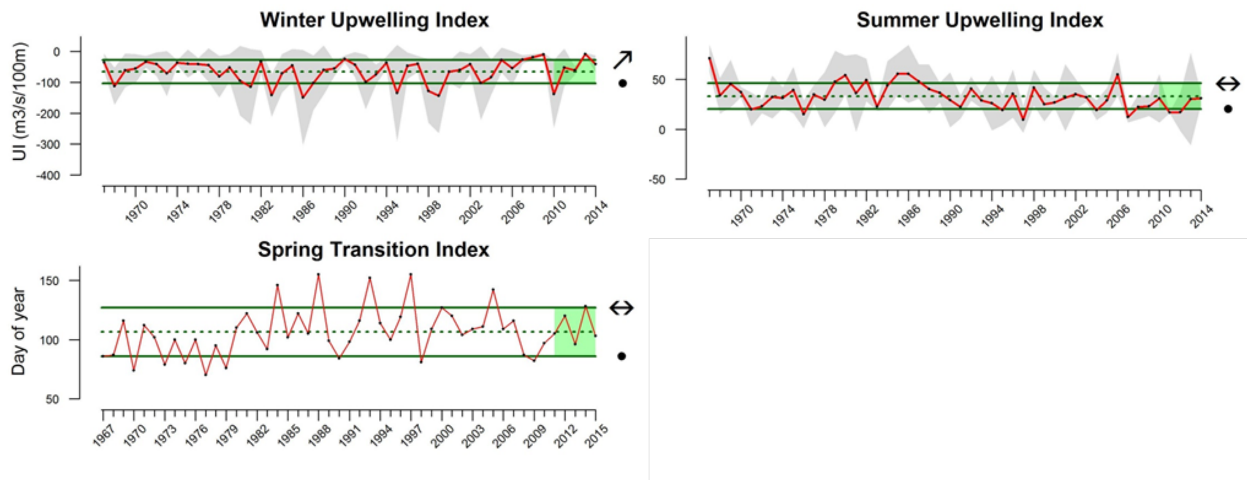

Figure 9. Indicators of upwelling in WAMSP waters. Upwelling indices for winter (Jan-Mar) and summer (Jun-Aug) and the Spring Transition Index calculated at 48°N, 125°W off La Push, WA. The gray shaded region in each plot represents ±1 s.d. of the mean.

OCEAN ACIDIFICATION

For seawater, an increase in dissolved CO_2 leads to decreases in pH (increased acidification) and carbonate concentration. Lower pH, pCO_2 and reduced availability of carbonate negatively impact organisms that rely on calcium carbonate ($CaCO_3$) for structural and protective shells (Barton et al. 2012). It is thus widely held that ocean acidification (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) and these organisms are typically important prey within marine food webs (e.g., pteropods). Predators that feed on OA-susceptible prey may be forced to switch to other prey types, increasing predation risk for those other species, or alter their distribution, thus changing trophic structure and food web dynamics of the region.

In order to quantify the status and trends of ocean acidification in the pelagic habitats of WAMSP waters, we selected the saturation level of aragonite, a type of carbonate used in the shells of many calcifiers, at two different depths along the Newport, OR Hydrographic Line. We also selected the partial pressure of CO_2 (pCO_2) in seawater measured by buoys off Cape Elizabeth and La Push, WA. Aragonite saturation decreased in nearshore waters, while it remained unchanged in offshore waters (Figure 10, top). The pCO_2 in surface waters showed no significant changes over the last five years of the dataset (Figure 10, bottom).

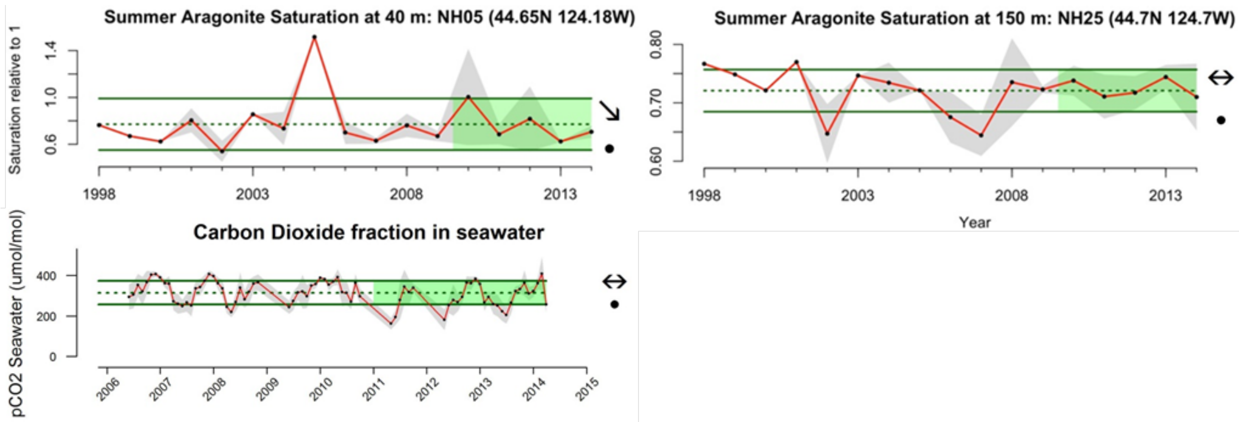

Figure 10. Indicators of ocean acidification in WAMSP waters. Top: aragonite saturation values at 40 m and 150 m depth at stations along the Newport, OR hydrographic line (data courtesy of Bill Peterson, NWFSC). Bottom: mean pCO_2 in surface waters measured by buoys located off Cape Elizabeth and La Push, WA. The gray shaded region in each plot represents ±1 s.d. of the mean. (Data courtesy of Adrienne Sutton, NOAA Pacific Marine Environmental Laboratory.)

CURRENTS, EDDIES AND PLUMES

The Columbia River represents a significant input of fresh, turbid water. These physical characteristics provide a convergence zone for zooplankton, and thus provide conditions favorable for high concentrations of prey for planktivorous organisms (Morgan et al. 2005b). We selected an index modeled by the Center for Coastal Margin Observation and Prediction Center models to calculate the volume of the Columbia River plume. We downloaded “Plume Volume” data with the “28 psu salinity cut-off” from the “db33” source file from CMOP’s Virtual Columbia River website (http://www.stccmop.org/datamart). The volume of the Columbia River plume was at historically high levels in 2011 (based on data from 1999 – 2014), but there were no significant trends in the annual mean volume over the last five years (Figure 11).

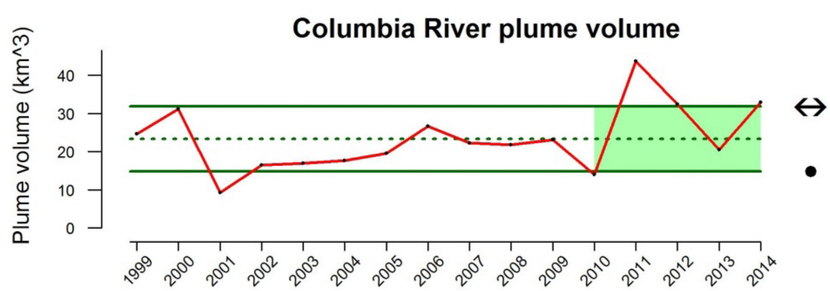

Figure 11. Average daily plume volume (km^3) of the Columbia River plume. Data from Center for Coastal Margin Observation and Prediction.

HABITAT

QUANTITY

The quantity of habitat available in the pelagic zone varies according to species' ability to tolerate various physical parameters, such as temperature, salinity, pressure, dissolved oxygen, turbidity, and light levels. For ectotherms, water temperature regulates rates of physiological, neurological, embryological and behavioral development (Brett 1971) and thus regulates individual's abilities to use certain parts of the pelagic zone. The thermocline and pycnocline denote steep changes in water temperature and salinity, respectively, and also represent the separation between warmer, nutrient-poor surface waters and cooler, nutrient-rich deep waters (Hazen et al. 2014). The shallower these clines, the more nutrients are available to the photic zone. The spatial extent of waters with low levels of dissolved oxygen (<1.4 ml L^{-1}) or waters with considerable amounts of suspended sediment are also important characteristics of the water column that contribute to areas of good habitat in the pelagic zone. Thus, thermocline and pycnocline depth in nearshore and offshore waters, the volume of the Columbia River plume and the proportion of the continental shelf exposed to hypoxic conditions were selected as indicators of habitat quantity in the pelagic zone.

The NWFSC's Plume Survey collects water-column profile data and calculates the thermocline and pycnocline depth at each station (e.g., Brodeur et al. 2003). We grouped nearshore (2 – 6 nm offshore) and offshore (26 – 36 nm offshore) stations on the Grays Harbor transect during the month of June. We downloaded "Plume Volume" data with the "28 psu salinity cut-off" from the "db33" source file from CMOP's Virtual Columbia River website (http://www.stccmop.org/datamart). All indicators remained unchanged over the last five years of their respective datasets and were within historical averages (Figure 12).

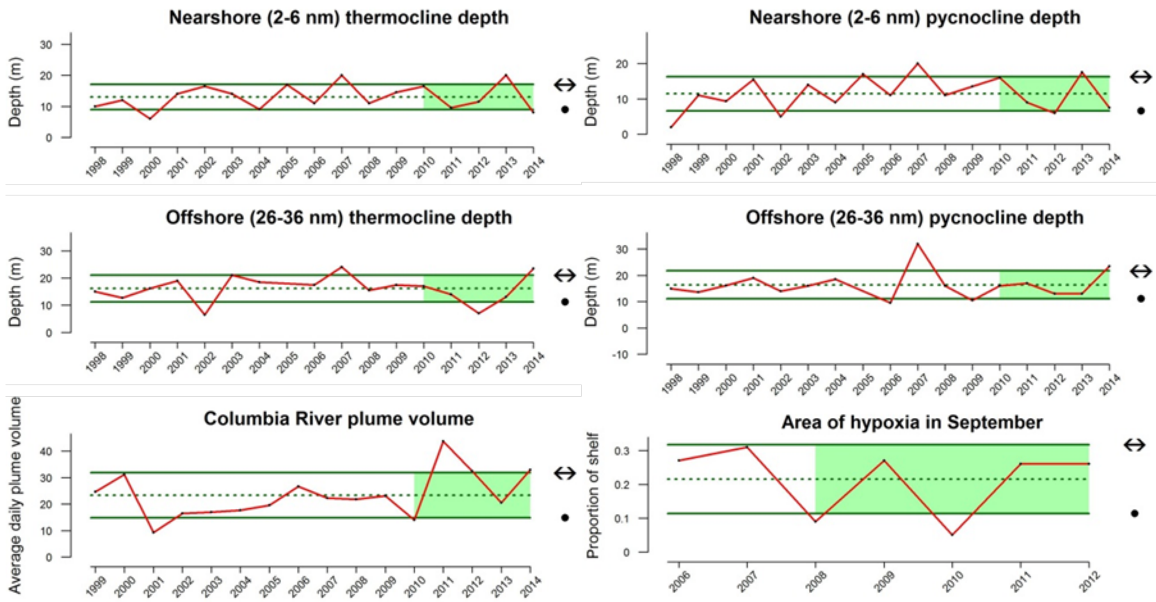

Figure 12. Indicators of habitat quantity in the pelagic zone. Nearshore (top; 2-6 nm offshore) and offshore (center; 26-36 nm offshore) thermocline (left) and pycnocline (right) depth in WAMSP waters. Bottom: Average daily plume volume of Columbia River and proportion of continental shelf exposed to hypoxic waters in September. Data courtesy of Cheryl Morgan, Oregon State University.

QUALITY

In WAMSP waters, good quality habitat is generally correlated with cooler, nutrient-rich waters which form the conditions necessary for high primary productivity and a high caloric-value prey base, whereas warmer, nutrient-poor waters generally result in a prey base that is of much lower nutritional quality (Hooff and Peterson 2006, Peterson 2009). The first selected indicator was sea surface temperature; see "Ocean Temperature" above in the Physical Driver section for status and trends of sea surface temperature. The other selected indicators for habitat quality in the pelagic zone were levels of nutrients (as measured by the ratio of nitrogen to phosphorous) in nearshore and offshore WAMSP waters. An increase in the nitrogen:phosphorous ratio encourages phytoplankton growth.

Both indicators of habitat quality showed no significant trends over the last five years of the dataset and values were within historical averages (Figure 13).

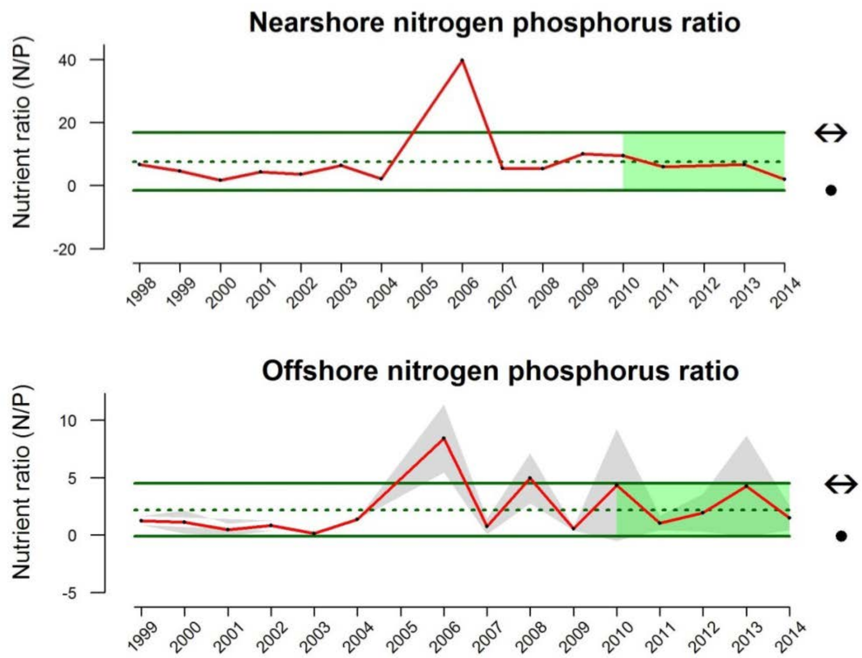

Figure 13. Indicators of habitat quality in the pelagic zone. The ratio of phosphorous (PO_4) to total nitrogen ($NO_3 + NO_2$) in June at nearshore (top; 2-6 nm offshore) and offshore (bottom; 26-36 nm offshore) stations of the NWFSC's Plume Survey. The gray shaded region represents ±1 s.d. of the mean (data courtesy of Cheryl Morgan, Oregon State University).

ECOLOGICAL COMPONENTS

FISHERIES SPECIES: FORAGE FISHES

Forage fish species support important commercial fisheries as well as a number of higher trophic level species in the pelagic zone, many of which are commercially exploited (e.g., rockfish, salmon) and/or legally protected (salmon, marine mammals, seabirds). In WAMSP pelagic waters, there are four primary forage fishes: whitebait smelt *Allosmerus elongatus,* Pacific herring *Clupea pallasii*, northern anchovy *Engraulis mordax*, and Pacific sardine *Sardinops sagax* (McClatchie et al. 2013). Such species are often the principal means of transferring production from primary and secondary trophic levels (phytoplankton and zooplankton) to 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 assessments of the forage fish community across the broader California Current ecosystem have 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).

POPULATION SIZE & CONDITION

To quantify the status and trends of population size and condition of forage fish species in WAMSP waters we selected two indicators. For population size, we selected the aggregate abundance of the dominant species as measured by nighttime surveys performed by the NWFSC along the coasts of Oregon and Washington with data being limited to only those transects in WAMSP waters. For population condition, we selected age structure as measured by the mean age of Pacific sardines from the commercial fishery in Washington State. Age at maturity was the most highly-rated indicator, but data were not available.

The aggregate abundance of the four most predominant forage fish species remained relatively unchanged from 2007 – 2011 (Figure 14 top). This survey using nighttime tows has been discontinued, so any further use of this as an indicator will require further funding for personnel to perform the survey. The mean age of Pacific sardines collected in Washington's commercial fishery decreased from 2009 – 2013 (Figure 14).

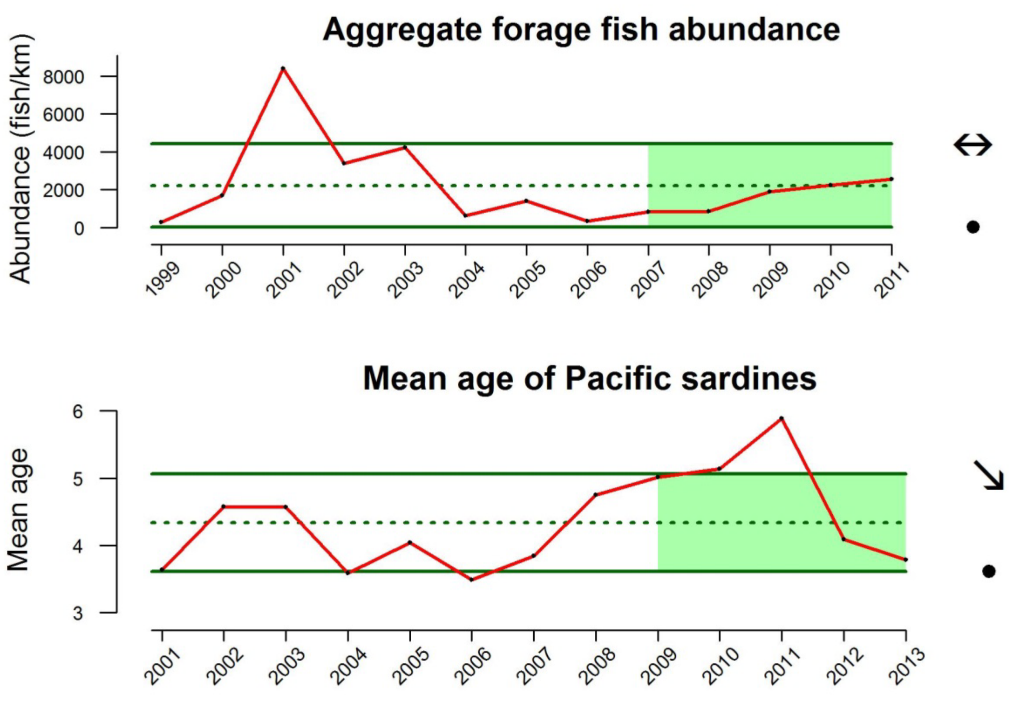

Figure 14. Indicators of population size and condition for forage fishes in WAMSP waters. Standardized abundance of predominant forage fish species (northern anchovy, Pacific herring, Pacific sardine and whitebait smelt) from the Willapa Bay transect of the NWFSC's Predator Survey. Data courtesy of Cheryl Morgan, Oregon State University Newport (top). Mean age (years) of Pacific sardines from landings from the Washington sardine fishery (data from Wargo and Henry 2014).

FISHERIES SPECIES: 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 WAMSP waters: Chinook, Coho (*Oncorhynchus kisutch*), chum (*O. keta*), pink (*O. gorbuscha*), sockeye (*O. nerka*) and steelhead (*O. mykiss*). Six stocks of salmon that enter WAMSP are listed by the Endangered Species Act: four stocks of Chinook salmon that are 'Threatened' (Lower Columbia, Puget Sound, Snake River Fall, Snake River Spring/Summer); one stock of Chinook salmon that is 'Endangered' (Upper Columbia Spring); and one stock of Coho salmon that is 'Threatened' (Lower Columbia). These listings dictate management at federal and state levels and are good reasons to include Chinook and Coho salmon in an assessment of WAMSP waters.

In pelagic waters, juvenile salmon feed on euphausiids, amphipods, decapods and forage fish such as Pacific herring (Peterson et al. 1982, Brodeur and Pearcy 1990) during their initial entry into the ocean. 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 PDO, SST anomalies, coastal upwelling, spring transition date, and copepod biomass anomalies (Peterson et al. 2014).

POPULATION SIZE

For population size, we selected two indicators: escapement of spawning adults for Washington coastal Chinook and Coho stocks, and the juvenile abundance of sub-yearling and yearling Chinook and yearling Coho stocks in the ocean. The escapement of Washington coastal Chinook has decreased over the last ten years (Figure 15, top), while escapement of Coho have varied widely over the same duration with a large decline over the last five years (Figure 15, bottom). Juvenile subyearling Chinook showed opposite trends in abundance over the last five years between June and September surveys (Figure 16, top panels), while the other indicators of Chinook juvenile abundance showed no trends and were within historical averages. The abundance and biomass of juvenile Coho salmon in June increased over the last five years, primarily due to one large cohort in 2013 (Figure 16, last two panels on the left).

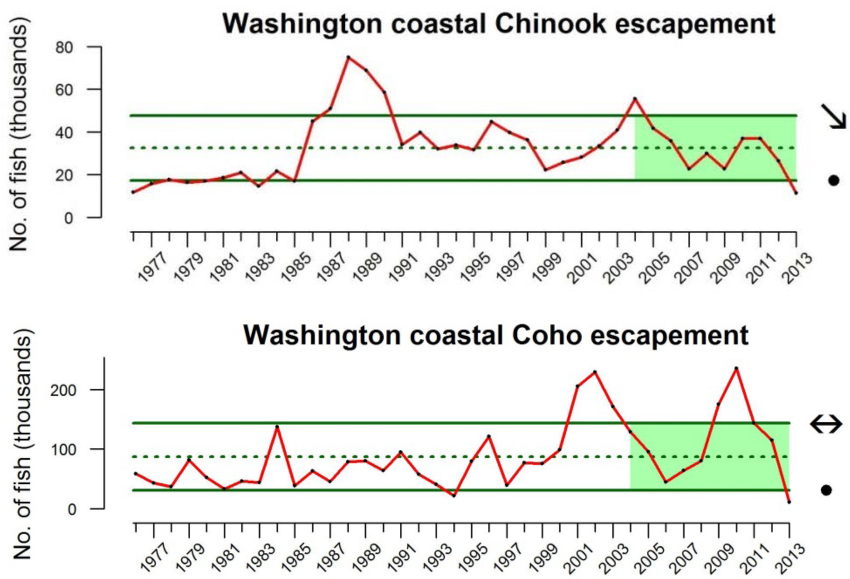

Figure 15. Summed escapement of Washington coastal Chinook (top; Willapa Fall, Grays Harbor Spring/Summer, Queets Fall, Hoh Spring/Summer, Hoh Fall, Quillayute Fall, Quillayute Summer) and Coho (bottom; Willapa, Grays Harbor, Quinault, Queets, Hoh, Quillayute) salmon. Escapement values from PFMC (2014).

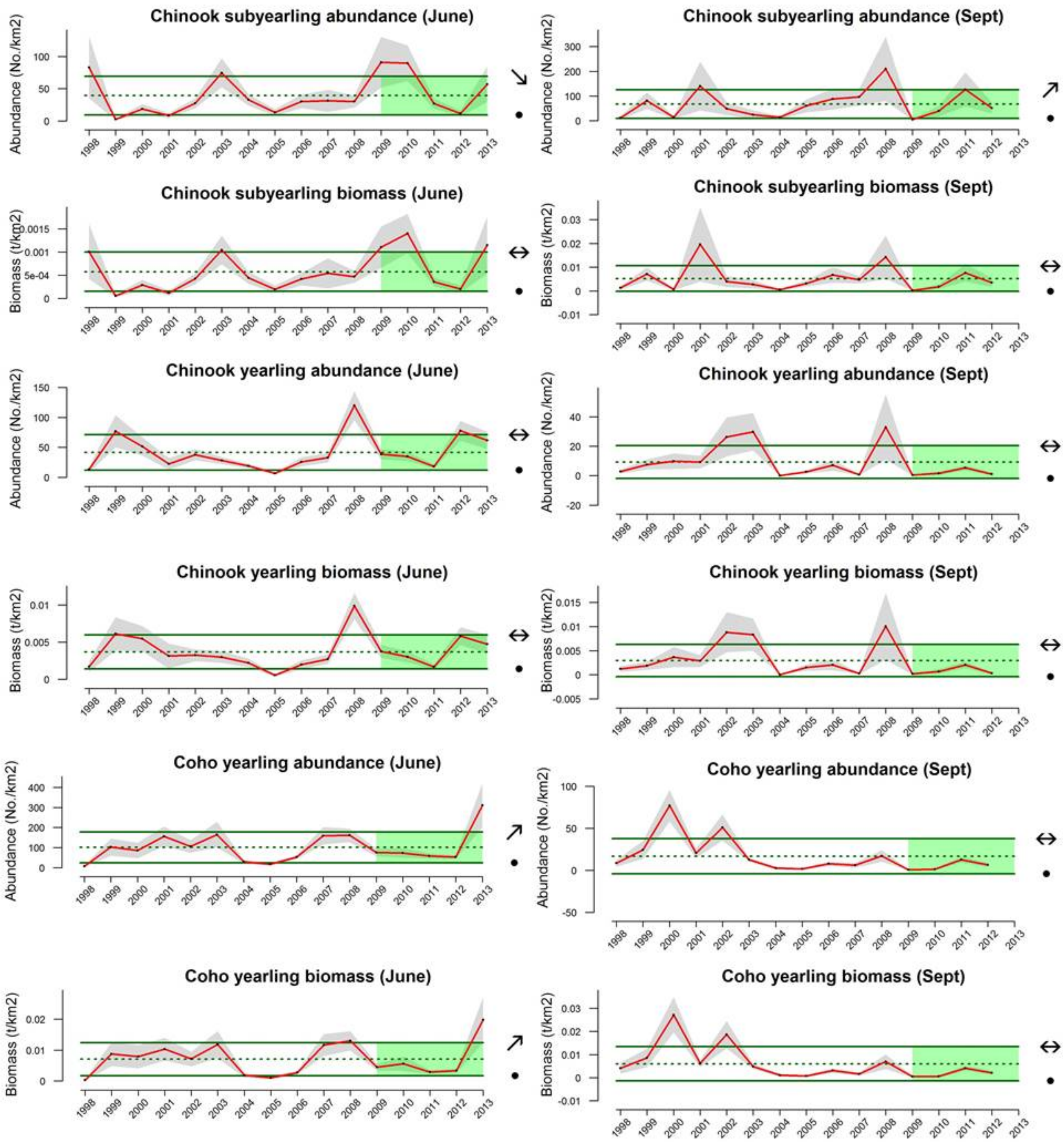

Figure 16. Abundance and biomass estimates of subyearling Chinook (top two rows), yearling Chinook (middle two rows) and yearling Coho salmon (bottom two rows) from NWFSC's Plume Survey in June (left panels) and September (right panels). The gray shaded region in each plot represents ±1 s.d. of the mean. (Data courtesy of Rick Brodeur, NWFSC, and Jim Ruzicka, Oregon State University.)

POPULATION CONDITION

For population condition of salmon in WAMSP waters, we selected age structure (as measured by the mean proportion of Fall Chinook spawning individuals from the Hoh, Queets and Quillayute Rivers that were age 5) and body growth (as measured by the growth hormone insulin-like growth factor 1 (IGF). The proportion of age-5 individuals declined over the past 10 years in Washington coastal stocks of Fall Chinook, while body growth for juvenile Coho increased over the last 5 years (Figure 17). This coincides with high abundance of juvenile Coho in 2013 (see Figure 16).

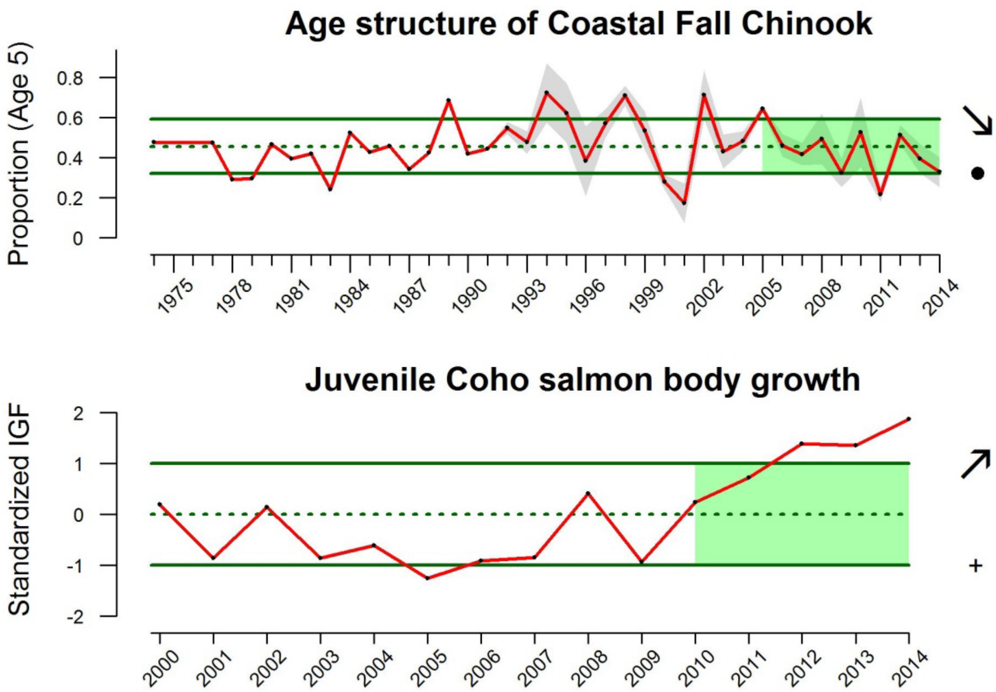

Figure 17. Indicators of population condition for salmon in WAMSP waters. Top: Mean proportion of age 5 individuals returning to the Quillayute (1992 – 2014), Queets (1974 – 2014), and Hoh (1996 – 2014) Rivers. The gray shaded region represents ±1 s.d. of the mean. (Data courtesy of David Low, WDFW, and tribal biologists from the Quinault Nation). Bottom: Standardized mean insulin-like growth factor (IGF) for juvenile Coho salmon. (Data courtesy of Brian Beckman, NWFSC.)

FISHERIES SPECIES: 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 offshore in the winter off 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 may dramatically increase.

POPULATION SIZE

For population size of Pacific hake in WAMSP waters, we selected the abundance index of hake as measured by the joint NWFSC/SWFSC's biennial acoustic survey. Intensity of backscatter attributable to hake has decreased over the last five years of this survey (Figure 18).

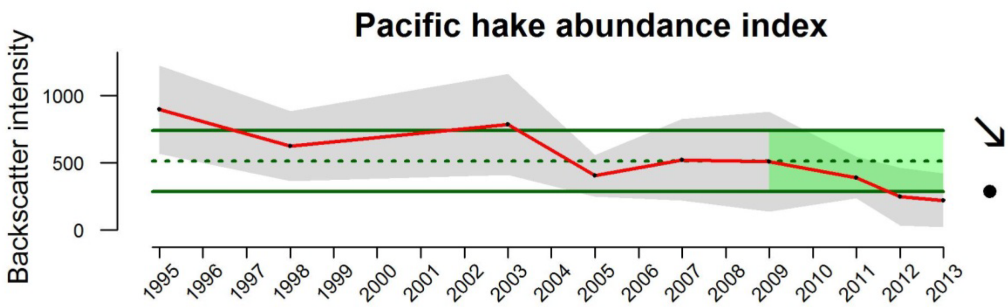

Figure 18. Average backscatter intensity (m/nm) of Pacific hake in WAMSP waters as observed from the joint NWFSC/SWFSC Sake cruise. The gray shaded region represents ±1 s.d. of the mean. (Data courtesy of Julia Clemons, NWFSC.)

POPULATION CONDITION

For population condition of Pacific hake in WAMSP waters, we selected age structure (as measured by the mean age of Pacific hake from the stock assessment (Taylor et al. 2015)) and condition factor as measured by lengths and weights collected during the joint NWFSC/SWFSC acoustic survey. No significant trends were found over the last five years (Figure 19).

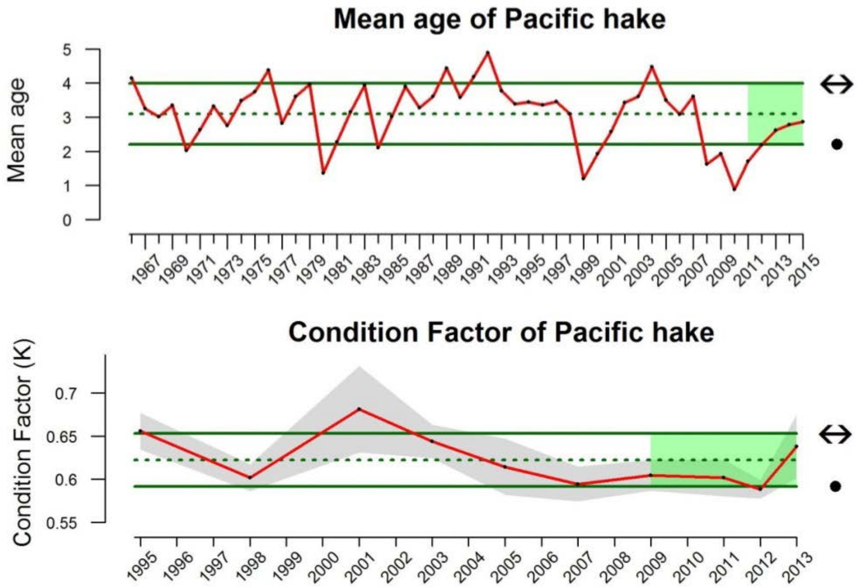

Figure 19. Indicators of population condition for Pacific hake. Top: Mean age of entire Pacific hake stock along the U.S. (data from Taylor et al. 2015). Bottom: Condition factor (Fulton's K) of Pacific hake collected during Joint NWFSC/SWFSC SaKE acoustic survey in WAMSP waters. The gray shaded region represents ±1 s.d. of the mean. (Data courtesy of Steve DeBlois, NWFSC.)

FOCAL TAXA: PHYTOPLANKTON

The phytoplankton community is the base of the food web for the entire marine community, thus the health and structure of this community is important to understand. Vertical migration of zooplankton from the seafloor to the surface in order to feed on phytoplankton is one important mechanism connecting the seafloor community to the phytoplankton community of the pelagic zone.

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 dominant taxa during different sampling cruises in the spring and summer of 2004-2006.

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 or dinoflagellate species involved (Vehmaa et al. 2012).

POPULATION SIZE AND CONDITION

Data capable of defining the status and trends of important phytoplankton species (*for Population size*) and the ratio of diatoms to dinoflagellates (*for Population condition*) are being analyzed by Vera Trainer and colleagues at the NWFSC. These data should be available soon to quantify the status and trends of phytoplankton communities across the entire WAMSP boundaries. As a broad-scale indicator of the total abundance of phytoplankton across WAMSP waters, satellite-derived quantities of chlorophyll a were selected to quantify spatio-temporal anomalies, mean chlorophyll levels and trends (Figure 20).

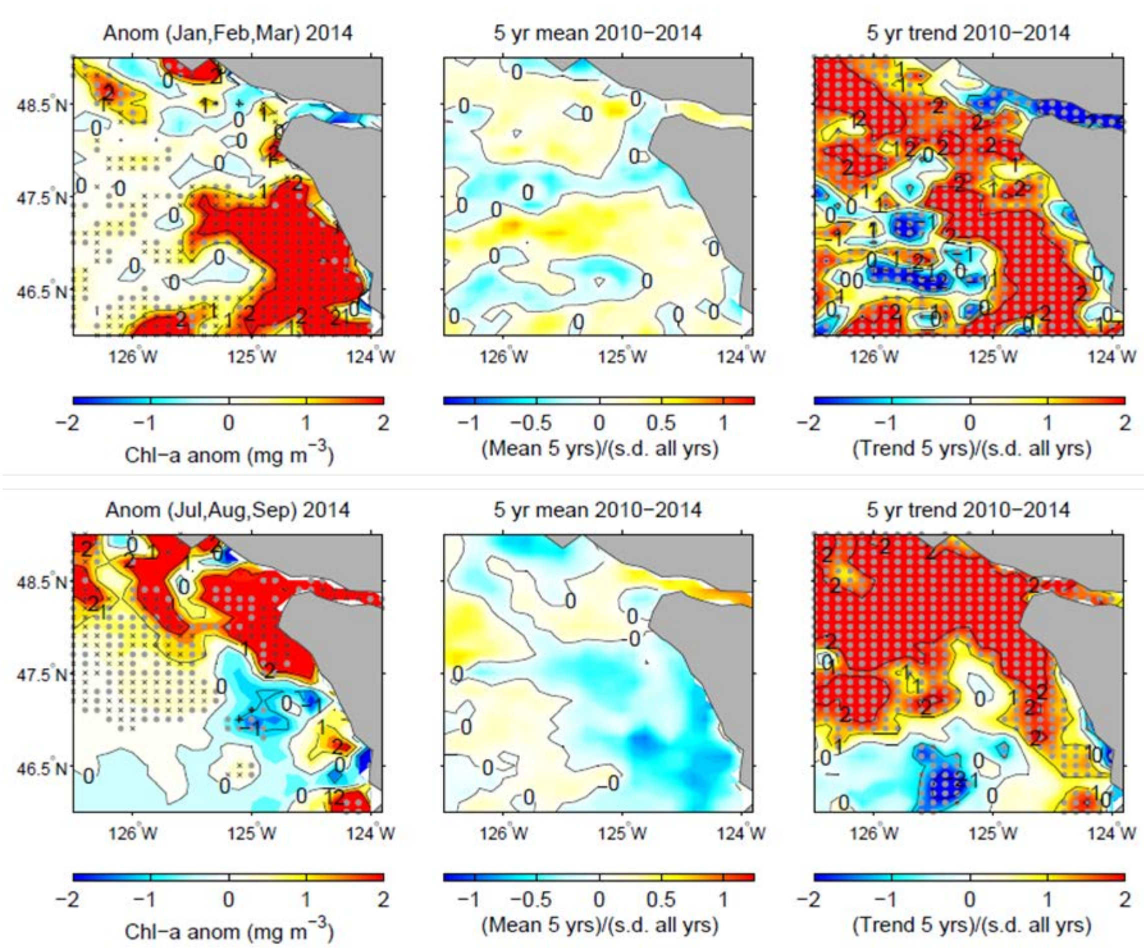

Figure 20. Chlorophyll-a (Chl-a) anomalies (left column*), 5-year means (center* column*) and 5-year trends (right* column*) for winter (*top row*) and summer (*bottom row*) from satellite observations. Gray dots represent a location where the chl-a anomaly or the 5-year trend value >1 s.d. of the long-term mean (using data from 2003-2013). The value of each grid cell in the 5-year mean and trend maps has been normalized by the long-term standard deviation of the time series at that grid cell. Figure courtesy of Isaac Schroeder,* SWFSC*.*

These maps show anomalously high levels of chlorophyll-a throughout WAMSP waters during the winter and in the northerly regions during the summer of 2014 (see red areas with gray dots in top left and bottom left of Figure 20, respectively). In addition, chlorophyll-a has been increasing broadly across WAMSP waters over the last five years in the winter and across the northerly regions in the summer.

FOCAL TAXA: ZOOPLANKTON

Zooplankton time series provide some of the best opportunities to understand marine ecosystem responses to climate change because zooplankton are a 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 considered 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. 2014).

POPULATION SIZE

In order to quantify the status and trends of the zooplankton community, we selected aggregate biomass of zooplankton. Aggregate biomass of zooplankton was measured using the prey field index. This is a measure of the predominant prey species of salmon in the northern California Current ecosystem. This index represents relative changes in the abundance of important zooplankton species. The full data set is comprised of bongo tows collected during the NWFSC's Plume Survey that samples the coasts of Oregon and Washington from 2 – 31 nautical miles offshore (Brodeur et al. 2003). NWFSC scientists are currently analyzing this full data set, but we use data from the Grays Harbor transect to calculate the mean prey field index for WAMSP waters. Variability in the prey field index has been increasing over the last five years, but there were no significant trends in abundance of zooplankton (Figure 21).

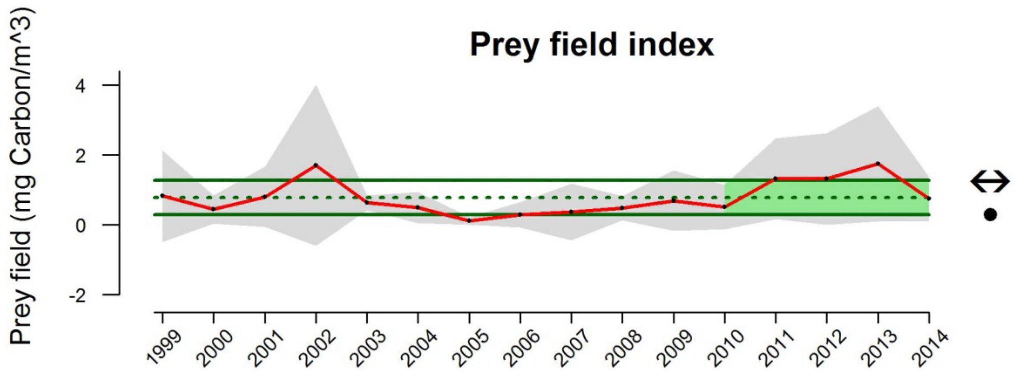

Figure 21. Relative abundance of important zooplankton species as calculated from bongo tows along the NWFSC's Plume Survey's Grays Harbor transect line. Broader coverage of the entire WAMSP region will be available upon publication. Shading is 1 s.d. of the mean. Data courtesy of Cheryl Morgan, NWFSC.

POPULATION CONDITION

For population condition, we selected the northern copepod biomass anomaly. The northern copepod biomass anomaly describes changes in the relative biomass of lipid-rich copepod species that are important prey for numerous pelagic species in WAMSP waters. This indicator is calculated at the Newport, OR hydrographic line. Data from this line are generally considered to be representative of the entire northern California Current region, and studies comparing the copepod community sampled at the Newport Hydrographic line with the copepod community sampled by the NWFSC's Plume Survey across Washington State showed relatively no differences (Lamb 2011).

There were no significant trends in the northern copepod anomaly over the last 5 years, but a dramatic decrease in the abundance of northern copepod species occurred during 2014 (Figure 22). This may be a leading indicator of the quality of prey resources throughout WAMSP waters over the next few years.

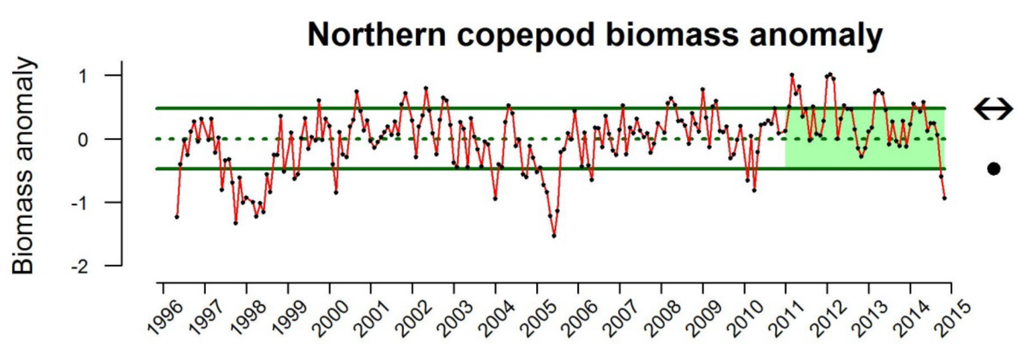

Figure 22. The northern copepod biomass anomaly shows the relative change in the composition of the copepod community from northern species (positive values) to southern species (negative values) during the year and during oceanographic regime changes (data courtesy of Bill Peterson, NWFSC).

FOCAL TAXA: SEABIRDS

Seabirds are relatively numerous and 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).

POPULATION SIZE AND CONDITION

As indicators of population size and condition of the pelagic seabird community in WAMSP waters, we selected the abundance of albatrosses from the Coastal Observation and Seabird Survey Team (COASST) surveys and ratio of first year to second year individuals in COASST counts as an indicator of reproductive success, respectively, for the two major species: Laysan *Phoebastria immutabilis* and black-footed *Phoebastria nigripes* albatross. **We were not able to assemble this data in time for this report.**

FOCAL TAXA: MARINE MAMMALS

There are at least 29 species of marine mammals that inhabit or transit through WAMSP waters at some point in their lives. Similar to salmon, marine mammals are taxa group about which people feel strongly. Ecologically, they are important because they are top predators in different parts of the food web. Studies have explored the diets of California sea lions *Zalophus californianus* and linked diet to abundances of their prey (Lowry 1999), which include several commercial species: Pacific hake, market squid *Doryteuthis opalescens*, Pacific sardine, northern anchovy, Pacific mackerel *Scomber japonicus*, and jack mackerel *Trachurus symmetricus*. The abundance and condition of gray whale *Eschrichtius robustus* as they migrate through Washington waters is largely determined by environmental variability on the Arctic feeding grounds (Moore 2008). Off the coast of southern Washington, harbor porpoise *Phocoena phocoena* were the most sighted marine mammals in nearshore waters during small-boat surveys in 2008 and 2009, whereas Dall's porpoise *Phocoenoides dalli* were the most frequently-sighted species offshore (Oleson and Hildebrand 2012). In the 2008 Olympic Coast National Marine Sanctuary cetacean survey, humpback whales *Megaptera novaeanglidae* were the most frequently-sighted species followed by Dall's porpoise (Oleson and Hildebrand 2012).

POPULATION SIZE AND CONDITION

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); however, California sea lions of all age/sex classes are accessible on land, making them an easy target for monitoring. For indicators of population size and condition of marine mammals in WAMSP waters, we selected pup production and daily growth of California sea lion pups. Mean pup production has varied wildly since 2009, but no general trends were observed (Figure 23). We did not analyze daily growth of sea lion pups directly, but two dramatically low years of pup growth have occurred over the last three years, suggesting that decreases in the California sea lion population are likely to occur over the next few years (Figure 24).

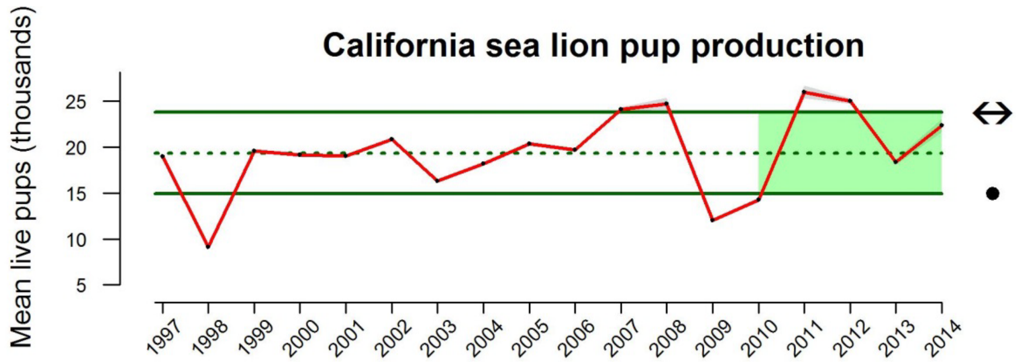

Figure 23. California sea lion pup production across the California Current ecosystem. Data courtesy of Sharon Melin, NOAA National Marine Mammal Laboratory.

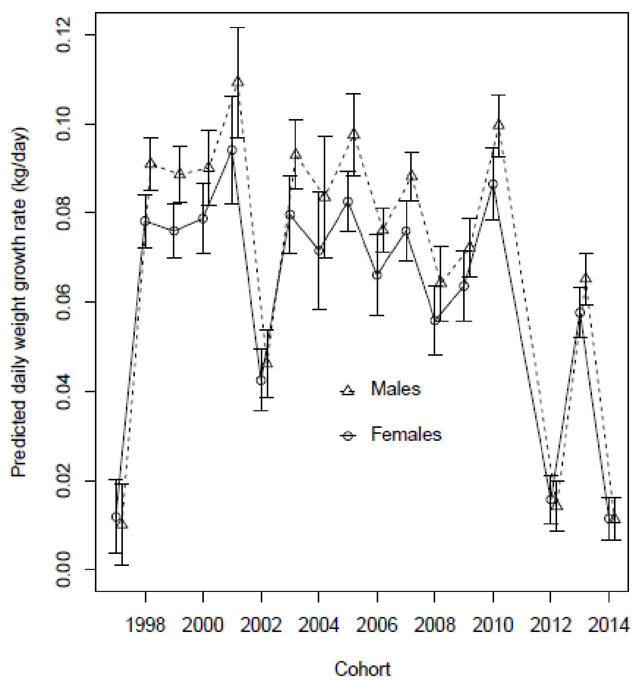

Figure 24. Predicted daily growth rate of female (circles) and male (triangle) California sea lion pups between 4 – 7 months old at San Miguel Island, 1997 – 2014. Figure and data courtesy of Sharon Melin, NOAA National Marine Mammal Laboratory.

ECOSYSTEM HEALTH OF THE PELAGIC ZONE

Indicators for ecosystem health of the pelagic habitat are ecosystem and community level indices that were chosen to track two community level aspects of WAMSP waters: biodiversity and trophic structure.

There are five indicators that were selected to assess the status and trends of the pelagic zone's community structure: Simpson's diversity index of the pelagic fish community, forage fish biomass in aggregate, gelatinous zooplankton biomass, zooplankton abundance/biomass, and copepod species anomaly. Three of these indicators, aggregate forage fish biomass, aggregate zooplankton abundance and the copepod species anomaly, have been described above in their respective "Focal taxa" sections.

BIODIVERSITY

Calculating the diversity of the pelagic fish community is a topic of great interest and will require a much more in-depth analysis than we were capable of performing for this report. The NWFSC's Plume Survey collects a broad range of species from the pelagic fish community and will be the best dataset to attempt to calculate a measure of diversity. Further collaboration with experts from the NWFSC will be required.

TROPHIC STRUCTURE

Monitoring changes in the abundance of gelatinous zooplankton is important for understanding changes in trophic interactions in the pelagic habitat. Gelatinous zooplankton, particularly jellyfish, compete with forage fishes and juvenile salmon for similar prey items (Miller and Brodeur 2007, Suchman et al. 2008); thus, changes in jellyfish abundance could result in changes in the abundance and distribution of prey and the foraging ability of other pelagic species leading to overall changes in community structure. Over the last five years of the dataset, there were no significant trends in the abundance or biomass of the large sea nettle jellyfish *Chrysaora fuscescens* (Figure 25).

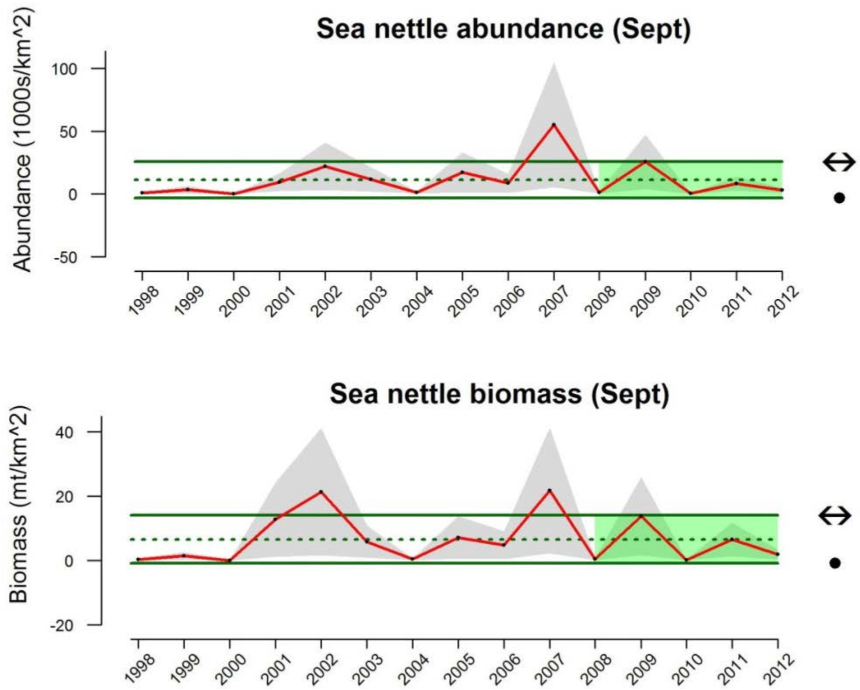

*Figure 25. Standardized abundance (top) and biomass (bottom) of sea nettle jellyfish (*Chrysaora fuscescens*) in September along the Washington coast, from the mouth of the Columbia River northward. The gray shaded region in each plot represents ±1 s.d. of the mean. Data courtesy of Jim Ruzicka, Oregon State University.*

HUMAN ACTIVITIES

BIOLOGICAL EXTRACTIONS

Fishing provides important services to society, including production of food, employment, livelihood and recreation. At the same time, fisheries have the 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. Here, we present the status and trends of landings in WAMSP waters for three major pelagic commercial fisheries, recreational fisheries and total fisheries. Landings of Pacific hake and total fisheries landings across WAMSP waters have increased over the last five years, but are within historical averages (Figure 26), while the landings of coastal pelagic and highly migratory species were above historical averages.

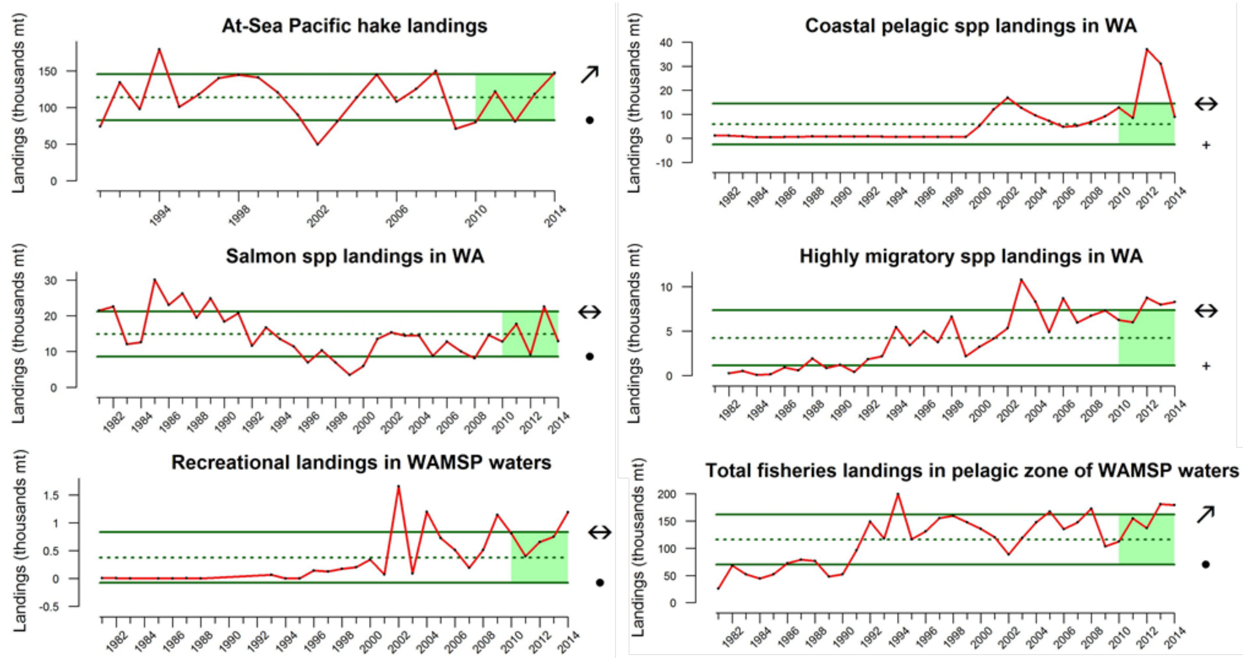

Figure 26. Commercial landings of Pacific hake (from the At-Sea Pacific Hake fishery regions of Vancouver and Columbia), coastal pelagic species, salmon, and highly migratory species; recreational and total fisheries landings in the pelagic habitats of WAMSP waters.

LAND ACTIVITIES

Land-based activities can often result in the downstream run-off of various pollutants. These non-point sources of pollution have been identified as the greatest pollution threat to oceans and coasts (Panetta 2003, U. S. Commission on Ocean Policy 2004). For WAMSP waters, we developed four indicators of pollution that may have an impact on specific components of the pelagic habitat: (1) atmospheric deposition, as estimated from mean concentrations of sulfates ([SO_4^{2-}]) as measured by the National Atmospheric Deposition Program; (2) organic pollution, estimated as a normalized index of pesticide concentrations in streams that drain into WAMSP waters as measured by the U.S. Geological Survey; (3) inorganic pollution, estimated as a normalized index of all reported chemical releases to land and water as measured by the U.S. Environmental Protection Agency’s Toxic Release Inventory for sites that drain into WAMSP waters; and (4) marine debris, estimated from standardized counts of specific debris items as measured by the National Marine Debris Program. For each of these indicators, we used the same data as Andrews et al. (2015) but limited the data to watersheds that drain into WAMSP waters. All four of these indicators showed no trends and were within historical averages over the last five years of their respective datasets (Figure 27).

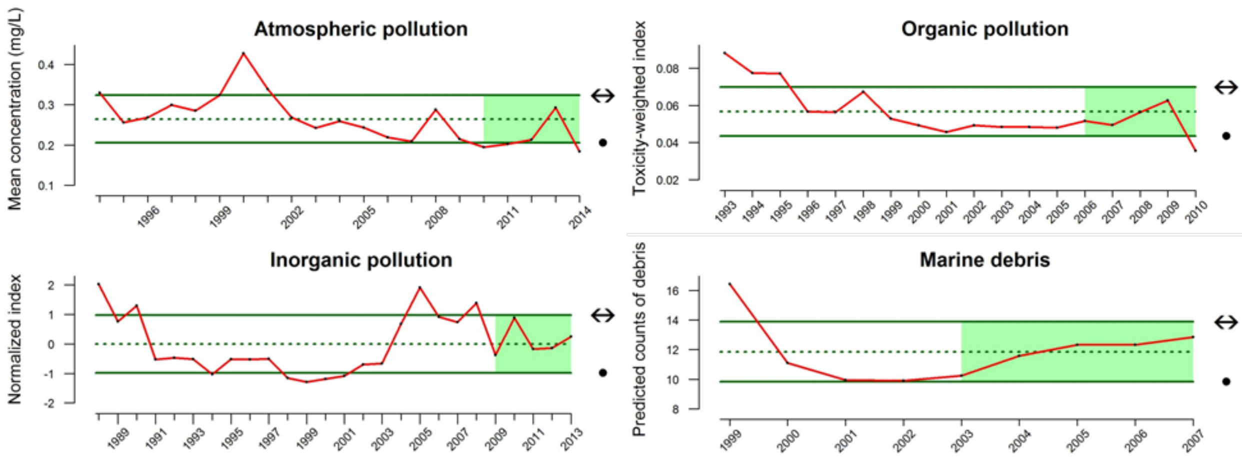

Figure 27. Indicators of pollution from atmospheric deposition (mean concentration of sulfates; data from the National Atmospheric Deposition Program), organic pollution (normalized index of pesticide concentrations in WAMSP streams; data from the U.S. Geological Survey), inorganic pollution (normalized index of all reported chemical releases at sites that drain into WAMSP waters; data from the U.S. Environmental Protection Agency's Toxic Release Inventory), and marine debris (standardized counts of specific debris items; data from Ribic et al. (2012)).

OCEAN-BASED 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 potential impacts of commercial shipping activity on WASMSP waters are numerous, but we used commercial shipping activity as a proxy for 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 (Halpern et al. 2008). The U.S. Army Corps of Engineers monitors the movement of vessels, and data of each ship's entrance and clearance from U.S. ports are available from the Navigation Data Center (http://www.navigationdatacenter.us/data/data1.htm). **Calculating volume of water disturbed from foreign and domestic vessels requires more time than was available during this project,** but the NWFSC has made these calculations at the coastwide scale and simply needs to rescale the data and focus on ship movement within WAMSP waters.

In order to measure the status and trends of ocean-based pollution, we selected an indicator that combines the activity of commercial vessels and the volume of WAMSP ports into one metric. **We were unable to quantify the status and trends of this indicator** because the commercial shipping activity indicator (which must be rescaled from coastwide to WAMSP waters) is a major component of this indicator.

Seafood demand was the final human activity that we included under "Ocean-based activities". This indicator quantifies the total consumption of edible and non-edible products from the sea. Seafood products from WAMSP waters are consumed across the United States and are exported internationally.

Total edible and non-edible seafood demand provides an estimate of what is being used and the relative pressure on resources within WAMSP waters. Seafood demand has been increasing relatively consistently since the early 1970’s and was above historical averages from 2009-2013 (Figure 28).

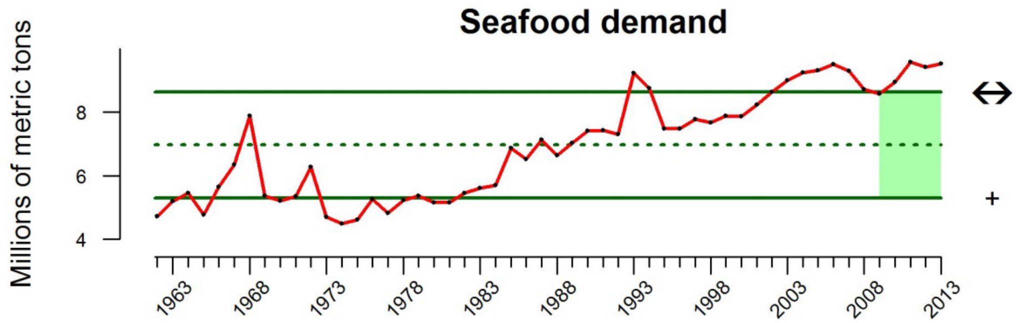

Figure 28. Total consumption of edible and non-edible fisheries products in the United States.

SUMMARY: SEAFLOOR HABITAT

CONCEPTUAL MODEL OF THE SEAFLOOR ZONE

The seafloor habitat type represents all bottom habitats below ~30 m depth in Washington State waters. The conceptual model outlined below (Figure 29) and in graphical form in Appendix 1 represents the dominant physical drivers, ecological components and interactions and human activities that characterize seafloor habitat within WAMSP waters. Suites of physical drivers and human activities affect the ecological components (i.e., the seafloor food web) and habitats within which the ecological components dwell. Humans derive wellbeing from many components and processes within the seafloor habitat, as well as the human activities that the seafloor habitat facilitates.

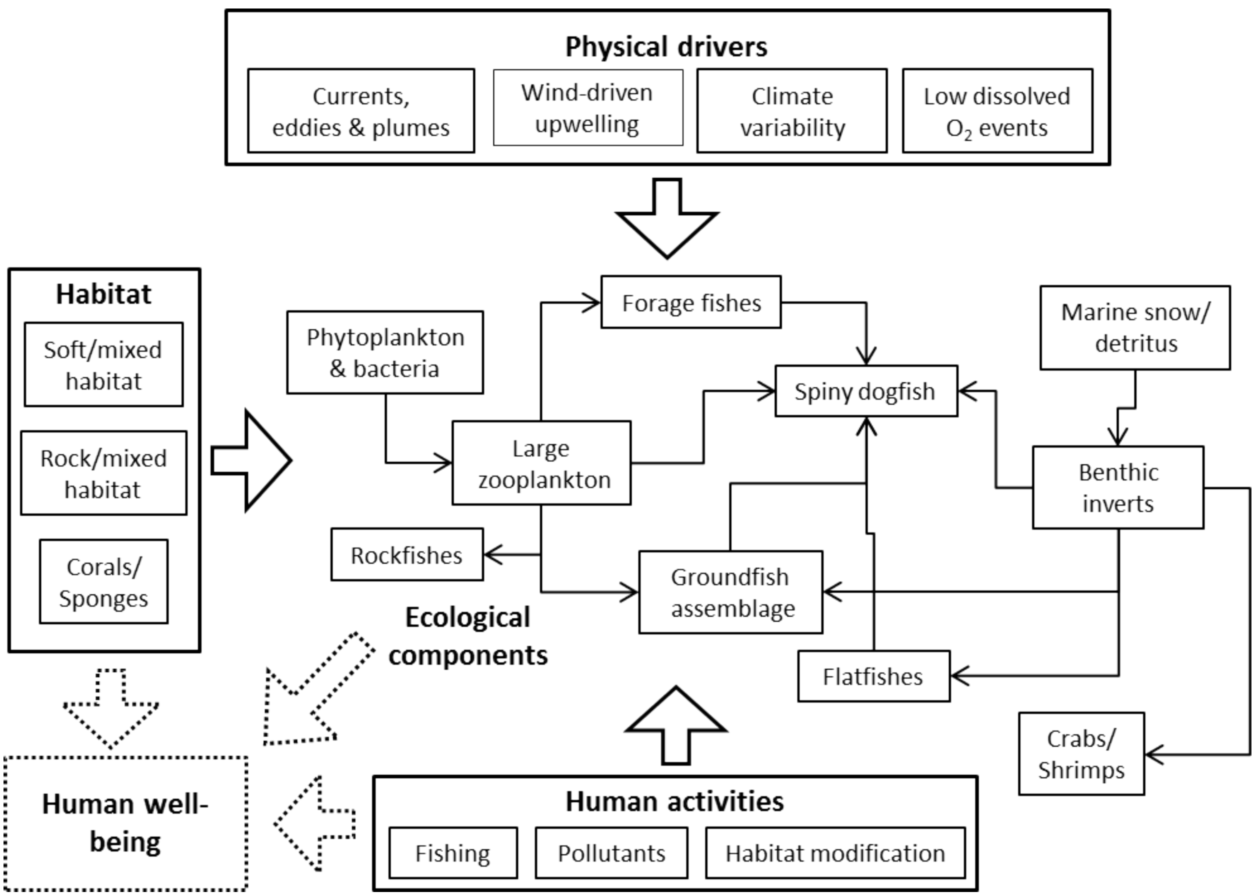

Figure 29. Conceptual model of important physical drivers, habitat, ecological components, and human activities for the seafloor habitat.

In the following sections, we briefly describe the importance and report on the status and trends (when data was available) of each indicator selected for the components shown in the conceptual model above.

Table 5. Summary of indicators and times series duration for each component's key attributes for WAMSP seafloor habitat. † indicates data are presently being analyzed.

Component	Attribute	Indicator	Time period of available data
Physical drivers			
Climatic	Water temperature	Seafloor temperature	2003 – 2014
		Pacific Decadal Oscillation	1900 – 2015
	El Niño events	Multivariate El Niño Index	1950 – 2015
		Northern Oscillation Index	1948 – 2014
	Source waters	North Pacific Gyre Oscillation index	1950 – 2015
		Northern copepod anomaly	1996 – 2015
Oceanographic	Upwelling	Upwelling index	1967 – 2014
		Spring transition index	1967 – 2015
	Currents, eddies, plumes	Columbia River plume volume	1999 – 2014
	Low dissolved oxygen (DO) events	DO continental shelf/slope	2009 - 2014
		DO at Newport, OR, 150 m	1998 - 2014
		Area of hypoxia (Sept)	2006 - 2012
Habitat			
Physical and biogenic habitat	Quantity	Substrate type map	NA
		Biogenic habitat map	NA
	Quality	Seafloor temperature	2003 – 2012
		DO continental shelf/slope	2009 - 2014
		DO at Newport, OR, 150 m	1998 - 2014
		Area of hypoxia (Sept)	2006 - 2012
Ecological components			
Phytoplankton and bacteria	Population size	Phytoplankton biomass	NA†
	Population condition	Diatoms: dinoflagellate ratio	NA†
Zooplankton	Population size	Prey field index	1999 - 2014
		Aggregate biomass	NA†
	Population condition	Northern copepod anomaly	1996 - 2015
Marine snow and detritus	Population size	Not yet evaluated	NA
	Population condition	Not yet evaluated	NA
Benthic invertebrates	Population size	Aggregate biomass	NA
	Population condition	Spatial structure/distribution	NA†
Crustaceans	Population size	Crab abundance (CPUE)	2003 - 2013
	Population condition	Condition factor (K)	2006 - 2014
Forage fishes		**Section under development**	NA
Groundfish	Population size	Groundfish spp. abundance (CPUE)	2003 - 2013
	Population condition	Groundfish spp. size/age-structure	2003 - 2014
Ecosystem health	Biodiversity	Simpson's diversity	2003 - 2013
		Species richness	2003 - 2013

Component	Attribute	Indicator	Time period of available data
	Trophic structure	Mean trophic level of groundfish	2003– 2013
		Northern copepod anomaly	1996 - 2015
		Ratio of scavengers to total biomass	2003 - 2013
Human activities			
Biological extractions	Fishing	Fisheries landings	1981 - 2014
Ocean-based activities	Seafood demand	Seafood consumption	1962– 2013
	Habitat modification	Distance trawled	1999 - 2012
Land-based activities	Pollution	Atmospheric	1994– 2014
		Organic	1993 - 2010
		Inorganic	1988 – 2013
		Marine debris	1999 - 2007

PHYSICAL DRIVERS

CLIMATE VARIABILITY

SEAFLOOR TEMPERATURE

Temperature is one of the most important drivers in the ocean. Ocean temperature regulates the rate of metabolism for most organisms and regulates the base of the food web. In WAMSP waters, cooler temperatures generally result in a prey base that contains energy-rich northern species, which promote high growth in consumers, whereas warmer temperatures generally promote southern species that are of much lower nutritional quality (Hooff and Peterson 2006, Peterson 2009). As indicators of ocean temperatures in WAMSP waters, we selected seafloor temperatures off the Washington coast as measured during the NWFSC's Groundfish Bottom Trawl Survey of the continental shelf and slope from 55 – 1280 m during the summer months, and the Pacific Decadal Oscillation (PDO) as a broad-scale indicator of changes in ocean temperatures in the North Pacific. Over the last five years, seafloor temperatures across the continental shelf and slope showed no trend, whereas the PDO shifted from a cool phase to a warm phase (Figure 30).

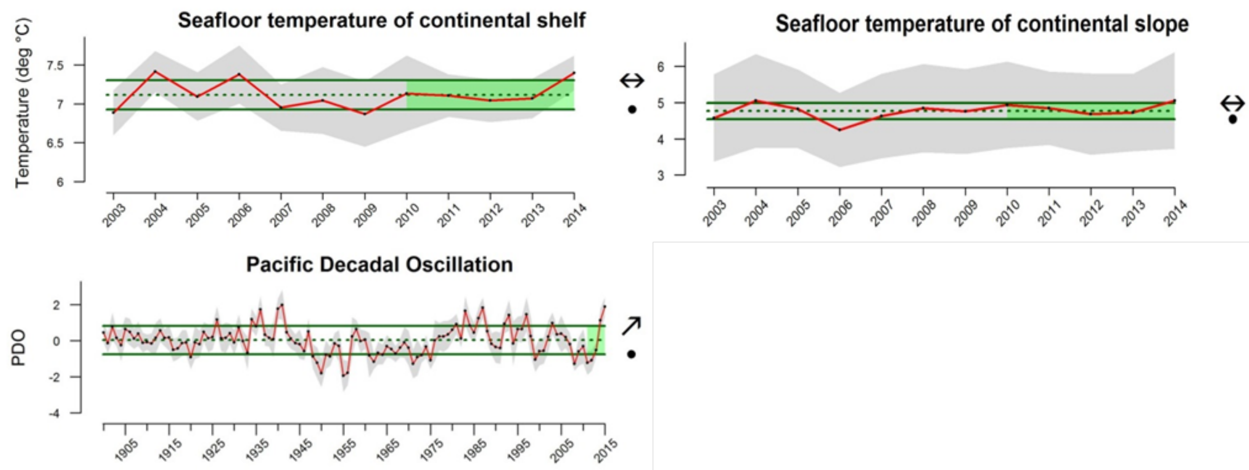

Figure 30. Indicators of seafloor temperature in WAMSP waters. Top: Seafloor temperatures measured across the continental shelf (left) and slope (right) by the NWFSC's Groundfish Bottom Trawl Survey (data courtesy of Beth Horness, NWFSC). Bottom: Annual mean Pacific Decadal Oscillation (PDO) index through June 2015. The gray shaded region in each plot represents ±1 s.d. of the mean.

TIMING AND FREQUENCY OF EL NIÑO EVENTS

El Niño Southern Oscillation (ENSO) events result from variations in sea level pressure, winds and sea surface temperatures between the eastern and western tropical Pacific. Patterns in the tropics have wide-reaching consequences on the physical attributes in WAMSP waters. El Niño events result in ecosystem-wide effects from changes in species composition to lack of prey availability and breeding failure in top predators, while La Niña events can increase productivity in the system (Chavez 2002). El Niño conditions in WAMSP waters are associated with warmer surface water, weaker upwelling winds and lower nutrient availability at the surface; however, the effects of any given ENSO event are highly variable. As indicators of the timing and frequency of El Niño events in WAMSP waters, we selected the Multivariate El Niño Index (MEI) and the Northern Oscillation Index (NOI). The MEI represents patterns in six main observed variables over the tropical Pacific to identify the status of ENSO. The NOI measures atmospheric teleconnections between the western equatorial Pacific and the north Pacific and is the difference between sea level pressure at the climatological location of the North Pacific High (NPH) and sea level pressure at Darwin, Australia. Large positive (negative) values correspond to a strong (weak) NPH that will result in more (less) coastal upwelling. During an El Niño the influence of the NPH is diminished and the NOI has large negative values. While NOI tracks interannual changes of atmospheric forcing that are relevant to WAMSP waters, it is still a very broad index when evaluating changes in SST.

The MEI has increased over the last five years, while the NOI has shown no trend (Figure 31).

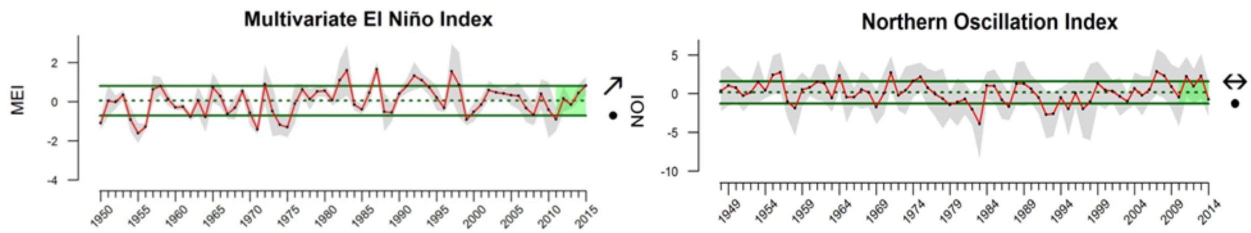

Figure 31. Indicators of changes in the timing and frequency of El Niño events in the North Pacific. Shading is 1 s.d. of the mean.

SOURCE WATERS

Subarctic and tropical waters are important contributors of source waters to WAMSP waters (Bograd et al. 2008). Source water changes may lead to broad-scale changes in nutrients and hypoxia in the broader California Current (Bograd et al. 2008). Increases in subarctic source waters can result in changes in the food web by supplying larger, lipid-rich northern copepods and other plankton, compared to the smaller, often lipid-poor warm water copepods occurring in subtropical waters. We selected the North Pacific Gyre Oscillation (NPGO) and the northern copepod biomass anomaly as indicators of changes in source waters for WAMSP waters. The NPGO, which describes changes in salinity, nutrients and chlorophyll-a in the California Current ecosystem, has decreased significantly over the last five years (Figure 32, left). The northern copepod anomaly showed no overall trend over the last five years, but there has been a significant decrease beginning in 2014. This decrease suggests large shifts in the source waters for WAMSP waters, from cooler, productive sub-arctic water sources to warmer, less productive water from subtropical sources (Figure 32, right).

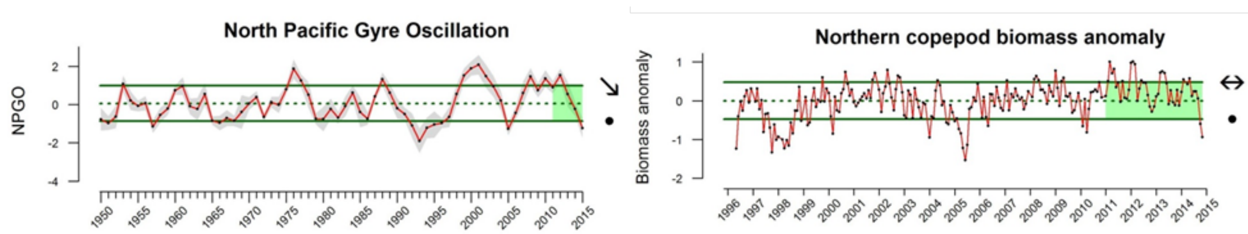

Figure 32. Indicators of changes in source waters to WAMSP waters. Left: the annual North Pacific Gyre Oscillation (NPGO). The gray shaded region represents ±1 s.d. of the mean. (Data courtesy of Emanuele Di Lorenzo, http://www.o3d.org/npgo/). Right: the northern copepod biomass anomaly, showing the change in the copepod community from northern species (positive values) to southern species (negative values) within years and during oceanographic regime changes. (Data courtesy of Bill Peterson, NWFSC.)

UPWELLING

Washington MSP waters reside within the broader California Current ecosystem, which is an eastern boundary current system largely driven by upwelling forces that bring deep, cold, nutrient-rich waters to the surface. 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

(Bograd et al. 2009). 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. Upwelling in WAMSP waters generally 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). We selected the Upwelling Index (UI) calculated off La Push, WA in the winter and summer and the Spring Transition Index (STI) as indicators of upwelling in WAMSP waters. We downloaded monthly mean values of the UI from NOAA's Pacific Fisheries Environmental Laboratory website (http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/upwelling.html) and calculated winter (Jan – Mar) and summer (Jun – Aug) averages. The STI is the day of the year in which upwelling is at its minimum value and is calculated directly from the UI. The winter upwelling index increased while the more relevant summer upwelling index remained unchanged over the last five years (Figure 33; top panels). The spring transition index has been widely variable over the last five years with no significant trend (Figure 33; bottom).

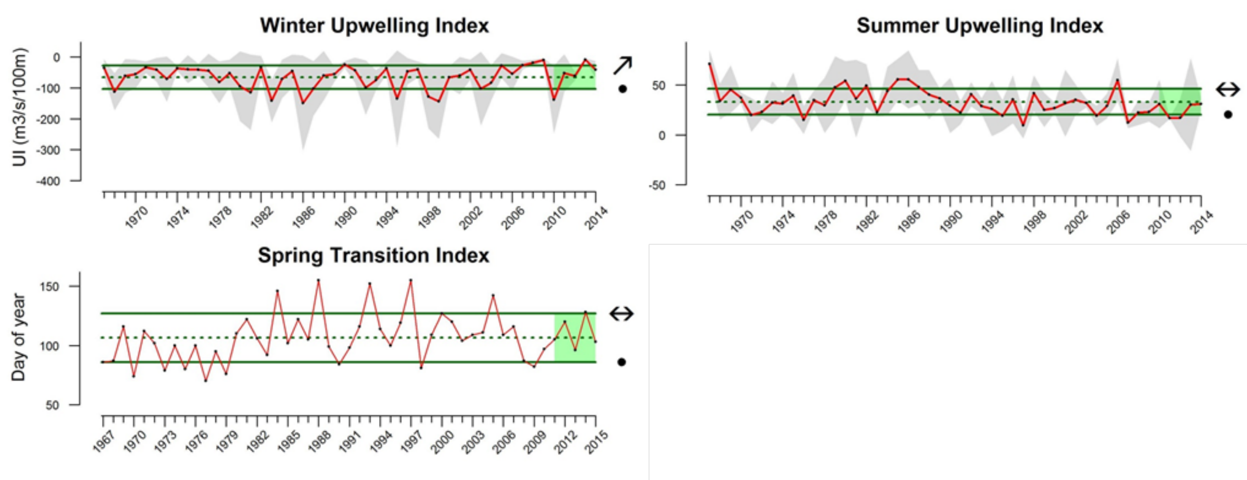

Figure 33. Indicators of upwelling in WAMSP waters. Upwelling indices for winter (Jan-Mar) and summer (Jun-Aug) and the Spring Transition Index calculated at 48°N, 125°W off La Push, WA. The gray shaded region in each plot represents ±1 s.d. of the mean.

LOW DISSOLVED OXYGEN EVENTS

Low dissolved oxygen (DO) concentrations in coastal and shelf waters off Washington State are a relatively recent issue (Grantham et al. 2004, Bograd et al. 2008). When DO concentrations fall below 1.4 ml L^{-1}, the waters are considered to be 'hypoxic'. DO concentrations in the ocean are dependent on a number of physical and biological processes, including circulation, ventilation, air-sea exchange, production and respiration. There is evidence that the frequency, duration and spatial coverage of hypoxic events have been increasing over the last 20 years (Diaz and Rosenberg 2008), potentially due to increased stratification (reduced vertical mixing) and a decrease in the DO in 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 experience negative impacts on early life history growth when exposed to low DO for extended periods (Rabalais and Turner 2001, Kidwell et al. 2009).

DO is measured by several research programs that are relevant to quantifying the status and trends for WAMSP waters. We selected three indicators of DO for the seafloor habitat. First, DO is measured in each tow of the NWFSC's West Coast Groundfish Bottom Trawl Survey. The survey occurs in WAMSP waters during the months of May and August and samples depths from 55 – 1280 meters, thus providing information across a broad spatial domain of WAMSP waters. Second, the NWFSC collects DO every two weeks from stations ranging from 5 – 31 nm offshore along the Newport, OR hydrographic line (we used the station 25nm offshore at a depth of 150m). Third, the NWFSC's Plume Survey performs CTD casts which collect dissolved oxygen data at 6 – 8 stations along transects from the Columbia River to La Push, WA from ~30 – 180 m depth from 1998 - 2014. The bottom trawl survey provides measurements along the continental shelf (average depth of tows = 126m) and slope (average depth of tows = 674m) during the summer months from 2009 - 2014, while the Newport hydrographic line provides detailed bi-weekly data from 1998 – 2014. Data from the plume survey have been analyzed to calculate the proportion of the continental shelf exposed to hypoxic conditions.

None of the three indicators showed annual trends over the past five years, and data were within historical averages of the datasets (Figure 34). However, with the possible exception of the DO dataset from the Newport hydrographic line (Figure 34, lower left), these time series are very short, and their status and trends should be interpreted with caution.

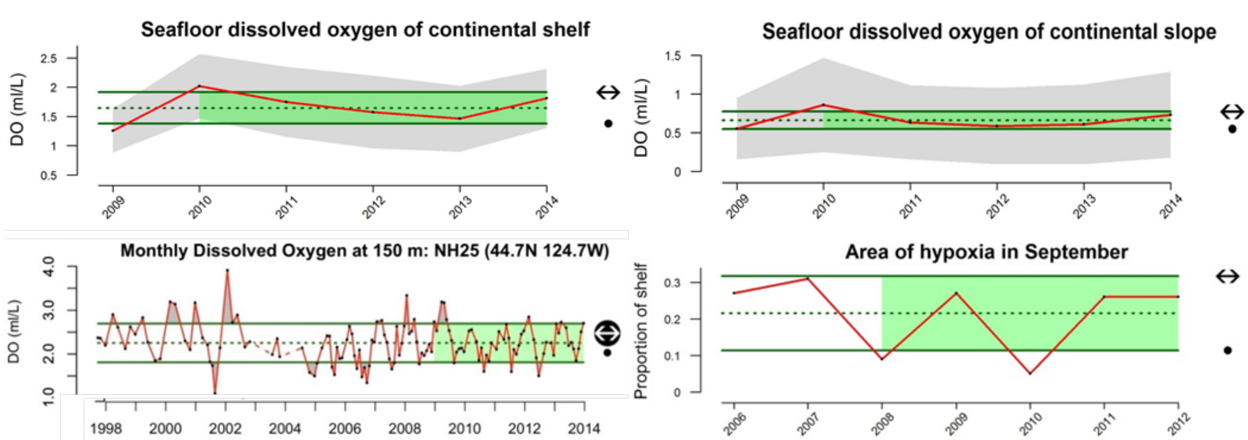

Figure 34. Indicators of seafloor dissolved oxygen (DO) concentrations. Top: DO (ml/L) on the continental shelf and slope of WAMSP waters (data courtesy of Beth Horness, NWFSC). The gray shaded region in each plot represents ±1 s.d. of the mean. Bottom left: DO at 150m on the Newport, OR hydrographic line (data courtesy of Bill Peterson, NWFSC). Bottom right: proportion of WAMSP shelf that was hypoxic (DO < 1.4 ml/L) in the NWFSC plume survey (data courtesy of Cheryl Morgan, Oregon State University).

CURRENTS, EDDIES AND PLUMES

See "*Pelagic zone habitat: Physical drivers: Currents, Eddies and Plumes*" for a description of this component and the selected indicators. Other indicators of currents specific to the seafloor are still under development, including the poleward rate of movement of the California Undercurrent as captured by current meters on the continental slope in 500 m of water offshore the west coast of Vancouver Island, British Columbia, Canada (Thomson and Krassovski 2010).

HABITAT

QUANTITY

The seafloor off Washington's coast is predominantly made up of soft sediments (Figure 35). 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 (McClure et al. 2015).

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 deepwater biogenic habitat occurs in the northernmost region in the Juan de Fuca Canyon area (Figure 35). Other areas of deepwater biogenic habitat likely occur and potentially suitable habitat for deep-sea corals has been modeled by Guinotte and Davies (2012). However, broad-scale temporal data capable of showing changes in the areal extent or density of these biogenic and physical habitats do not exist.

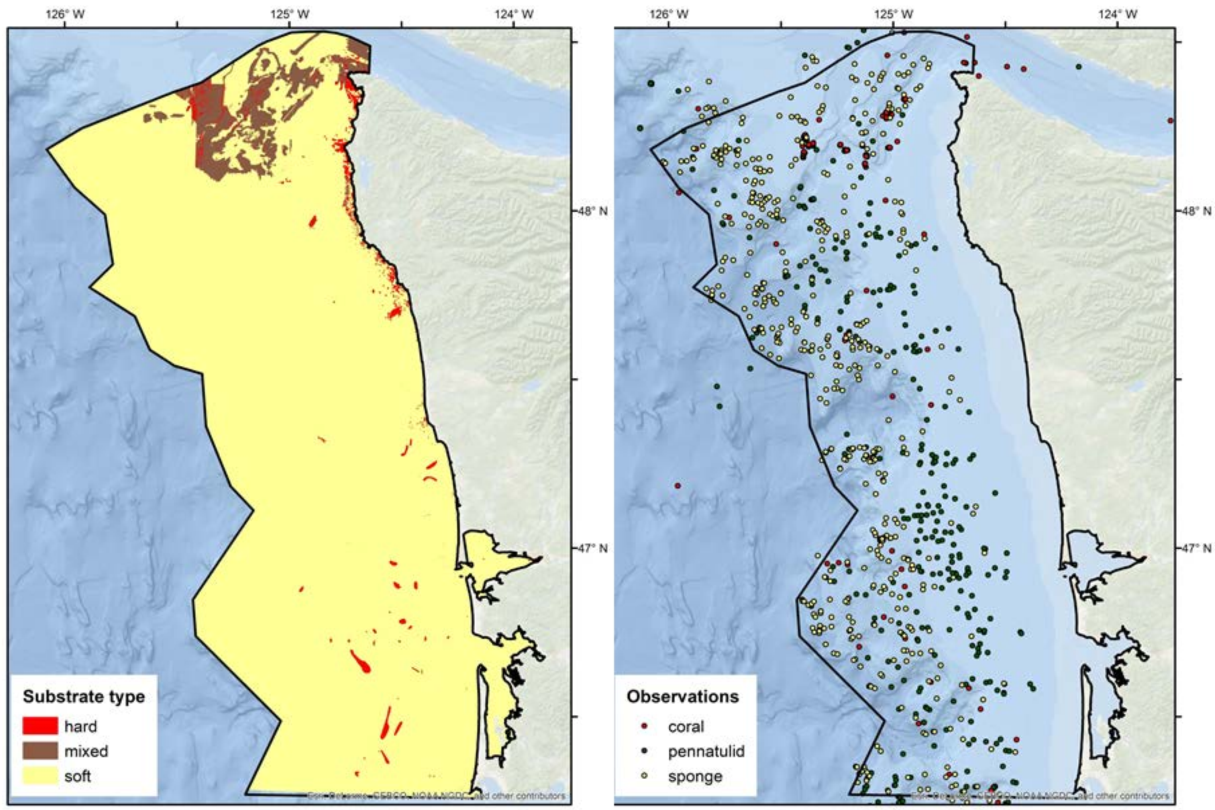

Figure 35. WAMSP seafloor habitat maps, including substrate types (left) and biogenic habitats (right). Biogenic data are observations of deep-sea corals, pennatulids (sea pens) and sponges (data from McClure (2015)).

QUALITY

In WAMSP waters, good quality habitat is generally correlated with cooler, nutrient-rich waters, which form the conditions necessary for a high caloric-value prey base, whereas warmer, nutrient-poor waters generally result in a prey base that are of much lower nutritional quality (Hooff and Peterson 2006, Peterson 2009). See "Seafloor Temperature" and "Low Dissolved Oxygen Events" above in the Physical Drivers section for status and trends of seafloor habitat quality.

ECOLOGICAL COMPONENTS

FISHERIES SPECIES: GROUNDFISH (ROCKFISHES AND FLATFISHES)

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 rockfish assemblage consists of numerous species. Thirty of the fifty-four rockfish species (*Sebastes* spp.) identified in NOAA's groundfish bottom-trawl survey have been collected in Washington State waters during the past ten years (B. Horness, NWFSC, unpublished data). The most abundant rockfish species are the yellowtail (*Sebastes flavidus*) and canary rockfish (*S. pinniger*). 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 *S. ruberrimus*) have diets that vary in amounts of 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 WAMSP waters, Dover sole *Microstomus pacificus,* arrowtooth flounder *Atheresthes stomias*, and rex sole *Glyptocephalus zachirus* are the most abundant in bottom-trawl surveys. Dover and rex sole primarily feed on deposit feeders, sea stars, brittle stars, and polychaetes, while arrowtooth flounder and another common species, petrale sole *Eopsetta jordani*, prey considerably on Pacific hake, small flatfish, and small planktivorous fish. Other predators of small flatfish include spiny dogfish *Squalus suckleyi*, skates and rays and yelloweye rockfish, while predators of large flatfish are generally other large flatfish or pelagic sharks (Dufault et al. 2009). Sablefish *Anoplopoma fimbria* and lingcod *Ophiodon elongatus* are voracious opportunistic predators and lucrative fisheries species.

In WAMSP waters, the most abundant and most variable member of the groundfish community is the spiny dogfish. This species is particularly interesting because its diet consists of prey from both pelagic and benthic taxa, suggesting it may provide a pathway for energy transfer between the seafloor and pelagic habitats (Brodeur et al. 2009, Dufault et al. 2009).

POPULATION SIZE

As indicators of population size for the groundfish assemblage, we selected catch-per-unit-effort estimates calculated from the NWFSC's West Coast Groundfish Bottom Trawl Survey from tows occurring in WAMSP waters. We selected species that are representative of the various life-histories within the groundfish assemblage: greenstriped rockfish *Sebastes elongatus*, yelloweye rockfish, darkblotched rockfish *Sebastes crameri*, longspine thornyhead *Sebastolobus altivelis*, Dover sole, rex sole, arrowtooth flounder, petrale sole, sablefish, lingcod and spiny dogfish. All but two of the selected species showed no trends and were within historical averages of the bottom-trawl survey over the last five years (Figure 36 - 38). Petrale sole (Figure 37) and lingcod (Figure 38) increased between 2009 – 2013, but were within historical CPUE averages.

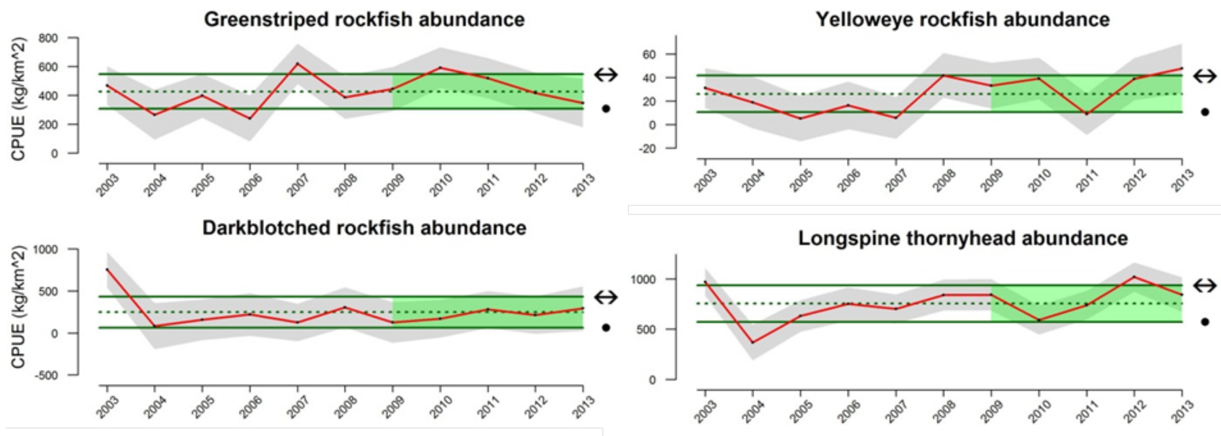

Figure 36. Catch-per-unit-area (CPUE; kg/km^2) of select rockfish and thornyhead species in WAMSP waters as calculated by swept-area methods of the NWFSC's Groundfish Bottom Trawl Survey. The gray shaded region in each plot represents ±1 s.e. of the mean (data courtesy of Beth Horness, NWFSC).

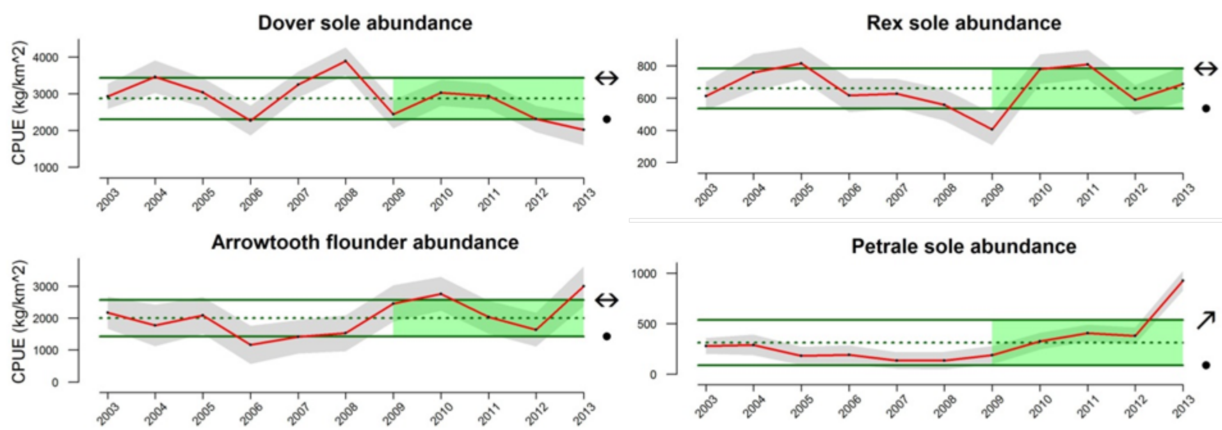

Figure 37. Catch-per-unit-area (CPUE; kg/km^2) of select flatfish species in WAMSP waters as calculated by swept-area methods of the NWFSC's Groundfish Bottom Trawl Survey. The gray shaded region in each plot represents ±1 s.e. of the mean (data courtesy of Beth Horness, NWFSC).

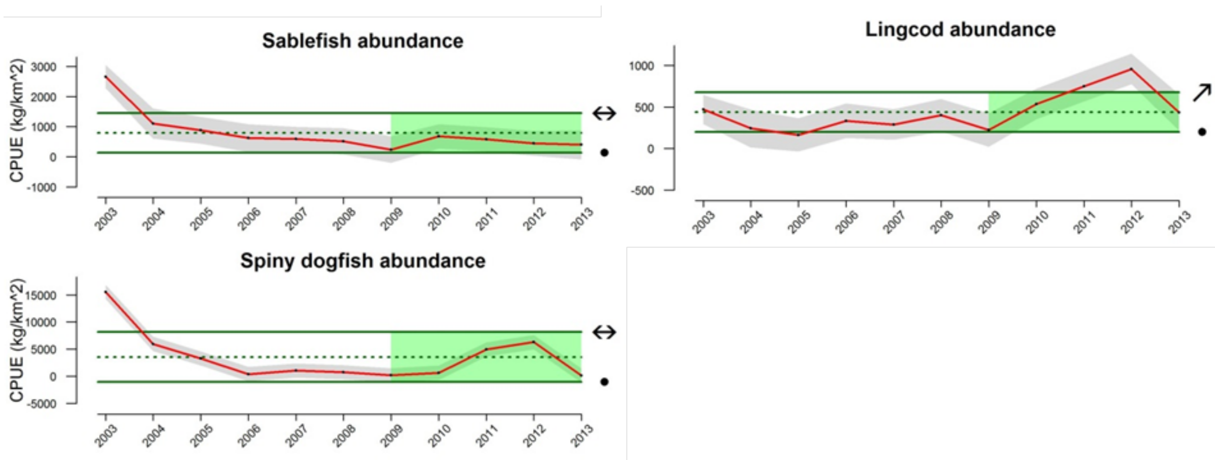

Figure 38. Catch-per-unit-area (CPUE; kg/km^2) of select other groundfish species in WAMSP waters as calculated by swept-area methods of the NWFSC's Groundfish Bottom Trawl Survey. The gray shaded region in each plot represents ±1 s.e. of the mean (data courtesy of Beth Horness, NWFSC).

POPULATION CONDITION

As indicators of population condition for the groundfish assemblage, we selected age structure of females for the same suite of species identified above as sampled by the NWFSC's Groundfish Bottom Trawl Survey in WAMSP waters. For many of these species, age determination has not occurred yet or did not occur across the entire duration of the survey, thus we used size structure as a proxy for age structure for these species and present both below (Figure 39 – 44).

Age structure in the rockfish complex showed high variability in darkblotched rockfish average age since 2009, but no significant trends (Figure 39). Using size structure showed an increase in average length for greenstriped rockfish and a decrease in average length for longspine thornyhead over the last five years (Figure 40). We had comparable data for both age and length for darkblotched rockfish and these two indicators showed similar patterns throughout the time series (Figure 39 - 40).

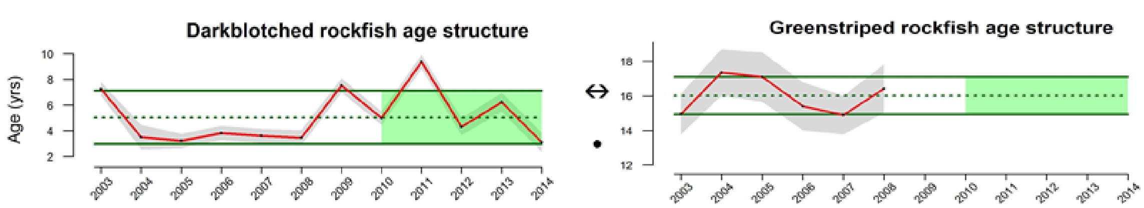

Figure 39. Mean age (yrs) of female darkblotched (left) and greenstriped (right) rockfish sampled from WAMSP waters during the NWFSC's Groundfish Bottom Trawl Survey. The gray shaded region in each plot represents ±1 s.e. of the mean (data courtesy of Beth Horness, NWFSC). No age structure data were available for female yelloweye rockfish or longspine thornyheads.

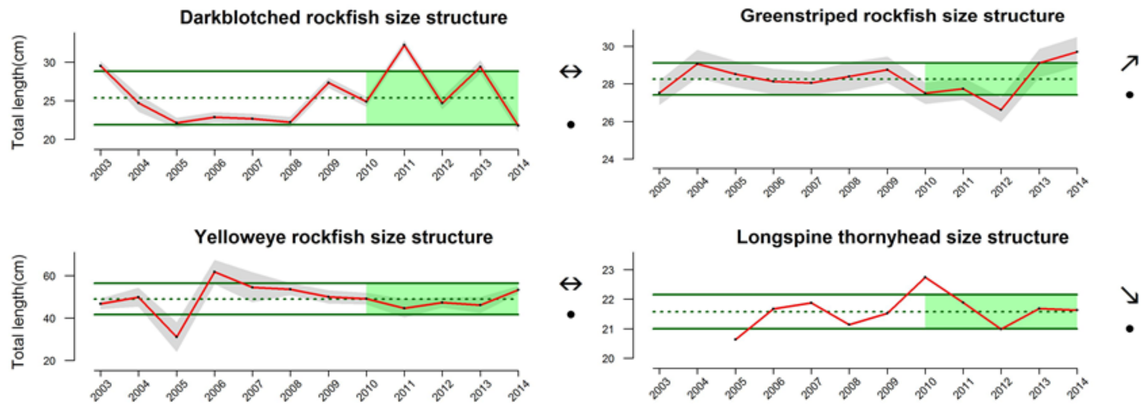

Figure 40. Mean length (cm) of female darkblotched, greenstriped and yelloweye rockfish and longspine thornyhead sampled from WAMSP waters during the NWFSC's Groundfish Bottom Trawl Survey. The gray shaded region in each plot represents ±1 s.e. of the mean (data courtesy of Beth Horness, NWFSC).

Age structure among flatfish species revealed an increase in average age of female petrale sole from 2010 – 2014 (Figure 41, upper left). Average lengths of female petrale and rex sole also increased over the last five years of the dataset (Figure 42). Similar patterns between age structure and size structure were also observed in flatfish species (Figure 41 - 42).

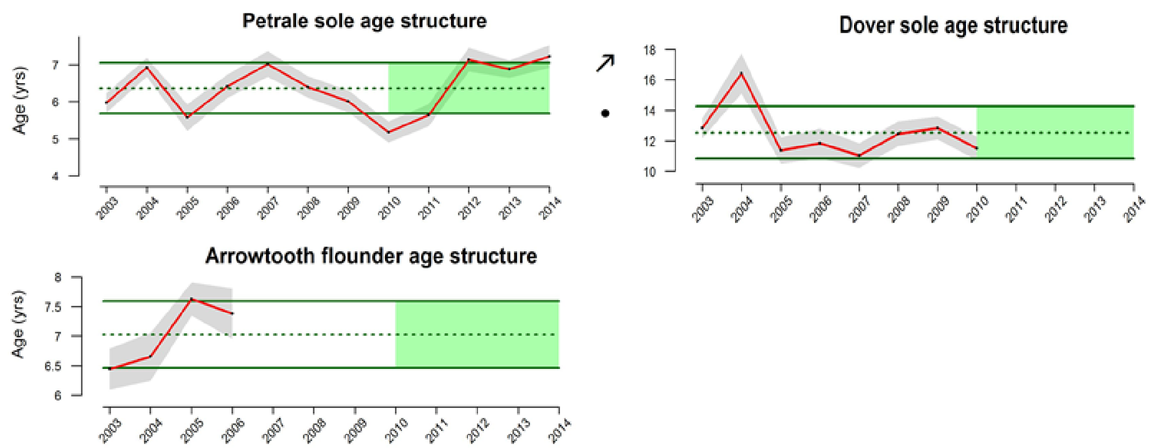

Figure 41. Mean age (yrs) of female petrale sole, dover sole and arrowtooth flounder sampled from WAMSP waters during the NWFSC's Groundfish Bottom Trawl Survey. The gray shaded region in each plot represents ±1 s.e. of the mean (data courtesy of Beth Horness, NWFSC). No age structure data were available for female rex sole.

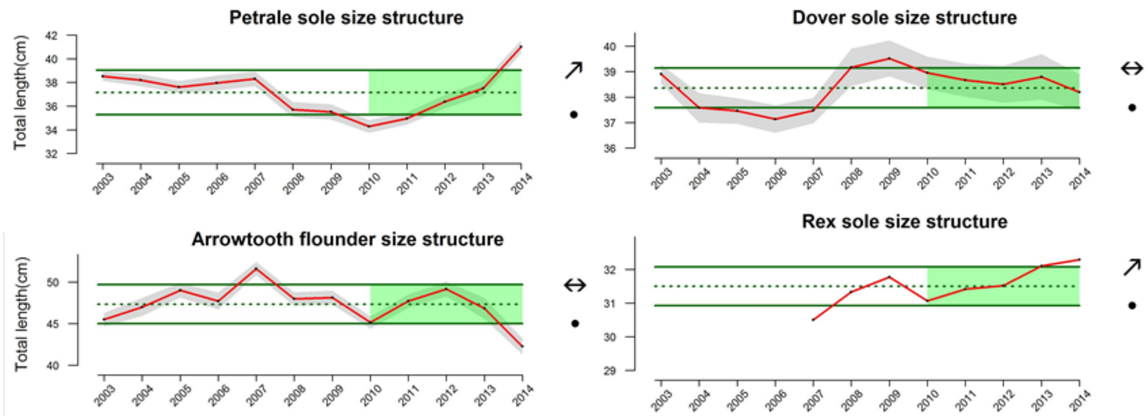

Figure 42. Mean length (cm) of female petrale sole, dover sole, arrowtooth flounder and rex sole sampled from WAMSP waters during the NWFSC's Groundfish Bottom Trawl Survey. The gray shaded region in each plot represents ±1 s.e. of the mean (data courtesy of Beth Horness, NWFSC).

Age structure for female sablefish showed no recent trend (Figure 43), while average length of females increased over the last five years for both sablefish and lingcod (Figure 44). As with other species, age structure of lingcod was correlated with size structure in years when both indicators were available.

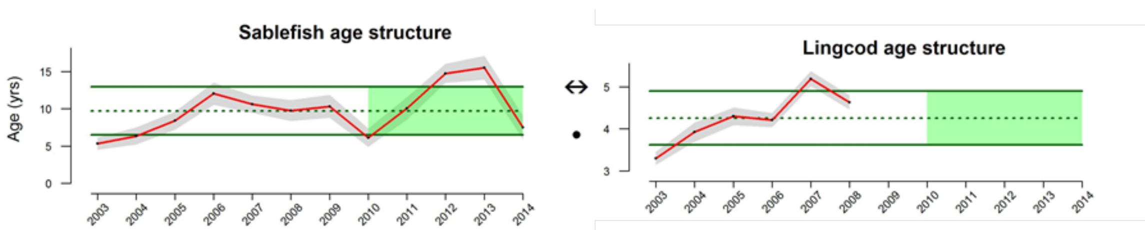

Figure 43. Mean age (yrs) of female sablefish and lingcod sampled from WAMSP waters during the NWFSC's Groundfish Bottom Trawl Survey. The gray shaded region in each plot represents ±1 s.e. of the mean (data courtesy of Beth Horness, NWFSC).

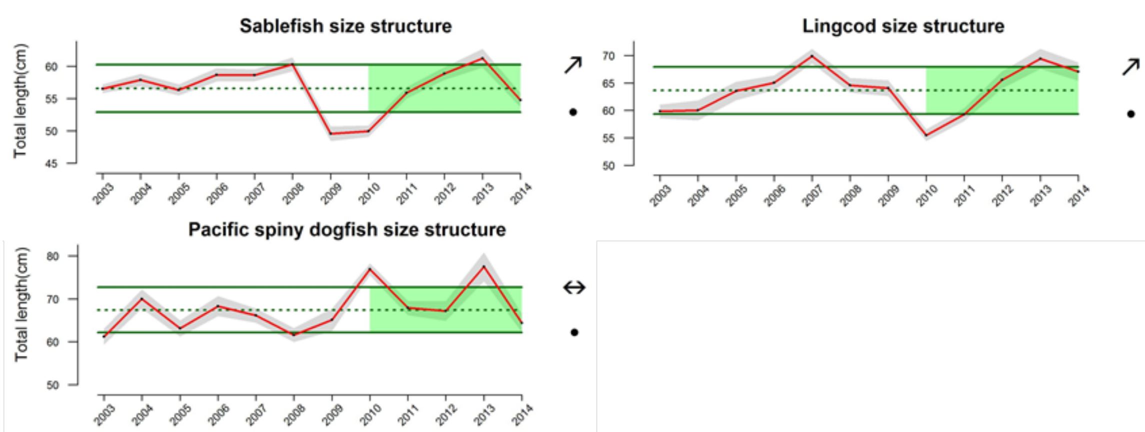

Figure 44. Average length (cm) of female sablefish, lingcod and Pacific spiny dogfish sampled from WAMSP waters during the NWFSC's Groundfish Bottom Trawl Survey. The gray shaded region in each plot represents ±1 s.e. of the mean (data courtesy of Beth Horness, NWFSC).

FISHERIES SPECIES: CRUSTACEANS

One of the most important commercial fisheries in Washington is Dungeness crab *Metacarcinus magister*, with average ex-vessel values of roughly $20 million annually (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). Dungeness crabs primarily prey upon deposit feeders (amphipods, isopods, etc.) and 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 Grays 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 lower recruitment (Hannah 1993). Little information is known about the abundance of these species off the coast of Washington, but they are all considered 'stable' populations 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 *Gadus macrocephalus*, and octopus; Pacific hake have 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.

POPULATION SIZE

There are no fishery-independent crustacean-specific surveys, but the NWFSC's Groundfish Bottom Trawl Survey captures two crab species in high abundance: Dungeness crab and tanner crab *Chionoecetes tanneri*. As indicators of crustacean population size in WAMSP waters, we quantified the catch-per-unit-effort (kg/km^2) of each species in tows made in WAMSP waters. Both species increased from 2009–2013, but were within historical averages of the trawl survey (Figure 45).

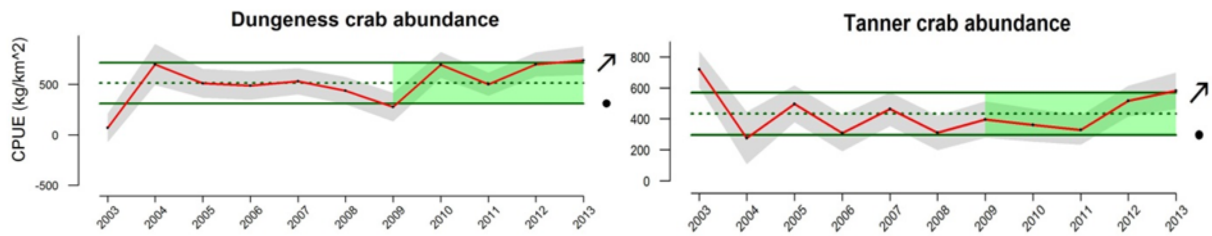

Figure 45. Catch-per-unit-effort of Dungeness (top) and Tanner (bottom) crabs in WAMSP waters as sampled by the NWFSC's Groundfish Bottom Trawl Survey. The gray shaded region in each plot represents ±1 s.e. of the mean (data courtesy of Beth Horness, NWFSC).

POPULATION CONDITION

The selected population condition indicators for crustaceans were condition factor (K), population growth rate and spatial structure of the population. There are no broad-scale, long-term fisheries-independent surveys that collect individual length/weight information across the entire population for Dungeness crab or any shrimp species. Individual carapace widths and weights are recorded for tanner crabs during the NWFSC's Groundfish Bottom Trawl Survey and allow for the calculation of condition factor. Population growth rate was calculated from trawl survey abundance estimates (**Error! Reference source not found.**). This survey would also allow for the calculation of the spatial distribution of Dungeness crabs and tanner crabs; however, it is unknown whether this would represent the bulk of the population, as the survey does not sample in nearshore areas < 55m in depth. Spatial anomaly plots of Dungeness and tanner crab spatial distributions with 5-year means and trends (similar to those for SST and chlorophyll-a described in the "*Pelagic habitat*") could be developed with more time.

Condition factor of female tanner crabs collected in the NWFSC Groundfish Bottom Trawl Survey has increased over the most recent five years of the time series (Figure 46). This follows a period of decline from at least 2006 (the first year data were available) until 2011. The recent data are within the long-term average.

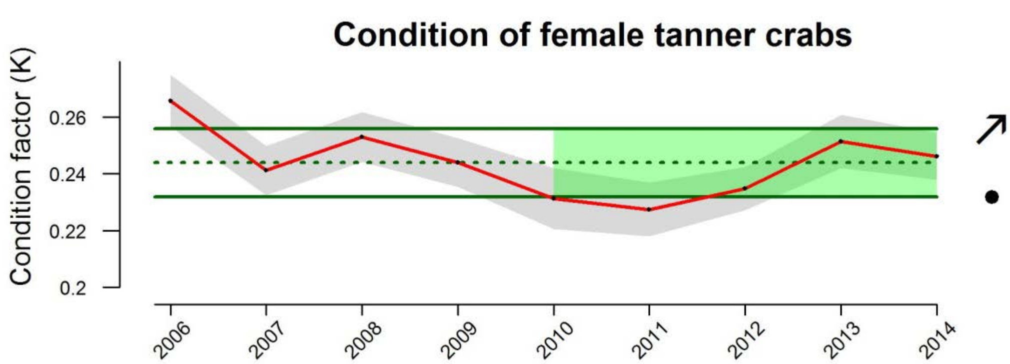

Figure 46. Condition factor (K) of female tanner crabs in WAMSP waters as sampled by the NWFSC's Groundfish Bottom Trawl Survey. The gray shaded region in each plot represents ±1 s.e. of the mean (data courtesy of Beth Horness, NWFSC).

FOCAL TAXA: PHYTOPLANKTON AND BACTERIA

The phytoplankton community is the base of the food web for the vast majority of the marine community, thus the health and structure of this community is important to understand. Vertical migration of zooplankton from near-bottom waters to the surface in order to feed on phytoplankton is one important mechanism connecting the seafloor community to the phytoplankton community of the pelagic zone, as is the sinking of detrital organic matter and marine snow from the pelagic zone.

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 dominant taxa during different sampling cruises in the spring and summer of 2004-2006.

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 or dinoflagellate species involved (Vehmaa et al. 2012).

POPULATION SIZE AND CONDITION

Phytoplankton total biomass and the ratio of diatoms to dinoflagellates were selected as the best indicators of population size and condition for the seafloor phytoplankton community, respectively. However, **we were unable to find any broad-scale, long term data sets that were capable of producing time series of phytoplankton biomass and quantifying the ratio of diatoms to dinoflagellates within the seafloor habitat.**

FOCAL TAXA: MARINE SNOW AND DETRITUS

Marine snow is a macroscopic aggregate of organic and inorganic particles including bacteria, phytoplankton, detritus, fecal pellets, feeding structures, trapped living organisms, and biominerals. The feeding structures of larvaceans are a common component aggregating other particles together (Alldredge and Silver 1988). These aggregations contribute 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 marine 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).

POPULATION SIZE AND CONDITION

Indicators for this component have not been evaluated to date.

FOCAL TAXA: ZOOPLANKTON

Zooplankton time series provide some of the best opportunities to understand marine ecosystem responses to climate change because zooplankton are a 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 considered 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 leading indicators of what may happen to regional commercial fish stocks several years later (Mackas et al. 2007, Peterson et al. 2014).

POPULATION SIZE

In order to quantify the status and trends of the zooplankton community, we selected aggregate biomass of zooplankton. Aggregate biomass of zooplankton was measured using the prey field index. This is a measure of the predominant prey species of salmon in the northern California Current ecosystem. This index represents relative changes in the abundance of important zooplankton species. The full data set is comprised of bongo tows collected during the NWFSC's Plume Survey that samples the coasts of Oregon and Washington from 2 – 31 nautical miles offshore (Brodeur et al. 2003). NWFSC scientists are currently analyzing this full data set, but we use data from the Grays Harbor transect to calculate the mean prey field index for WAMSP waters. Variability in the prey field index has been increasing over the last five years, but there were no significant trends in abundance of zooplankton ().

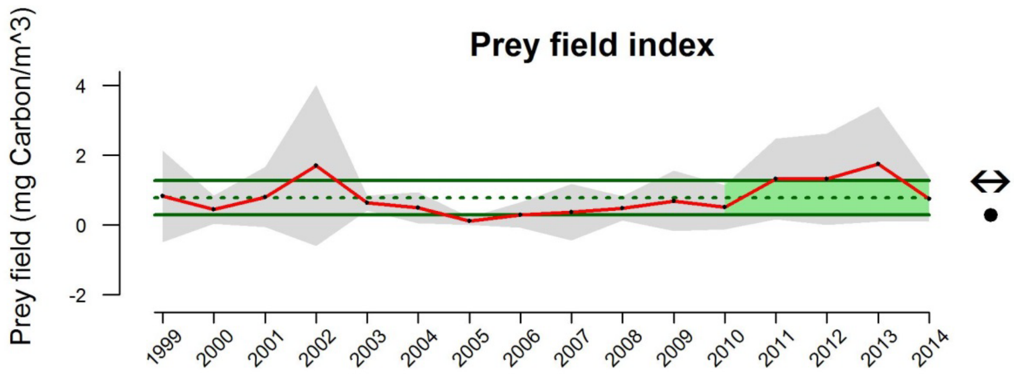

Figure 47. Relative abundance of important zooplankton species as calculated from bongo tows along the NWFSC's Plume Survey's Grays Harbor transect line. Broader coverage of the entire WAMSP region will be available upon publication. The gray shaded region represents ±1 s.d. of the mean. Data courtesy of Cheryl Morgan, Oregon State University.

POPULATION CONDITION

For population condition, we selected the northern copepod biomass anomaly, an index that describes changes in the relative biomass of lipid-rich boreal copepod species that are important prey for numerous consumer species in WAMSP waters. This indicator is calculated at the Newport, OR hydrographic line. Data from this line are generally considered to be representative of the entire northern California Current region, and studies comparing the copepod community sampled at the Newport Hydrographic line with the copepod community sampled by the NWFSC's Plume Survey across Washington State showed relatively no differences (Lamb 2011).

There were no significant trends in the northern copepod anomaly over the last 5 years, but a dramatic decrease in the abundance of northern copepod species occurred during 2014 (Figure 48). This may be a leading indicator of declining quality of prey resources throughout WAMSP waters over the next few years.

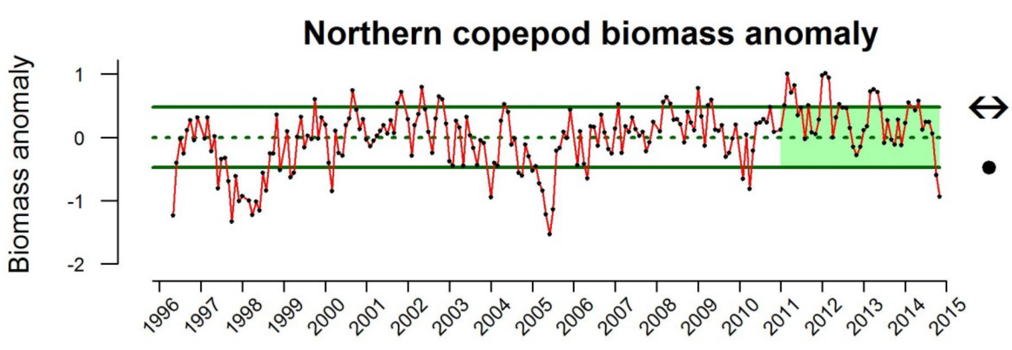

Figure 48. The northern copepod biomass anomaly shows the relative change in the composition of the copepod community from northern species (positive values) to southern species (negative values) during the year and during oceanographic regime changes (data courtesy of Bill Peterson, NWFSC).

FOCAL TAXA: BENTHIC INVERTEBRATES

The benthic invertebrate community consists of deposit feeders, shelled benthos, and a variety of large crustaceans (see *Fisheries species: Crustaceans* above). Deposit feeders are a diverse guild that includes amphipods, isopods, Thalassinid shrimp, snails, sea cucumbers, worms, polychaetes, sea slugs 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 (24%), and Pacific halibut *Hippoglossus stenolepis* (20%) (Dufault et al. 2009). Recycling capabilities and importance to valuable fish species make deposit feeders an important component of the seafloor habitat.

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 they may incur decreased growth and/or survival (Kaplan et al. 2010).

POPULATION SIZE

For population size of benthic invertebrates, we selected aggregate biomass of benthic invertebrates. The NWFSC's Groundfish Bottom Trawl Survey records counts and combined weights of invertebrates by species. These counts and weights are recorded to the lowest taxonomic level possible by the researchers on board. **These data were not available in time to include in this report.**

POPULATION CONDITION

For population condition of benthic invertebrates, we selected the aggregate spatial structure or spatial distribution patterns of benthic invertebrates. **Data to complete this analysis were not available in time to include in this report,** but anomaly maps, similar to those produced for SST and chlorophyll-a in the *Pelagic zone* habitat*,* could be produced to show annual anomalies and 5-year means and trends.

FOCAL TAXA: FORAGE FISHES

This component is still under development. We have been unable to determine whether indicators of forage fishes in the pelagic zone (see "*Pelagic zone: Ecological Components: Fisheries species: Forage fishes"*) are relevant to the abundance and distribution of forage fishes on the seafloor. Because forage fishes exhibit patterns of diel vertical migration pattern from the surface at night to deeper depths during the day, it may be reasonable to use the same indicators for the seafloor as used for the pelagic zone; however, this needs to be further examined.

ECOSYSTEM HEALTH OF THE SEAFLOOR HABITAT

Indicators for community structure are ecosystem and community level indices that were chosen to track two community level aspects of WAMSP waters: diversity and trophic structure.

BIODIVERSITY

Species diversity is an integrative measure that encompasses species richness (the number of species in the ecosystem) and species evenness (how individuals or biomass are distributed among species within the ecosystem) (Pimm 1984). Diversity has remained a central theme in ecology and is frequently seen as an indicator of the wellbeing of ecological systems (Magurran 2013). Recent reviews of correlations between diversity and ecosystem function (productivity and stability) in terrestrial and marine systems suggest that while the relationship is complex, species-rich communities are more stable (Hooper et al. 2005, Stachowicz et al. 2007).

We selected two indicators for seafloor biodiversity, both pertaining to the groundfish community that is monitored annually via the NWFSC Groundfish Bottom Trawl Survey. Simpson's index is a dominance measure that estimates the probability that any two individuals drawn at random from an infinitely large community would belong to different species (Magurran 2013). Species richness, which is a count of the number of species present, can provide an extremely useful measure of diversity if the study area can be successfully delimited in space and time and the constituent species enumerated and identified (Magurran 2013). Studies have shown that species richness tends to decline with fishing, primarily based on trawling/dredging effects on benthic invertebrate communities (Gaspar et al. 2009, Reiss et al. 2009).

In order to quantify the status and trends of biodiversity of the seafloor community, we selected Simpson diversity and species richness of the groundfish community. These metrics were calculated using data from the NWFSC's Groundfish Bottom Trawl Survey and methods from Williams et al. (2014). Neither indicator showed a recent trend, nor did the short-term mean of either indicator differ from the long-term mean (Figure 49).

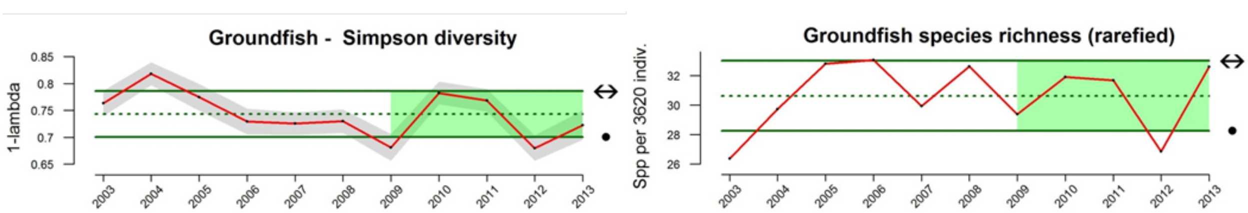

Figure 49. Indicators of biodiversity in the seafloor habitats of WAMSP waters. Top: Simpson diversity of groundfish. The gray shaded region represents ±1 s.e. of the mean. Bottom: species richness. (Data courtesy of Beth Horness, NWFSC.)

TROPHIC STRUCTURE

Trophic structure refers to the ways in which community ecology in a habitat is influenced by food web interactions. Characterizing trophic structure in a community relies on both empirical observations and on theoretical interpretations of species relationships. We selected three indicators for representing trophic structure in the seafloor habitat of WAMSP waters: mean trophic level, the northern copepod anomaly, and the relative abundance of scavengers.

Mean trophic level (MTL) provides a synoptic view of the organization of trophic structure in marine ecosystems, and is a pervasive and heavily discussed indicator used to measure marine ecosystem status, especially in communities dominated by exploited species (Pauly and Watson 2005, Essington et al. 2006, Branch et al. 2010). Conceptually, MTL is linked to top-down control and trophic cascades; a decline in MTL represents a decrease in the ability of predators to 'control' prey populations and may have far-reaching consequences to ecological communities (Daskalov 2002, Estes et al. 2004, Pauly and Watson 2005, Baum and Worm 2009). MTL was calculated using data from WAMSP waters during the NWFSC's Groundfish Bottom Trawl Survey, according to methods presented in Williams et al. (2014).

The northern copepod anomaly shows up as an indicator throughout this report. Within the broader California Current ecosystem, shifts in anomalies of zooplankton species 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 2009, Peterson et al. 2014). The cold water group usually dominates the coastal zooplankton community during the summer upwelling season (typically May through September), 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 this northern copepod anomaly 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 total food web uptake of wax esters and fatty acids, compounds which appear to be essential for many forage fishes if they are to grow and survive through the winter (Williams et al. 2014). The northern copepod biomass anomaly was calculated using data from the Newport Hydrographic Line as calculated in Peterson et al. (2014).

Scavengers play significant roles in the ecosystem by recycling dead and decomposing organic matter back into the food web. Human interference in the marine ecosystem has likely increased the abundance and number of species that forage on carrion (Britton and Morton 1994). For example, many fishing operations discard dead bycatch or fishery offal to the ocean floor, or damage organisms on the seabed with bottom-contact fishing gears (Ramsay et al. 1998). Scavenger population increases may be related to these types of fishing activities (Britton and Morton 1994, Ramsay et al. 1998, Demestre et al. 2000). The indicator presented here includes multiple groundfish species and three species of crab that are considered to be scavengers (Dufault et al. 2009) and were quantified in WAMSP waters by the NWFSC's West Coast Groundfish Bottom Trawl Survey.

Mean trophic level of the groundfish community in WAMSP waters decreased, while the ratio of scavengers to total biomass increased from 2009 – 2013 (Figure 50). The northern copepod anomaly showed no overall trend over the last five years, but there was a significant decrease during 2014 suggesting large shifts in the source waters for the WAMSP waters, from cooler, productive sub-arctic water sources to warmer, less productive water subtropical sources (Figure 50).

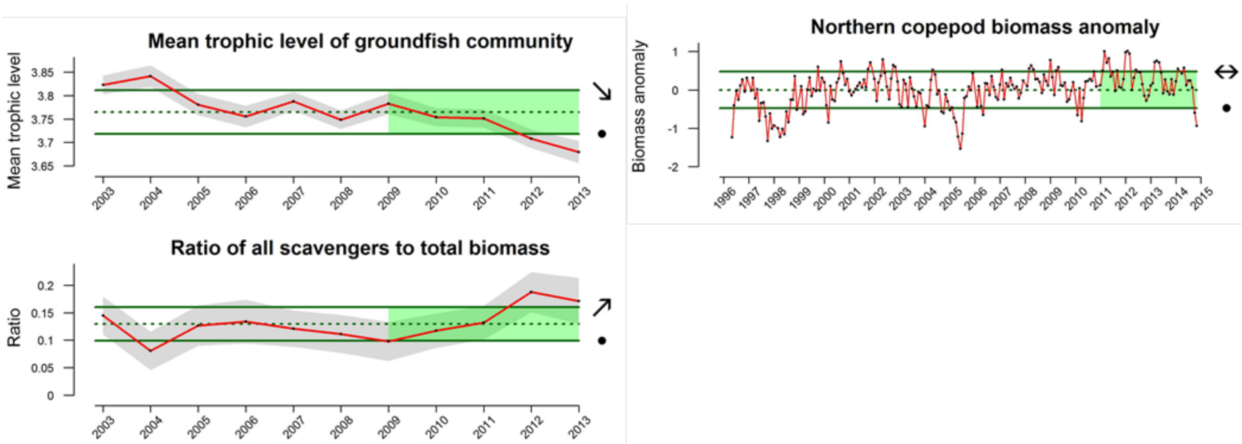

Figure 50. Indicators of trophic structure in WAMSP seafloor habitats. Groundfish mean trophic level (top left) and the ratio of benthic scavenger biomass to total biomass (bottom left) were derived from the NWFSC's Groundfish Bottom Trawl Survey (data courtesy of Beth Horness, NWFSC). Gray shaded regions represent ±1 s.e. of the mean. The northern copepod biomass anomaly (top right) was calculated from plankton tows along the Newport, OR hydrographic line (data courtesy of Bill Peterson, NWFSC).

HUMAN ACTIVITIES

BIOLOGICAL EXTRACTIONS

Fishing provides important services to society, including production of food, employment, livelihood and recreation. At the same time, fisheries have the 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. Here, we present the status and trends of landings in WAMSP waters for three major seafloor commercial fisheries, recreational fisheries and total fisheries. Landings of shrimp in WAMSP waters have increased over the last five years, particularly in 2014 when landings were nearly double the previous maximum landings in 1988 (Figure 51). Commercial landings of groundfish (excluding Pacific hake) have been at historically low levels over the last decade. All other landings showed no particular trends and were within historical averages over the last five years.

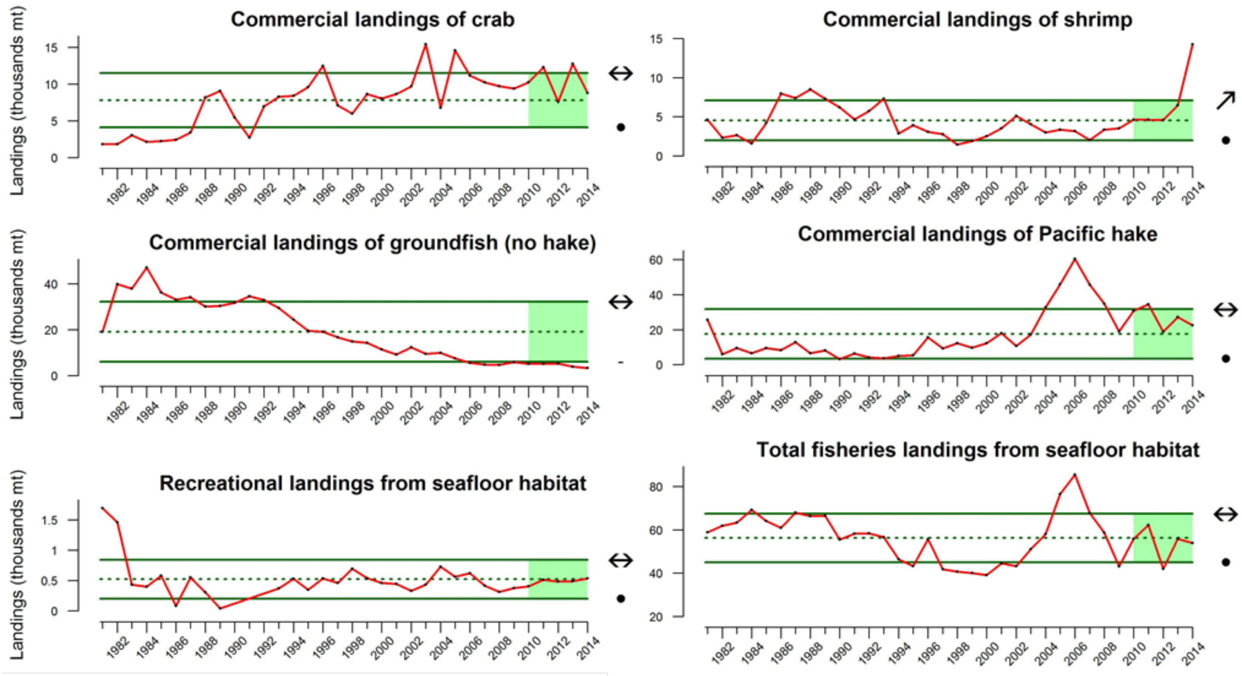

Figure 51. Commercial landings of crab, shrimp, groundfish (excluding Pacific hake), and Pacific hake; recreational and total fisheries landings from seafloor habitats of WAMSP waters. Data from the Pacific Fisheries Information Network (http://pacfin.psmfc.org/), At-Sea Hake Observer Program (courtesy of Vanessa Tuttle, NWFSC), and the Recreational Fisheries Information Network (http://www.recfin.org/).

LAND-BASED ACTIVITIES

Land-based activities can often result in the downstream run-off of various pollutants. These non-point sources of pollution have been identified as the greatest pollution threat to oceans and coasts (Panetta 2003, U. S. Commission on Ocean Policy 2004). For WAMSP waters, we developed four indicators of pollution that may have an impact on specific components of the seafloor habitat: (1) atmospheric deposition, as estimated from mean concentrations of sulfates ([SO_4^{2-}]) as measured by the National Atmospheric Deposition Program; (2) organic pollution, estimated as a normalized index of pesticide concentrations in streams that drain into WAMSP waters as measured by the U.S. Geological Survey; (3) inorganic pollution, estimated as a normalized index of all reported chemical releases to land and water as measured by the U.S. Environmental Protection Agency's Toxic Release Inventory for sites that drain into WAMSP waters; and (4) marine debris, estimated from standardized counts of specific debris items as measured by the National Marine Debris Program. For each of these indicators, we used the same data as Andrews et al. (2015) but limited the data to watersheds that drain into WAMSP waters. All four of these indicators showed no trends and were within historical averages over the last five years of their respective datasets (Figure 52). Further studies should explore whether estimates of pollutant loadings in seafloor sediments correlate with these land-based loadings to fully understand the utility of these indicators.

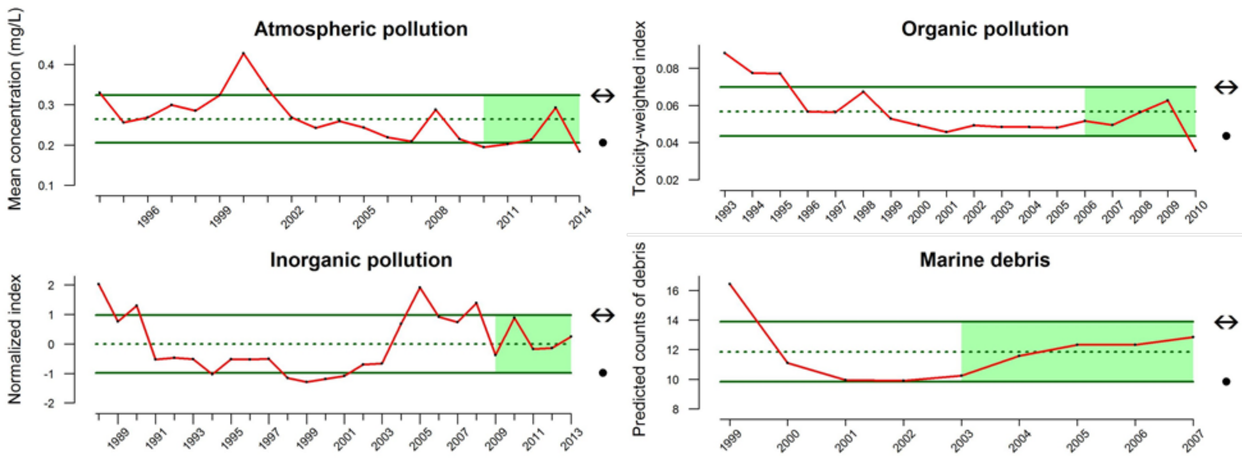

Figure 52. Indicators of pollution from atmospheric deposition (mean concentration of sulfates; data from the National Atmospheric Deposition Program), organic pollution (normalized index of pesticide concentrations in WAMSP streams; data from the U.S. Geological Survey), inorganic pollution (normalized index of all reported chemical releases at sites that drain into WAMSP waters; data from the U.S. Environmental Protection Agency's Toxic Release Inventory), and marine debris (standardized counts of specific debris items; data from Ribic et al. (2012)).

OCEAN-BASED ACTIVITIES

SEAFOOD DEMAND

Demand for seafood products drives extraction of fish and shellfish from oceans around the globe. To quantify this driver, we selected total consumption of edible and non-edible fisheries products by U.S. residents. Seafood products from WAMSP waters are consumed across the U.S. and exported globally. Total edible and non-edible seafood demand provides an estimate of what is being used and the relative pressure on resources within WAMSP waters. Seafood demand has been increasing relatively consistently since the early 1970's and was above historical averages from 2009-2013 (Figure 53).

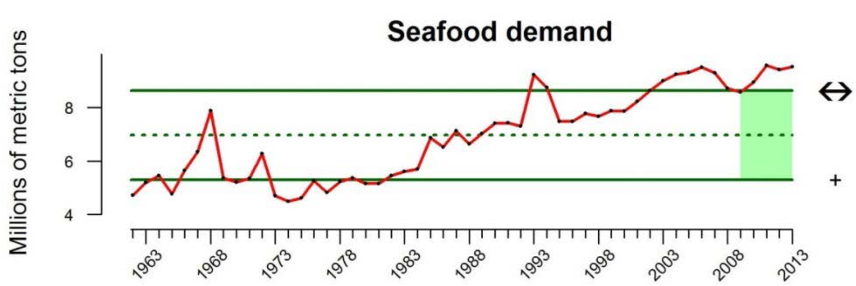

Figure 53. Total consumption of edible and non-edible fisheries products in the United States.

HABITAT MODIFICATION

Fishing can alter benthic habitats if intense use of trawls and other bottom gear disturbs and destroys bottom topography and associated communities, from (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 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).

Essential fish habitat (EFH) is habitat necessary for fish spawning, breeding, feeding, or growth to maturity. In WAMSP waters, EFH designations and marine protected areas, in combination with gear regulation measures, have been used to reduce adverse impacts of fisheries on vulnerable habitats. The introduction of rockfish conservation areas as management measures to prevent overfishing has made additional seafloor areas inaccessible to fishing during some or all of the year. As indicators of habitat modification, we selected distance trawled along seafloor in the form of both time series and anomaly plots. Data on distance trawled in WAMSP waters are available from the NWFSC's West Coast Observer Program, but we were unable to get updated data in time to include in this report. Thus, the figures below pertain to bottom-trawling effort across the entire coast from 1999 to 2012.

Bottom trawling along the seafloor across the entire U.S. West Coast decreased from 2008 – 2012 (Figure 54). Bottom trawling effort specific to WAMSP waters likely followed this same trend.

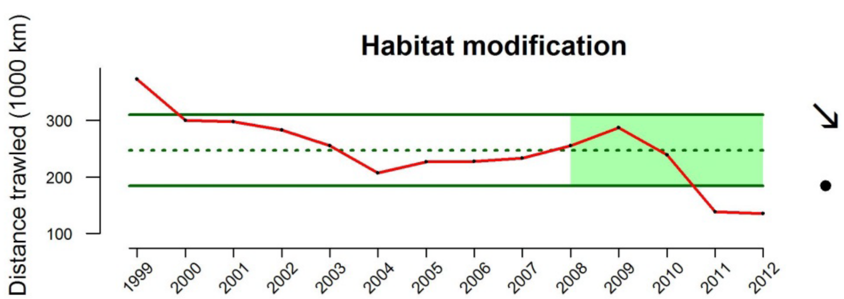

Figure 54. Distance trawled along seafloor habitats across U.S. West Coast (data from McClure et al. (2015)).

Similar to anomaly plots of SST and chlorophyll-a (Figures 6 and 20), plots showing the relative difference, short term means and short term trends in bottom trawling effort could be developed as spatial indicators of seafloor habitat modification. For example, distance trawled within WAMSP waters showed large positive and negative spatiotemporal anomalies after EFH conservation area closures were implemented in June 2006 (Figure 55).

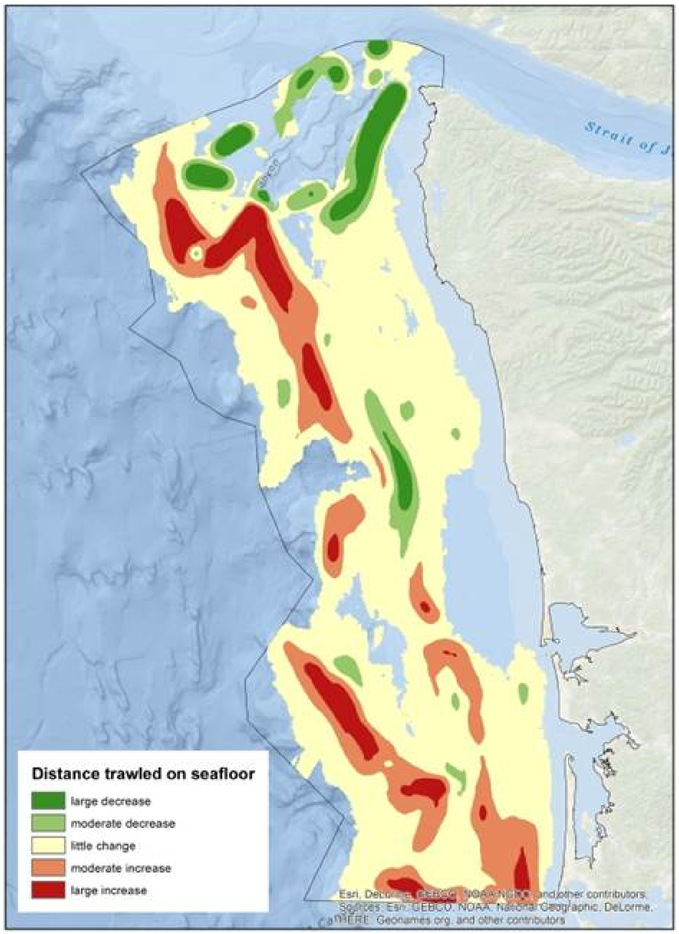

Figure 55. Temporal change in bottom trawling effort prior to (2002 – June 2006) and after (July 2006 – 2010) implementation of essential fish habitat conservation closure areas (data from McClure et al. (2015)).

SUMMARY: KELP FOREST HABITAT

CONCEPTUAL MODEL OF KELP FOREST HABITAT

We include two general types of habitat in our definition of kelp forest habitat for WAMSP waters: (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 <30 m. We included rocky reefs in this category because many of the species that inhabit kelp forests also inhabit shallow rocky reefs without kelp. We used 30 m as a cut-off point from seafloor habitat because this is often cited as the lower depth limit for most local kelps and other structure-forming algae due to light limitations (Mumford 2007, Springer et al. 2007). The conceptual model below (Figure 56) and in graphical form in Appendix 1 represents the dominant physical drivers, ecological components and interactions, and human activities that characterize the kelp forest habitat of WAMSP waters. Suites of physical drivers and human activities affect the ecological components (i.e., the kelp forest food web) and the surrounding water column within which the ecological components dwell. Humans derive wellbeing from many components and processes within the ecosystem, as well as the human activities that the kelp forest habitat facilitates.

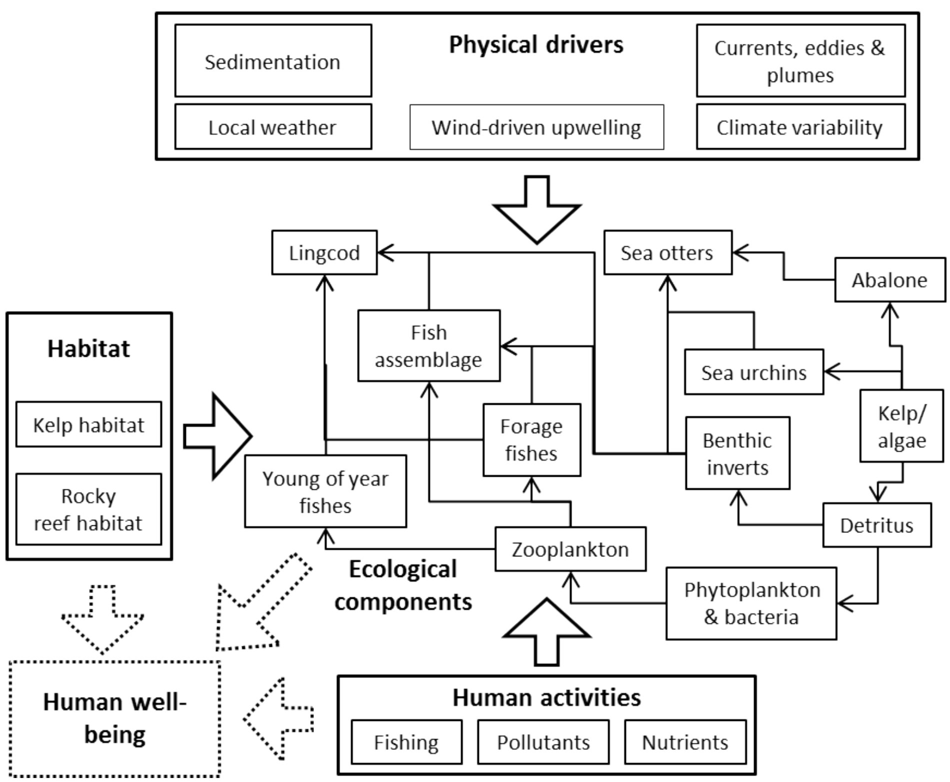

Figure 56. Conceptual model of important physical drivers, habitat, ecological components, and human activities for the kelp forest habitat.

In the following sections, we briefly describe the importance and report on the status and trends (when data was available) of each indicator selected for the components shown in the conceptual model.

Table 6. Summary of indicators and times series duration for each component's key attributes for WAMSP kelp forest habitat. † indicates data are presently being analyzed.

Component	Attribute	Indicator	Time period of available data
Physical drivers			
Climatic	Water temperature	Sea surface temperature	2000 – 2014
		Pacific Decadal Oscillation	1900 – 2015
	El Niño events	Multivariate El Niño Index	1950 – 2015
		Northern Oscillation Index	1948 – 2014
	Source waters	North Pacific Gyre Oscillation index	1950 – 2015
		Northern copepod anomaly	1996 – 2015
Oceanographic	Upwelling	Upwelling index	1967 – 2014
		Spring transition index	1967 – 2015
	Currents, eddies, plumes	Columbia River plume volume	1999 - 2014
	Sediment dynamics	Columbia River plume volume	1999 - 2014
	Local weather	Wind gusts – Destruction Island	1984 - 2014
Habitat			
Physical Habitat	Quantity	Aerial extent of floating kelp	1989 – 2012
	Quality	Nitrogen: phosphorus ratio	1998 - 2014
		Nearshore DO concentration	2006 - 2012
Ecological components			
Phytoplankton and bacteria	Population size	Aggregate phytoplankton biomass	NA †
	Population condition	Diatom: dinoflagellate ratio	NA †
Zooplankton	Population size	Aggregate zooplankton biomass	NA
	Population condition	Northern copepod anomaly	NA
Sea urchins	Population size	Population abundance	2015
	Population condition	Reproductive output	NA
Lingcod	Population size	Population abundance	2015
	Population condition	Age structure	NA
Abalone	Population size	Population abundance	2015
	Population condition	Reproductive output	NA
Fish assemblage	Population size	Population abundance of rockfishes, perches, surfperches	2015
	Population condition	Reproductive output	NA
Sea otters	Population size	Population abundance	1989 - 2013
	Population condition	Reproductive output	1997 - 2013
Ecosystem health	Biodiversity	Simpson's diversity	NA
		Species richness	NA
	Trophic structure	Mean trophic level	NA
		Areal extent of kelp forest	1989 – 2012
Human activities			
Biological extractions	Fishing	Recreational landings	1980 - 2014

Component	Attribute	Indicator	Time period of available data
Land-based activities	Nutrient input	Fertilizer input	1945 - 2010
	Pollution	Atmospheric pollution	1994 – 2014
		Organic pollution	1993 - 2010
		Inorganic pollution	1988 - 2013
		Marine debris	1999 - 2007

PHYSICAL DRIVERS

CLIMATE VARIABILITY

Climate variability represents broad spatial scale, long-term natural variability; short-term, event-driven variability; and an anthropogenic global warming signal. Increases in atmospheric CO_2 continue to put pressure on marine ecosystems through warming of the oceans, but separating anthropogenic from natural processes is difficult. Kelp forest habitat will be affected by large-scale atmospheric forcing patterns associated with climate change. As basin-scale climate regime phases change, kelp forest communities will be exposed to the effects of changes in sea-surface temperature, the timing and frequency of El Niño events, source waters, transport currents, upwelling and frequency and/or variability of severe storms.

SEA SURFACE TEMPERATURE

Temperature is one of the most important drivers in the ocean. Ocean temperature regulates the rate of metabolism for most organisms and regulates the base of the food web. In WAMSP waters, cooler temperatures generally result in a prey base that contains northern species, which are rich in wax esters and fatty acids that promote high growth in consumers, whereas warmer temperatures generally result in a prey base consisting of southern species that are of much lower nutritional quality (Hooff and Peterson 2006, Peterson 2009). As indicators of sea surface temperatures in kelp forest habitats, we selected sea-surface temperature (SST) from stationary buoys and the Pacific Decadal Oscillation (PDO). The Olympic Coast National Marine Sanctuary (OCNMS) maintains oceanographic sampling buoys throughout the OCNMS, which encompasses most kelp forest habitats in WAMSP waters. Moorings data are available through the OCNMS website (http://olympiccoast.noaa.gov/science/oceanography/). We used the nearshore buoys (buoys stationed between 15 – 18 m depth) and calculated monthly sea-surface temperature averages (from temperature sensors at the surface) across all buoys to quantify the status and trends of this indicator. Values for the PDO were downloaded from the University of Washington's website for the Joint Institute for the Study of the Atmosphere and Ocean (JISAO; http://research.jisao.washington.edu/pdo/). Both indicators of sea-surface temperature increased over the last five years with particularly high values in 2013 and 2014 (Figure 57).

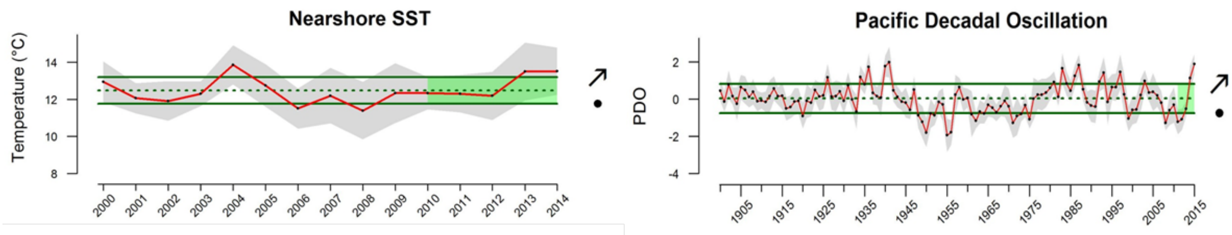

Figure 57. Left: Average sea-surface temperatures at nearshore (15 – 18 m depth) Olympic Coast National Marine Sanctuary mooring stations (data from OCNMS Oceanographic moorings website). Right: Annualized mean Pacific Decadal Oscillation (PDO). The gray shaded region in each plot represents ±1 s.d. of the mean.

TIMING AND FREQUENCY OF EL NIÑO EVENTS

El Niño Southern Oscillation (ENSO) events result from variations in sea level pressure, winds and sea-surface temperatures between the eastern and western tropical Pacific. Patterns in the tropics have wide-reaching consequences on the physical attributes in WAMSP waters. El Niño events result in ecosystem-wide effects from changes in species composition to lack of prey availability and breeding failure in top predators, while La Niña events can increase productivity in the system (Chavez 2002). El Niño conditions in WAMSP waters are associated with warmer surface water, weaker upwelling winds and lower nutrient availability at the surface; however, the effects of any given ENSO event are highly variable. As indicators of the timing and frequency of El Niño events in WAMSP waters, we selected the Multivariate El Niño Index (MEI) and the Northern Oscillation Index (NOI). The MEI represents patterns in six main observed variables over the tropical Pacific to identify the status of ENSO. The NOI measures large-scale atmospheric teleconnections, specifically the difference between sea level pressure at the climatological location of the North Pacific High (NPH) and at Darwin, Australia. Positive NOI values correspond to more coastal upwelling, while during an El Niño the influence of the NPH is diminished and the NOI has large negative values. While NOI tracks interannual changes of atmospheric forcing that are relevant to WAMSP waters, it is still a very broad index when evaluating changes in SST.

Values for the MEI were downloaded from NOAA's Earth System Research Laboratory's website (http://www.esrl.noaa.gov/psd/enso/mei/) and values for the Northern Oscillation Index were downloaded from NOAA's Pacific Fisheries Environmental Laboratory' website (http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/NOIx/noix.html). The MEI has increased over the last five years, while the NOI has shown no trend (Figure 58).

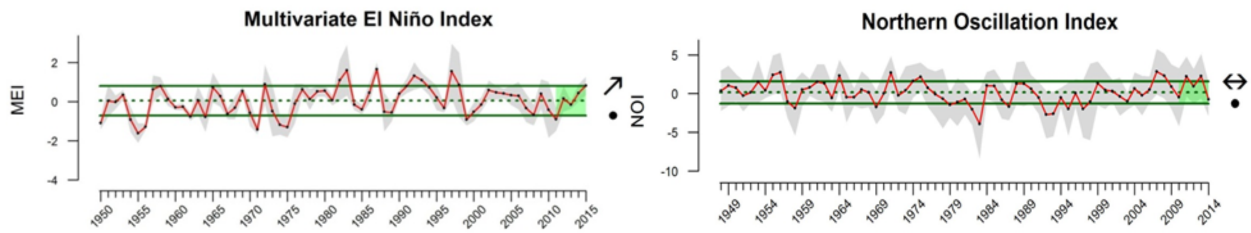

Figure 58. Indicators of changes in the timing and frequency of El Niño events in the North Pacific. Shading is 1 s.d. of the mean.

SOURCE WATERS

Subarctic and tropical waters are important contributors of source waters to WAMSP waters (Bograd et al. 2008). Source water changes may lead to large-scale changes in nutrients and hypoxia in the broader California Current (Bograd et al. 2008). Increases in subarctic source waters can result in changes in the food web by supplying larger, lipid-rich northern copepods and other plankton, compared to the smaller, often lipid-poor warm water copepods occurring in subtropical waters. We selected the North Pacific Gyre Oscillation (NPGO) and the northern copepod biomass anomaly as indicators of changes in source waters for WAMSP waters. We downloaded values for the NPGO from the ENSO/NPGO website (http://www.o3d.org/npgo/). The northern copepod biomass anomaly was calculated using biomass estimates of northern and southern species of copepods collected along the Newport Hydrographic Line and calculated as in Peterson et al. (2014).

The NPGO, which describes changes in salinity, nutrients and chlorophyll-a in the California Current ecosystem, has decreased significantly over the last five years (Figure 59). The northern copepod anomaly showed no overall trend over the last five years, but there has been a significant decrease beginning in 2014, suggesting large shifts in the source waters for the WAMSP waters, from cooler, productive sub-arctic water sources to warmer, less productive water from subtropical sources (Figure 59).

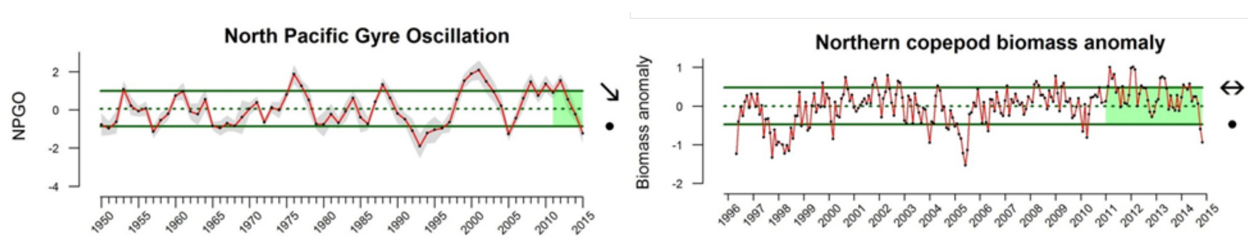

Figure 59. Indicators of changes in source waters to WAMSP waters. Left: the North Pacific Gyre Oscillation (NPGO). The gray shaded region represents ±1 s.d. of the mean. (Data: Emanuele Di Lorenzo, http://www.o3d.org/npgo/). Right: the northern copepod biomass anomaly shows the change in the copepod community from northern species (positive values) to southern species (negative values) during the year and during oceanographic regime changes (data courtesy of Bill Peterson, NWFSC).

UPWELLING

Washington MSP waters reside within the broader California Current ecosystem, which is an eastern boundary current system largely driven by upwelling forces that bring deep, cold, nutrient-rich waters to the surface. 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 (Bograd et al. 2009). 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. Upwelling in WAMSP waters generally 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). We selected the Upwelling Index calculated off La Push, WA in the winter and summer and the Spring Transition Index as indicators of upwelling in WAMSP waters. We downloaded monthly mean values of the UI from NOAA's Pacific Fisheries Environmental Laboratory website (http://www.pfeg.noaa.gov) and calculated winter (Jan – Mar) and summer (Jun – Aug) averages. The STI is the day of the year in which upwelling is at its minimum value and is calculated directly from the UI.

The winter upwelling index increased while the more relevant summer upwelling index remained unchanged over the last five years (Figure 60 top panels). The spring transition index has been widely variable over the last five years with no significant trend (Figure 60 bottom).

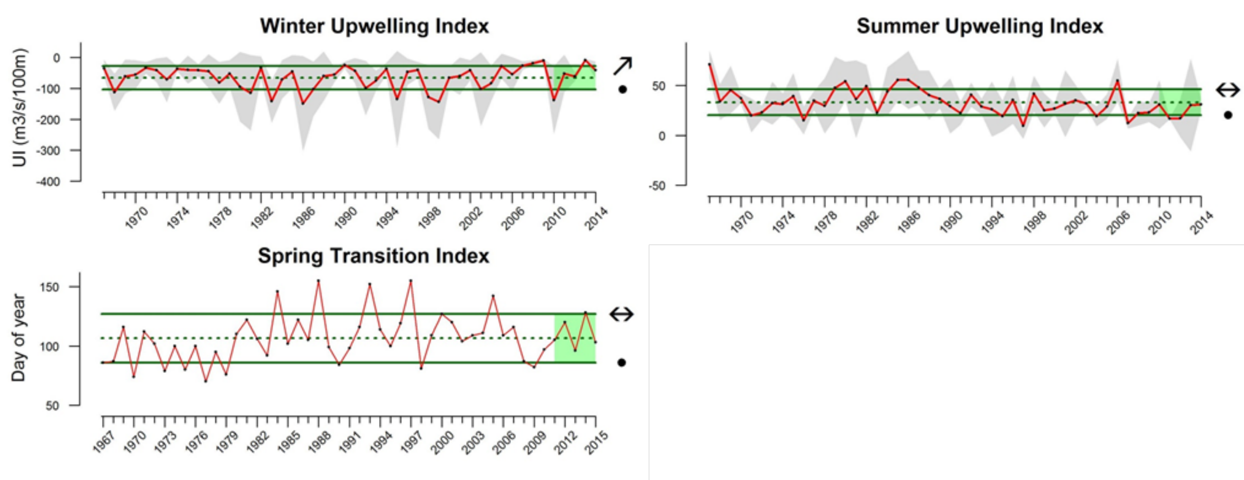

Figure 60. Indicators of upwelling in WAMSP waters. Upwelling indices for winter (Jan-Mar) and summer (Jun-Aug) and the Spring Transition Index calculated at 48°N, 125°W off La Push, WA. Shading is 1 s.d. of the mean.

CURRENTS, EDDIES AND PLUMES

The Columbia River represents a significant input of fresh, turbid water into kelp forest habitats. These physical characteristics provide a convergence zone for zooplankton, and thus provide conditions favorable for high concentrations of prey for planktivorous organisms (Morgan et al. 2005b). We selected an index modeled by the Center for Coastal Margin Observation and Prediction Center to calculate the volume of the Columbia River plume. We downloaded "Plume Volume" data with the "28 psu salinity cut-off" from the "db33" source file from CMOP's Virtual Columbia River website (http://www.stccmop.org/datamart).

The volume of the Columbia River plume was at historically high levels in 2011 (based on data from 1999 – 2014), but there were no significant trends in the annual mean volume over the last five years (Figure 61).

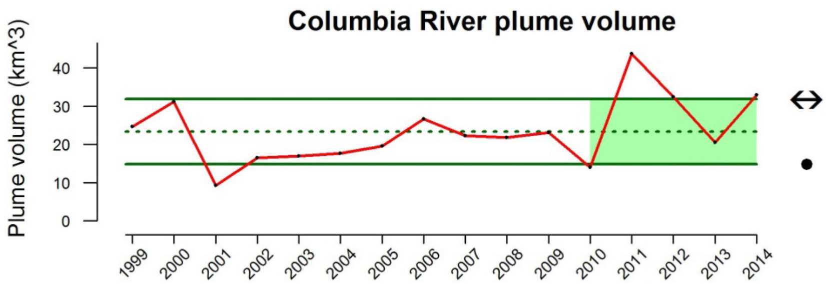

Figure 61. Average daily plume volume (km^3) of the Columbia River plume. Data from Center for Coastal Margin Observation and Prediction.

SEDIMENT DYNAMICS

Sediment runoff from shorelines, dredging activities, or storm-driven waves on the beach all contribute to the suspension of sediments in the water column. Turbid waters decrease recruitment success of kelp sporophytes. Reduced densities of bull kelp adults and sporophytes have been observed in areas of landslides (Shaffer and Parks 1994, Konar and Roberts 1996). Thus, processes such as sedimentation that limit light penetration to the bottom are important for the sustainability of kelp forest habitats.

In order to quantify the status and trends of sediment dynamics, we selected the volume of the Columbia River plume as it provides a major source of freshwater and sediment to the Washington coastline. See "*Currents, Eddies and Plumes*" and Figure 61 above for a description, status and trends of this indicator.

LOCAL WEATHER

Storm-driven waves have the potential to dislodge kelp plants. Under typical 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 Niño conditions, more frequent and more severe storms can significantly decrease the extent and density of kelp plants. During the 1997 El Niño event, total kelp canopy cover in Washington decreased by 32%; bull kelp populations decreased by 75%, compared to 8% reductions for the giant kelp *Macrocystis pyrifera*) (Berry et al. 2001).

Although strong storms and wave action can reduce the size of bull kelp beds, this species has the ability to rapidly recolonize denuded areas following the removal of competitive dominants such as *Macrocystis*. For example, following the ENSO-related reductions in kelp cover along the Washington coast described above, *Nereocystis* populations increased by 423% in 1998 (Berry et al. 2001). Thus, disturbance events may actually promote bull kelp canopy coverage, owing to release from competition with other algal species for resources (Springer et al. 2007, Skewgar and Pearson 2011).

In order to capture changes in these potentially deleterious storm events, we selected average wind gusts. Wind gust (m/s) data were retrieved from the National Data Buoy Center's website for Destruction Island. We calculated average monthly wind gusts and then used these values to calculate the annual average of wind gusts. Wind gusts showed no short-term trends and were relatively low in 2013 and 2014, but still within the historical long-term average (Figure 62). Interestingly, the variability around the mean during 2013 and 2014 was less than most years of the dataset, with 2013 having the least variation (gray shaded region in Figure 62).

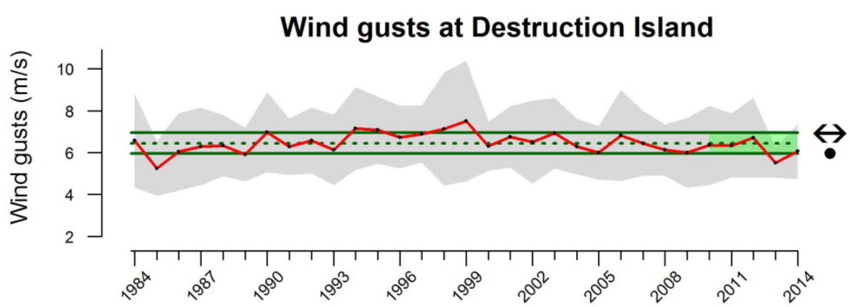

Figure 62. Annual mean wind gusts as measured by National Buoy Data Center's buoy at Destruction Island, WA. The gray shaded region represents ±1 s.d. of the mean.

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 30 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.

The two dominant canopy-forming kelp species in Washington waters are giant kelp and bull kelp. 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, generally in areas with lower tidal energy (Mumford 2007). Kelp canopies provide attachment substrate for sessile organisms and refuges for young fish (Carr 1991). The complex structure of kelps 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 octopuses and snails use kelps as habitat, and sea urchins feed on them.

QUANTITY

The total extent of a kelp bed's surface canopy and characteristics such as density affect 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 interannually, 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).

To quantify the status and trends of the quantity of kelp forest habitats, we selected areal coverage. We used aerial extent of floating kelp beds as calculated by Washington State's Department of Natural Resources and available through the ShoreZone Inventory. These data were derived from photo interpretation of low tide aerial photography in the late summer. Kelp habitat increased rapidly in the late 1990's and has been widely variable since with no consistent trend and within historical averages over the last five years (Figure 63).

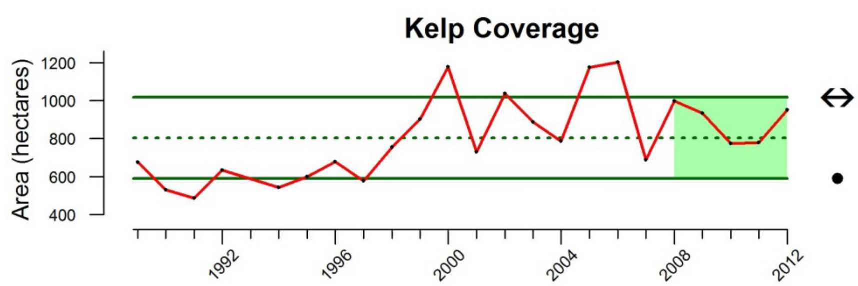

Figure 63. Areal extent of floating kelp Nereocystis luetkeana and Macrocystis pyrifera within WAMSP waters. Data are from Washington State's Department of Natural Resources and available from the ShoreZone Inventory (https://fortress.wa.gov/dnr/adminsa/DataWeb/dmmatrix.html).

QUALITY

In WAMSP waters, good quality habitat is generally correlated with cooler, nutrient-rich waters, which form the conditions necessary for a high caloric-value prey base, whereas warmer, nutrient-poor waters generally result in a prey base that is of much lower nutritional quality (Hooff and Peterson 2006, Peterson 2009). Additionally, the spatial extent of waters with low levels of dissolved oxygen (DO; <1.4 ml L^{-1}) is an important characteristic that contributes to areas of good habitat quality in kelp forests and rocky reefs. See "Sea Surface Temperature" above in the Physical Drivers section for status and trends of SST near kelp forest habitats. We also selected the ratio of nitrogen to phosphorus and the concentration of DO in nearshore waters to quantify changes in habitat quality. An increase in the nitrogen:phosphorous ratio encourages phytoplankton growth.

For the nitrogen to phosphorus ratio, we used data collected on dissolved nitrogen (NO_2 and NO_3) and phosphorus (PO_4) from the nearshore stations (2 – 6 nm offshore) of the NWFSC's Plume Survey's Grays Harbor transect. Total dissolved nitrogen was summed and divided by the concentration of phosphorus at each station and averaged across stations for each year. Data across all transects in Washington will be available upon publishing of this data. For DO, we used data collected by the OCNMS oceanographic moorings which are typically recording data from May to October. Data from CTDs fitted with oxygen sensors on nearshore buoys (15 m depth off of Cape Alava, Cape Elizabeth and Kalaloch, WA) were averaged for each month and then averaged across each site to calculate average DO concentrations across nearshore WAMSP waters. The ratio of nitrogen to phosphorus remained relatively unchanged in the nearshore regions over the last five years, whereas DO concentrations decreased dramatically in 2012 resulting in a decreasing trend from 2008 – 2012 (Figure 64).

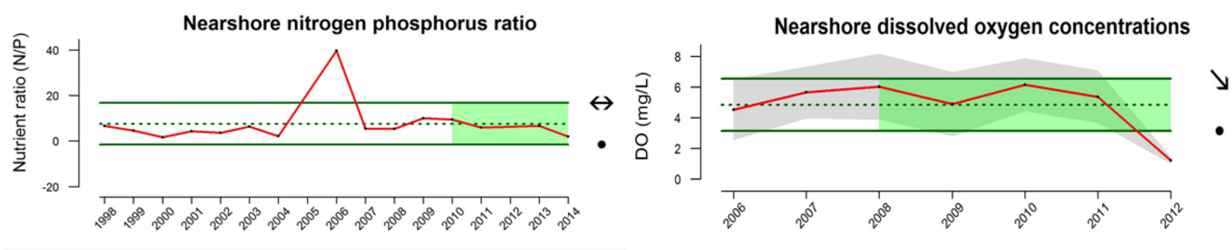

Figure 64. Indicators of kelp forest habitat quality. Left: Average ratios of total dissolved nitrogen (NO_3 + NO_2) to phosphorous (PO_4) in June at nearshore (2-6 nm offshore) stations of the NWFSC's Plume Survey's Grays Harbor transect (data courtesy of Cheryl Morgan, Oregon State University). Right: Average concentrations of dissolved oxygen (DO) on seafloor at nearshore (15 m depth) stations across the northern Washington coastline (data from Olympic Coast National Marine Sanctuary oceanographic moorings). The gray shaded region represents ±1 s.d. of the mean.

ECOLOGICAL COMPONENTS

FISHERIES SPECIES: LINGCOD

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). Recreational fishing for lingcod occurs in shallow rocky reefs and the kelp forests from April or May to September or October depending on fishing location.

POPULATION SIZE

In order to quantify status and trends of population size of lingcod, we selected population abundance. Surveys of the fish assemblage in WAMSP kelp forests have rarely been performed and only one site has any significant amount of data for the Washington outer coast in the REEF database (http://www.reef.org); thus, **we were unable to quantify status and trends of population size of lingcod in kelp forest habitats.** New monitoring surveys of WAMSP kelp forest will begin summer 2015 by the NWFSC and the OCNMS. Without historical information, it will take several years of repeated surveys in order to quantify status and trends of population abundance of lingcod within kelp forest habitats.

POPULATION CONDITION

In order to quantify status and trends of population size of lingcod, we selected age structure. Surveys of kelp forest and shallow rocky reefs would most likely be performed with non-lethal methods, such as SCUBA surveys or hook-and-line fishing with capture, sample and release methods. Using these sampling methods, age will not be recorded, but size could substitute for age based on established age-length relationships for lingcod. Because consistent surveys have not been performed, **we were unable to quantify status and trends of population condition.**

FOCAL TAXA: PHYTOPLANKTON AND BACTERIA

The phytoplankton community is the principal base of the food web for the vast majority of the marine community, thus the health and structure of this community is important to understand. 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 dominant taxa during different sampling cruises in the spring and summer of 2004-2006.

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 or dinoflagellate species involved (Vehmaa et al. 2012).

POPULATION SIZE

In order to quantify population size of the phytoplankton community, we selected aggregate phytoplankton biomass or numbers. Cell counts of individual species collected across WAMSP coastlines are being quantified and analyzed by the Marine Microbes and Toxins program the NWFSC. **However, these data were not available at the time of this report.** Once published, these data should enable quantification of the status and trends of population size.

POPULATION CONDITION

To quantify population condition of the phytoplankton community, we selected the ratio of diatoms to dinoflagellates. Phytoplankton communities are highly ephemeral and vary over short time scales (days to weeks). Thus, capturing blooms of specific phytoplankton species can be limited by sampling frequency. Monitoring efforts are underway by the Marine Microbes and Toxins program at the NWFSC and Washington Department of Fish and Wildlife and the University of Washington through the Olympic Region Harmful Algal Bloom (ORHAB) project. **Data suitable for quantifying the ratio of diatoms to dinoflagellates were not available at the time of this report;** data are being analyzed and should be available soon to quantify the status and trends of phytoplankton condition across WAMSP waters.

FOCAL TAXA: ZOOPLANKTON

Zooplankton time series provide some of the best opportunities to understand marine ecosystem responses to climate change because zooplankton are a foundation of the ocean food web, linking oceanographic conditions and primary production to upper trophic levels and fueling the delivery of ocean and estuarine 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 considered 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. 2014).

POPULATION SIZE

In order to quantify the status and trends of the zooplankton community, we selected aggregate biomass of zooplankton. **We were unable to locate datasets within kelp forests capable of quantifying the status and trends of the size of the zooplankton community.**

POPULATION CONDITION

For population condition, we selected the northern copepod biomass anomaly. The northern copepod biomass anomaly describes changes in the relative biomass of lipid-rich copepod species that are important prey for numerous pelagic species in WAMSP waters. **We were unable to locate datasets within kelp forests capable of quantifying the status and trends of the condition of the zooplankton community.**

FOCAL TAXA: 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 are commonly known as urchin barrens (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 *Enhydra lutris* 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.

POPULATION SIZE

In order to quantify the status and trends of population size for sea urchins, we selected population abundance. Surveys of WAMSP kelp forests have not been done on a regular basis, and thus **data are not available for this indicator.** Estimates of sea urchins are available from three time periods (1987, 1995 and 1999) from Kvitek et al. (1989, 1998), but these estimates were performed using different methods (diver visual counts versus video recorded counts). New monitoring surveys of WAMSP kelp forest will begin summer 2015 by the NWFSC and the OCNMS. In conjunction with contemporary surveys, the historical data should provide historical context to future estimates of population abundance of sea urchins and other benthic invertebrates.

POPULATION CONDITION

In order to quantify the status and trends of population condition for sea urchins, we selected reproductive output as measured by recruitment. Similar to population size, **data are not available for this indicator;** new monitoring surveys of WAMSP kelp forests in conjunction with historical information from Kvitek et al. (1989, 1998) should provide data to quantify the status and trends of population condition of sea urchins and other benthic invertebrates.

FOCAL TAXA: ABALONE

The Pinto or Northern abalone *Haliotis kamtschatkana* is a federally listed Species of Concern. It ranges from Sitka, Alaska, to Pt. Conception, California; it is predominantly found in Washington, British Columbia, and Alaska, but its 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. Juveniles and adults graze on macroalgae and kelp.

Dramatic declines have occurred throughout their range, with no indication of recovery despite commercial fishery closures since 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) for food, and interactions with competitors 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).

POPULATION SIZE

In order to quantify the status and trends of population size of abalone, we selected population abundance. Surveys of WAMSP kelp forests have not been done on a regular basis and even when performed, estimates of abalone were not recorded (Kvitek et al. 1989, 1998); thus, **we were unable to quantify status and trends of population size.** New monitoring surveys of WAMSP kelp forest will begin summer 2015 by the NWFSC and the OCNMS. Without historical information, it will take several years of repeated surveys in order to quantify status and trends of population abundance of abalone.

POPULATION CONDITION

In order to quantify the status and trends of population condition for sea urchins, we selected reproductive output as measured by recruitment. Similar to population size, **we were unable to locate data to quantify status and trends of population condition**, but new monitoring surveys of WAMSP kelp forests may provide data capable of quantifying the status and trends of population condition of abalone.

FOCAL TAXA: FISH ASSEMBLAGE

There are several important components of the fish assemblage in kelp forests. Young-of-year (YOY) fishes take advantage of refuge and abundant food supplies in kelp forest habitats. 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 larger fishes, seabirds and marine mammals. Other conspicuous members 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*), surfperches (*Rhacochilus vacca* and *Cymatogaster aggregata*), and lingcod. Many species in the fish assemblage are opportunistic predators, feeding on a wide variety of zooplankton, benthic invertebrates, forage fishes, and other piscivorous fishes. Lingcod are generally the top fish predator in kelp forests and shallow rocky reefs (see above, *Fishery species: Lingcod*).

POPULATION SIZE

In order to quantify the status and trends of population size of the kelp forest fish assemblage, we selected population abundance of rockfishes and surfperches. Rockfishes represent a mid-trophic level of the fish assemblage while surfperches (family Embiotocidae) represent lower trophic levels within the assemblage. Surveys of the fish assemblage in WAMSP kelp forests have rarely been performed and only one site has any significant amount of data for the Washington outer coast in the REEF database (http://www.reef.org); thus, **we were unable to quantify status and trends of population size of the kelp forest assemblage.** New monitoring surveys of WAMSP kelp forest will begin in the summer of 2015 by the NWFSC and the OCNMS. Without historical information, it will take several years of repeated surveys in order to quantify status and trends of population abundance of the kelp forest fish assemblage.

POPULATION CONDITION

In order to quantify the status and trends of population condition of the kelp forest fish assemblage, we selected reproductive output as measured by recruitment of young-of-year rockfishes. As stated above, surveys of WAMSP kelp forests have not been regularly performed, so **we were unable to find data capable of quantifying status and trends of population condition.** New monitoring surveys of WAMSP kelp forest will begin in the summer of 2015 by the NWFSC and the OCNMS, and will eventually include sampling of postlarval fish settlement. Without historical information, it will take several years of repeated surveys in order to quantify status and trends of population condition of the kelp forest fish assemblage.

FOCAL TAXA: SEA OTTERS

Sea otters inhabit nearshore waters up to 40 m 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 include 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.

Sea otters once lived along most of the North Pacific coast from California to Japan, but were extirpated from most of their range by the early 1900s because of the fur trade (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).

POPULATION SIZE

The sea otter population is surveyed by the Washington Department of Fish and Wildlife and the U.S. Fish and Wildlife Service annually using aerial surveys (Jeffries and Jameson 2014). These surveys provide annual counts of individuals across all WAMSP coastal waters from the Columbia River to Cape Flattery to Tongue Point (just west of Port Angeles, WA). The abundance of sea otters in WAMSP waters has increased steadily since 1989 and was above historical averages in 2013 (Figure 65).

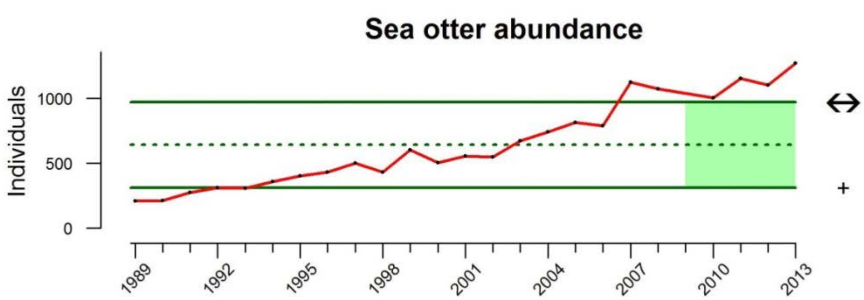

Figure 65. Abundance of sea otters within WAMSP waters (data from Jeffries and Jameson (2014)).

POPULATION CONDITION

During sea otter surveys, pups are counted along with independent individuals. As an indicator of population condition, we selected reproductive output as measured by the proportion of pups to independent individuals (Jeffries and Jameson 2014). Reproductive output of sea otters showed no trends and was within historical averages over the last five years of the dataset (Figure 66).

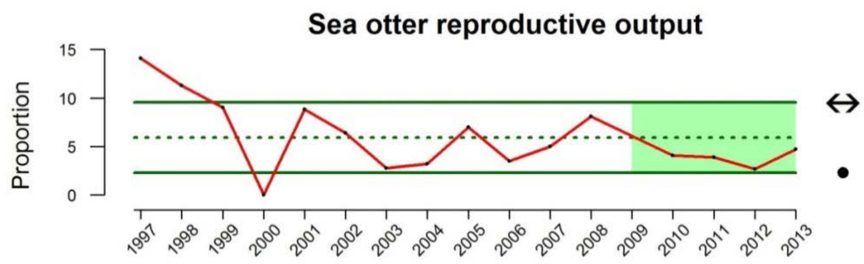

Figure 66. The proportion of sea otter pups to independent individuals during annual surveys of sea otter abundance across all WAMSP waters (data from Jeffries and Jameson (2014)).

ECOSYSTEM HEALTH OF THE KELP FOREST HABITAT

Indicators for community structure of the kelp forest are ecosystem and community level indices that were chosen to track two community level aspects of WAMSP waters: diversity and trophic structure.

BIODIVERSITY

Species diversity is an integrative measure that encompasses species richness (the number of species in the ecosystem) and species evenness (how individuals or biomass are distributed among species within the ecosystem) (Pimm 1984). Diversity has remained a central theme in ecology and is frequently seen as an indicator of the wellbeing of ecological systems (Magurran 2013). Recent reviews of correlations between diversity and ecosystem function (productivity and stability) in terrestrial and marine systems suggest that while the relationship is complex, species-rich communities are more stable (Hooper et al. 2005, Stachowicz et al. 2007).

We selected two indicators for kelp forest biodiversity: Simpson's diversity index and species richness. Simpson's index is a dominance measure that estimates the probability that any two individuals drawn at random from an infinitely large community would belong to different species (Magurran 2013). Species richness, which is a count of the number of species present, can provide an extremely useful measure of diversity if the study area can be successfully delimited in space and time and the constituent species enumerated and identified (Magurran 2013). Studies have shown that species richness tends to decline with fishing, primarily based on trawling/dredging effects on benthic invertebrate communities (Gaspar et al. 2009, Reiss et al. 2009).

Similar to many of the focal taxa components, the kelp forest habitats of WAMSP waters have not been regularly monitored for abundance of species; thus, **we were unable to locate data that were capable of quantifying status and trends of biodiversity.**

TROPHIC STRUCTURE

Trophic structure refers to the ways in which community ecology in a habitat is influenced by food web interactions. Characterizing trophic structure in a community relies on both empirical observations and on theoretical interpretations of species relationships. In order to quantify the status and trends of trophic structure in the seafloor community, we selected mean trophic level and the areal extent of floating kelp.

Mean trophic level (MTL) provides a synoptic view of the organization of trophic structure in marine ecosystems, and is a pervasive and heavily discussed indicator used to measure marine ecosystem status, especially in communities dominated by exploited species (Pauly and Watson 2005, Essington et al. 2006, Branch et al. 2010). Conceptually, MTL is linked to top-down control and trophic cascades; a decline in MTL represents a decrease in the ability of predators to 'control' prey populations and may have far-reaching consequences to ecological communities (Daskalov 2002, Estes et al. 2004, Pauly and Watson 2005, Baum and Worm 2009). **We were unable to locate data that could enable us to quantify status and trends of MTL in the kelp forests of the WAMSP area.**

The areal extents of kelp forests are directly related to high levels of diversity and complex trophic structure in subtidal communities (Dayton 1985). This complex structural component serves as a nursery and foraging area for a variety of fishes and invertebrates. The habitat provisioning role is therefore important for structuring the food web within the ecosystem. The total extent of a kelp bed's surface canopy and characteristics such as density affect 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. See "*Habitat: Quantity*" and Figure 63 for description, status and trends of this indicator.

HUMAN ACTIVITIES

BIOLOGICAL EXTRACTIONS

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.

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. Fisheries also 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.

In order to quantify the status and trends of recreational fishing in the kelp forest and shallow rocky reef habitats, we selected recreational landings. Quantifying fisheries removals in kelp forest may best be done using data reported to the Recreational Fisheries Information Network (RecFIN; www.recfin.org).

Data collected from shoreside dock samplers record general ocean locations of captured species, but some species may be caught in areas deeper than the 30 m we used to describe “kelp forest and shallow rocky reef” habitats for this report. We limited recreational landings to species that were most likely to be collected in shallow rocky reef or kelp forest habitats (e.g., shallow-water demersal and water column rockfishes, lingcod, cabezon *Scorpaenichthys marmoratus*, greenlings and surfperches). Recreational landings of kelp forest and shallow rocky reef associated species were relatively unchanged over the last five years and within historical averages (Figure 67).

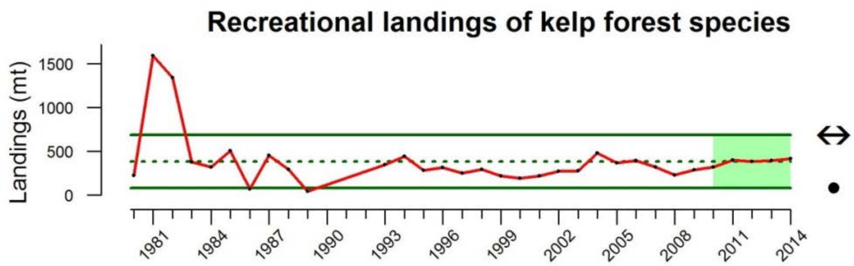

Figure 67. Recreational landings (mt) of kelp forest and shallow rocky reef species in ocean waters of Washington. Data from Recreational Fisheries Information Network.

LAND-BASED ACTIVITIES

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). Excessive nutrients accelerate eutrophication, which produces a wide range of impacts on aquatic ecosystems and fisheries, including algae blooms, declines in submerged aquatic vegetation (SAV), 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). Non-point sources of nutrients which affect stream and groundwater concentrations include fertilizer use, livestock manure, and atmospheric deposition (Ruddy et al. 2006).

In order to quantity the status and trends of nutrient input to kelp forest habitats, we selected fertilizer loadings as measured by the U.S. Geological Survey (Ruddy et al. 2006, Dubrovsky et al. 2010). Total nitrogen and phosphorus applied as fertilizers within counties whose watersheds drain into coastal Washington waters, the Columbia River or Puget Sound were summed independently, normalized, and summed together to create an index of total nutrient input to WAMSP waters. We included counties that drain into the Columbia River because of the potential influence of excess nutrients in the Columbia River plume, and we included counties that drain into Puget Sound because of the potential influence of the Juan de Fuca eddy re-circulating Puget Sound waters into WAMSP waters. Nutrient input to WAMSP waters showed no trends and was within historical averages over the final five years of the dataset (2006–2010; Figure 68); however, there was marked decline in nutrient input in 2009 and 2010.

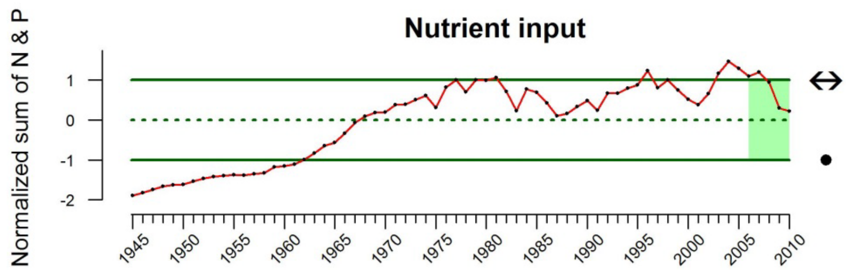

Figure 68. Normalized index of the sum of nitrogen and phosphorus applied as fertilizers in counties that drain into waters directly affecting WAMSP waters.

POLLUTION

Land-based activities can often result in the downstream run-off of various pollutants. These non-point sources of pollution have been identified as the greatest pollution threat to oceans and coasts (Panetta 2003, U. S. Commission on Ocean Policy 2004). For WAMSP waters, we developed four indicators of pollution that may have an impact on specific components of the kelp forest habitat: (1) atmospheric deposition, as estimated from mean concentrations of sulfates ([SO_4^{2-}]) as measured by the National Atmospheric Deposition Program; (2) organic pollution, estimated as a normalized index of pesticide concentrations in streams that drain into WAMSP waters as measured by the U.S. Geological Survey; (3) inorganic pollution, estimated as a normalized index of all reported chemical releases to land and water as measured by the U.S. Environmental Protection Agency's Toxic Release Inventory for sites that drain into WAMSP waters; and (4) marine debris, estimated from standardized counts of specific debris items as measured by the National Marine Debris Program. For each of these indicators, we used the same data as Andrews et al. (2015) but limited the data to watersheds that drain into WAMSP waters. All four of these indicators showed no trends and were within historical averages over the last five years of their respective datasets (Figure 69). Further studies should explore whether estimates of pollutant loadings in kelps or rocky reef sediments correlate with these land-based loadings to fully understand the utility of these indicators.

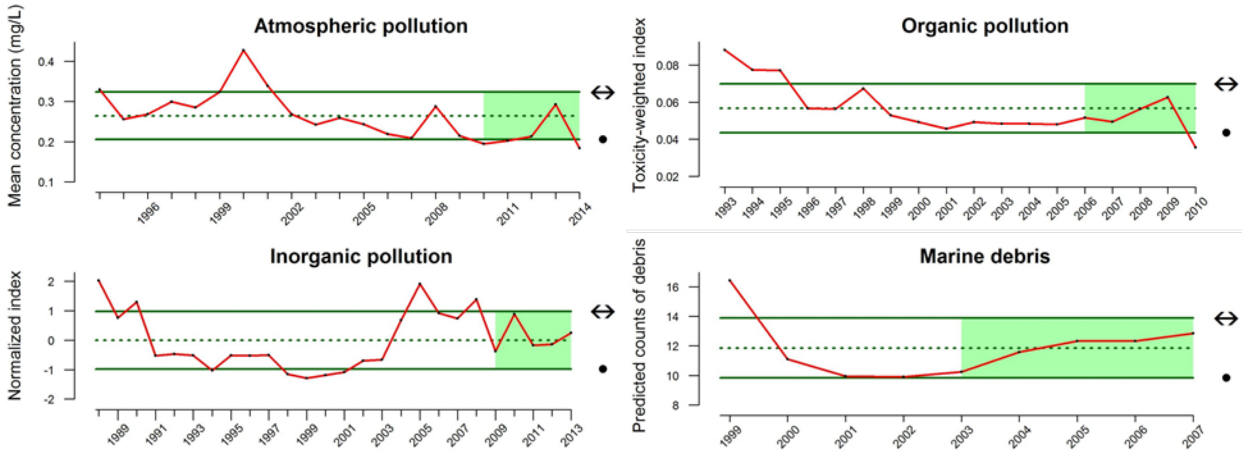

Figure 69. Indicators of pollution from atmospheric deposition (mean concentration of sulfates; data from the National Atmospheric Deposition Program), organic pollution (normalized index of pesticide concentrations in WAMSP streams; data from the U.S. Geological Survey), inorganic pollution (normalized index of all reported chemical releases at sites that drain into WAMSP waters; data from the U.S. Environmental Protection Agency's Toxic Release Inventory), and marine debris (standardized counts of specific debris items; data from Ribic et al. (2012)).

EXECUTIVE SUMMARY: ROCKY SHORES HABITAT

CONCEPTUAL MODEL OF ROCKY SHORES HABITAT

The rocky shores habitat represents rocky intertidal habitats in WAMSP waters. The conceptual model outlined below (Figure 70) and in graphical form in Appendix 1 represents the dominant physical drivers, ecological components and interactions and human activities that characterize the rocky shores habitat of WAMSP waters. Suites of physical drivers and human activities affect the ecological components (i.e., the rocky shores food web) and the surrounding water column within which the ecological components dwell. Humans derive wellbeing from many components and processes within the ecosystem, as well as the human activities that the rocky shores habitat facilitates.

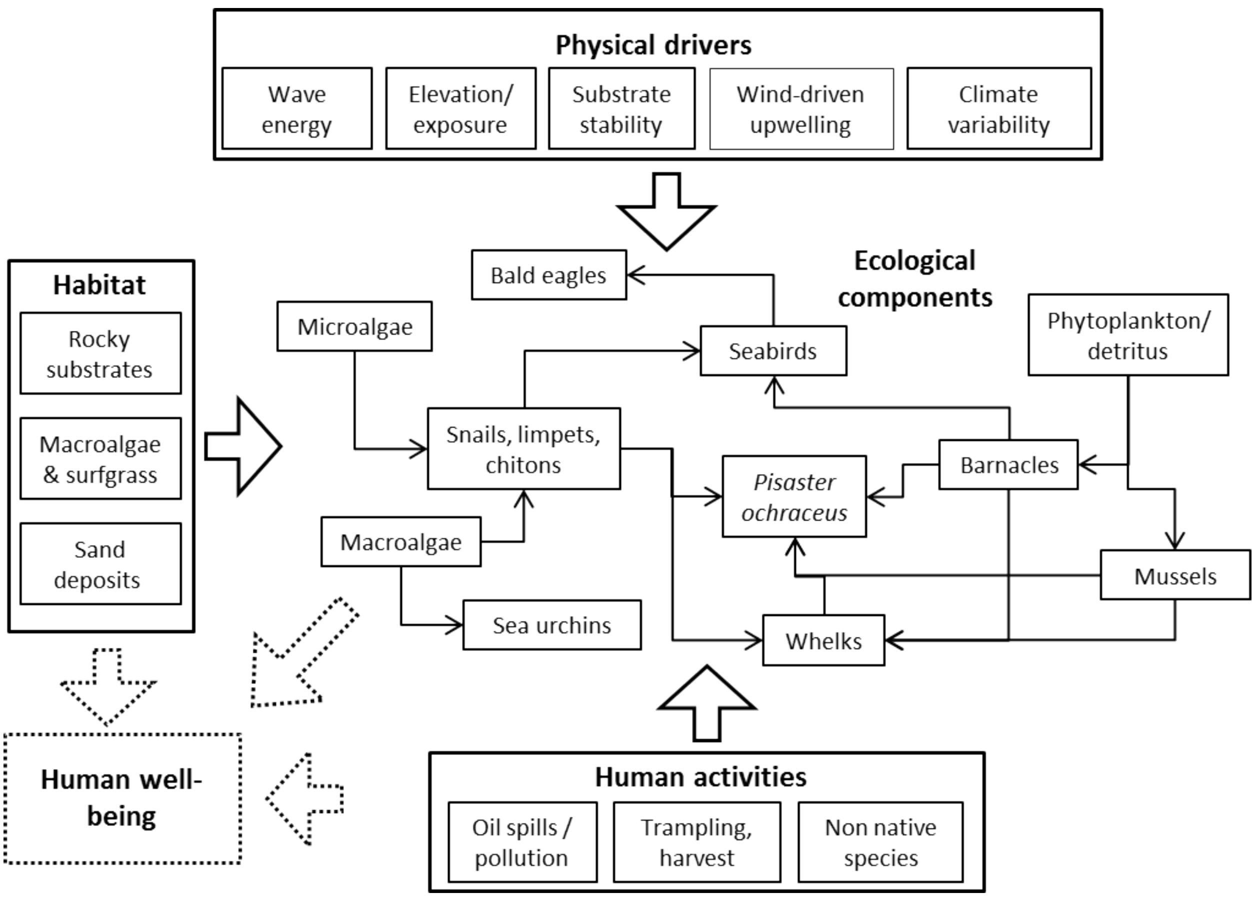

Figure 70. Conceptual model of important habitat, ecological components, physical drivers and human activities for the rocky shores habitat.

In the following sections, we briefly describe the importance and report on the status and trends (when data was available) of each indicator selected for the components shown in the conceptual model above.

Table 7. Summary of indicators and times series duration for each component's key attributes for WAMSP rocky shores habitat. † indicates data are presently being analyzed.

Component	Attribute	Indicator	Time period of available data
Physical drivers			
Climatic	Water temperature	Sea surface temperature	2000 – 2014
		Pacific Decadal Oscillation	1900 – 2015
	El Niño events	Multivariate El Niño Index	1950 – 2015
		Northern Oscillation Index	1948 – 2014
	Source waters	North Pacific Gyre Oscillation index	1950 – 2015
		Northern copepod anomaly	1996 – 2015
Oceanographic	Upwelling	Upwelling index	1967 – 2014
		Spring transition index	1967 – 2015
	Tidal elevation	Tidal elevation	NA†
	Wave energy	Wind speeds	1984 – 2014
		Maximum wave height	2004 – 2014
Habitat			
Physical Habitat	Quantity	% cover macroalgae	2007 – 2015†
		% cover bare rock	2007 – 2015†
	Quality	Boulder size composition	NA
		Rugosity	NA
Ecological components			
Phytoplankton	Population size	Aggregate abundance	NA†
	Population condition	Diatoms : dinoflagellates ratio	NA†
Crustaceans	Population size	Aggregate abundance	2007 – 2015†
	Population condition	Not evaluated	NA
Micro-Macroalgae	Population size	% cover	2007 – 2015†
	Population condition	Blade growth	NA
Pisaster ochraceus	Population size	Abundance	2007 – 2015†
	Population condition	Recruitment	2007 – 2015†
Mussels & barnacles	Population size	% cover	2007 – 2015†
	Population condition	Recruitment	2007 – 2015†
Grazing inverts	Population size	Aggregate abundance select spp.	2007 – 2015†
	Population condition	Recruitment select spp.	2007 – 2015†
Whelks	Population size	Aggregate abundance *Nucella spp*	2007 – 2015†
	Population condition	Recruitment	2007 – 2015†
Seabirds	Population size	Abundance of select spp.	NA†
	Population condition	Reproductive output of select spp.	NA
Ecosystem health	Biodiversity	Simpson's diversity	2007 – 2015†
		Species richness	2007 – 2015†
	Trophic structure	% cover of *Mytilus californianus*	2007 – 2015†

Component	Attribute	Indicator	Time period of available data
Human activities			
Biological extractions	Harvest/trampling	Beach attendance	2002 – 2014
Land-based activities	Pollution	Atmospheric pollution	1994 – 2014
		Organic pollution	1993 – 2010
		Inorganic pollution	1988 – 2013
		Marine debris	1999 – 2007
Ocean-based activities	Ocean-based pollution	Commercial shipping + Port volume	2001 – 2013†
	Non-native species	Port cargo volume	1993 – 2013

PHYSICAL DRIVERS

CLIMATE VARIABILITY

Climate variability represents broad spatial scale, long-term natural variability, short-term event-driven variability, and an anthropogenic global warming signal. Increases in atmospheric CO_2 continue to put pressure on marine ecosystems through warming of the oceans, but separating anthropogenic from natural processes is difficult. Rocky shoreline habitat will be affected by large-scale atmospheric forcing patterns associated with climate change. As basin-scale climate regime phases change, rocky shoreline communities will be exposed to the effects of changes in sea-surface temperature, the timing and frequency of El Nino events and source waters, in addition to local effects of weather and winds on wave energy and exposure.

SEA SURFACE TEMPERATURE

Temperature is one of the most important drivers in the ocean. Ocean temperature regulates the rate of metabolism for most organisms and regulates the base of the food web. In WAMSP waters, cooler temperatures generally result in a prey base that contains northern species, which are rich in wax esters and fatty acids that promote high growth in consumers, whereas warmer temperatures generally result in a prey base consisting of southern species that are of much lower nutritional quality (Hooff and Peterson 2006, Peterson 2009). As indicators of broad-scale sea surface temperatures across rocky shores habitats, we selected sea-surface temperature (SST) from stationary buoys and the Pacific Decadal Oscillation (PDO). The Olympic Coast National Marine Sanctuary (OCNMS) maintains oceanographic sampling buoys throughout the OCNMS, which encompasses most kelp forest habitats in WAMSP waters. Moorings data are available through the OCNMS website (http://olympiccoast.noaa.gov/science/oceanography/). We used the nearshore buoys (buoys stationed between 15 – 18 m depth) and calculated monthly sea-surface temperature averages (from temperature sensors at the surface) across all buoys to quantify the status and trends of this indicator. Values for the PDO were downloaded from the University of Washington's website for the Joint Institute for the Study of the Atmosphere and Ocean (JISAO; http://research.jisao.washington.edu/pdo/). Both indicators of sea-surface temperature increased over the last five years with particularly high values in 2013 and 2014 (Figure 71).

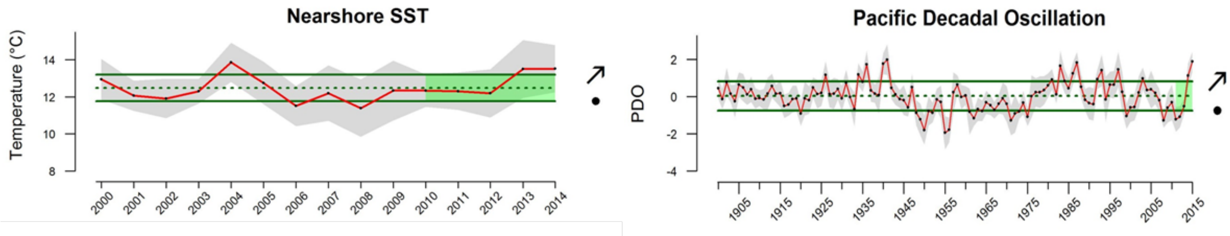

Figure 71. Left: Average sea-surface temperatures at nearshore (15 – 18 m depth) Olympic Coast National Marine Sanctuary mooring stations (data from OCNMS Oceanographic moorings website). Right: Annualized mean Pacific Decadal Oscillation (PDO). The gray shaded region in each plot represents ±1 s.d. of the mean.

TIMING AND FREQUENCY OF EL NIÑO EVENTS

El Niño Southern Oscillation (ENSO) events result from variations in sea level pressure, winds and sea-surface temperatures between the eastern and western tropical Pacific. Patterns in the tropics have wide-reaching consequences on the physical attributes in WAMSP waters. El Niño events result in ecosystem-wide effects from changes in species composition to lack of prey availability and breeding failure in top predators, while La Niña events can increase productivity in the system (Chavez 2002). El Niño conditions in WAMSP waters are associated with warmer surface water, weaker upwelling winds and lower nutrient availability at the surface; however, the effects of any given ENSO event are highly variable. As indicators of the timing and frequency of El Niño events in WAMSP waters, we selected the Multivariate El Niño Index (MEI) and the Northern Oscillation Index (NOI). The MEI represents patterns in six main observed variables over the tropical Pacific to identify the status of ENSO. The NOI measures large-scale atmospheric teleconnections, specifically the difference between sea level pressure at the climatological location of the North Pacific High (NPH) and at Darwin, Australia. Positive NOI values correspond to more coastal upwelling, while during an El Niño the influence of the NPH is diminished and the NOI has large negative values. While NOI tracks interannual changes of atmospheric forcing that are relevant to WAMSP waters, it is still a very broad index when evaluating changes in SST.

Values for the MEI were downloaded from NOAA's Earth System Research Laboratory's website (http://www.esrl.noaa.gov/psd/enso/mei/) and values for the Northern Oscillation Index were downloaded from NOAA's Pacific Fisheries Environmental Laboratory' website (http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/NOIx/noix.html). The MEI has increased over the last five years, while the NOI has shown no trend (Figure 72).

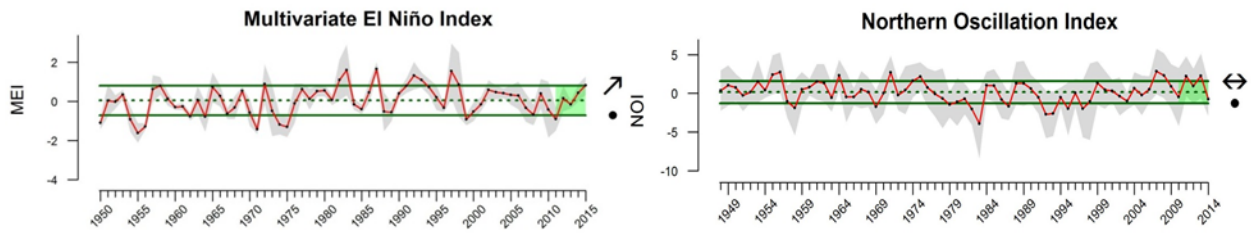

Figure 72. Indicators of changes in the timing and frequency of El Niño events in the North Pacific. Shading is 1 s.d. of the mean.

SOURCE WATERS

Subarctic and tropical waters are important contributors of source waters to WAMSP waters (Bograd et al. 2008). Source water changes may lead to large-scale changes in nutrients and hypoxia in the broader California Current (Bograd et al. 2008). Increases in subarctic source waters can result in changes in the food web by supplying larger, lipid-rich northern copepods and other plankton, compared to the smaller, often lipid-poor warm water copepods occurring in subtropical waters. We selected the North Pacific Gyre Oscillation (NPGO) and the northern copepod biomass anomaly as indicators of changes in source waters for WAMSP waters. We downloaded values for the NPGO from the ENSO/NPGO website (http://www.o3d.org/npgo/). The northern copepod biomass anomaly was calculated using biomass estimates of northern and southern species of copepods collected along the Newport Hydrographic Line and calculated as in Peterson et al. (2014).

The NPGO, which describes changes in salinity, nutrients and chlorophyll-a in the California Current ecosystem, has decreased significantly over the last five years (Figure 73). The northern copepod anomaly showed no overall trend over the last five years, but there has been a significant decrease beginning in 2014, suggesting large shifts in the source waters for the WAMSP waters, from cooler, productive sub-arctic water sources to warmer, less productive water from subtropical sources (Figure 73).

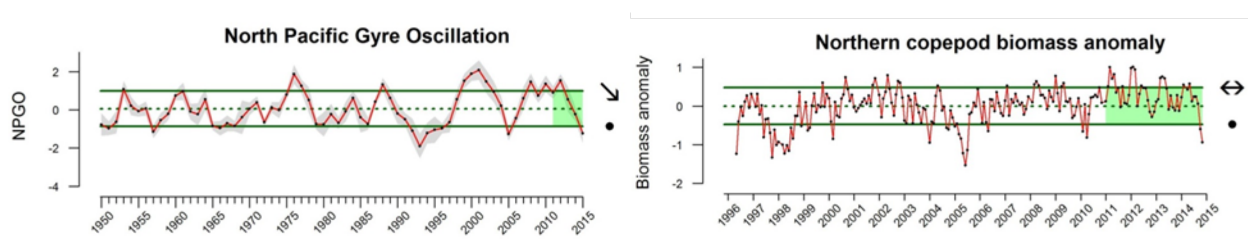

Figure 73. Indicators of changes in source waters to WAMSP waters. Left: the North Pacific Gyre Oscillation (NPGO). The gray shaded region represents ±1 s.d. of the mean. (Data: Emanuele Di Lorenzo, http://www.o3d.org/npgo/). Right: the northern copepod biomass anomaly shows the change in the copepod community from northern species (positive values) to southern species (negative values) during the year and during oceanographic regime changes (data courtesy of Bill Peterson, NWFSC).

UPWELLING

Washington MSP waters reside within the broader California Current ecosystem, which is an eastern boundary current system largely driven by upwelling forces that bring deep, cold, nutrient-rich waters to the surface. 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 (Bograd et al. 2009). 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. Upwelling in WAMSP waters generally 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). We selected the Upwelling Index calculated off La Push, WA in the winter and summer and the Spring Transition Index as indicators of upwelling in WAMSP waters. We downloaded monthly mean values of the UI from NOAA's Pacific Fisheries Environmental Laboratory website (http://www.pfeg.noaa.gov) and calculated winter (Jan – Mar) and summer (Jun – Aug) averages. The STI is the day of the year in which upwelling is at its minimum value and is calculated directly from the UI.

The winter upwelling index increased while the more relevant summer upwelling index remained unchanged over the last five years (Figure 74 top panels). The spring transition index has been widely variable over the last five years with no significant trend (Figure 74 bottom).

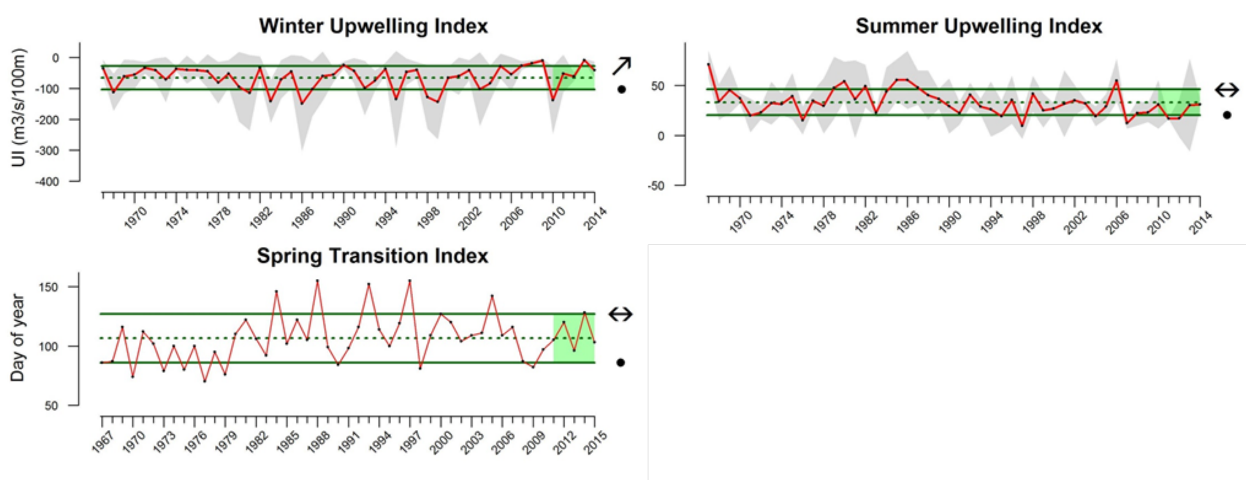

Figure 74. Indicators of upwelling in WAMSP waters. Upwelling indices for winter (Jan-Mar) and summer (Jun-Aug) and the Spring Transition Index calculated at 48°N, 125°W off La Push, WA. Gray shaded regions represent ±1 s.d. of the mean.

TIDAL ELEVATION

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 are important predictors of the assemblage of species present in rocky intertidal habitats (Knox 2000).

The distribution and abundance of species in the rocky intertidal community derives much of its variation from the tidal elevation of the habitat. Desiccation and thermal stress from exposure at low tide creates upper distributional limits for most species, while competition for space and predator-prey interactions drives the lower distribution limits (Paine 1966, 2002, Paine and Trimble 2004). The tidal elevation gradient results in a range of immersion/emersion and wave exposure conditions, which increases the diversity of algal communities 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 (Dethier 1991, Schoch and Dethier 1996).

In order to quantify the status and trends of tidal elevation, we selected tidal height. The Olympic National Park Service (ONPS) has been sampling four locations along the rocky shorelines of WAMSP waters (Point of the Arches, Sokol Point, Taylor Point and Starfish Point) since 2007 (Fradkin and Boetsch 2012). These surveys include measuring tidal elevations of fixed points on the rocky substrate. ONPS was analyzing these data at the time of writing this report and should have data available to quantify this indicator by the end of 2015. **Thus, we do not yet have information on status and trends of tidal elevation for WAMSP rocky shores.**

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).

In order to quantify the status and trend of wave energy on rocky shoreline, we selected wave height and wind speeds. For wave height, we downloaded wave height from NOAA's National Data Buoy Center's (NDBC) Grays Harbor buoy (http://www.ndbc.noaa.gov), which is located in about 40 m of water outside the mouth of Grays Harbor. We averaged the daily maximum wave height each month and then calculated annual averages from these monthly averages. For wind speeds, we downloaded wind gust speeds from the NDBC's buoy located at Destruction Island as this was the closest nearshore buoy in open waters measuring wind speeds. We then calculated average monthly wind gusts and calculated annual averages from these monthly mean values.

Average daily maximum wave heights decreased over the last five years of the dataset, but remained within historical averages (Figure 75 left). In addition, we observed that variation in wave height was at some of its lowest levels in 2013 and 2014. Wind gust speeds were relatively unchanged over the last five years of the dataset and were within historical averages (Figure 75 right). In 2013, variation in wind gust speeds were at their lowest levels across the entire time series and 2014 was in the lowest quartile as well. Decreased variation in wind gusts and daily maximum wave heights during recent years, suggests wave energy was not the driving physical force on rocky shorelines of previous years.

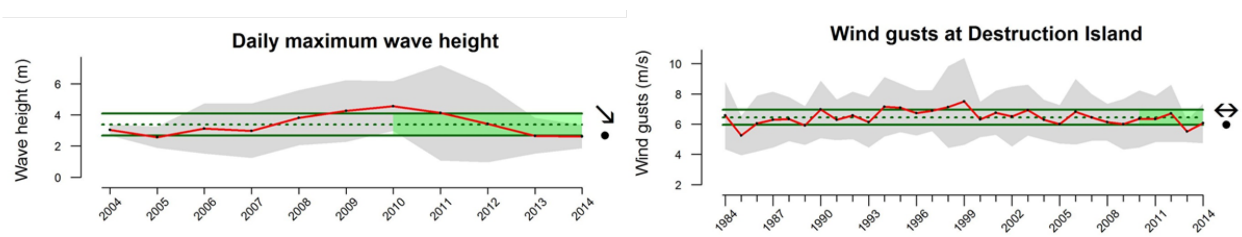

Figure 75. Indicators of wave energy. Left: average daily maximum wave height at National Data Buoy Center's Grays Harbor buoy. Right: average wind gusts at National Data Buoy Center's buoy at Destruction Island, WA. The gray shaded regions in each plot represent ±1 s.d. from the mean.

HABITAT

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.

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 biota in rocky areas.

QUANTITY

In order to quantify the quantity of habitat in rocky shores habitat, we selected percent cover of macroalgae and percent cover of bare rock. The ONPS has been sampling four locations along the rocky shorelines of WAMSP waters (Point of the Arches, Sokol Point, Taylor Point and Starfish Point) since 2007 (Fradkin and Boetsch 2012). These surveys include quantifying percent cover of algal and invertebrate species via transect and quadrat point contact methods. ONPS was analyzing these data at the time of writing this report and should have data available to quantify this indicator by the end of 2015. **Thus, we do not yet have information on status and trends of habitat quantity for WAMSP rocky shores.**

QUALITY

We selected boulder size composition and rugosity as indicators of habitat quality for rocky intertidal shorelines. Boulder size composition affects the diversity of space and physical conditions available to the community and rugosity is a measure of the substrate's complexity, which has analogous effects on space and physical conditions. These metrics do not appear to be measured during ONPS's monitoring efforts, and **we have been unable to locate other datasets that would be capable of quantifying the status and trends of these indicators.**

ECOLOGICAL COMPONENTS

FOCAL TAXA: PHYTOPLANKTON AND DETRITUS

The phytoplankton community is the principal base of the food web for the vast majority of the marine community, thus the health and structure of this community is important to understand. 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 dominant taxa during different sampling cruises in the spring and summer of 2004-2006.

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 or dinoflagellate species involved (Vehmaa et al. 2012).

POPULATION SIZE

In order to quantify population size of the phytoplankton community, we selected aggregate phytoplankton biomass or numbers. Cell counts of individual species collected across WAMSP coastlines are being quantified and analyzed by the Marine Microbes and Toxins program the NWFSC. **However, these data were not available at the time of this report.** Once published, these data should enable quantification of the status and trends of population size.

POPULATION CONDITION

To quantify population condition of the phytoplankton community, we selected the ratio of diatoms to dinoflagellates. Phytoplankton communities are highly ephemeral and vary over short time scales (days to weeks). Thus, capturing blooms of specific phytoplankton species can be limited by sampling frequency. Monitoring efforts are underway by the Marine Microbes and Toxins program at the NWFSC and Washington Department of Fish and Wildlife and the University of Washington through the Olympic

Region Harmful Algal Bloom (ORHAB) project. **Data suitable for quantifying the ratio of diatoms to dinoflagellates were not available at the time of this report;** data are being analyzed and should be available soon to quantify the status and trends of phytoplankton condition across WAMSP waters.

FOCAL TAXA: MACRO- AND MICROALGAE

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 the complex structure, highly productive waters and physical disturbances present within the rocky intertidal habitats (Schoch and Dethier 1996, Knox 2000, Menge and Branch 2001).

POPULATION SIZE

In order to quantify the population size of rocky intertidal algae, we selected percent cover. The ONPS has been sampling four locations along the rocky shorelines of WAMSP waters (Point of the Arches, Sokol Point, Taylor Point and Starfish Point) since 2007 (Fradkin and Boetsch 2012). These surveys include quantifying percent cover of algal and invertebrate species via transect and quadrat point contact methods. ONPS was analyzing these data at the time of writing this report and should have data available to quantify this indicator by the end of 2015. **Thus, we do not yet have information on status and trends of macro- and microalgae population size for WAMSP rocky shores.**

POPULATION CONDITION

In order to quantify the population size of rocky intertidal algae, we selected blade growth. Growth of individual algal plants is commonly measured by punching a hole in the algal blade near the holdfast and measuring growth as the punchhole grows away from the holdfast. The ONPS survey does not measure growth and **we were unable to locate any data capable of quantifying status and trends of this indicator**.

FOCAL TAXA: PISASTER OCHRACEOUS

The ochre seastar *Pisaster ochraceus* is the most ubiquitous 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 (Paine 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* itself has few predators, but in this region may be subject to disease outbreaks, such as sea star wasting disease (SSWD), which could be exacerbated by climate change (Bates et al. 2009, Hewson et al. 2014). The last two years have seen an extensive outbreak out of SSWD across the entire U.S. West Coast. Major die-offs of this keystone species could have large effects on the rest of the rock intertidal community.

POPULATION SIZE

In order to quantify the population size of *P. ochraceus*, we selected population abundance. The ONPS has been sampling four locations along the rocky shorelines of WAMSP waters (Point of the Arches, Sokol Point, Taylor Point and Starfish Point) since 2007 (Fradkin and Boetsch 2012). These surveys include focused counts of sea stars at fixed plots. In addition, ONPS monitors two sites monthly for SSWD since 2013. ONPS was analyzing these data at the time of writing this report and should have data available to quantify this indicator by the end of 2015. **Thus, we do not yet have information on status and trends of *P. ochraceus* population size for WAMSP rocky shores.**

POPULATION CONDITION

In order to quantify the population condition of *P. ochraceus*, we selected reproductive output as measured by recruitment and proportion of population showing signs of SSWD. The ONPS has been sampling four locations along the rocky shorelines of WAMSP waters (Point of the Arches, Sokol Point, Taylor Point and Starfish Point) since 2007 (Fradkin and Boetsch 2012). These surveys include general transect and quadrat counts of invertebrates and algae, capable of detecting recruits of *P. ochraceus*, as well as focused counts of sea stars at fixed plots and the monthly monitoring for SSWD since 2013. ONPS was analyzing these data at the time of writing this report and should have data available to quantify this indicator by the end of 2015. **Thus, we do not yet have information on status and trends of *P. ochraceus* population condition for WAMSP rocky shores.**

FOCAL TAXA: MUSSELS AND BARNACLES

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 (Kozloff 1983, Wootton 1992, Meese 1993). 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 (Menge 2000).

POPULATION SIZE

In order to quantify the population size of mussels and barnacles, we selected percent cover of *M. californianus* and *B. glandula*. The ONPS has been sampling four locations along the rocky shorelines of WAMSP waters (Point of the Arches, Sokol Point, Taylor Point and Starfish Point) since 2007 (Fradkin and Boetsch 2012). These surveys include quantifying percent cover of algal and invertebrate species via transect and quadrat point contact methods. ONPS was analyzing these data at the time of writing this report and should have data available to quantify this indicator by the end of 2015. **Thus, we do not yet have information on status and trends of *M. californianus* and *B. glandula* population size for WAMSP rocky shores.**

POPULATION CONDITION

In order to quantify the population condition of mussels and barnacles, we selected recruitment of *M. californianus* and *B. glandula*. The ONPS has been sampling four locations along the rocky shorelines of WAMSP waters (Point of the Arches, Sokol Point, Taylor Point and Starfish Point) since 2007 (Fradkin and Boetsch 2012). These surveys include quantifying percent cover of algal and invertebrate species via transect and quadrat point contact methods. It's not clear whether these methods quantify new recruits, so further evaluation of this dataset will be necessary once the data have been published. ONPS was analyzing these data at the time of writing this report and should have data available to quantify this indicator by the end of 2015. **Thus, we do not yet have information on status and trends of *M. californianus* and *B. glandula* population condition for WAMSP rocky shores.**

FOCAL TAXA: GRAZING INVERTEBRATES

Dozens of grazing invertebrates occur along rocky shores of Washington's outer coast, most notably snails, limpets, chitons, urchins and small crustaceans. Two genera were ubiquitous at sites surveyed by Schoch and Dethier (1996): 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.

POPULATION SIZE

In order to quantify the population size of grazing invertebrates, we selected the aggregate abundance of *Littorina* snails and sea urchins. The ONPS has been sampling four locations along the rocky shorelines of WAMSP waters (Point of the Arches, Sokol Point, Taylor Point and Starfish Point) since 2007 (Fradkin and Boetsch 2012). These surveys include quantifying percent cover of algal and invertebrate species via transect and quadrat point contact methods and enumerating weakly mobile organisms via quadrat methods. ONPS was analyzing these data at the time of writing this report and should have data available to quantify this indicator by the end of 2015. **Thus, we do not yet have information on status and trends of *Littorina* snails and sea urchins population size for WAMSP rocky shores.**

POPULATION CONDITION

In order to quantify the population condition of grazing invertebrates, we selected recruitment of *Littorina* snails and sea urchins. The ONPS has been sampling four locations along the rocky shorelines of WAMSP waters (Point of the Arches, Sokol Point, Taylor Point and Starfish Point) since 2007 (Fradkin and Boetsch 2012). These surveys include quantifying percent cover of algal and invertebrate species via transect and quadrat point contact methods and enumerating weakly mobile organisms via quadrat methods. It's not clear whether these methods quantify new recruits, so further evaluation of this dataset will be necessary once the data have been published. ONPS was analyzing these data at the time of writing this report and should have data available to quantify this indicator by the end of 2015. **Thus, we do not yet have information on status and trends of *Littorina* snails and sea urchins population condition for WAMSP rocky shores.**

FOCAL TAXA: WHELKS

Whelks are a common predatory snail in rocky shore habitats that can be 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).

POPULATION SIZE

In order to quantify the population size of predatory whelks, we selected aggregate abundance of *Nucella spp*. The ONPS has been sampling four locations along the rocky shorelines of WAMSP waters (Point of the Arches, Sokol Point, Taylor Point and Starfish Point) since 2007 (Fradkin and Boetsch 2012). These surveys include quantifying percent cover of algal and invertebrate species via transect and quadrat point contact methods and enumerating weakly mobile organisms via quadrat methods. ONPS was analyzing these data at the time of writing this report and should have data available to quantify this indicator by the end of 2015. **Thus, we do not yet have information on status and trends of *whelks* population size for WAMSP rocky shores.**

POPULATION CONDITION

In order to quantify the population condition of predatory whelks, we selected recruitment of *Nucella spp*. The ONPS has been sampling four locations along the rocky shorelines of WAMSP waters (Point of the Arches, Sokol Point, Taylor Point and Starfish Point) since 2007 (Fradkin and Boetsch 2012). These surveys include quantifying percent cover of algal and invertebrate species via transect and quadrat point contact methods and enumerating weakly mobile organisms via quadrat methods. It's not clear whether these methods quantify new recruits, so further evaluation of this dataset will be necessary once the data have been published. ONPS was analyzing these data at the time of writing this report and should have data available to quantify this indicator by the end of 2015. **Thus, we do not yet have information on status and trends of *whelks* population condition for WAMSP rocky shores.**

FOCAL TAXA: SEABIRDS

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 (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).

POPULATION SIZE

In order to quantify the status and trends of population size, we selected population abundance of black oystercatchers, aggregate gulls and bald eagles. Counts of these species are available through the National Audubon Society's Christmas Bird Count survey, but **we were unable to determine whether these counts were representative of rocky shoreline abundances in time to include in this report.**

POPULATION CONDITION

In order to quantify the status and trends of population condition, we selected reproductive output of black oystercatchers, aggregate gulls and bald eagles. **We were unable to locate data capable of quantifying the status and trends of this indicator.**

ECOSYSTEM HEALTH OF THE ROCKY SHORES HABITAT

Indicators for ecosystem health of the rocky shorelines are ecosystem and community level indices that were chosen to track two community level aspects of WAMSP waters: diversity and trophic structure.

BIODIVERSITY

Species diversity is an integrative measure that encompasses species richness (the number of species in the ecosystem) and species evenness (how individuals or biomass are distributed among species within the ecosystem) (Pimm 1984). Diversity has remained a central theme in ecology and is frequently seen as an indicator of the wellbeing of ecological systems (Magurran 2013). Recent reviews of correlations between diversity and ecosystem function (productivity and stability) in terrestrial and marine systems suggest that while the relationship is complex, species-rich communities are more stable (Hooper et al. 2005, Stachowicz et al. 2007).

We selected two indicators for rocky shores biodiversity: Simpson's diversity index and species richness. Simpson's diversity is a dominance measure that estimates the probability that any two individuals drawn at random from an infinitely large community would belong to different species (Magurran 2013). Species richness, which is a count of the number of species present, can provide an extremely useful measure of diversity if the study area can be successfully delimited in space and time and the constituent species enumerated and identified (Magurran 2013). Studies have shown that species richness tends to decline with fishing, primarily based on trawling/dredging effects on benthic invertebrate communities (Gaspar et al. 2009, Reiss et al. 2009).

The ONPS has been sampling four locations along the rocky shorelines of WAMSP waters (Point of the Arches, Sokol Point, Taylor Point and Starfish Point) since 2007 (Fradkin and Boetsch 2012). These surveys include quantifying abundance of weakly mobile organisms using quadrats and quantifying percent cover of algal and invertebrate species via transect and quadrat point contact methods. Using data from the quadrat counts of weakly mobile organisms may provide data capable of calculating diversity and species richness. ONPS was analyzing these data at the time of writing this report and should have data available to quantify this indicator by the end of 2015. There is surely data available from Dr. Robert Paine's and Dr. Tim Wootten's work that could be used here, **but we were unable to investigate the spatial coverage and recent data collections of those historical datasets fully in time for this report.**

TROPHIC STRUCTURE

Trophic structure refers to the ways in which community ecology in a habitat is influenced by food web interactions. Characterizing trophic structure in a community relies on both empirical observations and on theoretical interpretations of species relationships. In order to quantify the status and trends of trophic structure in the rocky shores community, we selected areal cover of the mussel *Mytilus californianus*.

The abundance of mussel beds has been shown to relate to the community structure of rocky intertidal systems because of their ability to outcompete other species for space (Paine 1966, 1974). Percent cover of *M. californianus* has been quantified during the ONPS monitoring and should provide estimates capable quantifying the status and trends of this attribute. ONPS was analyzing these data at the time of writing this report and should have data available to quantify this indicator by the end of 2015. **Thus, we do not yet have information on status and trends of trophic structure for WAMSP rocky shores.**

HUMAN ACTIVITIES

BIOLOGICAL EXTRACTIONS

Rocky intertidal flora and fauna risk being harvested or collected during recreational tidepooling. Individuals can be 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 OCNMS (2008) 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 (Skewgar and Pearson 2011) concluded that trampling effects can be important and persistent at areas where human visitation is focused.

In order to capture some of these dynamics surrounding harvest, trampling and recreational tidepooling, we selected recreational beach use. We gathered estimates of visitors to Washington State beaches from Washington State Department of Parks and Recreation (WDPR) and summed the number of estimated visitors to parks identified as "State Beaches" along Washington's outer coast. Recreational beach use has decreased significantly over the last five years beginning in 2011 (Figure 76).

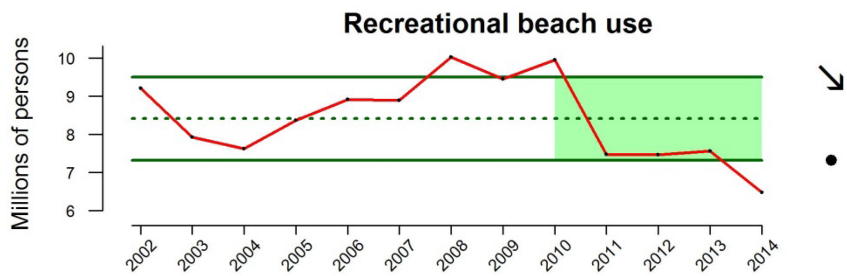

Figure 76. Visitors to Washington State Park Beaches. Data courtesy of Linda Burnett, WDPR.

LAND-BASED ACTIVITIES

POLLUTION

In their recent status report, the Olympic Coast National Marine Sanctuary (OCNMS 2008) 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 is 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 OCNMS (2008) 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.

Despite the apparent low risk, we developed four indicators of pollution that may have an impact on specific components of the kelp forest habitat: (1) atmospheric deposition, as estimated from mean concentrations of sulfates ([SO_4^{2-}]) as measured by the National Atmospheric Deposition Program; (2) organic pollution, estimated as a normalized index of pesticide concentrations in streams that drain into WAMSP waters as measured by the U.S. Geological Survey; (3) inorganic pollution, estimated as a normalized index of all reported chemical releases to land and water as measured by the U.S. Environmental Protection Agency's Toxic Release Inventory for sites that drain into WAMSP waters; and (4) marine debris, estimated from standardized counts of specific debris items as measured by the

National Marine Debris Program. For each of these indicators, we used the same data as Andrews et al. (2015) but limited the data to watersheds that drain into WAMSP waters. All four of these indicators showed no trends and were within historical averages over the last five years of their respective datasets (Figure 77). Further studies should explore whether estimates of pollutant loadings in sandy beach sediments correlate with these land-based loadings to fully understand the utility of these indicators.

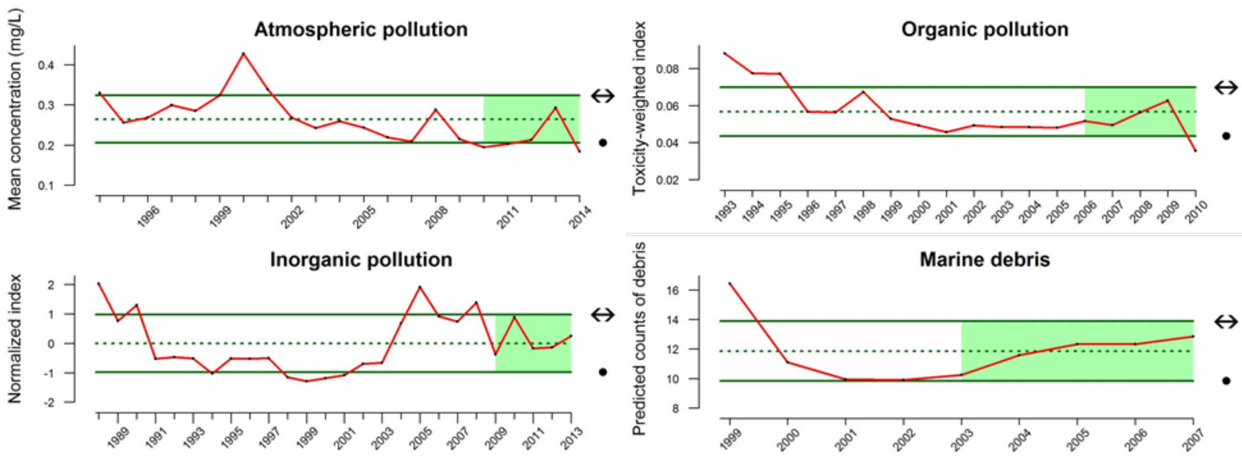

Figure 77. Indicators of pollution from atmospheric deposition (mean concentration of sulfates [SO_4^{2-}] as measured by the National Atmospheric Deposition Program), organic pollution (normalized index of pesticide concentrations in streams that drain into WAMSP waters as measured by the U.S. Geological Survey), inorganic pollution (normalized index of all reported chemical releases to land and water as measured by the U.S. Environmental Protection Agency's Toxic Release Inventory for sites that drain into WAMSP waters), and marine debris along northern West Coast beaches (standardized counts of specific debris items as measured by the National Marine Debris Program; data from Ribic et al. (2012)).

OCEAN-BASED ACTIVITIES

OCEAN-BASED POLLUTION

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 (OCNMS 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 (OCNMS 2008).

(OCNMS 2008) 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 (OCNMS 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 order to quantify the status and trends of ocean-based pollution, we selected a metric that is a combination of commercial shipping (distance of vessels traveled through and in waters near WAMSP waters) and port activity (volume of cargo in WAMSP ports). Monitoring the movement of vessels is performed by the U.S. Army Corps of Engineers and data of each ship’s entrance and clearance from U.S. ports are available from the Navigation Data Center (http://www.navigationdatacenter.us/data/data1.htm). **Calculating volume of water disturbed from foreign and domestic vessels requires more time than was available during this project**, but the NWFSC has made these calculations at the coastwide scale and simply need more time to limit ship movement within and near WAMSP waters. Thus, **we were unable to quantify the status and trends of this indicator** because the commercial shipping activity indicator (which must be rescaled from coastwide to WAMSP waters) is a major component of this indicator.

NON-NATIVE SPECIES

Introductions of non-native species into marine and estuarine waters are considered a significant threat to the structure and function of natural communities and to living marine resources in the United States (Carlton 2001, Johnson et al. 2008). The estimated damage from invasive species in the United States alone totals almost $120 billion per year (Pimentel et al. 2005). The mechanisms behind biological invasions are numerous, but generally include the rapid transport of invaders across natural barriers (e.g. plankton entrained in ship ballast water, organisms contained in packing material (Japanese eelgrass *Zostera japonica*) or fouling on aquaculture shipments, aquarium trade with subsequent release to natural environments) (Molnar et al. 2008). Non-native species can be released intentionally (e.g., fish stocking and pest control programs) or unintentionally during industrial shipping activities (e.g., ballast water releases), aquaculture operations, recreational boating, biotechnology, or from aquarium discharge.

In order to quantify the status and trends of non-native species in WAMSP waters, we selected port volumes of commercial shipping vessels in WAMSP ports. We retrieved vessel cargo data from the Army Corps of Engineer’s Navigation Data Center’s “Waterborne Commerce of the United States” files. Using waterway codes, we limited the dataset to outer coastal ports and summed the volume of shipping cargo for each year. This indicator increased over the last five years of the dataset but remained within historical averages (Figure 78). Further work to incorporate the effects of imported aquaculture products may help increase this indicator's ability to capture the potential of non-native introductions to WAMSP coastal estuaries.

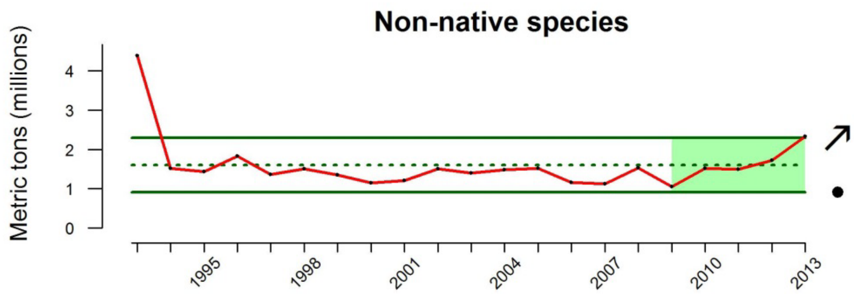

Figure 78. Indicator of non-native species for WAMSP coastal estuaries. Data are cargo volume (millions metric tons) of vessels loading or unloading into ports within Willapa Bay and Grays Harbor (data from U.S. Army Corps of Engineers, Navigation Data Center).

SUMMARY: SANDY BEACH HABITAT

CONCEPTUAL MODEL OF SANDY BEACH HABITAT

The sandy beach habitat represents sandy beaches that stretch along the southern shorelines in WAMSP waters. The conceptual model outlined below (Figure 79) and in graphical form in Appendix 1 represents the dominant physical drivers, ecological components and interactions and human activities that characterize sandy beach habitat of WAMSP waters. Suites of physical drivers and human activities affect the ecological components (i.e., the sandy beach food web) and the surrounding water column within which the ecological components dwell. Humans derive wellbeing from many components and processes within the ecosystem, as well as the human activities that sandy beach habitat facilitates.

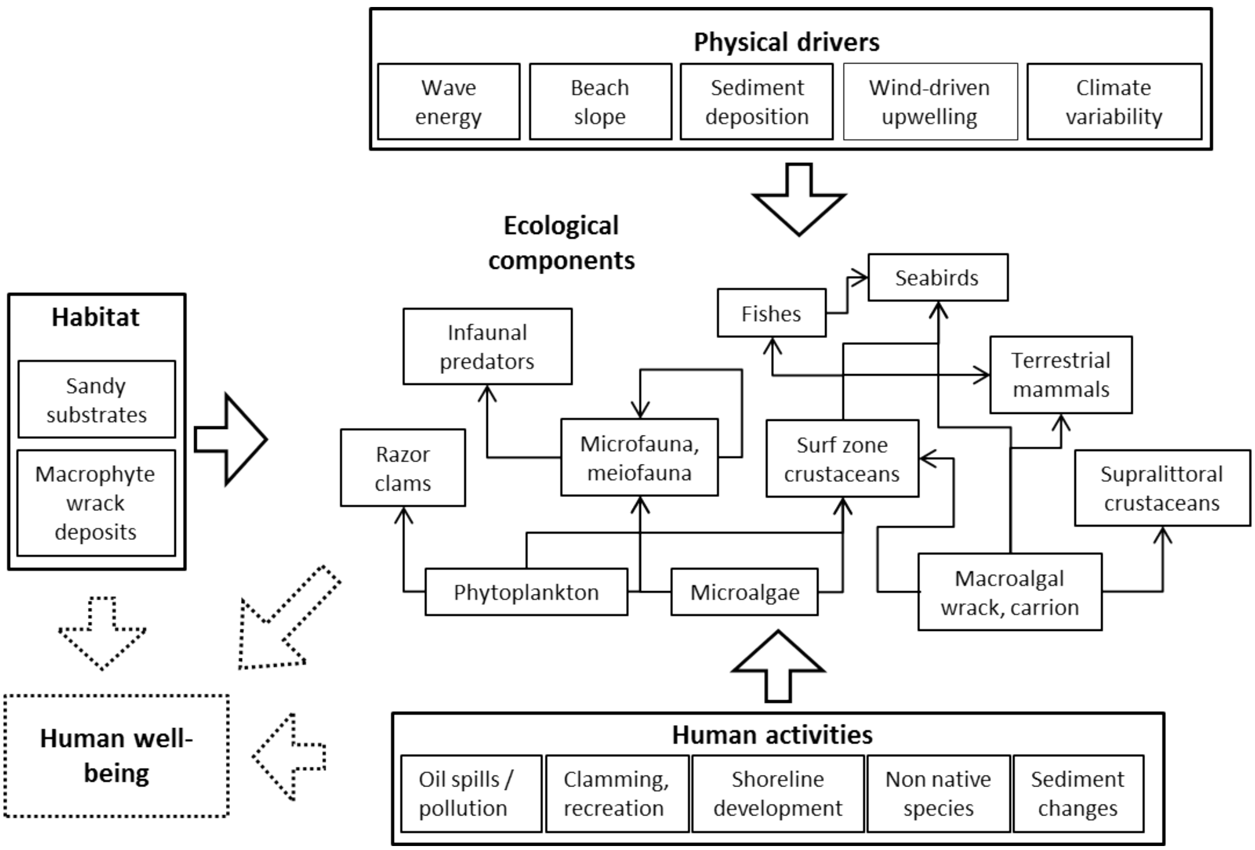

Figure 79. Conceptual model of important habitat, ecological components, physical drivers and human activities for the sandy beach habitat.

In the following sections, we briefly describe the importance and report on the status and trends (when data was available) of each indicator selected for the components shown in the conceptual model above.

Table 8. Summary of indicators and times series duration for each component's key attributes for WAMSP sandy beach habitat. † indicates data are presently being analyzed.

Component	Attribute	Indicator	Time period of available data
Physical drivers			
Climatic	Water temperature	Sea surface temperature	2000 – 2014
		Pacific Decadal Oscillation	1900 – 2015
	El Niño events	Multivariate El Niño Index	1950 – 2015
		Northern Oscillation Index	1948 – 2014
	Source waters	North Pacific Gyre Oscillation index	1950 – 2015
		Northern copepod anomaly	1996 – 2015
Oceanographic	Upwelling	Upwelling index	1967 – 2014
		Spring transition index	1967 – 2015
	Sediment deposition	Columbia River plume volume	1999 – 2014
		Maximum wave height	2004 – 2014
	Wave energy	Wind speeds	1984 – 2014
		Maximum wave height	2004 – 2014
Habitat			
Physical Habitat	Quantity	Beach slope	2004 – 2015†
		Sediment size composition	2004 – 2015†
	Quality	Water temperature	2000 – 2014
		Sediment quality index	NA
Ecological components			
Phytoplankton	Population size	Aggregate abundance	NA†
	Population condition	Diatoms : Dinoflagellates ratio	NA†
Crustaceans	Population size	Aggregate abundance	2004 – 2015†
	Population condition	Not evaluated	NA
Infaunal predators	Population size	Aggregate abundance	2004 – 2015†
	Population condition	Not evaluated	NA
Razor clams	Population size	Density	1997 – 2014
	Population condition	Recruitment	1997 – 2014
		Condition index	1994 – 2015
Surf zone fish assemblage	Population size	Population abundance	NA
	Population condition	Recruitment	NA
Seabirds & shorebirds	Population size	Population abundance	NA
	Population condition	Reproductive output	NA
Terrestrial mammals	Population size	Aggregate abundance	NA
	Population condition	Reproductive output	NA
Ecosystem health	Biodiversity	Simpson's diversity	NA
		Species richness	NA
	Trophic structure	Mean trophic level	NA
		Kelp wrack density	NA

Component	Attribute	Indicator	Time period of available data
Human activities			
Biological extractions	Fishing	Razor clam landings	1976 – 2014
Land-based activities	Pollution	Atmospheric pollution	1994 – 2014
		Organic pollution	1993 – 2010
		Inorganic pollution	1988 – 2013
		Marine debris	1999 – 2007
	Shoreline development	% shoreline armored	NA
	Sediment retention	Reservoir volume	1904 – 2015
Ocean-based activities	Non-native species	Port volume	1993 – 2013

PHYSICAL DRIVERS

CLIMATE VARIABILITY

Climate variability represents broad spatial scale, long-term natural variability; short-term, event-driven variability; and an anthropogenic global warming signal. Increases in atmospheric CO_2 continue to put pressure on marine ecosystems through warming of the oceans, but separating anthropogenic from natural processes is difficult. Sandy beach habitat will be affected by large-scale atmospheric forcing patterns associated with climate change. As basin-scale climate regime phases change, sandy beach communities will be exposed to the effects of changes in sea-surface temperature, the timing and frequency of El Niño events and source waters.

SEA SURFACE TEMPERATURE

Temperature is one of the most important drivers in the ocean. Ocean temperature regulates the rate of metabolism for most organisms and regulates the base of the food web. In WAMSP waters, cooler temperatures generally result in a prey base that contains northern species, which are rich in wax esters and fatty acids that promote high growth in consumers, whereas warmer temperatures generally result in a prey base consisting of southern species that are of much lower nutritional quality (Hooff and Peterson 2006, Peterson 2009). As indicators of broad-scale, sea surface temperatures across all sandy beach habitats, we selected sea-surface temperature (SST) from stationary buoys and the Pacific Decadal Oscillation (PDO). The Olympic Coast National Marine Sanctuary (OCNMS) maintains oceanographic sampling buoys throughout the OCNMS. Moorings data are available through the OCNMS website (http://olympiccoast.noaa.gov/science/oceanography/). We used the nearshore buoys (buoys stationed between 15 – 18 m depth) and calculated monthly SST averages (from temperature sensors at the surface) across all buoys to quantify the status and trends of this indicator. Values for the PDO were downloaded from the University of Washington's website for the Joint Institute for the Study of the Atmosphere and Ocean (JISAO; http://research.jisao.washington.edu/pdo/). Both indicators of broad-scale sea-surface temperature increased over the last five years, with particularly high values in 2013 and 2014 (Figure 80).

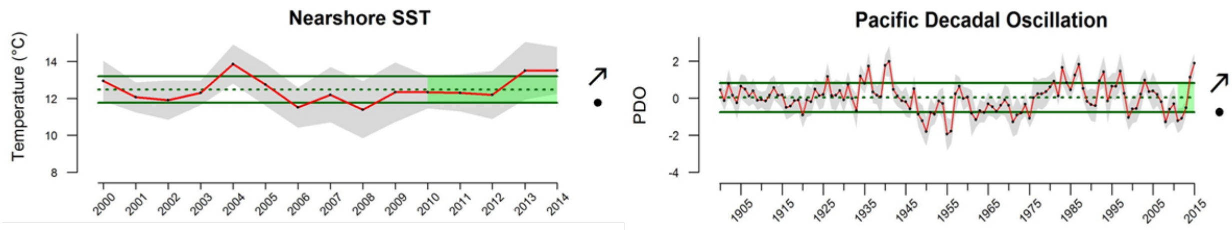

Figure 80. Left: Average sea-surface temperatures at nearshore (15 – 18 m depth) Olympic Coast National Marine Sanctuary mooring stations (data from OCNMS Oceanographic moorings website). Right: Annualized mean Pacific Decadal Oscillation (PDO). The gray shaded region in each plot represents ±1 s.d. of the mean.

TIMING AND FREQUENCY OF EL NIÑO EVENTS

El Niño Southern Oscillation (ENSO) events result from variations in sea level pressure, winds and sea-surface temperatures between the eastern and western tropical Pacific. Patterns in the tropics have wide-reaching consequences on the physical attributes in WAMSP waters. El Niño events result in ecosystem-wide effects from changes in species composition to lack of prey availability and breeding failure in top predators, while La Niña events can increase productivity in the system (Chavez 2002). El Niño conditions in WAMSP waters are associated with warmer surface water, weaker upwelling winds and lower nutrient availability at the surface; however, the effects of any given ENSO event are highly variable. As indicators of the timing and frequency of El Niño events in WAMSP waters, we selected the Multivariate El Niño Index (MEI) and the Northern Oscillation Index (NOI). The MEI represents patterns in six main observed variables over the tropical Pacific to identify the status of ENSO. The NOI measures large-scale atmospheric teleconnections, specifically the difference between sea level pressure at the climatological location of the North Pacific High (NPH) and at Darwin, Australia. Positive NOI values correspond to more coastal upwelling, while during an El Niño the influence of the NPH is diminished and the NOI has large negative values. While NOI tracks interannual changes of atmospheric forcing that are relevant to WAMSP waters, it is still a very broad index when evaluating changes in SST.

Values for the MEI were downloaded from NOAA's Earth System Research Laboratory's website (http://www.esrl.noaa.gov/psd/enso/mei/) and values for the Northern Oscillation Index were downloaded from NOAA's Pacific Fisheries Environmental Laboratory' website (http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/NOIx/noix.html). The MEI has increased over the last five years, while the NOI has shown no trend (Figure 81).

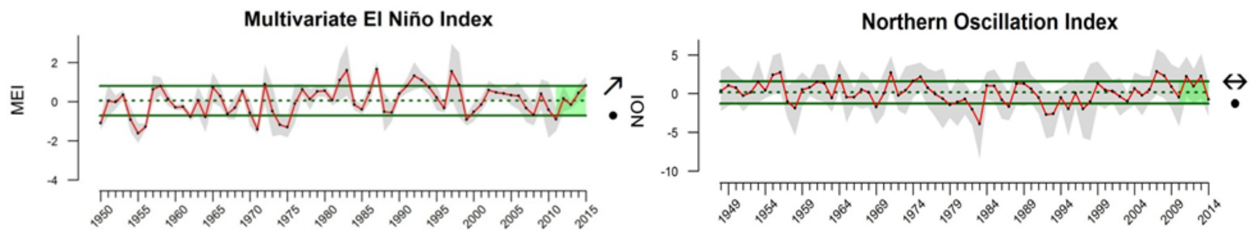

Figure 81. Indicators of changes in the timing and frequency of El Niño events in the North Pacific. The gray shaded region in each plot represents ±1 s.d. of the mean.

SOURCE WATERS

Subarctic and tropical waters are important contributors of source waters to WAMSP waters (Bograd et al. 2008). Source water changes may lead to large-scale changes in nutrients and hypoxia in the broader California Current (Bograd et al. 2008). Increases in subarctic source waters can result in changes in the food web by supplying larger, lipid-rich northern copepods and other plankton, compared to the smaller, often lipid-poor warm water copepods occurring in subtropical waters. We selected the North Pacific Gyre Oscillation (NPGO), which describes changes in salinity, nutrients and chlorophyll-a in the California Current ecosystem, and the northern copepod biomass anomaly as indicators of changes in source waters for WAMSP waters. We downloaded values for the NPGO from the ENSO/NPGO website (http://www.o3d.org/npgo/). The northern copepod biomass anomaly was calculated using biomass estimates of northern and southern species of copepods collected along the Newport Hydrographic Line and calculated as in Peterson et al. (2014).

The NPGO has decreased significantly over the last five years (Figure 8282). The northern copepod anomaly showed no overall trend over the last five years, but there has been a significant decrease beginning in 2014. This suggests a shift in the sources of WAMSP waters, from cooler, productive sub-arctic water to warmer, less productive subtropical water (Figure 82).

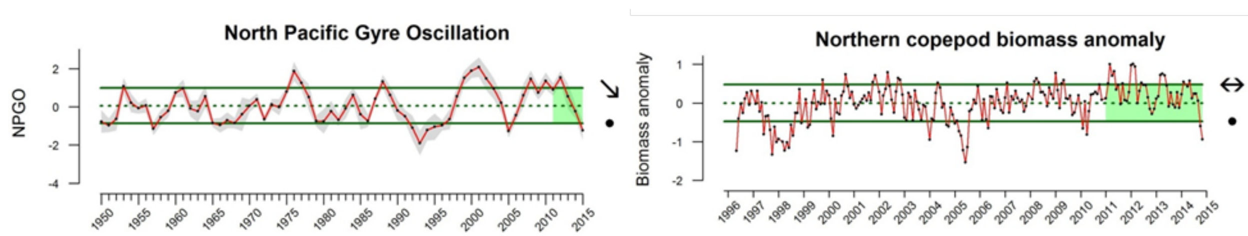

Figure 82. Indicators of changes in source waters to WAMSP waters. Left: the North Pacific Gyre Oscillation. The gray shaded region represents ±1 s.d. of the mean (data Emanuele Di Lorenzo, http://www.o3d.org/npgo/). Right: the northern copepod biomass anomaly, showing the change in the copepod community from northern species (positive values) to southern species (negative values) within years and during oceanographic regime changes (data courtesy of Bill Peterson, NWFSC).

UPWELLING

WAMSP waters reside within the broader California Current ecosystem, an eastern boundary current system largely driven by upwelling forces that bring deep, cold, nutrient-rich waters to the surface. 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 (Bograd et al. 2009). 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. Upwelling in WAMSP waters generally 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).

We selected the Upwelling Index (UI) calculated off La Push, WA in the winter and summer and the Spring Transition Index (STI) as indicators of upwelling in WAMSP waters. We downloaded monthly mean values of the UI from NOAA's Pacific Fisheries Environmental Laboratory website (http://www.pfeg.noaa.gov) and calculated winter (Jan – Mar) and summer (Jun – Aug) averages. The STI is the day of the year in which the cumulative UI for a calendar year is at its minimum value, and is calculated directly from the UI. The winter UI increased while the more relevant summer UI remained unchanged over the last five years (Figure 83 top panels). The STI has been widely variable over the last five years with no significant trend (Figure 83 bottom).

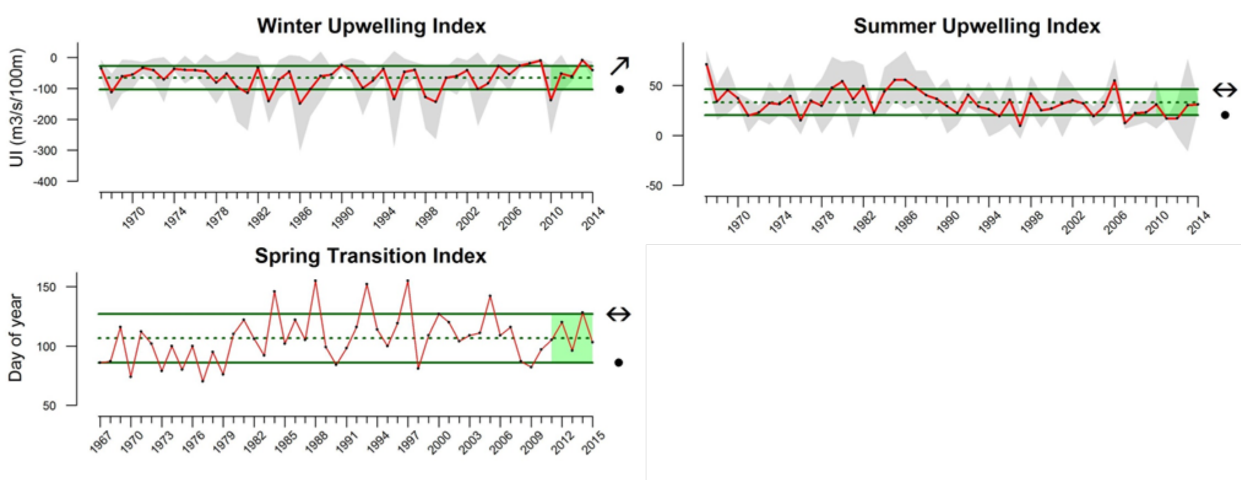

Figure 83. Indicators of upwelling in WAMSP waters. Top: upwelling indices for winter (Jan-Mar) and summer (Jun-Aug). Gray shaded regions in each plot represent ±1 s.d. of the mean. Bottom: the Spring Transition Index calculated at 48°N, 125°W off La Push, WA.

SEDIMENT DEPOSITION

Sediment dynamics at multiple spatial and temporal scales affect physical structure and functioning of sandy beach habitats in the WAMSP area. The basic structure of long-sloping beaches is driven by sediment transport processes such as tides, wind, and presence of shoreline macrophytes (McLachlan et al. 1993). Sandy beach habitats are defined laterally by littoral drift cells, which are discrete zones created by topography and longshore currents that define sediment sources (e.g., rivers, bluffs), transport, and deposition (e.g., beaches) (Inman and Nordstrom 1971). The Columbia River is a major supplier of sediment to the sandy beaches of WAMSP waters (Gelfenbaum and Kaminsky 2010). However, sediment supply from the Columbia River to the coastal zone has decreased considerably over the last 5+ decades due to construction of >200 dams in the Columbia River basin, which have reduced peak flows and trapped considerable amounts of sediment (Gelfenbaum and Kaminsky 2010). Wave energy has significant impact on the flow regime of water along the coast, thus influencing the transport of suspended sediments (Nowacki and Ogston 2013).

In order to quantify changes in the delivery of sediment to sandy beach habitats, we selected the volume of the Columbia River plume and wave height as indicators of sediment dynamics. The Columbia River plume volume represents a significant input of sediment to coastal and estuarine habitats in Washington and Oregon and is modeled by the Center for Coastal Margin Observation and Prediction Center. We downloaded "Plume Volume" data with the "28 psu salinity cut-off" from the "db33" source file from CMOP's Virtual Columbia River website (http://www.stccmop.org/datamart). For wave height, we downloaded wave height data from the NOAA National Data Buoy Center's (NDBC) Grays Harbor buoy (http://www.ndbc.noaa.gov), which is located in about 40 m of water outside the mouth of Grays Harbor. We averaged the daily maximum wave height each month and then calculated annual averages from these monthly averages.

The Columbia River plume was at its highest recorded volume in 2011 (based on data from 1999 – 2014), but there were no significant trends in the annual mean volume over the last five years, and the recent mean was within 1 SD of the long-term mean (Figure 84, left). Average daily maximum wave heights at the entrance to Grays Harbor decreased over the last five years of the dataset (Figure 84, right). Interestingly, in addition to decreases in the daily maximum wave height, we also observed a decrease in the variation around the mean for the years 2013 and 2014.

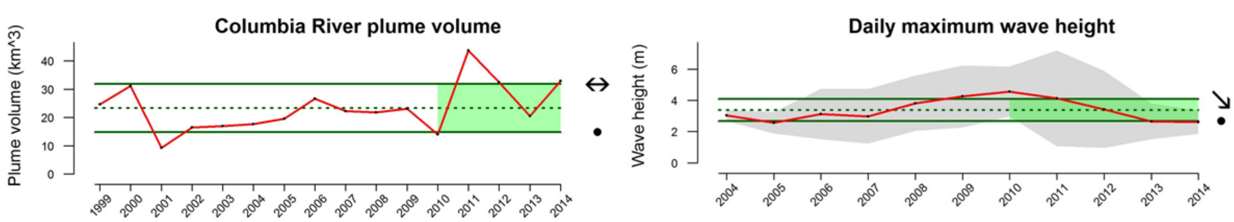

Figure 84. Indicators of sediment deposition in WAMSP sandy beach habitats. Left: average daily plume volume (km^3) of the Columbia River plume (data from Center for Coastal Margin Observation and Prediction). Right: average daily maximum wave height at National Data Buoy Center's Grays Harbor buoy. The gray shaded region represents ±1 s.d. of the mean.

WAVE ENERGY

Washington coast beaches are generally regarded as dissipative beaches that are relatively flat and have finer sand, high wave energy, large tide ranges, and broad surf zones, particularly south of Point Grenville (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 (Dahl 1952). On top of tidal incursions, which are highly predictable, wave surge caused by storms and wind events influences the structure of the sandy beach and the zonation of sandy beach communities (e.g., de Alava and Defeo 1991).

In order to capture the status and trends of wave energy effects on sandy beaches, we selected wave height and wind speed as indicators. See "*Sediment deposition*" above for a description of the wave height indicator. For wind speeds, we downloaded wind gust speeds from the NOAA National Data Buoy Center's buoy located at Destruction Island, as this was the closest nearshore buoy in open waters measuring wind speeds. We then calculated average monthly wind gusts and then calculated annual averages from these monthly mean values. Wind gust speeds were relatively unchanged over the last five years of the dataset and were within historical averages (Figure 85). However, we also observed that 2013 had the least amount of variation in wind gust speeds across the entire time series and 2014 was in the lowest quartile as well. This coincides with decreased wave height and variation in wave height (Figure 84) in the most recent years of these datasets.

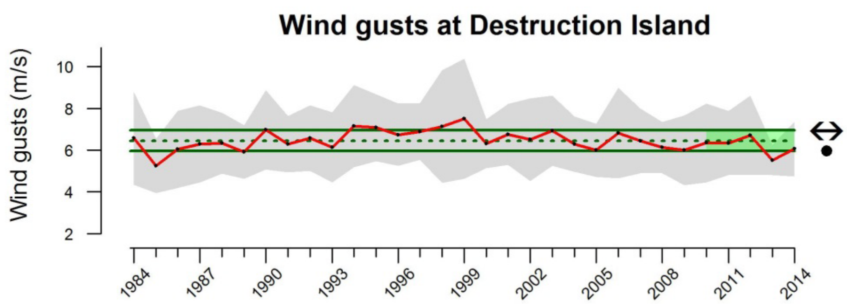

Figure 85. Average wind gusts at National Data Buoy Center's buoy at Destruction Island, WA. The gray shaded region represents ±1 s.d. of the mean.

HABITAT

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 coastal beaches are generally regarded as dissipative beaches, particularly south of Point Grenville (Gelfenbaum and Kaminsky 2010, Skewgar and Pearson 2011).

QUANTITY

Sediment grain size composition and beach profile data are primary characteristics used to define the amount of sandy beach habitat. Changes in these characteristics can be leading indicators of changes in the infaunal communities and species abundance. Beaches with steeper profiles and coarser sediments host very different, depauperate and sparse infaunal communities (McLachlan and Brown 2010). The Olympic National Park Service (ONPS) has performed annual sandy beach monitoring surveys from 2004 – 2015 that quantify the slope of the beach and sediment grain size composition at seven sites across the coast (Fradkin and Boetsch 2012). These data were being quality controlled for data assurance and were not fully analyzed by ONPS staff in time for this report, but represent the best long-term monitoring dataset for sandy beaches in WAMSP waters. Thus, **we were unable to quantify status and trends for habitat quantity.**

QUALITY

The quality of habitat available has been shown to influence the physiology, growth and behavior of individuals, and these translate into variation in demographic rates of sandy beach organisms (Defeo et al. 1997, Gomez and Defeo 1999). Indicators related to these processes are often important for identifying mechanisms responsible for changes in population size and condition of species-of-interest or changes in ecosystem health.

In order to quantify the status and trends of habitat quality, we selected water temperature and sediment quality index as indicators. For water temperature, the WDFW Shellfish Program monitors the temperature of the surf zone waters during twice-weekly sampling of surf waters for harmful algal blooms at four southern beaches: Long Beach, Twin Harbors, Westport and Tokeland. We calculated monthly averages for each location and used these values to calculate annualized mean temperatures across surf zone WAMSP waters. Data used to calculate the sediment quality index in Puget Sound (Dutch et al. 2013) were not available in sandy beaches in WAMSP waters, so we were unable to quantify status and trends for this indicator. Over the last five years of the dataset, surf zone water temperatures have increased, but remain within historical averages (Figure 86).

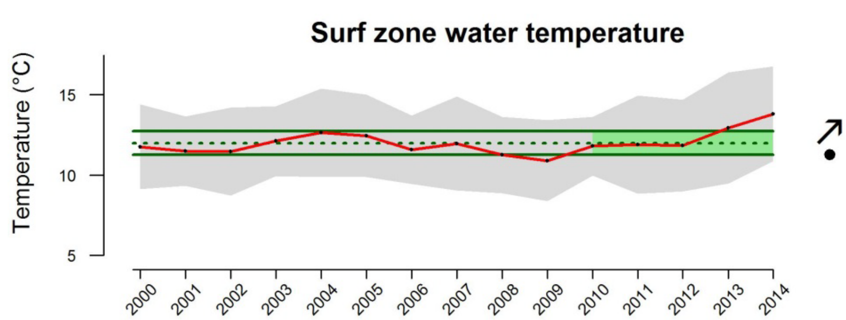

Figure 86. Water temperature of the surf zone from sandy beaches in WAMSP waters. Data from Washington Department of Fish & Wildlife Shellfish Program. The gray shaded region represents ±1 s.d. of the mean.

We were unable to find any data sources related to sediment quality on WAMSP sandy beaches, and thus we cannot quantify status and trends of this indicator at this time. Such data would be valuable to develop as a baseline for sandy beach sediment conditions in the event of natural or anthropogenic perturbations in the future.

ECOLOGICAL COMPONENTS

FISHERIES SPECIES: RAZOR CLAMS

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).

POPULATION SIZE

In order to quantify status and trends of population size of razor clams, we selected population abundance as measured by density of clams. The WDFW conducts annual surveys of razor clam populations using water pumps and suction sampling methods at five locations: Long Beach, Twin Harbors, Copalis, Mocrocks, and Kalaloch. Recruits (≥ 76 mm shell length) and pre-recruits (< 76 mm shell length) are measured and counted and standardized to density (clams/m^2). The density of razor clams has increased over the last five years, but was still within historical averages (Figure 87). Variation in density was very high in 2013 and 2014, suggesting much higher spatial differences among sites than normal.

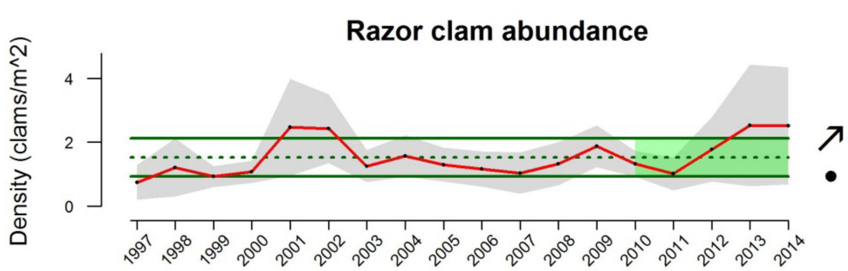

Figure 87. Density of razor clams ≥ 76 mm shell length on four beaches of southern WAMSP waters. Data courtesy of Daniel Ayres, WDFW. The gray shaded region represents ±1 s.d. of the mean.

POPULATION CONDITION

To quantify the status and trends of population condition for razor clams, we selected recruitment and condition index as indicators. The WDFW conducts annual surveys of razor clam populations using water pumps and suction sampling methods at five locations: Long Beach, Twin Harbors, Copalis, Mocrocks, and Kalaloch. Recruits (≥ 76 mm shell length) and pre-recruits (< 76 mm shell length) were measured and counted and standardized to density (clams/m^2). Recruitment of razor clams showed no trends over the last five years of the dataset, and was within historical averages of the time series (Figure 88, left). The WDFW calculates condition index for razor clams at Long Beach and Copalis. Data were available from 1994–2008 and 2012–2015. **Because there were only three data points in the last five years, we were unable to calculate current status and trends of razor clam condition index;** however current estimates were within historical averages of the entire time series (Figure 88, right).

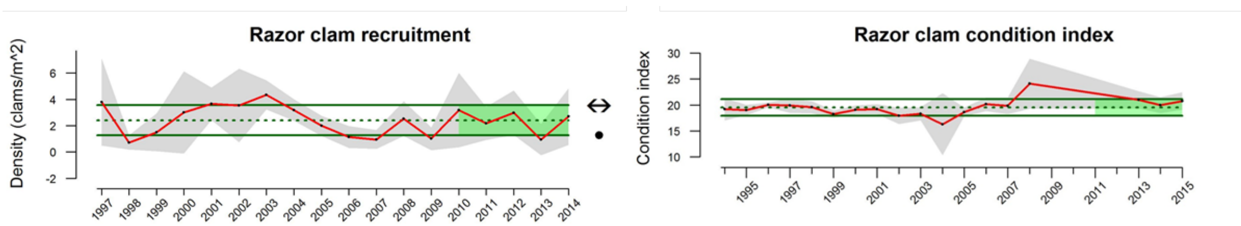

Figure 88. Indicators of population condition for razor clams. Left: recruitment of razor clams < 76 mm shell length on four beaches of southern WAMSP waters (data courtesy of Daniel Ayres). Right: condition index of razor clams from Long Beach and Copalis beaches. The gray shaded regions in each plot represent ±1 s.d. from the mean.

FOCAL TAXA: PHYTOPLANKTON AND BACTERIA

The phytoplankton community is the base of the food web for the vast majority of the marine community, thus the health and structure of this community is important to understand. 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). Movements coastal water masses can transport large volumes of coastally produced phytoplankton onto sandy beaches, where they contribute to local food web production (Odebrecht et al. 2014).

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 dominant taxa during different sampling cruises in the spring and summer of 2004-2006.

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 or dinoflagellate species involved (Vehmaa et al. 2012).

The phytoplankton community is particularly of interest to the sandy beach habitat due to the effects of harmful algal blooms on the shellfish fisheries. Shellfish feed on toxin-producing phytoplankton which can cause various levels of discomfort to death in humans, when they consume affected shellfish. 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.

POPULATION SIZE

In order to quantify population size of the phytoplankton community, we selected aggregate phytoplankton biomass or numbers. Cell counts of individual species collected across WAMSP coastlines are being quantified and analyzed by the Marine Microbes and Toxins program the NWFSC. **Thus, we do not yet have information on status and trends of phytoplankton population size for WAMSP sandy beaches.** Once published, these data should be capable of quantifying status and trends of population size.

POPULATION CONDITION

In order to quantify population condition of the phytoplankton community, we selected the ratio of diatoms to dinoflagellates. Phytoplankton communities are highly ephemeral and vary over short time scales (days to weeks). Thus, capturing blooms of specific phytoplankton species can be limited by sampling frequency. Monitoring efforts are underway by the Marine Microbes and Toxins program at the NWFSC and Washington Department of Fish and Wildlife and the University of Washington through the Olympic Region Harmful Algal Bloom (ORHAB) project. **Thus, we do not yet have information on status and trends of phytoplankton population condition for WAMSP sandy beaches.** Data that will enable quantification of the ratio of diatoms to dinoflagellates are being analyzed and these data should be available soon to quantify the status and trends of phytoplankton condition across WAMSP waters.

FOCAL TAXA: CRUSTACEANS

Numerous crustaceans inhabit sandy beach habitats along the Washington coastline. Amphipods and isopods are most numerous and are important grazers of detritus and phytoplankton decaying in the sediments (Robertson and Lucas 1983). These crustaceans are also an important prey resource for the thousands of resident and migratory shorebirds (Hughes 1982). Thus, these sandy beach crustacean communities provide an important pathway for nutrient cycling and energy transfer from lower to upper trophic levels (Griffiths et al. 1983, Heymans and McLachlan 1996).

POPULATION SIZE

In order to quantify population size of crustaceans in sandy beach habitat, we selected the aggregate abundance of amphipods and isopods. The Olympic National Park Service (ONPS) surveys the sandy beach habitat annually with core samples perpendicular to the shoreline. The most abundant species are counted and could be used to quantify changes in population size. The ONPS was analyzing the data at the time of this report and should have results by the end of 2015. **Thus, we do not yet have information on status and trends of crustacean population size for WAMSP sandy beaches.**

POPULATION CONDITION

We were not able to evaluate indicators for this attribute in time to include in this report.

FOCAL TAXA: INFAUNAL PREDATORS

Polychaete and *Nemertean* worms are common infaunal predators. Similar to other infaunal species, these species are an important pathway for recycling nutrients from the interstitial regions of the sandy beach. Polychaete and *Nemertean* worms are the primary prey for small flatfish, thus transferring energy that would be locked up in the beach sediments to higher trophic levels (Griffiths et al. 1983, Heymans and McLachlan 1996).

POPULATION SIZE

In order to quantify population size of crustaceans in sandy beach habitat, we selected the aggregate abundance of amphipods and isopods. The Olympic National Park Service (ONPS) surveys the sandy beach habitat annually with core samples perpendicular to the shoreline. The most abundant species are counted and could be used to quantify changes in population size. The ONPS was analyzing the data at the time of this report and should have results by the end of 2015. **Thus, we do not yet have information on status and trends of infaunal predator population size for WAMSP sandy beaches.**

POPULATION CONDITION

We were not able to evaluate indicators for this attribute in time to include in this report.

FOCAL TAXA: SURF ZONE FISH ASSEMBLAGE

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, OCNMS 2008, Skewgar and Pearson 2011), and some (e.g., surf smelt *Hypomesus pretiosus*) spawn in intertidal sand substrate (OCNMS 2008). Common fishes are sculpins (family Cottidae), sand lance (*Ammodytes hexapterus*), surfperches (family Embiotocidae), juvenile tomcod (*Microgadus proximus*), and flatfishes (mainly family Pleuronectidae). These assemblages are often dominated by large numbers of juvenile fish and individuals that move great distances along the shore, but these patterns vary with temperature, salinity and day of year (Marin Jarrin and Shanks 2011). Surf zone fishes are also common prey for seabirds and shorebirds.

POPULATION SIZE

In order to quantify population size of the surf zone fish assemblage, we selected population abundance of surfperches and flatfishes. **We were unable to locate any datasets capable of quantifying the status and trends of population size for the surf zone fish assemblage.**

POPULATION CONDITION

In order to quantify population condition of the surf zone fish assemblage, we selected recruitment of surfperches and flatfishes. **We were unable to locate any datasets capable of quantifying the status and trends of population condition for the surf zone fish assemblage.**

FOCAL TAXA: SEABIRDS AND SHOREBIRDS

We were unable to evaluate indicators for this component due to time constraints.

FOCAL TAXA: TERRESTRIAL MAMMALS

The influence of terrestrial mammals on marine or estuarine ecosystems is not well known. Foraging along the shores of the ocean, terrestrial mammals provide a mechanism of energy-transfer from the marine ecosystem to terrestrial ecosystems. Mammals such as raccoons may forage in areas of large kelp wrack deposits, while grazers such as deer may forage in the upper reaches of the beach where grasses and sand dunes meet. All these interaction provide a subsidy between the marine and terrestrial systems.

POPULATION SIZE

In order to quantify population size of terrestrial mammals, we selected aggregate abundance of visiting mammals. **We were unable to locate any datasets capable of quantifying the status and trends of population size for terrestrial mammals.**

POPULATION CONDITION

In order to quantify population condition of terrestrial mammals, we selected reproductive output as measured by visiting young. **We were unable to locate any datasets capable of quantifying the status and trends of population condition for terrestrial mammals.**

ECOSYSTEM HEALTH OF SANDY BEACH HABITAT

Indicators for ecosystem health of the sandy beach habitat are ecosystem and community level indices that were chosen to track two community level aspects of WAMSP waters: biodiversity and trophic structure.

BIODIVERSITY

Species diversity is an integrative measure that encompasses species richness - the number of species in the ecosystem, and species evenness - how individuals or biomass are distributed among species within the ecosystem (Pimm 1984). Diversity has remained a central theme in ecology and is frequently seen as an indicator of the wellbeing of ecological systems (Magurran 2013). Correlations between diversity and ecosystem function (productivity and stability) have been reviewed recently for terrestrial and marine systems, suggesting that the relationship is complex but communities are more stable at higher richness (Hooper et al. 2005, Stachowicz et al. 2007).

We selected two indicators for sandy beach biodiversity: Simpson's diversity index and species richness. Simpson's index is a dominance measure that estimates the probability that any two individuals drawn at random from an infinitely large community would belong to different species (Magurran 2013). Species richness, which is a count of the number of species present, can provide an extremely useful measure of diversity if the study area can be successfully delimited in space and time and the constituent species enumerated and identified (Magurran 2013). Studies have shown that species richness tends to decline with fishing, primarily based on trawling/dredging effects on benthic invertebrate communities (Gaspar et al. 2009, Reiss et al. 2009).

In order to quantify the status and trends of biodiversity, we selected Simpson's diversity measure and species richness. The surveys of the ONPS enumerate only the most abundant species in their core sampling; thus measurements of diversity or species richness cannot be calculated from this data. W**e were unable to locate any other data that were suitable for quantifying status and trends of biodiversity.**

TROPHIC STRUCTURE

In order to quantify the status and trends of trophic structure in the sandy beach habitat, we selected mean trophic level and the density of kelp wrack on the beach.

Mean trophic level provides a synoptic view of the organization of trophic structure in marine ecosystems, and is a pervasive and heavily discussed indicator used to measure marine ecosystem status, especially in communities dominated by exploited species (Pauly and Watson 2005, Essington et al. 2006, Branch et al. 2010). Conceptually, MTL is linked to top-down control and trophic cascades; a decline in MTL represents a decrease in the ability of predators to 'control' prey populations and may have far-reaching consequences to ecological communities (Daskalov 2002, Estes et al. 2004, Pauly and

Watson 2005, Baum and Worm 2009). Similar to diversity metrics, **we were unable to locate data that were suitable for quantifying status and trends of mean trophic level in the sandy beach food web.**

Kelp wrack on the beach is an important resource for the numerous grazers in the sandy beach community. Similar to kelp's importance in contributing to high levels of diversity and complex trophic structure of subtidal communities (Dayton 1985), kelp wrack on the beach provides similar structure and nourishment to a diverse sandy beach community (Griffiths et al. 1983, Ince et al. 2007). This habitat provisioning role is therefore important for structuring the food web within the ecosystem. Trends in kelp wrack on the beach thus provide insight into ecosystem condition and also provide important information to interpret trends in infaunal and macrofaunal populations. **We were unable to locate data that were suitable for quantifying status and trends of kelp wrack biomass on the beach.**

HUMAN ACTIVITIES

BIOLOGICAL EXTRACTIONS

Commercial and recreational clam digging for razor clams is an important source of revenue, food supply, cultural relevance and human well-being in southwest Washington. Commercial landings are recorded with the WDFW, but recreational landings are not recorded. We extracted landings from WDFW's Commercial Fishing website. Commercial landings have been variable over the past five years, but have shown no trend (Figure 85). Commercial landings are at the highest point of the time series, following steady increases from the late 1990s until the late 2000s.

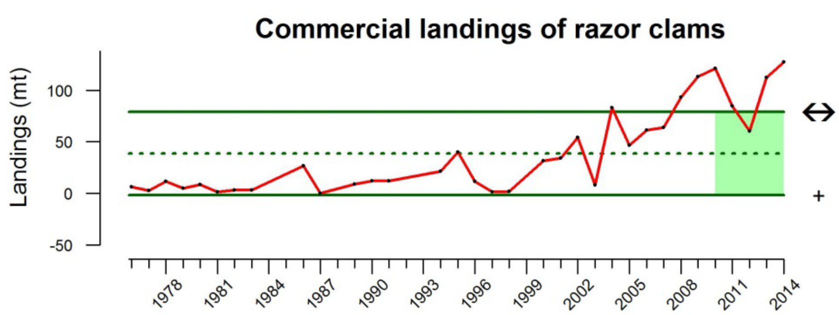

Figure 89. Commercial landings (metric tons) of razor clams in Washington State.

LAND-BASED ACTIVITIES

POLLUTION

Land-based activities can often result in the downstream run-off of various pollutants. These non-point sources of pollution have been identified as the greatest pollution threat to oceans and coasts (Panetta 2003, Policy 2004). For WAMSP waters, we selected four indicators of pollution that may have an impact on specific components of the sandy beach habitat: : (1) atmospheric deposition, as estimated from mean concentrations of sulfates ([SO_4^{2-}]); (2) organic pollution, estimated as a normalized index of pesticide concentrations in streams that drain into WAMSP waters; (3) inorganic pollution, estimated as a normalized index of all reported chemical releases to land and water that drain into WAMSP waters; and (4) marine debris. For each of these indicators, we used the same data as Andrews et al. (2015) but limited the data to watersheds that drain into WAMSP waters. All four of these indicators showed no trends and were within historical averages over the last five years of their respective datasets (Figure 90). Further studies should explore whether estimates of pollutant loadings in sandy beach sediments correlate with these land-based loadings to fully understand the utility of these indicators.

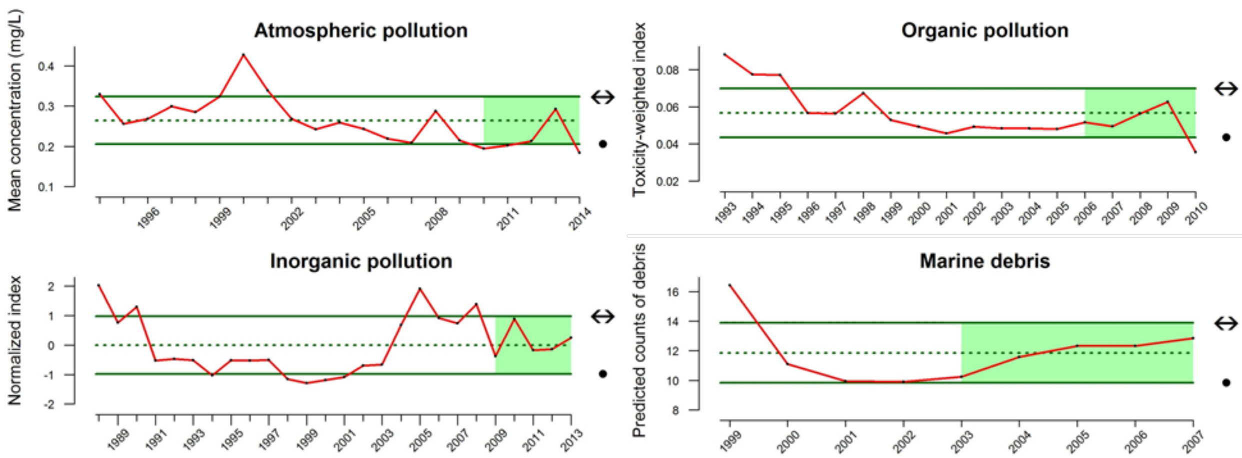

Figure 90. Indicators of pollution from atmospheric deposition (mean concentration of sulfates; data from the National Atmospheric Deposition Program), organic pollution (normalized index of pesticide concentrations in WAMSP streams; data from the U.S. Geological Survey), inorganic pollution (normalized index of all reported chemical releases at sites that drain into WAMSP waters; data from the U.S. Environmental Protection Agency's Toxic Release Inventory), and marine debris (standardized counts of specific debris items; data from Ribic et al. (2012)).

SHORELINE DEVELOPMENT

Shoreline modifications are generally related to construction of a physical element such as a dike, breakwater, dredged basin, or fill, but they can include other actions such as clearing, grading, application of chemicals, or significant vegetation removal. Shoreline modifications usually are undertaken in support of or in preparation for a shoreline use; for example, fill (shoreline modification) required for a cargo terminal (industrial use) or dredging (shoreline modification) to allow for a marina (boating facility use).

To quantify the status and trends of shoreline modification in the coastal estuaries of WAMSP waters, we selected proportion of coastline armored as the preferred indicator. Data for the proportion of shoreline armored throughout the sandy beach habitat were not available as a time series. The Environmental Sensitivity Index (ESI) has mapped the shorelines of Washington State and identified "armored" sections of the shoreline, but no "armored" sections are observed in their latest maps for the outer shoreline of Washington (National ESI Shoreline – aggregate map; available at: http://response.restoration.noaa.gov/oil-and-chemical-spills/oil-spills/response-tools/national-esi-shoreline.html). **Therefore, we could not estimate the status and trends of shoreline modification in WAMSP sandy beach habitats.**

SEDIMENT RETENTION

Sediment input to the sandy beach habitat is driven by discharge from rivers and erosion of coastal bluffs. Modified freshwater flow regimes can occur with the introduction of dams and their associated reservoirs. Reservoirs can affect the timing of river discharge as well as the amount of discharged sediment and dissolved constituents (Milliman et al. 2008). Rivers are important conduits of large amounts of particulate and dissolved minerals and nutrients to the oceans, and play a key role in the global biogeochemical cycle (Dai et al. 2009). Humans are simultaneously increasing the river transport of sediment and dissolved constituents through soil erosion activities, and decreasing this flux to the coastal zone through sediment retention in reservoirs (Syvitski et al. 2005, Milliman et al. 2008). The net result is a global reduction in sediment flux by about 1.4 BT/year over pre-human loads. The seasonal delivery of sediment to the coast and estuaries affects the dynamics of nutrient fluxes to the coast and has serious implications to coastal fisheries, coral reefs, and seagrass communities (Syvitski et al. 2005). One example is a reduction in natural dissolved silicate loads, which translates into silicon limitation in the coastal zone that discourages diatom blooms and favors nuisance and toxic phytoplankton, thereby compromising the integrity of coastal food webs (Vorosmarty and Sahagian 2000).

In order to quantify the status and trends of sediment retention, we selected the available capacity of reservoirs behind dams that drain into WAMSP waters as measured by Washington State's Dam Inventory. According to this indicator, there have been relatively few instances of changes in reservoir capacity for coastal counties, and we observed no change over the last five years of the dataset (Figure 91). As is, this indicator is unlikely to capture changes in the retention of freshwater and sediments and we would recommend a new indicator or additional investigation into actual reservoir volumes instead of reservoir capacity.

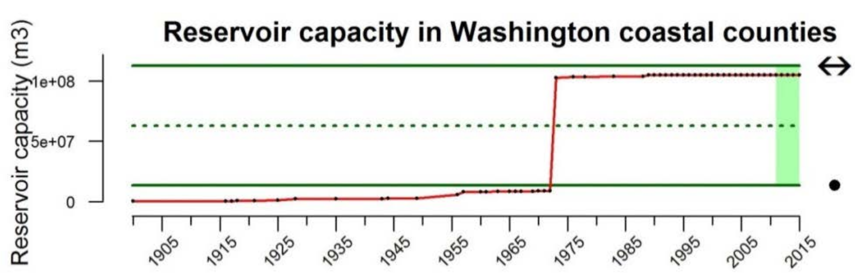

Figure 91. Reservoir capacity of dams that drain into WAMSP waters. Data from Washington Department of Ecology's Inventory of Dams.

NON-NATIVE SPECIES

Introductions of non-native species into marine and estuarine waters are considered a significant threat to the structure and function of natural communities and to living marine resources in the United States (Carlton 2001, Johnson et al. 2008). The estimated damage from invasive species in the United States alone totals almost $120 billion per year (Pimentel et al. 2005). The mechanisms behind biological invasions are numerous, but generally include the rapid transport of invaders across natural barriers (e.g. plankton entrained in ship ballast water), use of organisms as packing material (e.g., Japanese eelgrass *Zostera japonica*), fouling on aquaculture shipments, and aquarium trade with subsequent release to natural environments (Molnar et al. 2008). Non-native species can be transported and released intentionally (e.g., fish stocking and pest control programs) or unintentionally during industrial shipping activities (e.g., ballast water releases), aquaculture operations, recreational boating, biotechnology, or from aquarium discharge.

To quantify the status and trends of non-native species in WAMSP waters, we selected port volumes of commercial shipping vessels in WAMSP ports. We retrieved vessel cargo data from the U.S. Army Corps of Engineer's Navigation Data Center's "Waterborne Commerce of the United States" records. Using waterway codes, we limited the dataset to outer coastal ports and summed the volume of shipping cargo for each year. This indicator increased over the last five years of the dataset but remained within historical averages (Figure 92). Further work to incorporate the effects of imported aquaculture products may help increase this indicator's ability to capture the potential of non-native introductions to WAMSP coastal estuaries.

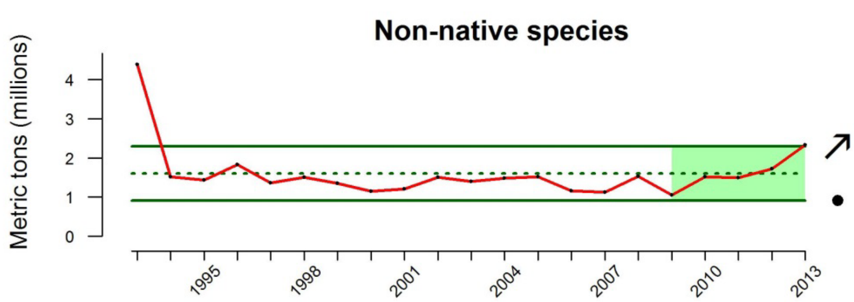

Figure 92. Indicator of non-native species for WAMSP coastal estuaries. Data are cargo volume (millions metric tons) of vessels loading or unloading into ports within Willapa Bay and Grays Harbor (data from U.S. Army Corps of Engineers, Navigation Data Center).

EXECUTIVE SUMMARY: LARGE COASTAL ESTUARIES

CONCEPTUAL MODEL OF LARGE COASTAL ESTUARY HABITAT

Coastal estuaries are semi-enclosed, brackish bodies of water that form where certain rivers meet the ocean. They are highly productive ecosystems that support a wide range of species at different life history stages, along with numerous ecosystem services. They are also important transitional systems that are linked to freshwater, terrestrial and marine processes. The conceptual model shown below (Figure 93) and in stylized form in Appendix 1 represents the dominant physical drivers, ecological interactions, and human activities that characterize the coastal estuarine zone of WAMSP waters. In particular, the conceptual model is intended to represent Willapa Bay and Grays Harbor, the two largest coastal estuaries in the WAMSP area. Suites of physical drivers and human activities affect the ecological components (i.e., the estuarine food web) and the surrounding water column within which the ecological components dwell. Humans derive wellbeing from many components and processes within the ecosystem, as well as the human activities that these large estuaries facilitate.

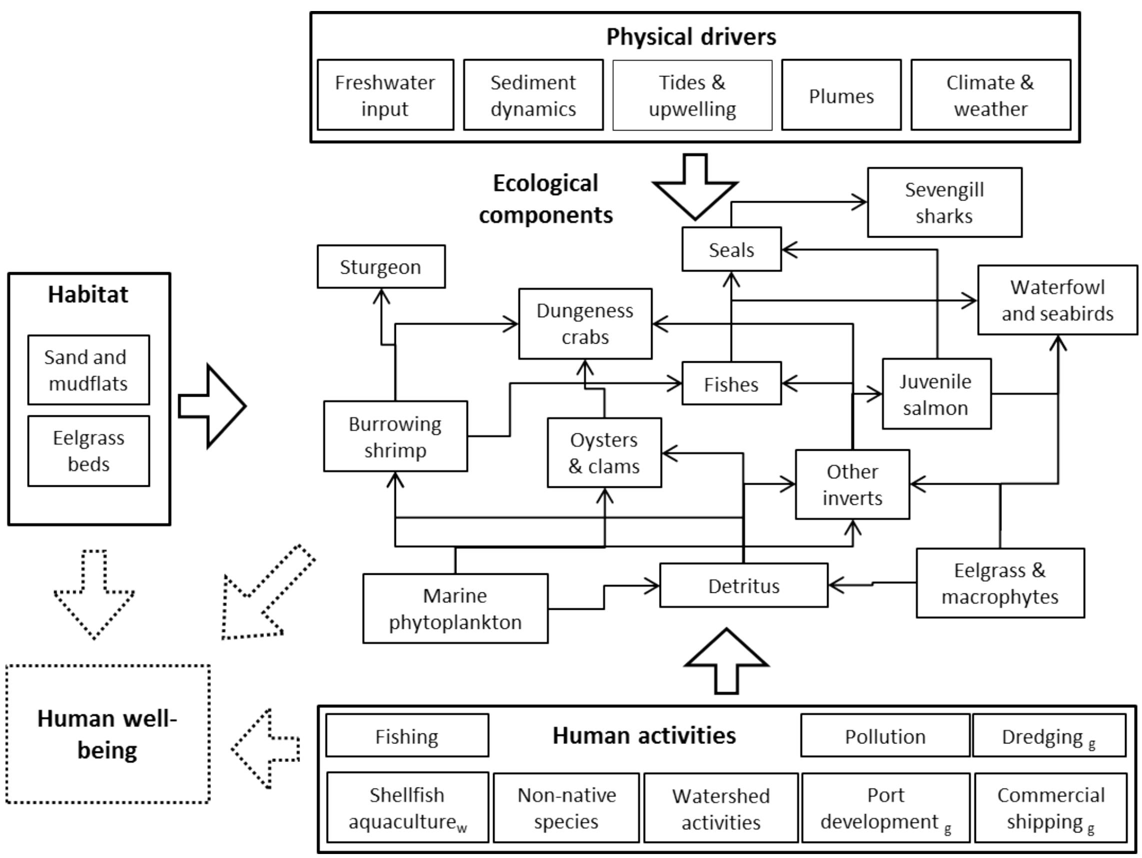

Figure 93. Conceptual model of important habitat, ecological components, physical drivers and human activities (g: primarily in Grays Harbor; w: primarily in Willapa Bay) for coastal estuary habitat.

In the following sections, we briefly describe the importance and report on the status and trends (when data were available) of each indicator selected for the components in the conceptual model above.

Table 9. Summary of indicators and times series duration for each component's key attributes for WAMSP coastal estuary habitat. † indicates data are presently being analyzed.

Component	Attribute	Indicator	Time period of available data
Physical drivers			
Climatic	Sea surface temperature (SST)	Sea Surface Temperature	~2005 - 2014
		Pacific Decadal Oscillation	1900 – 2015
	El Niño events	Multivariate El Niño Index	1950 – 2015
		Northern Oscillation Index	1948 – 2014
	Source waters	North Pacific Gyre Oscillation index	1950 – 2015
		Northern copepod anomaly	1996 – 2015
	Sea level	Mean sea level	1973 - 2015
Oceanographic	Upwelling	Upwelling index	1967 – 2014
		Spring transition index	1967 – 2015
	Freshwater input	River discharge	1973 - 2014
	Currents, eddies, plumes	Columbia River plume volume	1999 – 2014
	Sediment dynamics	Columbia River plume volume	1999 – 2014
		River discharge	1973 – 2014
		Wind gusts speed	2005 – 2014
	Tides and circulation	Pycnocline depth	NA†
Ocean acidification	Aragonite saturation	Aragonite saturation	1998 - 2014
	pCO_2	Mean pCO_2 in surface waters	2006 - 2014
Habitat			
Open water	Quantity	River discharge	1973 – 2014
		Areal wetland coverage	NA
	Quality	Dissolved oxygen	2003 - 2014
		Sea surface temperature	~2005 - 2014
		Chlorophyll -a	2003 - 2015†
Sand and mud flats	Quantity	Areal extent of sand and mud flats	NA
	Quality	Sediment quality index	NA
Biogenic habitat	Quantity	Extent of eelgrass & invertebrates	NA
	Quality	Oyster condition index	1955 – 2015
Ecological components			
Phytoplankton and bacteria	Population size	Aggregate phytoplankton counts	NA†
		Chlorophyll-a concentrations	NA†
	Population condition	Diatom: dinoflagellate ratio	NA
Zooplankton	Population size	Aggregate zooplankton biomass	NA
	Population condition	Northern copepod anomaly	NA
Burrowing shrimp	Population size	Population density estimates	1988 - 2007
	Population condition	Age structure	NA
Oysters and clams	Population size	Density	NA
		Recruitment	1936 - 2008

Component	Attribute	Indicator	Time period of available data
	Population condition	Oyster condition index	1955 - 2015
Dungeness crabs	Population size	Total biomass and	NA
		Megalopae abundance	NA
	Population condition	Population growth rate	NA
		Reproductive output	NA
Estuarine fishes	Population size	Abundance of select spp.	2011 - 2013
	Population condition	Age structure	NA
		Condition factor (K)	NA
Salmon	Population size	Escapement	1976 - 2012
		Young-of-year abundance	2011 - 2013
	Population condition	Population growth rate	1982 - 2013
		Ratio of wild to hatchery	2011 - 2013
Sturgeon	Population size	Population abundance	NA
	Population condition	Age structure	NA
Waterfowl and seabirds	Population size	Abundance of select spp.	NA†
	Population condition	Reproductive output	NA
Sevengill sharks	Population size	Population abundance	NA
	Population condition	Reproductive output	NA
Harbor seals	Population size	Population abundance	1975 - 1999
	Population condition	Reproductive output	NA
Ecosystem health	Biodiversity	Simpson's diversity	2011 – 2013
		Species density	2011 – 2013
	Trophic structure	Mean trophic level	NA
		Northern copepod anomaly	NA
		Scavenger biomass ratio	NA
Human activities			
Biological extractions	Commercial fishing	Commercial landings of salmon	1981 - 2014
	Shellfish aquaculture	Shellfish production	1986 - 2013
Watershed activities	Nutrient input	Fertilizer loadings	1945 - 2010
	Pollution	Atmospheric pollution	1994 – 2014
		Organic pollution	1993 - 2010
		Inorganic pollution	1988 - 2013
		Marine debris	1999 - 2007
	Chemical controls	Acres treated with herbicide	1997 - 2014
	Shoreline modification	Proportion of armored coastline	NA
	Sediment & H_2O input	Reservoir capacity	1900 - 2015
Ocean-based activities	Commercial shipping	# of vessel trips	2001 - 2012
	Non-native species	Port volume	1993 - 2013
	Dredging	Dredge volumes	1997 - 2014
	Seafood demand	Seafood consumption	1962 - 2013

PHYSICAL DRIVERS

We identified seven primary categories of physical drivers that affect the coastal estuarine community: freshwater input, sediment dynamics, upwelling, tides, plumes, climate variability and ocean acidification. Within the indicator evaluation framework, these seven categories represent key attributes or groups of key attributes (see Figure 3 in *Overview of methods and conceptual framework*).

FRESHWATER INPUT

Freshwater input represents riverine contributions to an estuary's water budget. These contributions vary seasonally, related to periods of rainfall, snowmelt and dry conditions; and also at annual or decadal scales related to weather and climate patterns in the Northeast Pacific. Spatial variations occur at local scales related to the discharge of water from tributaries and circulation patterns affected by geographic features, tides, winds, and other physical features (Banas et al. 2004). Freshwater inputs affect the estuary's water column stratification or mixing and salinity patterns, and also introduce suspended or dissolved materials (sediments, nutrients, pollutants, etc.). These properties in turn affect estuarine production and the distribution, biology and ecology of organisms (Ruesink et al. 2003). Freshwater inputs are also linked to key natural features (e.g., migrations of anadromous fishes) and human activities (e.g., irrigation, transportation and recreation).

We selected average river discharge as the indicator of freshwater input into Willapa Bay and Grays Harbor. This indicator was calculated using U.S. Geological Survey river flow gauges within the Satsop, Chehalis, Wynoochee, Humptulips, Naselle and Willapa Rivers. For each estuary, we summed the annualized average daily discharge volumes from each of the rivers flowing into Grays Harbor and Willapa Bay. Freshwater inputs to the estuaries showed expectedly similar long-term temporal patterns, and had no trends or departures from historical averages over the last five years (Figure 94).

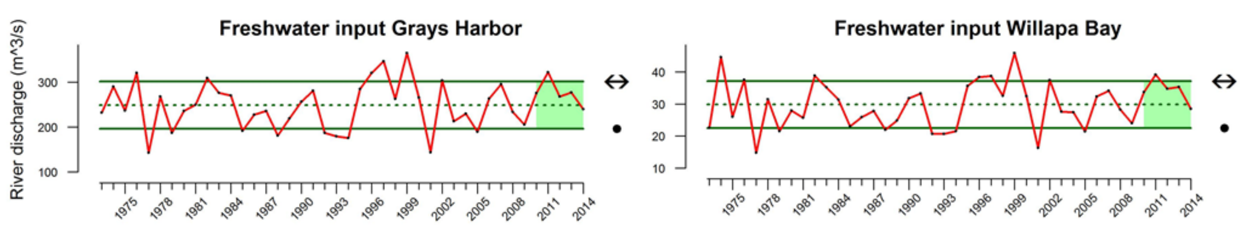

Figure 94. Annualized average daily discharge volumes (m^3/s) of rivers flowing into Grays Harbor (Satsop, Chehalis, Wynoochee and Humptulips Rivers) and Willapa Bay (Naselle and Willapa Rivers). Data from U.S. Geological Survey's National Water Information System.

SEDIMENT DYNAMICS

Sediment dynamics at multiple spatial and temporal scales affect physical structure and functioning of coastal estuaries in the WAMSP area. Both major estuaries, in particular Willapa Bay, are characterized by extensive tidal channels, mudflats, low islands, sand bars and barrier beaches. The basic structure of these features is driven by sediment transport processes such as tides, internal estuarine circulation, wind, the presence of macrophytes and other biota, and drainage dynamics from tributaries (Mariotti and Fagherazzi 2012). The source of most coarse and fine sediments that feed these systems is riverine input. Sand that forms barrier beaches and spits is largely supplied by the Columbia River and driven onto shore or into the bays by strong wave action, tides and storms (Gelfenbaum and Kaminsky 2010). However, sediment supply from the Columbia River to the coastal zone has decreased considerably over the last 5+ decades due to construction of >200 dams in the Columbia River basin, which have reduced peak flows and trapped considerable amounts of sediment (Gelfenbaum and Kaminsky 2010). Wind alters the flow regime of water through estuarine channels and flats, enhancing flow and increasing suspended sediment concentrations (Nowacki and Ogston 2013).

We selected river discharge, Columbia River plume volume and estuarine wind speed as three indicators of sediment dynamics for the large coastal estuaries. River discharge of tributaries into the two estuaries was described previously (see *Freshwater Input* and Figure 94 above).The Columbia River plume volume represents a significant input of sediment to coastal and estuarine habitats in Washington and Oregon and is modeled by the Center for Coastal Margin Observation and Prediction Center. We downloaded "Plume Volume" data with the "28 psu salinity cut-off" from the "db33" source file from CMOP's Virtual Columbia River website (http://www.stccmop.org/datamart). Wind gust velocities are recorded at the Toke Point buoy (NOAA National Data Buoy Center) inside Willapa Bay; we calculated monthly averages and then generated annual averages using the monthly averages.

The Columbia River plume was at its highest recorded volume in 2011 (based on data from 1999 – 2014), but there were no significant trends in the annual mean volume over the last five years, and the recent mean was within 1 SD of the long-term mean (Figure 95, left). Mean wind gust velocities at Toke Point have been fairly stable over the relatively short time series (2005-2014), and show no recent trends or departures from the long-term mean (Figure 95, right).

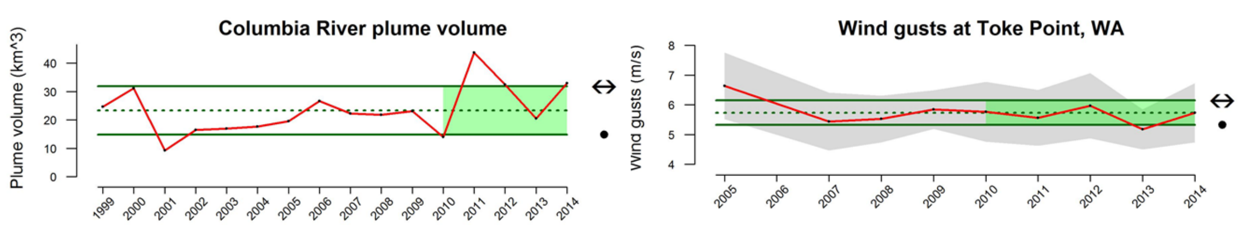

Figure 95. Indicators of sediment dynamics in WAMSP large coastal estuaries. Left: Average daily plume volume (km^3) of the Columbia River plume. Data are from the Center for Coastal Margin Observation and Prediction. Right: annual means of wind gust velocities recorded at the Toke Point observing buoy (data courtesy of NOAA National Buoy Data Center).

UPWELLING

WAMSP waters reside within the broader California Current ecosystem, an eastern boundary current system largely driven by upwelling forces that bring deep, cold, nutrient-rich waters to the surface. 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 (Bograd et al. 2009). Upwelling is the principal physical force that brings nutrients into the coastal estuaries. These nutrients support primary production, most significantly during the spring and summer months. The location, timing and intensity of upwelling all vary from year to year due to local- and basin-scale factors. Upwelled waters are known to increase the salinity and boost nutrient levels in large coastal estuaries in the WAMSP area (Roegner et al. 2002, Hickey and Banas 2003, Banas et al. 2004).

We selected the Upwelling Index (UI) calculated off La Push, WA in the winter and summer and the Spring Transition Index (STI) as indicators of upwelling in WAMSP waters. We downloaded monthly mean values of the UI from NOAA's Pacific Fisheries Environmental Laboratory website (http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/upwelling.html) and calculated winter (Jan – Mar) and summer (Jun – Aug) averages. The STI is the day of the year in which the cumulative UI for a calendar year is at its minimum value, and is calculated directly from the UI. The winter UI increased while the more relevant summer UI remained unchanged over the last five years (Figure 96 top panels). The STI has been widely variable over the last five years with no significant trend (Figure 96 bottom).

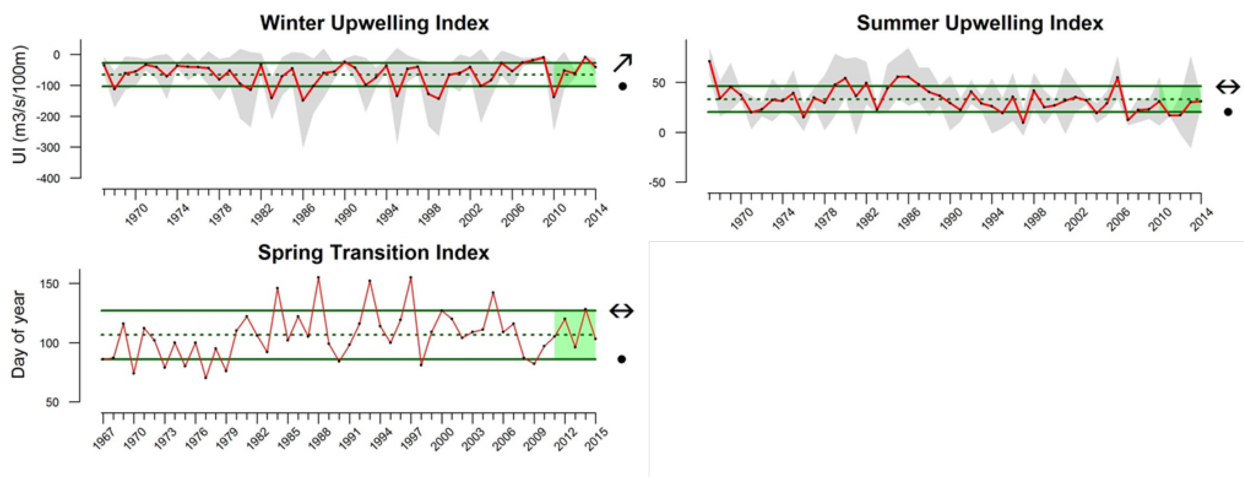

Figure 96. Indicators of upwelling in WAMSP waters. Top: upwelling indices for winter (Jan-Mar) and summer (Jun-Aug). Gray shaded regions in each plot represent ±1 s.d. of the mean. Bottom: the Spring Transition Index calculated at 48°N, 125°W off La Push, WA.

TIDES & CIRCULATION

Like many small estuaries along the outer coast of the Pacific Northwest, Willapa Bay and Grays Harbor are tidally dominated drowned river mouths (Emmett et al. 2000, Hickey and Banas 2003). In tidally dominated estuaries, tidal inputs are the dominant source of water and power of water masses relative to river inputs or waves (Dalrymple et al. 1992). Tides in the region are on mixed, semi-diurnal periods (i.e., two high tides and two low tides each day, with one cycle of greater amplitude than the other).

Tidal amplitudes are large in both estuaries; for example, the mean daily tidal amplitude in Willapa Bay is 2.7 m, with a maximum range of 4-5 m during spring-neap tides and tidal current velocities >1.0 m/s at the mouth (Hickey et al. 2002, Barry et al. 2013). Tide ranges can be exacerbated by storms or longer-term climate anomalies such as El Niño events (Emmett et al. 2000). At least half of the volume of both Willapa Bay and Grays Harbor is in their intertidal zones (Hickey and Banas 2003), which leads to the large, exposed mud and sand flats, macrophyte beds and oyster reefs at low tides. Both systems have tidal prisms making up ~50% of their total volume at mean high water, implying a high degree of tidal flushing, particularly in summer months when riverine inputs are low (Hickey and Banas 2003). This also results in weak stratification in the summer but stronger stratification in winter when higher amounts of precipitation increase river discharges. Stratification, in turn, affects the nature of primary production in the estuaries, particularly in the summer when estuarine production is driven by coastal ocean processes and weak stratification in the bays promotes production throughout the water column (Hickey et al. 2002). Thus, it is important to track tide-driven dynamics relative to other water sources (wind-driven waves, river inputs) in these systems.

As an indicator of tidal and circulation dynamics in the large coastal estuaries, we selected stratification of the water column as derived from pycnocline depth. **However, data were not available in time to include an analysis of status and trends for this indicator.**

COLUMBIA RIVER PLUME

The Columbia River plume is a major oceanographic feature that brings buoyant freshwater into the coastal estuaries, along with sediment, nutrients, carbon, and particulate organic matter that fuel productivity. The Columbia River plume also modifies tidal flushing of the estuaries, affecting residence times and transport within the estuaries, with biologically important consequences for plankton and larval fish (Simenstad et al. 1990). The plume is frequently over the Washington shelf and intrudes into the estuaries in both summer and winter when prevailing winds slacken or reverse (Hickey et al. 2005). At times, a strong front along the seaward side of the plume can inhibit the movement of patches of toxic algae, preventing accumulation of harmful biotoxin levels in razor clams and other shellfish within the estuaries. The combination of mesoscale features and coastal trapped waves on the Washington coast creates mixing and upwelling and makes primary productivity higher than would be expected from local wind stress values (Hickey and Banas 2008).

We selected Columbia River plume volume as the indicator of the status of the Columbia River plume in relation to other sources of water and nutrients in the WAMSP large estuaries. See “*Sediment Dynamics”* above for description of the status and trends of Columbia River plume volume.

CLIMATE VARIABILITY

SEA SURFACE TEMPERATURE

Sea surface temperatures (SSTs) in WAMSP waters and the broader California Current ecosystem vary at multiple time scales: seasonally due in large part to upwelling, interannually due to regional-scale forcing, and at the broadest scales due to natural, low-frequency variability and anthropogenic climate change. Upwelling timing and strength greatly influences SST and productivity in WAMSP waters. Many species in the California Current are thermally limited directly (Song et al. 2012) or indirectly through trophic interactions (Wells et al. 2008). ENSO events and climatic forcing have the greatest influence on interannual temperatures, resulting in changes in species composition and biodiversity. SSTs in the world's oceans are predicted to warm by up to 6°C by 2100 (IPCC 2007). Multiple studies have observed or predicted temperature-driven range shifts in marine organisms (Hazen et al. 2012, Sunday et al. 2012), spatial changes in productivity and diversity (Rijnsdorp et al. 2009), and changes in timing of fish migrations (Spence and Hall 2010). Long-term warming in the California Current may be buffered by upwelling of cooler water, but changes in source waters and stratification may limit any buffering effect.

As indicators of SST in the large coastal estuaries, we selected two indicators: SSTs within the estuaries (measured with buoys and satellite data) and the Pacific Decadal Oscillation (PDO). SST was measured using NOAA's National Data Buoy Center buoys at Toke Point and Westport, WA, while the PDO index is a basin-scale indicator. Data was variable and missing at times at buoys within the estuaries, but an increase in SST in the winter in Grays Harbor was captured with SST data in 2015 (Figure 97). The increasing trend in SST was also captured by the PDO, as it has increased rapidly over the last five years (Figure 98). Similar SST maps to those shown in the "*Pelagic: Climate Variability: Ocean temperature*" section above are also a highly-ranked indicator for quantifying the status and trends of SST in the coastal estuaries, **but we did not have time to produce these maps prior to completion of this report.**

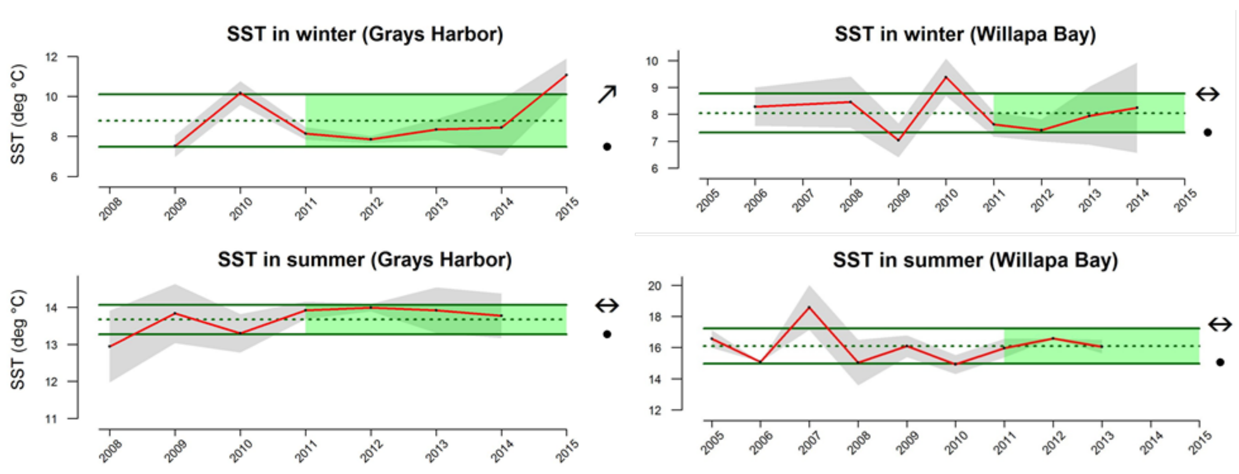

Figure 97. Average annual sea-surface temperatures (SST) in the winter (top) and summer (bottom) in Grays Harbor (left) and Willapa Bay (right) as measured by NOAA's National Data Buoy Center buoys. Gray shaded regions represent ±1 s.d. of the mean.

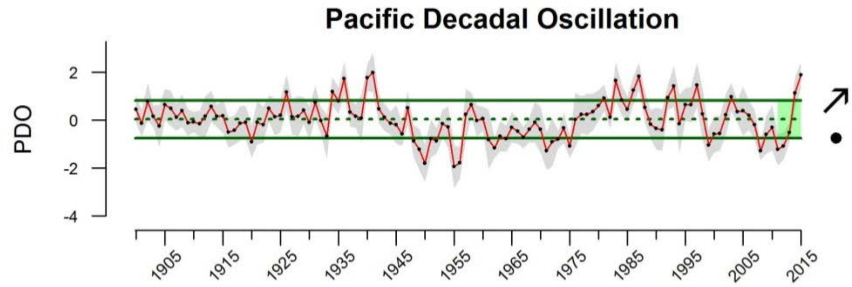

Figure 98. Pacific Decadal Oscillation (PDO) index. The gray shaded region represents ±1 s.d. of the annual mean.

TIMING AND FREQUENCY OF EL NINO EVENTS

El Niño Southern Oscillation (ENSO) events result from variations in sea level pressure, winds and SST between the eastern and western tropical Pacific. Patterns in the tropics have wide-reaching consequences on the physical attributes in WAMSP waters. El Niño events result in ecosystem-wide effects from changes in species composition to lack of prey availability and breeding failure in top predators, while La Niña events can increase productivity in the system (Chavez 2002). El Niño conditions in WAMSP waters are associated with warmer surface water, weaker upwelling winds and lower nutrient availability at the surface, and ENSO events have been linked to production variation in WAMSP estuaries (Thom et al. 2003). However, the effects of any given ENSO event are highly variable.

As indicators of the timing and frequency of El Niño events in WAMSP waters, we selected the Multivariate El Niño Index (MEI) and the Northern Oscillation Index (NOI). The MEI represents patterns in six main observed variables over the tropical Pacific to identify the status of ENSO. The NOI measures large-scale atmospheric teleconnections, specifically the difference between sea level pressure at the climatological location of the North Pacific High (NPH) and at Darwin, Australia. Positive NOI values correspond to more coastal upwelling, while during an El Niño the influence of the NPH is diminished and the NOI has large negative values. While NOI tracks interannual changes of atmospheric forcing that are relevant to WAMSP waters, it is still a very broad index when evaluating changes in SST.

The MEI has increased over the last five years, while the NOI has shown no trend, and both are within long-term historical averages (Figure 99).

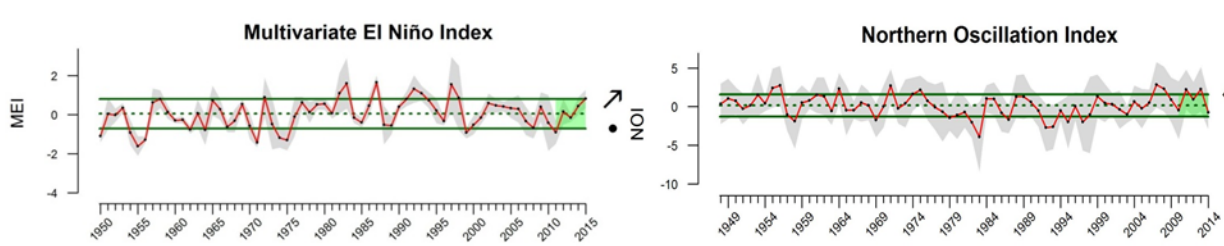

Figure 99. Indicators of changes in the timing and frequency of El Niño events in the North Pacific. The gray shaded region represents ±1 s.d. of the mean.

SOURCE WATERS

Subarctic and tropical waters are important contributors of source waters to WAMSP waters (Bograd et al. 2008). Source water changes may lead to broad-scale changes in nutrients and hypoxia in the broader California Current (Bograd et al. 2008). Increases in subarctic source waters can result in changes in the food web by supplying larger, lipid-rich northern copepods and other plankton, compared to the smaller, often lipid-poor warm water copepods occurring in subtropical waters. We selected the North Pacific Gyre Oscillation (NPGO) and the northern copepod biomass anomaly as indicators of changes in source waters for WAMSP waters. The NPGO, which describes changes in salinity, nutrients and chlorophyll-a in the California Current ecosystem, has decreased significantly over the last five years (Figure 100, left). The northern copepod anomaly showed no overall trend over the last five years, but there has been a significant decrease beginning in 2014. This decrease suggests large shifts in the source waters for WAMSP waters, from cooler, productive sub-arctic water sources to warmer, less productive water from subtropical sources (Figure 100, right).

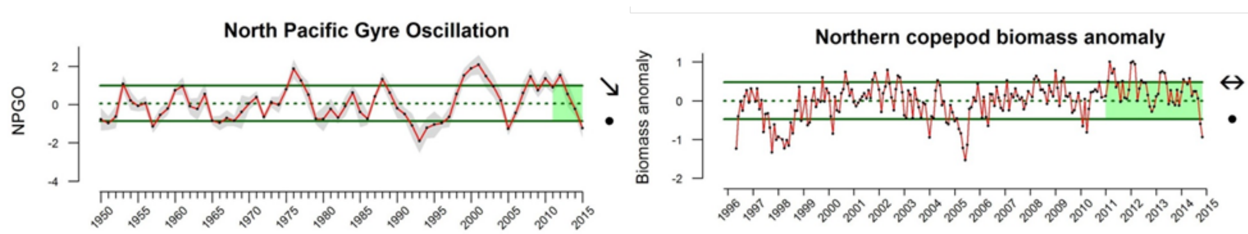

Figure 100. Indicators of changes in source waters to WAMSP waters. Left: the annual North Pacific Gyre Oscillation (NPGO). The gray shaded region represents ±1 s.d. of the mean. (Data courtesy of Emanuele Di Lorenzo, http://www.o3d.org/npgo/). Right: the northern copepod biomass anomaly, showing the change in the copepod community from northern species (positive values) to southern species (negative values) within years and during oceanographic regime changes. (Data courtesy of Bill Peterson, NWFSC.)

SEA LEVEL

As global temperatures rise, sea water warms and expands, glaciers and ice caps melt, increasing the freshwater input to the ocean, causing sea level to rise (Radić and Hock 2011). Multiple time scales are associated with sea level rise. On multi-decadal time scales, steric changes in the density field are often attributed to climate variability, while seasonal to interannual time scale variations are due to atmospheric and oceanic effects that can result in geostrophic readjustments. Records of sea level rise must be multiple decades in length to distinguish actual trends over naturally occurring low-frequency signals that derive from atmospheric and oceanic forcing (Parker 1991). Studies indicate that sea levels changed very over the past two millennia, but have been climbing steadily since 1900 (NOAA: http://oceanservice.noaa.gov/facts/sealevel.html), about 18 cm total during the 20th century (Department of Ecology: http://www.ecy.wa.gov/climatechange/2012ccrs/coasts.htm). New developments in technology and satellite altimetry can give more accurate readings and indicate sea level is now rising at 0.3 cm per year (http://oceanservice.noaa.gov/facts/sealevel.html) but rates are predicted to accelerate (Hazen et al. 2014) due to global climate change.

As an indicator of sea level rise, we selected mean sea level as measured at station 9440910, inside Willapa Bay at Toke Point, WA. These data are available from NOAA's Tides & Currents Program. We used the entire data set to calculate the status and trends because this indicator is best measured over multidecadal scales. Using the entire 43-year dataset, there has been no trend in mean sea level at this location (Figure 101). This is based on a simple analysis of the monthly means. Using these same data, NOAA's Tides and Currents Program provides an analysis that suggests mean sea level is rising at 0.35 ± 1.01 mm/year (see http://tidesandcurrents.noaa.gov/sltrends/sltrends_station.shtml?stnid=9440910).

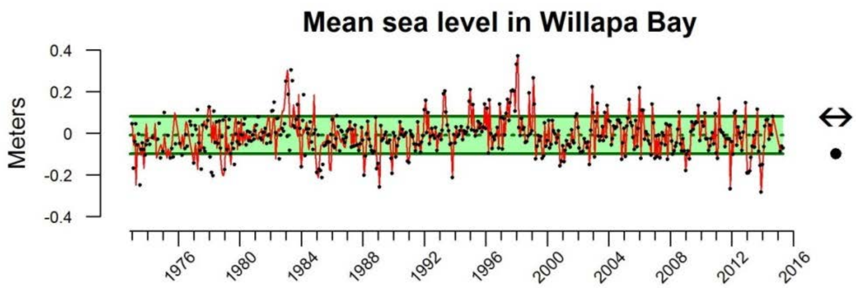

Figure 101. Monthly mean sea level at Toke Point, WA. Data from NOAA's Tides & Currents Program.

OCEAN ACIDIFICATION

For seawater, an increase in dissolved CO_2 leads to decreases in pH (increased acidification) and carbonate concentration. Lower pH and reduced availability of carbonate negatively impact organisms that rely on calcium carbonate ($CaCO_3$) for structural and protective shells, or that have metabolic or behavioral processes that are sensitive to pH (Barton et al. 2012). It is widely held that ocean acidification (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) and these organisms are typically important prey within marine food webs (e.g., crustaceans, pteropods). Predators that feed on OA-susceptible prey may be forced to switch to other prey types, increasing predation risk for those other species, or may alter their distribution, thus changing trophic structure and food web dynamics of the region.

Ocean acidification is a particular concern for the WAMSP coastal estuaries because of the importance of shellfish aquaculture for local economies and the ecology of the systems. Shellfish such as oysters and clams form the bulk of the aquaculture industry in Willlapa Bay and Grays Harbor, in particular the Pacific oyster *Crassostrea gigas*. Bivalve mollusks like Pacific oysters form calcareous shells and are dependent upon availability of $CaCO_3$ within days of hatching. Coastal hatcheries that provide oyster growers with larval oysters experienced high larval oyster mortality for many years in the last decade, and a major contributing factor appears to have been ocean acidification (Barton et al. 2012), in particular the reduced saturation state of aragonite, a particularly soluble form of $CaCO_3$ that is found in the shells of many calcifiers.

In order to quantify the status and trends of ocean acidification in the large coastal estuaries of WAMSP waters, we selected the saturation level of aragonite at two different depths along the Newport, OR Hydrographic Line. Summer averages at 40 m and 150 m depth stations were used. We also selected the partial pressure of CO_2 (pCO_2) in seawater, measured by the National Data Buoy Center's buoy off Cape Elizabeth and the Northwest Association of Networked Ocean Observing Systems' (NANOOS) buoy off La Push, WA. Monthly averages across both of these sites were calculated from data retrieved from the Carbon Dioxide Information Analysis Center's website. Aragonite saturation decreased in nearshore waters (40 m depth), while it remained unchanged in offshore waters over the last five years of the dataset (Figure 102, top). The pCO_2 in surface waters offshore of Cape Elizabeth and La Push, WA showed no significant changes over the last five years of the dataset (Figure 102, bottom).

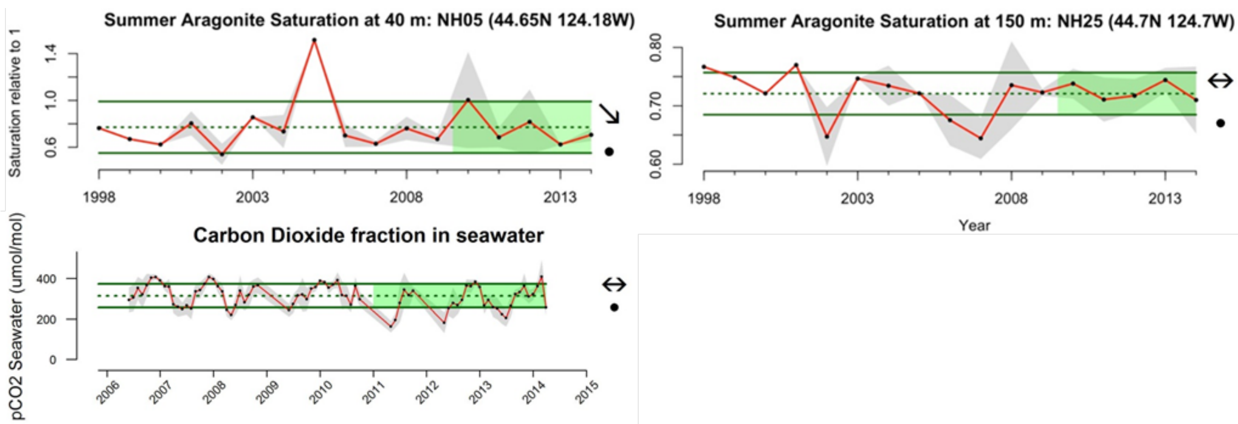

Figure 102. Indicators of ocean acidification in WAMSP waters. Top: aragonite saturation values at 40m and 150m depth at stations along the Newport, OR hydrographic line (data courtesy of Bill Peterson, NWFSC). Bottom: mean pCO_2 in surface waters measured by buoys located off Cape Elizabeth and La Push, WA. The gray shaded region in each plot represents ±1 s.d. of the mean. (Data courtesy of Adrienne Sutton, NOAA Pacific Marine Environmental Laboratory.)

HABITAT

Habitat in the WAMSP large coastal estuaries varies widely, from highly saline oceanic waters to brackish waters at tributary mouths. Structured habitat also varies, from wide expanses of sand and mud flats to natural shorelines rimmed with eelgrass (native and non-native), surfgrass, and structure-forming invertebrates to shorelines armored with breakwaters, rip-rap and retaining walls. Estuary habitat quantity and quality are shaped by large scale geomorphic and climate drivers as well as human activities at local spatial extents (Greene et al. 2014).

In this section, we focused on developing indicators of natural habitat for the open waters, sand and mud flats and biogenic habitat.

QUANTITY

Understanding the distribution and/or abundance of specific types of physical or biogenic habitat is important for understanding changes in the distribution and abundance species that rely on specific habitats, and for management actions directed at species, human activities, or ecosystem services supported by the habitat. Habitat characteristics are often used to delineate the distribution of species or to define spatial management boundaries that regulate specific activities such as fishing. Indicators related to these characteristics are often important for identifying mechanisms responsible for changes in population size and condition of focal species, or changes in the structure of the ecosystem.

OPEN WATERS

In order to quantify changes in the quantity of open marine and freshwater influence in the estuaries, we selected river flow and the areal inundated wetland coverage as indicators. Rivers supply freshwater, sediment and other materials which are important for the continued functioning of estuarine processes; thus, river discharge strongly influences the quantity of these physical habitat characteristics and the limits the distribution and abundance of estuarine species. See "*Freshwater Input*" above for the description and status and trends of this indicator. The areal extent of wetlands (tidally inundated areas) provides a variety of ecosystem services, including flood and erosion control, water purification, energy production and nutrient cycling, and cover and structure for a diversity of species (Zedler and Kercher 2005, Visintainer et al. 2006, Barbier et al. 2011). We were unable to locate data providing changes over time in the areal extent of tidal wetlands for Washington's coastal estuaries; thus, **we were unable to quantify status and trends of wetland habitat quantity.**

SAND AND MUD FLATS

For sand and mud flats, we selected areal extent of these habitats. Unfortunately, understanding changes in the amount of area covered by these habitats was limited by available data. Snapshots in time of the area covered by sand and mud flats were available from the U.S. Fish and Wildlife Service's National Wetlands Inventory, but quantifying changes in time would require detailed analyses using data from sources such as satellite and LIDAR imagery; thus **we were unable to quantify the status and trends of sand and mudflat habitat quantity.**

BIOGENIC HABITAT

For biogenic habitats, we selected areal extent of eelgrass beds—consisting of the native eelgrass *Zostera marina* and the non-native *Z. japonica*—and structure-forming invertebrates, which mostly consist of the non-native Pacific oyster *Crassostrea gigas*, which provides three-dimensional habitat in the form of naturally sustained reefs as well as cultivated stands reflecting several different aquaculture methods. Both eelgrass and oysters are significant components of estuarine production in these systems (Ruesink et al. 2006), and both provide habitat for numerous species (Hosack et al. 2006). Similar to the limitations on physical habitat, however, quantifying the changes in biogenic habitat were limited to snapshots in time and **we could not quantify the status and trends of biogenic habitat quantity.**

QUALITY

The quality of habitat available has been shown to influence the physiology, growth and behavior of individuals, and these effects translate into variation in demographic rates of many estuarine organisms.

Indicators related to these processes are often important for identifying mechanisms responsible for changes in population size and condition of focal species or changes in ecosystem health.

OPEN WATER

To quantify the quality of estuarine open water habitats, we selected temperature, dissolved oxygen and chlorophyll-a. Water temperature is one of the most important habitat quality metrics because most estuarine species are subject to physiological limits related to temperature. See "*Sea-Surface Temperature*" above for description of data, status and trends for this indicator.

Dissolved oxygen (DO) in estuarine habitats is widely acknowledged as an important indicator of habitat quality for fish. Seasonal changes in DO occur throughout WAMSP waters as a result of oxygen-poor waters being upwelled from the ocean depths and re-distributed to nearshore and estuarine habitats. Washington State's Department of Ecology measures dissolved oxygen in Willapa Bay and we used data at 10 m depth at the Toke Point station to quantify changes in dissolved oxygen within the coastal estuaries. Dissolved oxygen at Toke Point decreased over the last five years, but was still similar to the long-term average of this relatively short data set (2003 – 2014; Figure 103). DO levels were well above the widely-cited "hypoxia" threshold of 1.4 mg/L that is associated with severe physiological stress for many aquatic fauna.

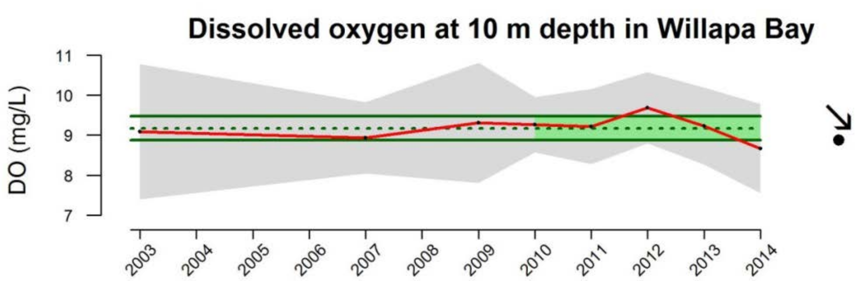

Figure 103. Dissolved oxygen concentrations at 10 m depth at Toke Point in Willapa Bay, WA.

Water column chlorophyll-a is a direct measure of phytoplankton biomass and therefore a useful indicator for basal elements of food availability in estuarine habitats. We explored using satellite data to describe changes in chlorophyll-a concentrations across the estuaries, but it should be noted that the precision of measurements in nearshore and estuarine habitats can be reduced due to reflectance and other issues. Calibrating satellite-based measurements along the coast with lab assays is currently an active area of research, **but we have not included maps of surface chlorophyll-a owing to the present levels of uncertainty.**

SAND AND MUD FLATS

In order to quantify the status and trends of the quality of sand and mud flats, we selected sediment quality. This indicator should capture the concentrations of chemical contaminants in sediment, sediment toxicity to benthic organisms and benthic community composition. In Puget Sound, the

Washington Department of Ecology's marine sediment monitoring programs produce an index of sediment quality (Dutch et al. 2009, Dutch et al. 2013). This index has not been replicated for the coastal estuaries; thus, **we were unable to find data that were capable of representing temporal changes in sand and mud flat quality in the coastal estuaries.**

BIOGENIC HABITAT

For biogenic habitats, we selected fish and/or shellfish growth in order to quantify the status and trends of habitat quality. One of the most supported indicators of habitat quality is the resultant growth and production of the organisms that reside within the habitat. We were unable to locate data capable of quantifying the status and trends of fish growth within eelgrass beds of the coastal estuaries, but we were able to use condition index of Pacific oysters as calculated by the Washington Department of Fish and Wildlife, according to the methods of Schumacker et al. (1998). The oyster condition index of Pacific oysters averaged across four sites (Oysterville, Stackpole, Stony Point and Parcel A) within the oyster reserves of Willapa Bay was slightly above the long-term averages over the last five years, and has been increasing slowly since the early 1990's (Figure 104).

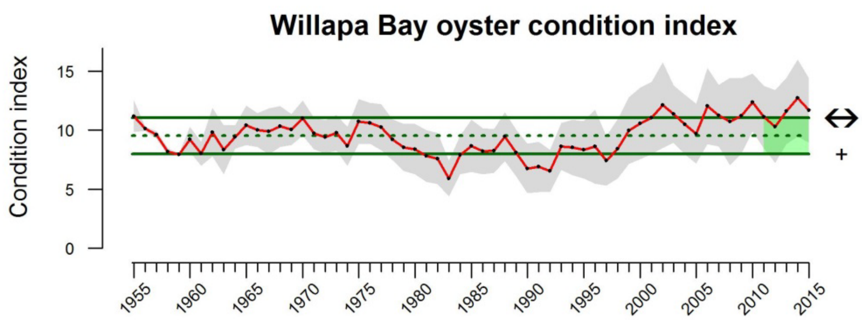

Figure 104. Condition index of Pacific oysters in Willapa Bay oyster reserves. Gray shaded regions represent ±1 s.d. of the mean (data courtesy of Daniel Ayres, WDFW).

ECOLOGICAL COMPONENTS

FISHERIES SPECIES: 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 WAMSP waters: Chinook, Coho (*Oncorhynchus kisutch*), chum (*O. keta*), pink (*O. gorbuscha*), sockeye (*O. nerka*) and steelhead (*O. mykiss*). Six stocks of salmon that enter WAMSP are listed by the Endangered Species Act: four stocks of Chinook salmon that are 'Threatened' (Lower Columbia, Puget Sound, Snake River Fall, Snake River Spring/Summer); one stock of Chinook salmon that is 'Endangered' (Upper Columbia Spring); and one stock of Coho salmon that is 'Threatened' (Lower Columbia). These listings dictate management at federal and state levels and are good reasons to include Chinook and Coho salmon in an assessment of WAMSP waters.

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 PDO, SST anomalies, coastal upwelling, spring transition date, and copepod biomass anomalies (Peterson et al. 2014).

POPULATION SIZE

For population size of salmon in the coastal estuaries, we selected two indicators: escapement of spawning adults for Willapa and Grays Harbor Chinook and Coho stocks, and the abundance of young-of-year Chinook and Coho wild stocks in Grays Harbor. We used data from PFMC (2014)to sum the total natural escapement of Willapa Bay and Grays Harbor Chinook and Coho salmon. Natural escapement of both Chinook and Coho was unchanged and consistent with historical averages (Figure 105).

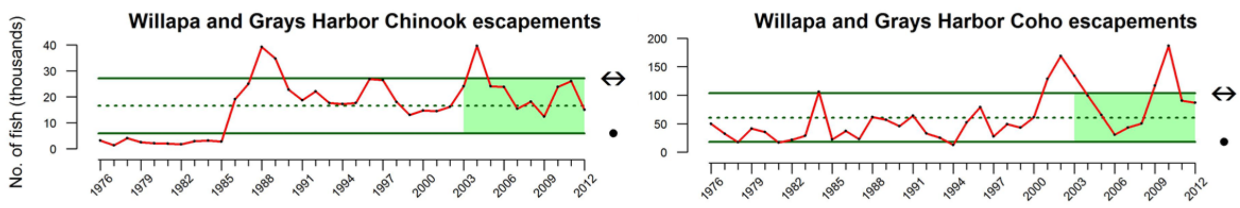

Figure 105. Summed natural escapement of Chinook (left) and Coho (right) stocks returning to Willapa Bay and Grays Harbor estuaries. Data from PFMC (2014).

The abundance of wild young-of-year (YOY) Chinook and Coho was quantified using counts from beach seines throughout Grays Harbor from 2011 – 2013 by the Wild Fish Conservancy (Sandell et al. 2013). There were not enough years of data to calculate status and trends, but 2012 appeared to be a better year for YOY wild Chinook, while 2011 was better for YOY wild Coho (Figure 106). In future analyses, historical data from the NWFSC's Anna Kagley from the late 1990's and early 2000's might be included in this analysis and provide more context and a better measure of current status of YOY salmon in the coastal estuaries.

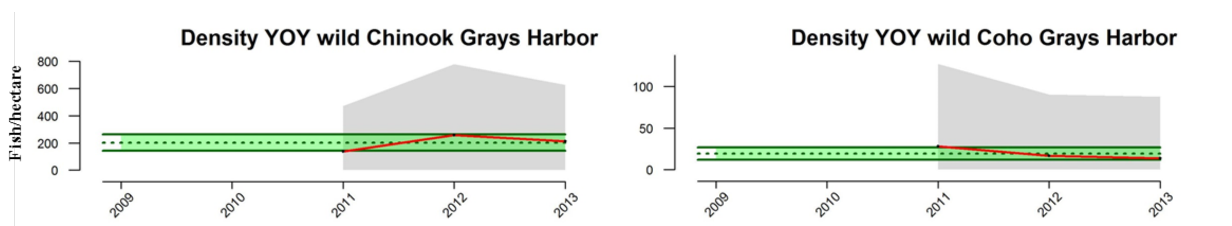

Figure 106. Density (fish/hectare) of young-of-year (YOY) wild Chinook (left) and Coho (right) in Grays Harbor. Gray shaded regions represent ±1 s.d. from the mean. Data from Sandell et al. (2013).

POPULATION CONDITION

In order to quantify the population condition of coastal estuarine salmon stocks, we selected the population growth rate and the ratio of wild versus hatchery young-of-year Chinook individuals. Population growth rate was measured as lambda (λ), the proportional change per year in the 5-year geometric mean of natural escapement. We used a 10-year time period for the analysis of status and trends in order to account for generation times in salmon. We found no trends in the population growth rates for either wild Chinook or Coho salmon stocks from Willapa Bay and Grays Harbor (Figure 107). The population growth rate for wild Chinook has been relatively invariable over the since the mid-1990's, whereas it has been highly variable for wild Coho (Figure 107).

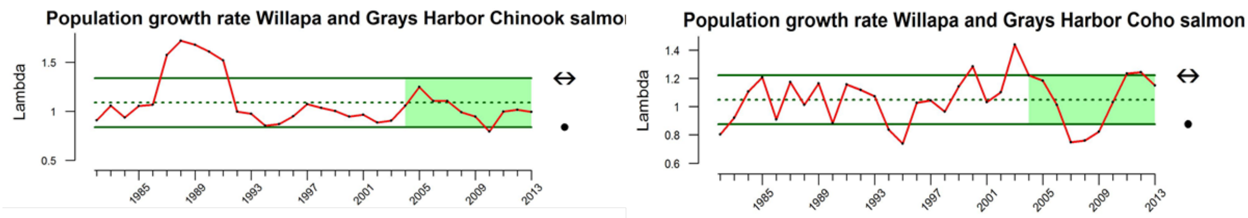

Figure 107. Population growth rate (lambda) of wild Chinook (left) and Coho (right) salmon returning to Willapa Bay and Grays Harbor. Data from PFMC (2014).

The ratio of wild versus hatchery young-of-year (YOY) Chinook salmon was calculated from beach seine counts by Sandell et al. (2013). There were not enough years of data to complete the analysis of status and trends (Figure 108), but further data from the late 1990's and early 2000's collected by the NWFSC's Anna Kagley may provide further data to help put recent years' data into historical context.

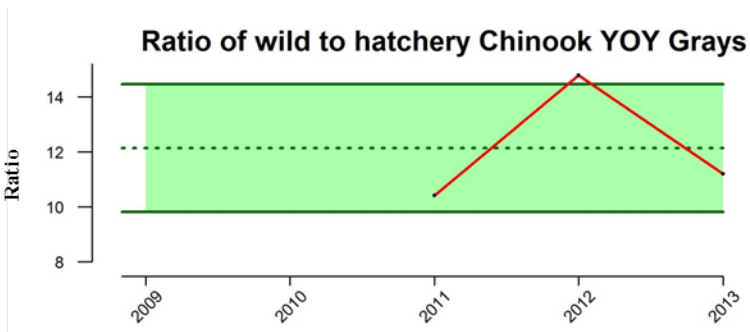

Figure 108. Ratio of wild to hatchery Chinook young-of-year (YOY) in Grays Harbor. Data from Sandell et al. (2014).

FISHERIES SPECIES: OYSTERS AND CLAMS

Pacific oysters and manila clams *Venerupis philippinarum* are important shellfish aquaculture, commercial and recreational harvest species in the coastal estuaries. The shellfish farming industry is the largest employer in Pacific County, Washington. Pacific oysters are a non-native species that were introduced across the U.S. West Coast from 1880 – 1920, as the native Olympia oyster *Ostrea lurida* became scarce after overharvesting (Ruesink et al. 2006). Pacific oysters are found on firm or rocky substrates intertidally to ~7 meters depth. Oysters filter-feed seawater for phytoplankton and organic particulates. While submerged, oysters can siphon about 26 liters of seawater an hour. This feeding strategy offers ecosystem services to the coastal estuaries by removing excess plankton blooms and nutrients from the water. Oyster farming in Willapa Bay produces over 23% of the nation's oysters and two thirds of Washington State's oysters on an annual basis (PCEDC 2009). Manila clams are also a non-native species that was introduced via oyster seed shipments from Japan. They inhabit a variety of substrates, from gravel to mud to sand, above the half-tide level. Growth is quite rapid with the clams reaching marketable size in two years.

POPULATION SIZE

As an indicator of population size of oysters and manila clams in the coastal estuaries, we selected density and recruitment of oysters and clams. Natural recruitment and growth of Pacific oysters occurs within the Willapa Bay oyster reserves, and market-sized individuals are sold from these reserves each year by the WDFW. However, harvest is performed on only the best individuals and is dependent on market forces, so these efforts are not representative of the population size of the oyster population. Altering the methods of selecting oysters for sale within the reserve could allow for estimates of density that could indicate population size over time. However, at this time, we could not find any broad-scale estimates of density capable of quantifying status and trends. Recruitment of oyster larvae has been recorded, and these data provide estimates of natural recruitment of oyster spat within Willapa Bay (Trimble et al. 2009, Dumbauld et al. 2011). Recent recruitment measurements collected by Jennifer Ruesink (University of Washington) and colleagues have not been published, but we used estimates of recruitment (numbers of spat per shell) from 1936 – 2008 to provide historical context (Dumbauld et al. 2011). Recruitment of Pacific oysters has been highly variable throughout the time series and showed no trends. Recruitment was within historical averages over the last five years of the time series, although levels of recruitment in 2006 -2008 were some of the lowest levels observed (Figure 109).

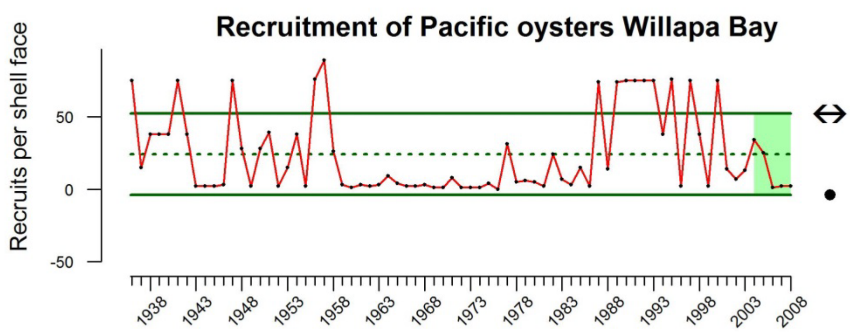

Figure 109. Recruitment (# recruits per shell face) of Pacific oysters to shell strings deployed in Willapa Bay oyster reserves. Data from Dumbauld et al. (2011).

POPULATION CONDITION

In order to quantify the condition of oysters and clams in coastal estuaries, we selected the oyster condition index. This is a long-standing index of the condition and value of oysters and is measured as a ratio between the weight of the oyster meat and the volume of the oyster's shell (Schumacker et al. 1998). For status and trends of oyster condition index, see "*Habitat: Biogenic Habitat*" above.

FISHERIES SPECIES: DUNGENESS CRABS

Dungeness crab *Metacarcinus magister* is the target of commercial and recreational fisheries in WAMSP waters. Along the Pacific coast, Dungeness crabs live in the intertidal zone out to a depth of 170 meters. Washington's coastal commercial crab grounds extend from the Columbia River to Cape Flattery near Neah Bay and include the estuary of the Columbia River, Grays Harbor, and Willapa Bay.

POPULATION SIZE

For population size of Dungeness crabs in coastal estuaries, we selected total biomass estimates and megalopae abundance. Routine fisheries-independent surveys of Dungeness crab abundance are not performed anywhere along the U.S. West Coast and we could not find any datasets within the coastal estuaries capable of quantifying status and trends. Recruitment of Dungeness crab larvae within coastal estuaries has been captured in May and June using light traps (Roegner et al. 2003), but **monitoring has not been performed on a consistent basis that could be used to quantify status and trends of population size.**

POPULATION CONDITION

In order to quantify the status and trends of population condition of Dungeness crabs, we selected population growth rate and reproductive output. **Similar to indicators of population size, we were unable to locate data capable of quantifying status and trends for either of these indicators.**

FOCAL TAXA: PHYTOPLANKTON AND BACTERIA

The phytoplankton community is the base of the food web for the vast majority of the marine community, thus the health and structure of this community is important to understand. 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). Movements of these water masses and tidal incursions transport coastally produced phytoplankton into Willapa Bay and Grays Harbor (Hickey and Banas 2003).

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 dominant taxa during different sampling cruises in the spring and summer of 2004-2006.

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 or dinoflagellate species involved (Vehmaa et al. 2012).

POPULATION SIZE

In order to quantify population size of the phytoplankton community, we selected aggregate phytoplankton biomass or numbers and satellite-derived chlorophyll-a concentrations. Cell counts of individual species collected across WAMSP coastlines are being quantified and analyzed by the Marine Microbes and Toxins program the NWFSC. **However, these data were not available at the time of this report.** Once published, these data should enable quantification of the status and trends of population size.

Water column chlorophyll-a is a direct measure of phytoplankton biomass and therefore a useful indicator for basal elements of food availability in estuarine habitats. We explored using satellite data to describe changes in chlorophyll-a concentrations across the estuaries, but it should be noted that the precision of measurements in nearshore and estuarine habitats can be reduced due to reflectance and other issues. Calibrating satellite-based measurements along the coast with lab assays is currently an active area of research, **but we have not included maps of surface chlorophyll-a owing to the present levels of uncertainty.**

POPULATION CONDITION

In order to quantify population condition of the phytoplankton community, we selected the ratio of diatoms to dinoflagellates. Phytoplankton communities are highly ephemeral and vary over short time scales (days to weeks). Thus, capturing blooms of specific phytoplankton species can be limited by sampling frequency. Monitoring efforts are underway by the Marine Microbes and Toxins program at the NWFSC and Washington Department of Fish and Wildlife and the University of Washington through the Olympic Region Harmful Algal Bloom (ORHAB) project. **Data suitable for quantifying the ratio of diatoms to dinoflagellates were not available at the time of this report;** data are being analyzed and should be available soon to quantify the status and trends of phytoplankton condition across WAMSP waters.

FOCAL TAXA: ZOOPLANKTON

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 and estuarine 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 considered 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. 2014).

POPULATION SIZE

In order to quantify the status and trends of the zooplankton community, we selected aggregate biomass of zooplankton. **We were unable to locate datasets within the coastal estuaries capable of quantifying the status and trends of the size of the zooplankton community.**

POPULATION CONDITION

For population condition, we selected the northern copepod biomass anomaly. The northern copepod biomass anomaly describes changes in the relative biomass of lipid-rich copepod species that are important prey for numerous pelagic species in WAMSP waters. **We were unable to locate datasets within the coastal estuaries capable of quantifying the status and trends of the condition of the zooplankton community.**

FOCAL TAXA: BURROWING SHRIMP

Two species of burrowing shrimp, the mud shrimp *Upogebia pugettensis* and the ghost shrimp *Neotrypaea californiensis*, are particularly of interest within the coastal estuaries due to their interactions with shellfish and the shellfish industry. The burrowing of these species resuspends and destabilizes the sand and mud sediments, which can result in shellfish sinking or being buried beneath the sediment, and therefore dying (Feldman et al. 2000). However, these native shrimp are important components of the estuarine food web as prey to birds and fish, including green sturgeon *Acipenser medirostris* which are listed as "Threatened" by the Endangered Species Act. Moreover, the presence of burrowing shrimp reduces the density and spread of the non-native Japanese eelgrass *Zostera japonica* (Dumbauld and Wyllie-Echeverria 2003), which has been invading upper tidal flats where Manila clams are farmed. Thus, there are complex industry, conservation and food web interactions associated with burrowing shrimp in the coastal estuaries.

POPULATION SIZE

In order to quantify the status and trends of burrowing shrimp in coastal estuaries, we selected density as an indicator. Estimates of density have been calculated at small scales from direct methods of extracting shrimp from their burrows and correlating those numbers with the numbers of burrow openings observed at the sediment surface. Subsequently, at much larger spatial scales, density estimates have been made by simply counting the number of burrow openings and then applying the relationship between burrow openings and number of shrimp from the small-scale observations (Dumbauld et al. In Review). These estimates have not yet been published, but suggest large decreases in burrowing shrimp population densities in Willapa Bay between 2006 and 2010 (Dumbauld et al. In Review). Data from a site near the Palix River mouth in Willapa Bay were used to quantify the status and trends of burrowing shrimp from 1998 through 2007 (Cassidy 2008). Densities of burrowing shrimp at this one site steadily decreased from the mid-1990s to the end of this time series, and as of 2007, burrowing shrimp were at historically low levels (Figure 110).

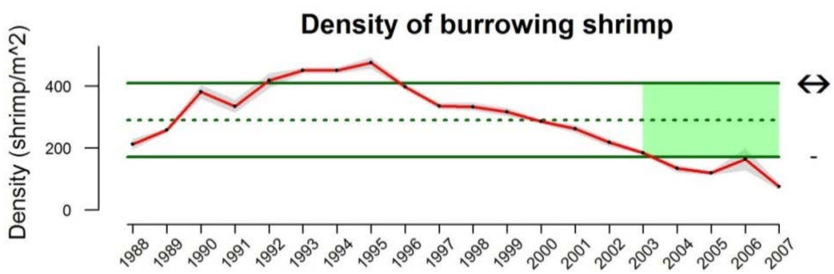

Figure 110. Densities of burrowing shrimp at Palix River location within Willapa Bay. Gray shaded region represents ±1 s.d. from the mean. Data from Cassidy (2008)

POPULATION CONDITION

For population condition, we selected age structure to quantify the status and trends of burrowing shrimp. Understanding the age structure of burrowing shrimp can help to identify the abundance of individuals within specific cohorts and help to predict the recruitment of burrowing shrimp in the future. Having this ability would be useful for managing the control of these species. The age of burrowing shrimp can be identified using pigments known as lipofuscins (Cassidy 2008). These methods have been developed and validated, but they have not been applied to monitoring surveys over time; **thus, there were no data with which to quantify status and trends of burrowing shrimp age structure.**

FOCAL TAXA: OTHER INVERTEBRATES

We were unable to evaluate and select indicators for this component due to time constraints.

FOCAL TAXA: ESTUARINE FISHES

There are numerous fish species that inhabit Washington State's coastal estuaries. In 2012, researchers captured 44 non-salmonid species in beach seining surveys in Grays Harbor (Sandell et al. 2013). The most abundant of those species was the three-spined stickleback *Gasterosteus aculeatus*. Many of these fish species are year-round residents within the estuaries and are important prey resources to migratory and resident seabirds and other fishes.

POPULATION SIZE

To quantify the status and trends of other estuarine fishes, we selected population abundance of three-spined stickleback and English sole *Parophrys vetulus* as indicators. Three-spined stickleback is one of the most abundant species in the coastal estuaries (Sandell et al. 2013) and they are known to be highly sensitive to heavy metals (Wootton 1976), thus serving as a potential indicator of water quality as well. English sole are a demersal flatfish that is of commercial importance on the outer coast. We used data from beach seine surveys throughout Grays Harbor from 2011 – 2013. **This dataset was not long enough for a full quantification of the status and trends of population size for other estuarine fishes**, but a dataset from the late 1990s and early 2000s collected by the NWFSC's Anna Kagley may be combinable with the more recent data and provide some historical context for the recent abundance estimates (Figure 111).

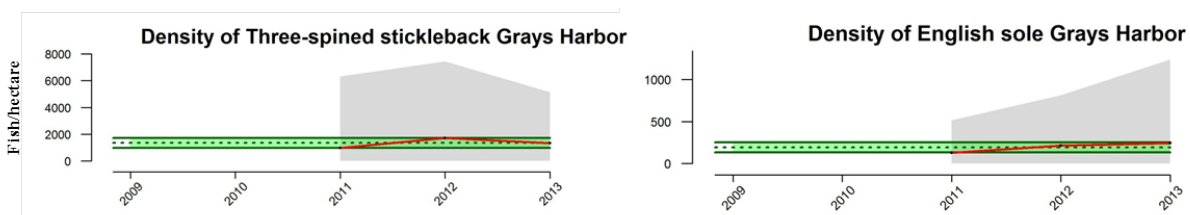

Figure 111. Density (fish/hectare) of three-spined stickleback (left) and English sole (right) in Grays Harbor. Data from Sandell et al. (2013). Gray shaded regions represent ± 1 s.d. from the mean.

POPULATION CONDITION

For population condition, we selected age structure and condition factor. **We were unable to locate any datasets that would enable quantifying status and trends for these indicators within the coastal estuaries.**

FOCAL TAXA: STURGEON

Sturgeons are highly migratory fishes. Green sturgeon occur in the coastal estuaries from approximately May through October (Lindley et al. 2011). White sturgeon *Acipenser transmontanus* are also seasonal residents of Washington's coastal estuaries. Green sturgeon have been listed as "Threatened" by the Endangered Species Act due to declining numbers and loss of habitat across the entire U.S. West Coast. While in the coastal estuaries, sturgeon's diets are dominated by burrowing shrimp (Dumbauld et al.

2008). White sturgeon is a desirable recreational fishery target in Willapa Bay, but commercial non-tribal fisheries were recently restricted from retaining any sturgeon.

POPULATION SIZE

In order to quantify the status and trends of population size for sturgeon, we selected population abundance. **We were unable to locate datasets from which to quantify population size for sturgeon in the coastal estuaries.**

POPULATION CONDITION

In order to quantify the status and trends of population condition for sturgeon, we selected age structure. **We were unable to locate datasets from which to quantify population condition for sturgeon in the coastal estuaries.**

FOCAL TAXA: WATERFOWL & SEABIRDS

Waterfowl and seabirds in the coastal estuaries represent a conspicuous component of the ecosystem, particularly during the migratory seasons. These higher trophic level predators prey on intertidal invertebrates and graze on eelgrass and surfgrass.

POPULATION SIZE

In order quantify the status and trends of population size for waterfowl and seabirds in the coastal estuaries, we selected population abundance of surf scoters and common murres. **We were unable to obtain data that were capable of quantifying the status and trends of population condition of waterfowl and seabirds in the coastal estuaries in time to include in this report.**

POPULATION CONDITION

In order to quantify the status and trends of population condition, we selected reproductive output. **We were unable to obtain data that were capable of quantifying the status and trends of population condition of waterfowl and seabirds in the coastal estuaries in time to include in this report.**

FOCAL TAXA: SEVENGILL SHARKS

Sevengill sharks *Notorynchus cepedianus* are top predators in the coastal estuaries. Sevengill sharks migrate along the U.S. West Coast and reside in Willapa Bay and Grays Harbor from spring to autumn. Sevengill sharks prey on harbor seals *Phoca vitullina*, Dungeness crabs and other species. As apex predators, changes in their population size or condition could have far-reaching effects throughout the estuarine food-web.

POPULATION SIZE

For population size of sevengill sharks, we selected population abundance. Surveys of sevengill sharks have never been performed; thus, **we were unable to quantify status and trends of population size.**

POPULATION CONDITION

To quantify the population condition of sevengill sharks, we selected reproductive output. Similar to population size, there are no efforts to monitor sevengill populations; thus, **we were unable to quantify status and trends of population condition.**

FOCAL TAXA: HARBOR SEALS

With the exception of sevengill sharks, harbor seals are apex predators in coastal estuaries. They haul out on rocks, reefs, and beaches and feed opportunistically on fishes and invertebrates in marine, estuarine, and occasionally fresh waters. Harbor seals generally are non-migratory; local movements are associated with such factors as tides, weather, season, food availability, and reproduction (Bigg 1981). However, some individuals monitored from Puget Sound have been observed moving > 100 km and traveling to Washington's outer coast (Peterson et al. 2012). Such large and mobile endothermic predators require high caloric intake to support growth, reproduction, and foraging activity. Given their abundance and trophic position, harbor seals likely make up an influential component of their marine ecosystems (Sergio et al. 2006, Heithaus et al. 2008).

POPULATION SIZE

In order to quantify the status and trends of population size, we selected population abundance as an indicator. Counts of seals at haul-out locations and aerial counts of harbor seals were performed in the past to quantify abundance of the Washington coastal stock, which was further broken into "coastal estuaries" and "Olympic Peninsula" groupings. These surveys were last performed in 1999 (Jeffries et al. 2003) and thus the best data are outdated by more than a decade. The harbor seal population increased dramatically between the beginning of the time series to the early 1990's and remained relatively unchanged until 1999 (Figure 112).

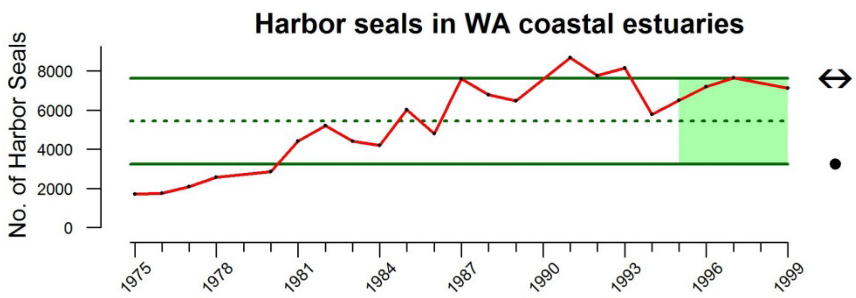

Figure 112. Average annual harbor seal haulout counts from coastal estuaries. Data from Jeffries et al. (2003).

POPULATION CONDITION

To quantify the status and trends of population condition, we selected reproductive output as the indicator. We were unable to locate data on pup counts for harbor seals in Washington coastal estuaries; thus, **we were unable to quantify the status and trends of population condition.**

COMMUNITY STRUCTURE OF LARGE COASTAL ESTUARIES

Indicators for community structure are ecosystem and community level indices that were chosen to track two community level aspects of WAMSP waters: diversity (Simpson diversity and species richness) and trophic structure (mean trophic level, scavenger biomass, and the northern copepod anomaly).

BIODIVERSITY

Species diversity is an integrative measure that encompasses species richness (the number of species in the ecosystem) and species evenness (how individuals or biomass are distributed among species within the ecosystem) (Pimm 1984). Diversity has remained a central theme in ecology and is frequently seen as an indicator of the wellbeing of ecological systems (Magurran 2013). Recent reviews of correlations between diversity and ecosystem function (productivity and stability) in terrestrial and marine systems suggest that while the relationship is complex, species-rich communities are more stable (Hooper et al. 2005, Stachowicz et al. 2007).

We selected two indicators for coastal estuary biodiversity: Simpson's diversity index and species density. Simpson's index is a dominance measure that estimates the probability that any two individuals drawn at random from an infinitely large community would belong to different species (Magurran 2013). Species density, which is a count of the number of species present, can provide an extremely useful measure of diversity if the study area can be successfully delimited in space and time and the constituent species enumerated and identified (Magurran 2013). Studies have shown that species density tends to decline with fishing, primarily based on trawling/dredging effects on benthic invertebrate communities (Gaspar et al. 2009, Reiss et al. 2009).

Biodiversity indicator data were derived from 568 beach seine sets conducted throughout Grays Harbor by Sandell et al. (2013) between 2011 and 2013. **This dataset was not long enough for a full quantification of the status and trends of biodiversity of estuarine fishes**, but a dataset from the late 1990s and early 2000s collected by the NWFSC's Anna Kagley may be combinable with the more recent data and provide some historical context for the recent abundance estimates (Figure 113).

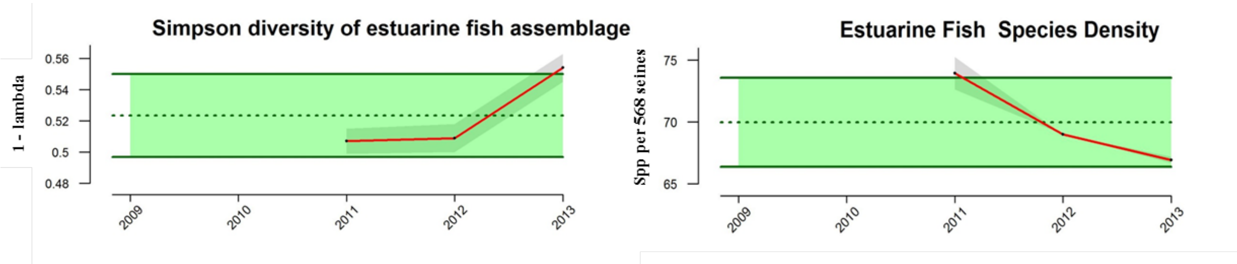

Figure 113. Indicators of biodiversity in the coastal estuaries. Left: Simpson diversity of the estuarine fish assemblage. Right: species density of the estuarine fish assemblage per 568 beach seine sets. Shaded regions in each plot represent ±1 s.d. of the mean. Data courtesy of Sandell et al. (2013)

TROPHIC STRUCTURE

Trophic structure refers to the ways in which community ecology in a habitat is influenced by food web interactions. Characterizing trophic structure in a community relies on both empirical observations and on theoretical interpretations of species relationships. In order to quantify the status and trends of trophic structure in the coastal estuaries, we selected mean trophic level, the northern copepod anomaly, and scavenger biomass.

Mean trophic level (MTL) provides a synoptic view of the organization of trophic structure in marine ecosystems, and is a pervasive and heavily discussed indicator used to measure marine ecosystem status, especially in communities dominated by exploited species (Pauly and Watson 2005, Essington et al. 2006, Branch et al. 2010). Conceptually, MTL is linked to top-down control and trophic cascades; a decline in MTL represents a decrease in the ability of predators to 'control' prey populations and may have far-reaching consequences to ecological communities (Daskalov 2002, Estes et al. 2004, Pauly and Watson 2005, Baum and Worm 2009). **We were unable to locate datasets that enabled us to calculate mean trophic level for the coastal estuaries.**

The northern copepod anomaly shows up as an indicator throughout this report and was selected as an indicator capable of representing changes in the trophic structure in coastal estuaries. Within the broader California Current ecosystem, shifts in anomalies of zooplankton species 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 2009, Peterson et al. 2014). 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 this northern copepod anomaly 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 total food web uptake of wax esters and fatty acids, compounds which appear to be essential for many forage fishes if they are to grow and survive through the winter (Williams et al. 2014). **However, we were unable to locate datasets that enabled us to quantify the northern copepod anomaly for the coastal estuaries.**

Scavengers play significant roles in the ecosystem by recycling dead and decomposing organic matter back into the food web. However, human interference in the marine ecosystem has likely increased the abundance and number of species that forage on carrion (Britton and Morton 1994). For example, many fishing operations discard dead bycatch or fishery offal to the ocean floor, or damage organisms on the seabed with bottom-contact fishing gears (Ramsay et al. 1998). Scavenger population increases may be related to these types of fishing activities (Britton and Morton 1994, Ramsay et al. 1998, Demestre et al. 2000). **However, we were unable to locate datasets that enabled us to calculate scavenger biomass ratio for the coastal estuaries.**

HUMAN ACTIVITIES

BIOLOGICAL EXTRACTIONS

COMMERCIAL FISHING

Fishing provides important services to society, including production of food, employment, livelihood and recreation. At the same time, fisheries have the 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. Here, we present the status and trends of commercial landings in estuarine WAMSP waters for salmon and other species. Landings of salmon in coastal estuarine waters have remained relatively unchanged over the last five years and were within historical averages of the dataset, whereas commercial landings of other species, such as sturgeon, were at historically low levels from 2010 – 2014 (Figure 114).

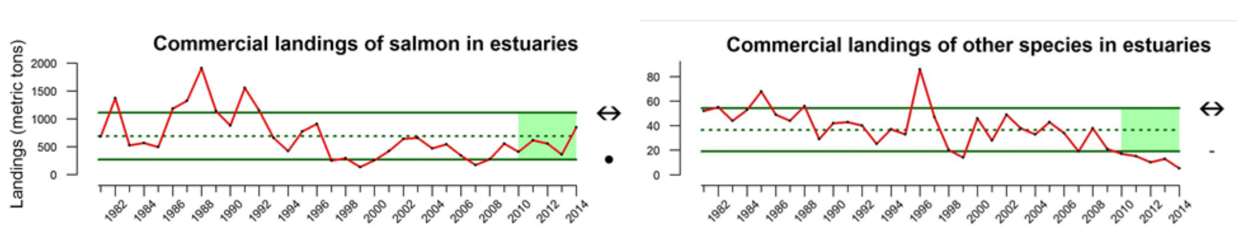

Figure 114. Commercial landings of all salmon species and other species caught in Willapa Bay and Grays Harbor reporting areas. Data from Pacific Fisheries Information Network.

SHELLFISH AQUACULTURE

The increased demand for seafood products in conjunction with declines in capture fisheries has led to worldwide increases in commercial aquaculture (Naylor et al. 2000, Sequeira et al. 2008). Aquaculture provides several socio-economic benefits, including improved nutrition and health and the generation of income and employment (Barg 1992). Environmental benefits of aquaculture include the prevention and control of aquatic pollution because of the inherent need for good water quality, the removal of excess nutrients and organic matter in eutrophic waters from the filtering action of mollusks and seaweeds, and the removal of incorporated nitrogen by shellfish when individuals are harvested (Barg 1992, Shumway et al. 2003). However, environmental impacts resulting from aquaculture production may include modifications to estuarine habitats, introductions of non-native species and alterations to the food web (Johnson et al. 2008). Shellfish aquaculture is an important industry to coastal estuarine communities in WAMSP waters: the shellfish farming industry is the largest employer in Pacific County, Washington, and Willapa Bay is considered the largest producer of oysters and clams in the United States. Oyster farming in Willapa Bay produces over 23% of the nation's oysters and two thirds of Washington State's oysters on an annual basis (PCEDC 2009).

Here, we used annual shellfish production estimates in metric tons from coastal estuarine regions, as reported by shellfish growers to the WDFW. Shellfish aquaculture increased steadily from the late 1990's to the mid 2000's, but was unchanged over the last five years and within historical averages of the dataset (Figure 115).

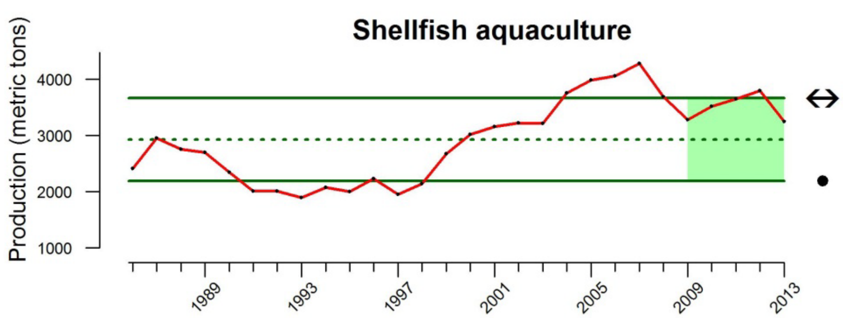

Figure 115. Shellfish production estimates as reported by shellfish growers in coastal estuaries of WAMSP waters (data courtesy of Marjorie Morningstar, WDFW).

WATERSHED ACTIVITIES

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). Excessive nutrients accelerate eutrophication, which produces a wide range of impacts on aquatic ecosystems and fisheries, including algae blooms, declines in submerged aquatic vegetation (SAV), 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). Non-point sources of nutrients which affect stream and groundwater concentrations include fertilizer use, livestock manure, and atmospheric deposition (Ruddy et al. 2006).

In order to quantity the status and trends of nutrient input to kelp forest habitats, we selected fertilizer loadings as measured by the U.S. Geological Survey (Ruddy et al. 2006, Dubrovsky et al. 2010). Total nitrogen and phosphorus applied as fertilizers within counties whose watersheds drain into coastal Washington waters, the Columbia River or Puget Sound were summed independently, normalized, and summed together to create an index of total nutrient input to WAMSP waters. We included counties that drain into the Columbia River because of the potential influence of excess nutrients in the Columbia River plume and we included counties that drain into Puget Sound because of the potential influence of the Juan de Fuca eddy re-circulating Puget Sound waters into WAMSP waters. Nutrient input to WAMSP waters showed no trends and was within historical averages over the final five years of the dataset (2006 – 2010; Figure 116); however, there was marked decline in nutrient input in 2009 and 2010.

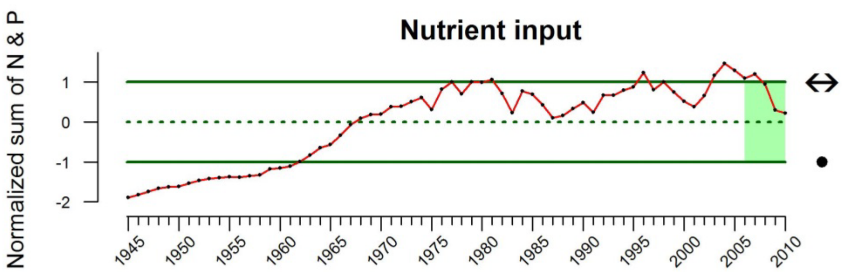

Figure 116. Normalized index of the sum of nitrogen and phosphorus applied as fertilizers in counties that drain into waters directly affecting WAMSP waters.

POLLUTION

Land-based activities can often result in the downstream run-off of various pollutants. These non-point sources of pollution have been identified as the greatest pollution threat to oceans and coasts (Panetta 2003, Policy 2004). For WAMSP waters, we developed four indicators of pollution that may have an impact on specific components of the coastal estuarine habitat: (1) atmospheric deposition, as estimated from mean concentrations of sulfates ($[SO_4^{2-}]$); (2) organic pollution, estimated as a normalized index of pesticide concentrations in streams that drain into WAMSP waters; (3) inorganic pollution, estimated as a normalized index of all reported chemical releases to land and water that drain into WAMSP waters; and (4) marine debris. For each of these indicators, we used the same data as Andrews et al. (2015) but limited the data to watersheds that drain into WAMSP waters. All four of these indicators showed no trends and were within historical averages over the last five years of their respective datasets (Figure 117). Further studies should explore whether estimates of pollutant loadings in estuarine vegetation and sediments correlate with these land-based loadings to fully understand the utility of these indicators.

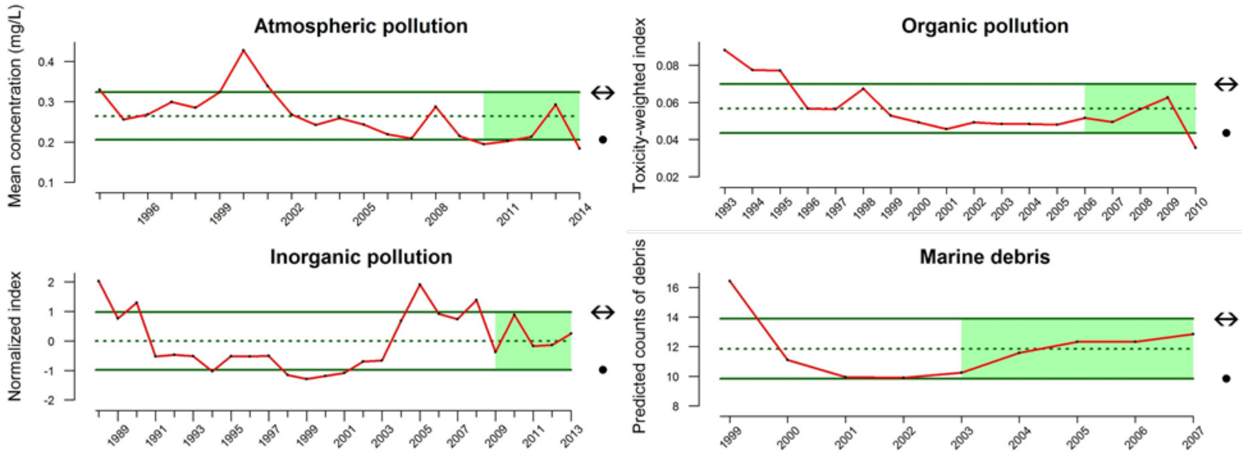

Figure 117. Indicators of pollution from atmospheric deposition (mean concentration of sulfates; data from the National Atmospheric Deposition Program), organic pollution (normalized index of pesticide concentrations in WAMSP streams; data from the U.S. Geological Survey), inorganic pollution (normalized index of all reported chemical releases at sites that drain into WAMSP waters; data from the U.S. Environmental Protection Agency's Toxic Release Inventory), and marine debris (standardized counts of specific debris items; data from Ribic et al. (2012)).

CHEMICAL CONTROLS

Two invasive species, the smooth cordgrass *Spartina alterniflora* and the Japanese eelgrass *Zostera japonica*, are being controlled by herbicides in Washington coastal estuaries. *S. alterniflora* has been nearly eradicated since taking over thousands of acres of upper wetland habitat in Willapa Bay in the 1990s. *Z. japonica* inhabits upper intertidal sand and mud flats and has increased its density and distribution dramatically throughout Willapa Bay over the last decade (Washington State Department of Ecology 2014). The increase in distribution of *Z. japonica* has resulted in the significant loss of shellfish growing habitat for the shellfish aquaculture industry. Herbicides have been applied to thousands of acres in Willapa Bay and Grays Harbor over the last few decades to control *S. alterniflora*, while 2014 was the first year herbicides were used to control *Z. japonica*. Over the last 60 years, ghost shrimp *Neotrypaea californiensis* and mud shrimp *Upogebia pugettensis*, which stir up sediments that bury shellfish or cause them to sink and die, have been controlled by insecticides.

In order to quantify the status and trends of chemical control agents within the coastal estuaries, we selected acres of habitat treated with chemical control agents. We were unable to locate data on the amount of habitat treated with insecticides, but we were able to quantify the amount of habitat treated with herbicides to control *S. alterniflora* and *Z. japonica*. Herbicide use between 1997 and 2014 peaked in 2002, with the *S. alterniflora* control effort, and then steadily declined until 2008, where it has remained relatively stable and within the long-term average range (Figure 108).

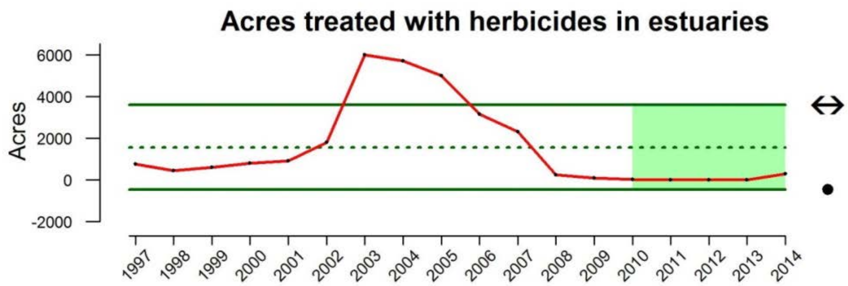

Figure 118. Number of acres treated with herbicides in Willapa Bay and Grays Harbor for the control of Spartina alterniflora *(1997 – 2014) and* Zostera marina (2014 only)*. Data from WSDA (2015) and Beugli (2014).*

SHORELINE MODIFICATION

Shoreline modifications are generally related to construction of a physical element such as a dike, breakwater, dredged basin, or fill, but they can include other actions such as clearing, grading, application of chemicals, or significant vegetation removal. Shoreline modifications usually are undertaken in support of or in preparation for a shoreline use; for example, fill (shoreline modification) required for a cargo terminal (industrial use) or dredging (shoreline modification) to allow for a marina (boating facility use).

To quantify the status and trends of shoreline modification in the coastal estuaries of WAMSP waters, we selected proportion of coastline armored as the preferred indicator. Data for the proportion of shoreline armored in the coastal estuaries were not available. The Environmental Sensitivity Index (ESI) has mapped the shorelines of Washington State and identified "armored" sections of the shoreline, but no "armored" sections are observed in their latest maps (National ESI Shoreline – aggregate map; available at: http://response.restoration.noaa.gov/oil-and-chemical-spills/oil-spills/response-tools/national-esi-shoreline.html). **Therefore, we could not estimate the status and trends of shoreline modification in WAMSP coastal estuaries.**

FRESHWATER AND SEDIMENT RETENTION

Freshwater and sediment input to coastal estuaries is driven by discharge from rivers. Modified freshwater flow regimes can occur with the introduction of dams and their associated reservoirs. Altered freshwater discharges can change the salinity gradient and pattern in salinity variation within estuaries and coastal systems, and can induce large shifts in community composition and ecosystem function (Gillanders and Kingsford 2002). Reservoirs affect the timing of discharge as well as the amount of discharged sediment and dissolved constituents (Milliman et al. 2008). Rivers are important conduits of large amounts of particulate and dissolved minerals and nutrients to the oceans, and play a key role in the global biogeochemical cycle (Dai et al. 2009). Humans are simultaneously increasing the river transport of sediment and dissolved constituents through soil erosion activities, and decreasing this flux to the coastal zone through sediment retention in reservoirs (Syvitski et al. 2005, Milliman et al. 2008).

The net result is a global reduction in sediment flux by about 1.4 BT/year over pre-human loads. The seasonal delivery of sediment to the coast and estuaries affects the dynamics of nutrient fluxes to the coast and has serious implications to coastal fisheries, coral reefs, and seagrass communities (Syvitski et al. 2005). One example is a reduction in natural dissolved silicate loads, which translates into silicon limitation in the coastal zone that discourages diatom blooms and favors nuisance and toxic phytoplankton, thereby compromising the integrity of coastal food webs (Vorosmarty and Sahagian 2000).

In order to quantify the status and trends of sediment and freshwater retention, we selected the available capacity of reservoirs behind dams that drain into the coastal estuaries as measured by Washington State's Dam Inventory. According to this indicator, there have been relatively few instances of changes in reservoir capacity in the catchments of coastal estuaries, and we observed no change over the last five years of the dataset (Figure 119). As is, this indicator is unlikely to capture changes in the retention of freshwater and sediments, and we would recommend a new indicator or additional investigation into actual reservoir volumes instead of reservoir capacity.

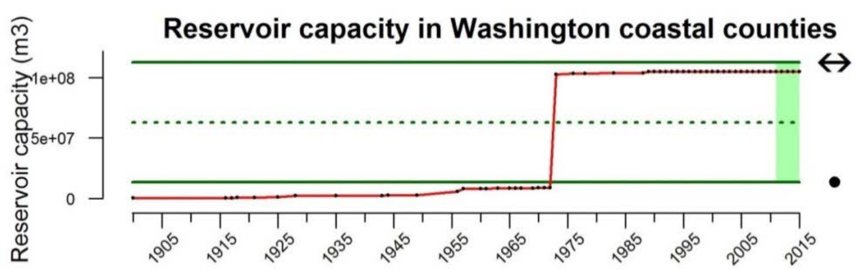

Figure 119. Reservoir capacity of dams that drain into WAMSP coastal estuaries. Data from Washington State's Dam Inventory.

OCEAN-BASED ACTIVITIES

COMMERCIAL SHIPPING

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 (relative to 2001 volume) by 2020 (AAPA 2012) due to the economic efficiencies of transporting goods via ocean waterways. Grays Harbor is the primary port that attracts commercial shipping vessels in WAMSP waters, but there is some activity into Willapa Bay.

In order to quantify the status and trends of commercial shipping in WAMSP coastal estuaries, we selected the number of trips that vessels make inbound and outbound from Grays Harbor and Willapa Bay ports, as measured by "Entrances and Clearances" data from the U.S. Army Corps of Engineers' Navigation Data Center for both foreign and domestic trips. Based on these data, commercial shipping has been at consistently low levels within WAMSP coastal estuaries for the previous decade (Figure 120).

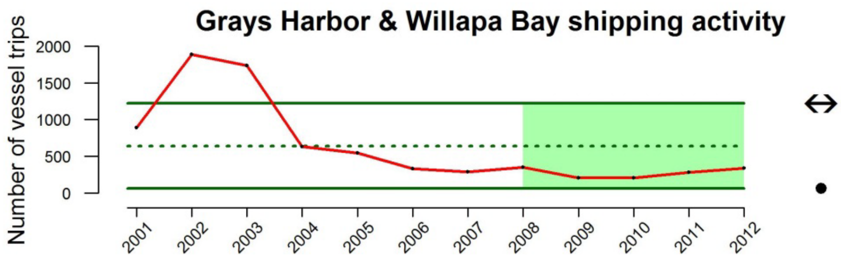

Figure 120. Commercial shipping activity in WAMSP coastal estuaries as measured by the number of trips made inbound and outbound for foreign and domestic trips. Data from U.S. Army Corps of Engineers' Navigation Data Center.

NON-NATIVE SPECIES

Introductions of non-native species into marine and estuarine waters are considered a significant threat to the structure and function of natural communities and to living marine resources in the United States (Carlton 2001, Johnson et al. 2008). The estimated damage from invasive species in the United States alone totals almost $120 billion per year (Pimentel et al. 2005). The mechanisms behind biological invasions are numerous, but generally include the rapid transport of invaders across natural barriers (e.g., plankton entrained in ship ballast water), use of organisms as packing material (e.g., Japanese eelgrass *Zostera japonica*), fouling on aquaculture shipments, and aquarium trade with subsequent release to natural environments (Molnar et al. 2008). Non-native species can be transported and released intentionally (e.g., fish stocking and pest control programs) or unintentionally during industrial shipping activities (e.g., ballast water releases), aquaculture operations, recreational boating, biotechnology, or from aquarium discharge.

To quantify the status and trends of non-native species in WAMSP coastal estuaries, we selected port volumes of commercial shipping vessels in Grays Harbor and Willapa Bay. We retrieved vessel cargo data from the U.S. Army Corps of Engineer's Navigation Data Center's "Waterborne Commerce of the United States" records. Using waterway codes, we limited the dataset to Willapa Bay and Grays Harbor ports and summed the volume of shipping cargo for each year. This indicator increased over the last five years of the dataset but remained within historical averages (Figure 121). Further work to incorporate the effects of imported aquaculture products may help increase this indicator's ability to capture the potential of non-native introductions to WAMSP coastal estuaries.

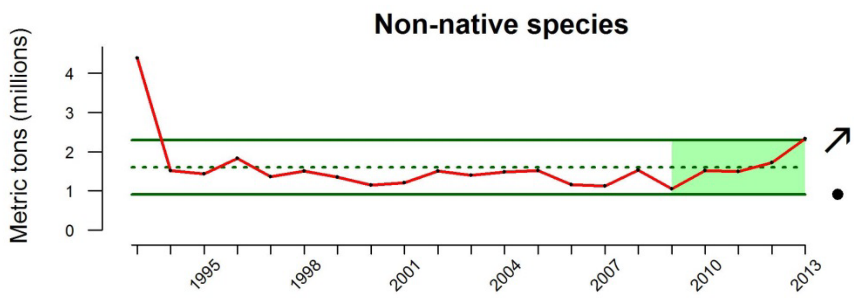

Figure 121. Figure 122. Indicator of non-native species for WAMSP coastal estuaries. Data are cargo volume (millions metric tons) of vessels loading or unloading into ports within Willapa Bay and Grays Harbor (data from U.S. Army Corps of Engineers, Navigation Data Center).

DREDGING

Dredging is the removal or displacement of any material from the bottom of an aquatic area (USACE 1983). It is required in many ports of the world to deepen and maintain navigation channels and harbor entrances, including in Grays Harbor. Excavation, transportation, and disposal of soft-bottom material can have various adverse impacts on marine or estuarine environments (Johnston 1981). These effects may be due to physical or chemical changes in the environment at or near the dredging site, and may include: reduced light penetration by increased turbidity; altered tidal exchange, mixing, and circulation; reduced nutrient outflow; increased saltwater intrusion; alteration, disruption, or destruction of areas in which fish live, feed and reproduce; re-suspension of contaminants affecting water quality; and creation of an environment highly susceptible to recurrent low dissolved oxygen levels.

In order to quantify the status and trends of the effects of dredging on WAMSP coastal estuaries, we selected dredge volumes taken from locations within the coastal estuaries. We also included dredge volumes within the Columbia River system, as these dredged volumes likely alter the supply of sediments to coastal and estuarine habitats in WAMSP waters. Over the last five years (and even the last ten years), dredging has been highly variable, with no observed trends (Figure 122).

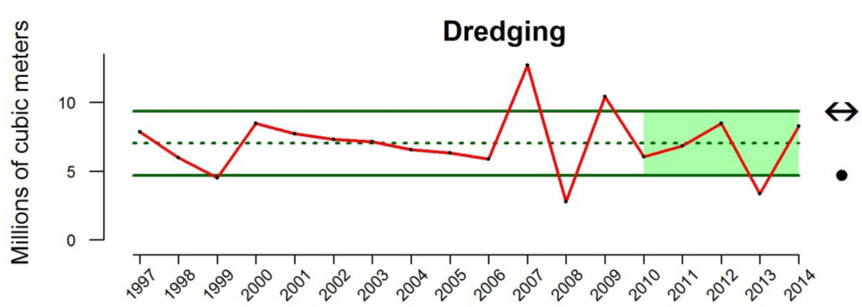

Figure 123. Dredged volumes by U.S. Army Corps of Engineers (USACE) and associated contractors at sites within WAMSP waters and the Columbia River system. Data from USACE Navigation Data Center.

SEAFOOD DEMAND

Demand for seafood products drives the extraction of fish and shellfish from oceans around the globe. In order to quantify this driver, we selected total consumption of edible and non-edible products from the sea by U.S. residents. Seafood products from WAMSP coastal estuaries are consumed across the United States as well as exported internationally. Total edible and non-edible seafood demand provides an estimate of what is being used and the relative pressure on resources within WAMSP coastal estuaries. Seafood demand has been increasing relatively consistently since the early 1970's and was above historical averages from 2009-2013 (Figure 113).

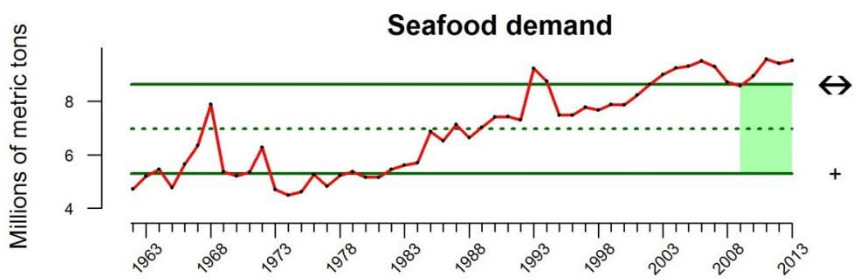

Figure 124. Total consumption of edible and non-edible fisheries products in the United States.

DATA GAPS

For each of the habitats, we have identified components of the conceptual models that we have been able to quantify status and trends (see Figures 125-130). We also distinguish among conceptual model components for which some of the indicators have been quantified but other have not. For many of the indicators of habitat quantity, data were available as 'snap-shots' in time, typically in the form of GIS map data, but these data were generally cobbled together across several years and have not been updated or have not had multiple surveys performed. Other indicators were identified as "still developing" based on data that was being analyzed at the time of this report. Finally, there were several components for which no data sets were available.

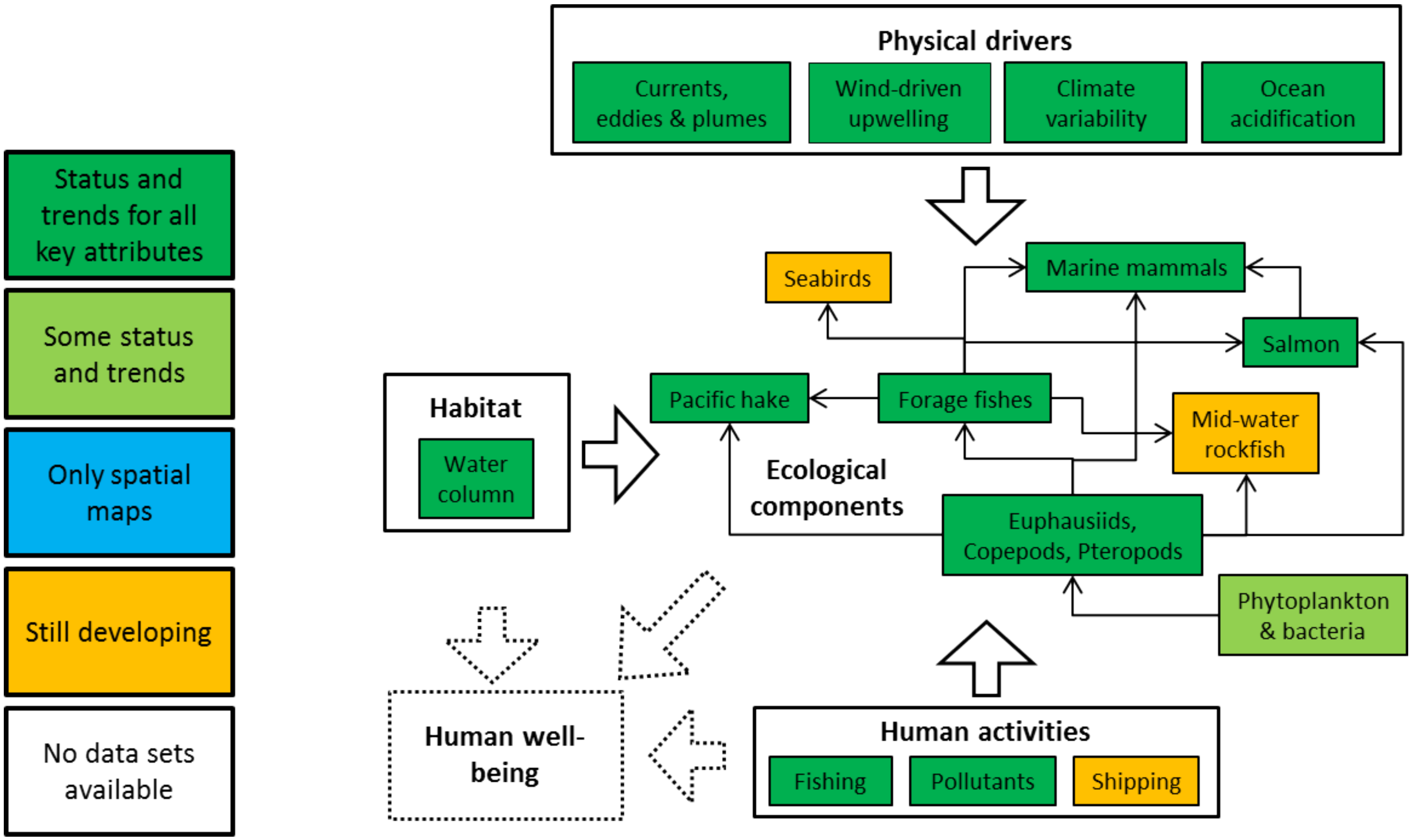

Figure 125. Present status and data gaps for the important components of the pelagic habitat's conceptual model in WAMSP waters

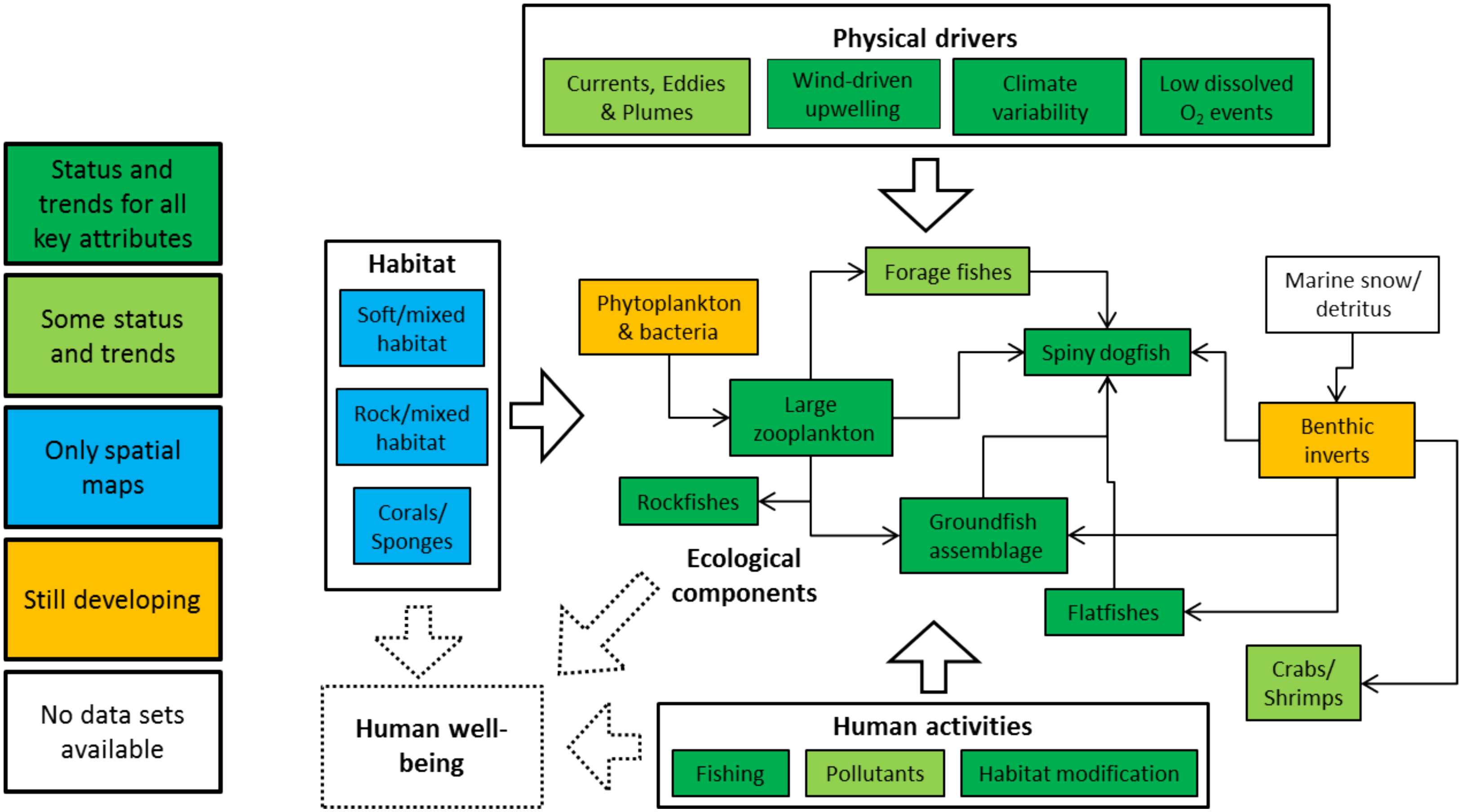

Figure 126. Present status and data gaps for the important components of the seafloor habitat's conceptual model in WAMSP waters.

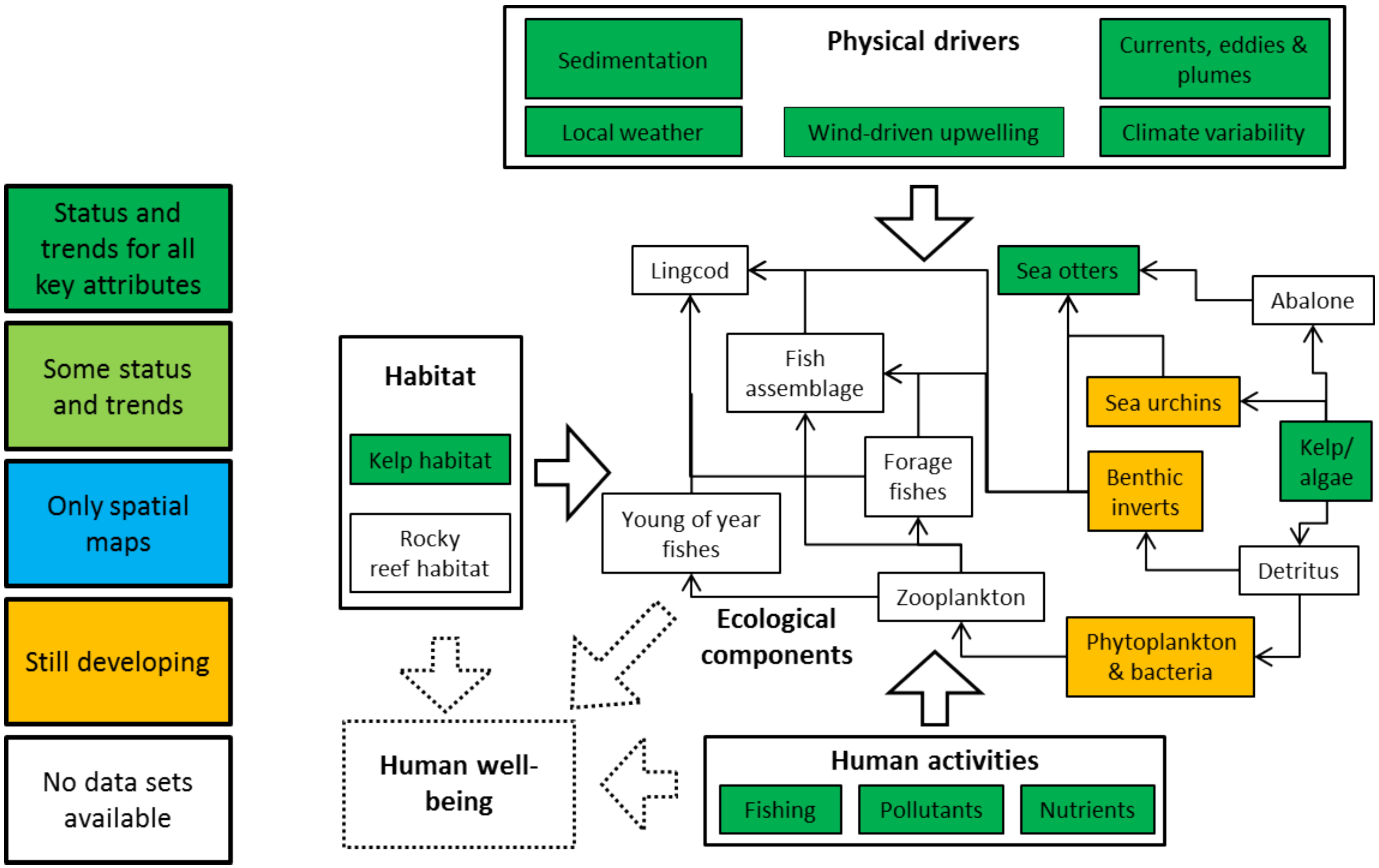

Figure 127. Present status and data gaps for the important components of the kelp forest habitat's conceptual model in WAMSP waters.

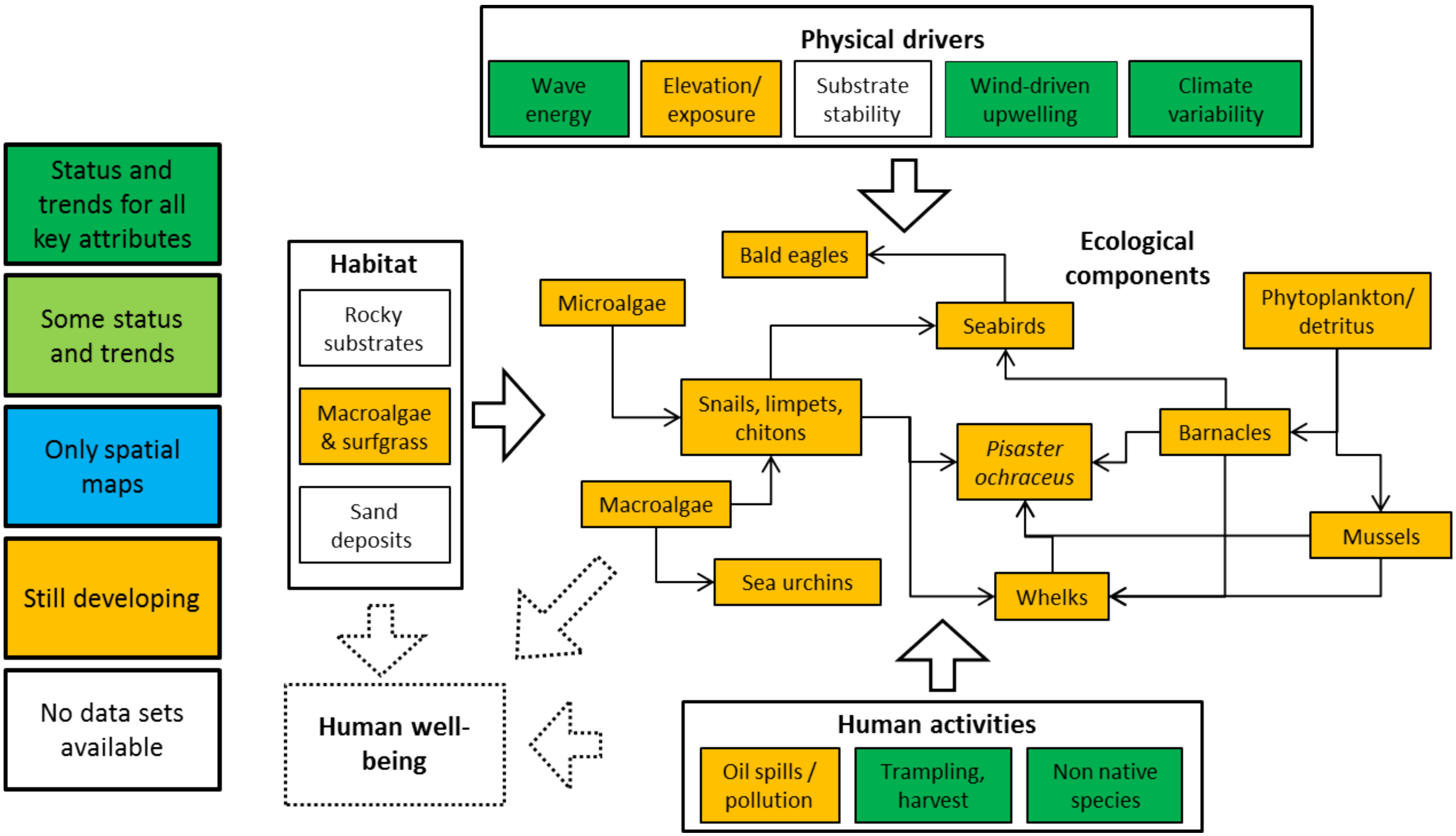

Figure 128. Present status and data gaps for the important components of the rocky shores habitat's conceptual model in WAMSP waters.

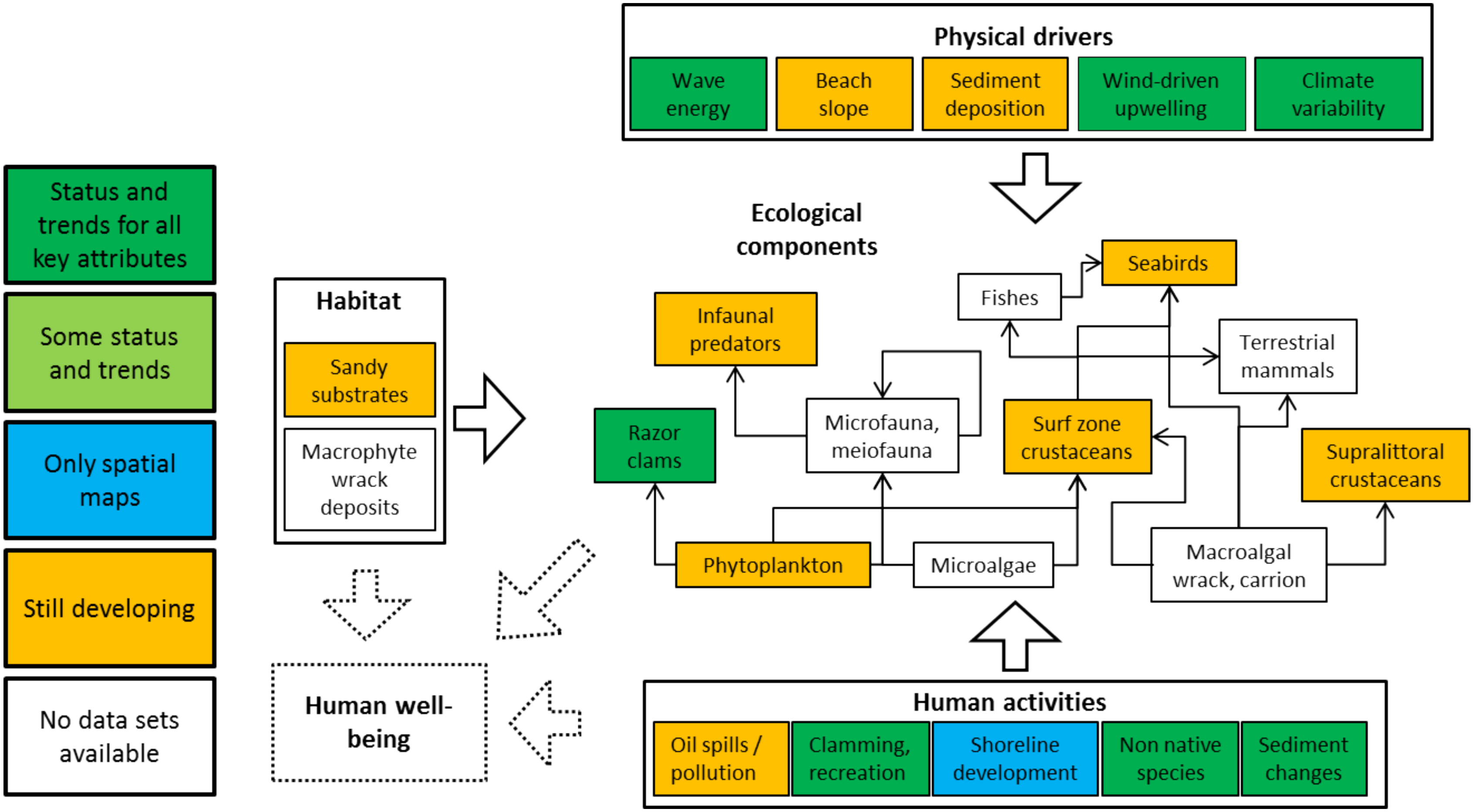

Figure 129. Present status and data gaps for the important components of the sandy beach habitat's conceptual model in WAMSP waters.

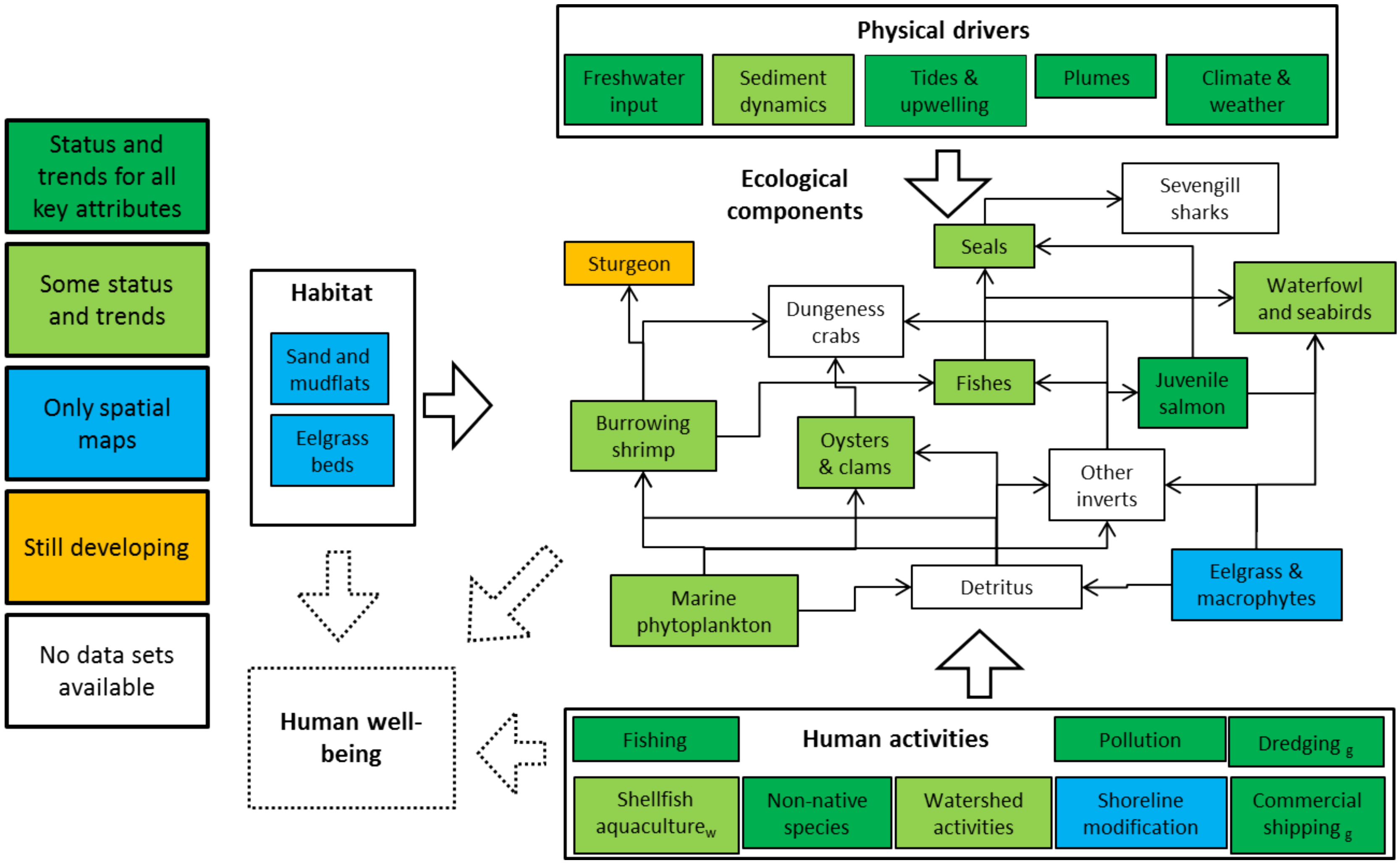

Figure 130. Present status and data gaps for the important components of the coastal estuary habitat's conceptual model in WAMSP waters.

NEXT STEPS

We developed the conceptual models of each habitat with the general goal of providing indicators, status and trends for the primary physical drivers, habitat and ecological components, and human activities most relevant. However, there are most likely too many indicators selected in this set of reports to be manageable for making management decisions relevant to Washington State's marine spatial planning process. Thus, it is our recommendation that Washington State's Marine Spatial Planning Team establish specific goals for each habitat or to identify the components across all habitats that are most relevant to the State.

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