Available Science Assessment Process (ASAP): Sea Level Rise in the Pacific Northwest and Northern California

2018




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Available Science Assessment Process (ASAP): Sea Level Rise in the Pacific Northwest and Northern California

2018

Final Report

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Table of Contents

List of Tables

List of Figures

Executive Summary

Climate change is one of the most pressing issues facing natural resource management. The disruptions it is causing require that we change how we consider and implement conservation and resource management in order to ensure the future of habitats, species, and human communities, whether that means adopting new management actions or adjusting the ways in which existing actions are implemented. However, practitioners often struggle with how to identify and prioritize specific climate adaptation actions, which are taken to either increase/enhance resilience or decrease vulnerability in a changing climate. Management actions may have a higher probability of being successful if they are informed by available scientific knowledge and findings. The goal of the Available Science Assessment Process (ASAP) is to synthesize and evaluate the body of scientific knowledge on specific, on-the-ground climate adaptation actions to determine the conditions, timeframes, and geographic areas where particular actions may be most effective for resource managers. This project identified sea level rise-related adaptation actions applied by resource managers, and evaluated the science behind those actions that may inform – if not improve – coastal planning and management in the Northwest.

Project Approach

Through the initial ASAP project focused on fire (Gregg et al. 2016), we examined the top mentioned climatic stressors in several federal, state, and tribal climate change strategy documents that have been developed at national, regional, and local scales; in this analysis, sea level rise was an oft-cited climate impact of concern. Sea level rise is having and will continue to have a wide range of effects on coastal habitats, species, and human communities, ranging from saltwater intrusion of freshwater ecosystems and aquifers to habitat conversion and infrastructure loss. Some of these effects are already causing forced relocation of coastal communities in Alaska (e.g., Kivalina, Newtok) and Washington State (e.g., Hoh). This project was designed to identify scientific evidence that coastal management priorities may change with sea level rise, and actions that can be practically taken now to address the long-term impacts associated with sea level rise. The project team derived a methodology that utilized literature reviews and interviews, an expert elicitation process, and extensive engagement with natural resource managers and scientists from federal, state, tribal, local, nongovernmental, and private entities in the Northwest to evaluate and synthesize the body of research on sea level rise adaptation actions. A Scientific Expert Panel was convened to provide independent scientific advice and recommendations to guide the project throughout its lifetime and evaluate the science behind specific climate adaptation actions.

The project was conducted through a series of consecutive phases, each dependent on the results of a previous phase. The first phase of the project examined the ecological and socioeconomic characteristics of Northwest shorelines, as well as observed and projected trends in global, regional, and local sea level rise rates. The second phase identified which sea level rise climate adaptation actions are in use by and of interest to regional managers through a content analysis of management plans and policies, and interviews with a representative set of resource managers. We then conducted a systematic literature search and screening to identify the current state and trajectory of scientific knowledge surrounding the use of adaptation actions to address sea level rise in consultation with a Scientific Expert Panel. The final phase consisted of a workshop series to engage scientists and managers in discussions about resource management and sea level rise.

Content Analysis of Gray Literature and Results of Manager Interviews

Natural and nature-based actions (NNBAs) were the top referenced sea level rise adaptation actions in the analysis of management (i.e. gray) literature sources and those most commonly being implemented by managers. Managers also indicated that existing NNBAs will continue to be used in the future, and additional NNBAs will be incorporated where possible (e.g., protecting upland/inland space, utilizing living shorelines). Structural sea level rise adaptation actions have variable reference when comparing the gray literature with actual implementation by managers. Specifically, protective structures (e.g., seawalls) were highly referenced in the literature, but are experiencing limited and declining use by interviewed managers, largely due to their cost, lifetime, and the potential for negative ecological impacts. Policy, regulatory, and planning actions represent areas of future adaptation growth and were some of the top referenced sea level rise adaptation actions in the gray literature. Although not currently being implemented by many managers, these actions are of high interest to managers for future implementation. We elected to prioritize NNBAs for the systematic review process because they are being implemented on the ground *now*, can be scientifically evaluated (an important criterion for the systematic review process), and best match the experience of the project team and the Scientific Expert Panel.

Systematic Mapping and Scientific Expert Panel Results

Three questions were used to guide the systematic literature search and screening:

1. Are the conditions, time frames, and geographic areas for use of existing nature-based tactics for restoring and maintaining coastal ecosystems and ecological functions changing in response to sea level rise? If so, how?
2. Are there any new nature-based tools or tactics being developed for restoring and maintaining coastal ecosystems and ecological functions specifically in response to sea level rise? If so, under what conditions, time frames and geographic areas would these actions may be most effective for resource managers?
3. As they incorporate sea level rise into planning and use of nature-based methods for restoring and maintaining coastal ecosystems and ecological functions, what additional science information should managers consider?

The combination of a systematic mapping approach and input from scientific experts revealed some supporting evidence on implementation conditions under which NNBAs could or should be implemented. The Scientific Expert Panel assessed the project approach and systematic mapping findings, suggested additional literature, and provided expert input on the science on and key research needs for the use of NNBAs to address sea level rise. The science advisors also suggested areas of research and keywords that might yield additional relevant information, such as terms that might uncover older literature or papers that address climate change and adaptation, but without using those specific terms. In general, the suite of adaptation options available to managers in a given location will be highly influenced by local geomorphology, coastal assets and values at risk, the level of sea level rise protection deemed necessary, and other site-specific factors. The screened literature generally indicated that in each location, the viability of ecological alternatives to hard armoring will need to be carefully considered by comparing costs and benefits of different adaptation approaches; in some cases, hardened structures may be the only adaptation option available in order to meet high flood safety standards.

Scientists-Managers Workshop Results

Thirty-three participants from 22 organizations attended the January 2018 workshops, including representatives from federal, tribal, state, county, and city agencies, non-profit organizations, and private consulting groups. Participants were invited to comment on the ASAP methods and discuss how the literature findings correlated with managers' experiences, in addition to collaboratively identifying key research and management needs and opportunities for sea level rise adaptation actions. Attendees selected specific actions to evaluate in terms of their strengths and limitations as adaptation approaches; these included beach nourishment, cobble berms/dynamic revetments, dune restoration, oyster reefs, relocation, land acquisition and managed retreat, and conservation easements.

Concluding Thoughts

The approach used in this project successfully helped us identify the range of sea level rise adaptation actions recommended in management plans and policies and implemented on the ground by resource managers, and an overall picture of the science behind NNBAs that address sea level rise. However, there are some limitations to these findings:

- Sea level rise itself is difficult to isolate from other coastal changes, such as storm surge and king tides;
- NNBAs are not an option for all coastal areas (e.g., hard structures may be the only option for eroding cliffs);
- Some of the science identified through the systematic mapping was relevant to specific types of coastlines in the region (e.g., outer coasts vs. Puget Sound) or outside of the project geography (e.g., the Netherlands), so identifying evidence that is consistent and applicable at a regional scale was challenging; and
- Alternative pools of literature may have yielded additional resources relevant to the research questions that to date have not been rigorously synthesized.

The purpose of this report is to describe and highlight salient features and results of this ASAP. The results presented herein are meant to stimulate discussion, and are not considered to be definitive or prescriptive in nature.

Introduction

Climate change presents a variety of impacts on natural and cultural resources of concern. Managers are presented with various options on how to prepare for and respond to these impacts, ranging from habitat restoration and designation of protected areas to increased public education and outreach and broad policy changes. Identifying and implementing climate adaptation actions – taken to either increase resilience or decrease vulnerability to climate change – are key steps in climate-informed planning and management. Several adaptation case studies and guidebooks have been released in recent years with recommendations of suitable adaptation actions to address different climate impacts of concern (U.S. Agency for International Development [USAID] 2009; National Oceanic and Atmospheric Administration [NOAA] 2010; Beavers et al. 2016). However, determining when, where, and how a particular action may be best implemented is more difficult to discern and is frequently determined by context and/or site-specific characteristics. The overarching goal of the Available Science Assessment Process (ASAP) is to identify, synthesize, and assess the body of scientific knowledge on specific, on-the-ground climate adaptation actions to determine the conditions, timeframes, and geographic areas where particular actions may be most effective for achieving resource management goals.

Project Approach

One of our objectives in the initial ASAP project, which was completed in 2016 and focused on managing fire in a changing climate, was to identify the climatic stressors cited most frequently in several federal, state, and tribal climate change strategy documents that have been developed at national, regional, and local scales. In this analysis, **sea level rise** was an oft-cited climate impact of concern. In addition, members of the Northwest Climate Adaptation Science Center's Stakeholder Advisory Committee have expressed a need for scientific syntheses on a number of climate-related topics, including the effects of sea level rise on Northwest coasts. Sea level rise is having and will continue to have a wide range of effects on coastal habitats, species, and communities, ranging from saltwater intrusion of freshwater ecosystems and aquifers to habitat conversion and infrastructure loss. Some of these effects are already causing forced relocation of entire coastal communities in Alaska (e.g., Shishmaref [Gregg 2010a] Kivalina [Gregg 2010b], Newtok [Feifel and Gregg 2010]) and Washington State (e.g., Hoh [Institute for Tribal Environmental Professionals 2012]). This project was designed to identify scientific evidence that coastal management priorities may change with sea level rise, and actions that can be practically taken now to address the long-term impacts associated with sea level rise.

This project was conducted with the support of a Scientific Expert Panel. We solicited their expertise and input on topics and literature related to natural and nature-based approaches to addressing sea level rise. In consultation with the Northwest Climate Adaptation Science Center, 11 potential candidates were identified from Washington, Oregon, and California. The candidates were prioritized based on their expertise related to coastal ecology, geology, and climate change. The ASAP team secured six advisors to provide input and guide the project throughout its duration.

The project was conducted through a series of consecutive phases, each dependent on the results of a previous phase. First, we examined the ecological and socioeconomic characteristics of Northwest shorelines, as well as observed and projected trends in global, regional, and local sea level rise rates to set the stage for the project. We then identified climate adaptation actions specific to sea level rise; conducted a content analysis of federal, tribal, state, and local plans and policies; and interviewed a representative set of resource managers in order to determine actions in use in the region (Phase 2). NNBAs emerged as the clear management priorities over hard engineering and policy-based approaches. We then used a hybrid approach of conducting a systematic mapping of the scientific evidence supporting the use of NNBAs to address sea level rise in consultation with a Scientific Expert Panel workshop (Phase 3). Phase 4 consisted of a workshop series to engage scientists and managers in discussions about resource management and sea level rise.

Purpose and Organization of Report

Section 1 presents details on the geographic context of the project – the coasts of Washington, Oregon, and northern California – and provides an overview of sea level rise trends, projections, and impacts. Section 2 presents the process and results of our effort to identify, prioritize, and select specific sea level rise-related climate adaptation actions around which to conduct a systematic mapping effort (Section 3). Section 4 presents discussions from the scientists-managers' workshops held in January 2018, while Section 5 concludes the report with an assessment of the project.

1. Project Context

Regional Shoreline Descriptions

The coastal shorelines of Washington, Oregon, and northern California are highly variable, formed over the last several million years by glaciation, plate tectonics, and volcanic activity. Dynamic processes of erosion and sedimentation driven by wave action, local topography and geology, and relative sea level rise have shaped coastlines into the complex systems of rocky shores, beaches, embayments, and river deltas that exist today (Shipman 2008).

Puget Sound (includes San Juan Islands)

The Puget Sound comprises all of the inland waters created by the Strait of Georgia and the Strait of Juan de Fuca (Dethier et al. 2016a). The Sound lies in the Puget Lowlands between the Cascade and Olympic mountain ranges, and was shaped by the advance and retreat of glaciers ~15,000 years ago (Shipman 2008). Deep channels and fjords were created by flowing water and then submerged, forming the complex structure of deep channels and bays that now exist – these include the Hood Canal on the eastern side of the Sound (Shipman 2008; Schwartz & Terich 2010). The Fraser River located in the southern Strait of Georgia and the Skagit River in the northern Puget Sound supply freshwater and finer sediment to create large deltas, although much of this sediment ends up being deposited into the deep channels of the Sound (Dethier et al. 2016a). The complex coastline also contains coastal bluffs, rocky cliffs, lagoons, coastal inlets, and many other embayments; many of these are protected by barrier beaches or spits (Shipman 2008; Schwartz & Terich 2010).

Up to 70% of the population of Washington lives on Puget Sound (National Research Council [NRC] 2012). Between 25–33% of Puget Sound shorelines have been armored over the last 100 years (Shipman 2010; Mauger et al. 2015), and alterations are greatest in the southern Sound and along the Everett–Seattle–Tacoma urban corridor (Dethier et al. 2016a). The northern end was settled more recently and is less armored, so the shoreline contains greater amounts of wrack and other marine debris (Dethier et al. 2016b). Examples of protected areas include aquatic reserves in Cherry Point (Whatcom County) and Fidalgo Bay (Skagit County), marine preserves in Friday Harbor and Shaw Island (San Juan County), the Padilla Bay National Estuarine Research Reserve (Skagit County), and the Nisqually and San Juan National Wildlife Refuges (Thurston and Pierce Counties, and San Juan County), among others.

Strait of Juan de Fuca

The coastline of the Strait of Juan de Fuca runs along the northern edge of the Olympic Peninsula from Cape Flattery east to Puget Sound (Schwartz & Terich 2010). Most of the coastline consists of steep rocky shores with extensive sea cliffs of sandstone and siltstone (Schwartz & Terich 2010). The cliffs are relatively unstable in many areas, especially between Pysht and Cape Flattery, and may slump or collapse when saturated (Washington State Department of Ecology 2014). At the base of the high cliffs at Cape Flattery, weathering processes have also created caves, rock ledges, shore platforms, islands, and sea stacks where softer rock has eroded away (Schwartz & Terich 2010). Pocket beaches occur where eroded sediment is deposited; they are mostly narrow and contain plentiful driftwood (Schwartz & Terich 2010). Wave action has also created numerous spits – most notably the Dungeness Spit (4.9 miles [8 km]) and Ediz Hook (3.5 miles [5.6 km]), which enclose tidal lagoons (Schwartz & Terich 2010). A few pocket estuaries can be found from Port Angeles inland towards the Puget Sound, and tidal wetlands occur at the mouth of the Pysht River, as well as in small areas within Crescent Bay, Dungeness Bay, and Discovery Bay (Washington State Department of Ecology 2014).

The coastline of the Strait is sparsely populated, with most development clustered in Port Angeles and Discovery Bay (Washington State Department of Ecology 2014). Shoreline modification is greatest around Port Angeles, where serious erosion of the spit has occurred due to reduced sediment delivery from river dams, cliff barricades, and shoreline development (Washington State Department of Ecology 2014). Protected areas include Dungeness National Wildlife Refuge and Shipwreck Point Nature Preserve.

Outer Coast of Washington

The outer coast of Washington lies between Cape Flattery and the mouth of the Columbia River (Skewgar & Pearson 2011). Rocky shores comprised of rugged cliffs, ramps, and platforms make up about a third of the northern coast (Skewgar & Pearson 2011); sea stacks, arches, and small islands can be found between the Quillayute River and Point Grenville (Schwartz & Terich 2010). Headlands alternate with pocket beaches fed by eroded sediment, and beach substrate varies widely, with loose material comprised of large boulders, cobble, gravel, and/or muddy sand (Skewgar & Pearson 2011). On the central coast, longer stretches of sandy beach begin to occur, and rock cliffs and platforms are sand-scoured (Skewgar & Pearson 2011). Along the southern coast, long stretches of sandy beach are broken up by large coastal estuaries at Grays Harbor, Willapa Bay, and the Columbia River, as well as by numerous small pocket estuaries (Skewgar & Pearson 2011). Estuary shorelines are complex in shape and contain large areas of mudflats, salt marsh, and tidal freshwater marshes; sand flats occur on the outer edges where wave action is stronger (Skewgar & Pearson 2011). Sand dunes occur in patches from the Copalis River on the southern coast to the Columbia River, but these are much smaller and less extensive than Oregon dune systems (Skewgar & Pearson 2011).

Relatively few people live along the outer coast of Washington, and most development is clustered around the barrier beaches that enclose Grays Harbor and Willapa Bay (Washington State Department of Ecology 2014). Large estuarine areas have been filled and diked to provide agricultural land, including up to 70% of wetlands within the Columbia River Estuary (Borde et al. 2003). Upstream dams have also reduced sediment delivery to the coast, especially on the Columbia River (Skewgar & Pearson 2011), and shoreline modification is greatest around the Willapa Bay and Grays Harbor river deltas, and the outer edge of Grays Harbor (Washington State Department of Ecology 2014). Protected areas include the Olympic Coast National Marine Sanctuary and the Grays Harbor and Willapa National Wildlife Refuges, among others.

Oregon Coast

The Oregon coastline covers 416 miles (669 km) (Gardner 2015), stretching from the northern edge of California to the Columbia river at the Washington border (Komar 2010). Coastline landforms were created during subduction of oceanic plates under the continental plate, leaving behind headlands, sea stacks, and islands where softer mudstone and siltstone eroded from sea cliffs (Komar 2010). These are most common along the southern coast, where uplift has also created marine terraces up to 1,640 ft (500 m) in elevation (Komar 2010). Beaches can stretch from 32.8–328 ft (10–100 m) in length; those along the southern coast are steeper and rockier than those on the northern coast (Komar 2010). Dunes are present along 45% of the coastline, and this area includes the 40–mile long (64 km) Oregon Dunes Recreation Area between Florence and North Bend/Coos Bay on the southern coast; this is the most extensive coastal dune complex in North America (Komar 2010).

The Oregon coast is home to 225,000 people, which make up only 6.5% of the state's population, and population density is low at an average of 29 people per square mile (Oregon Coastal Management Program 2016). Around 5.4% of the coastline is armored, with 92% of the 22.5 armored miles (36.2 km) concentrated on the northern coastline around Clatsop and Lincoln Counties where human populations are high, and in Tillamook County where significant erosion occurs despite low population densities (Gardner 2015). Many estuaries and tidal wetlands have been altered, and eleven of the 43 small estuaries have jettied entrances, including Yaquina, Coos, and Rogue Bays (Ruggiero et al. 2010).

Northern California Coast

The Northern California coast from Cape Mendocino north to the Oregon border covers approximately 140 miles (225 km) of largely inaccessible coastline featuring rocky cliffs, dunes, beaches, and tide pools shaped by the forces of plate tectonics. The region is home to approximately 163,000 people and its rugged terrain has limited residential and commercial coastal development. Rivers draining the North Coast mountain ranges carry high sediment loads to the nearshore environment, forming alluvial floodplains and deltas (CDFW 2015). Other important habitats include coastal redwood forests, tidal marsh, freshwater wetlands, intertidal mudflats, and seagrass beds. Beach and dune habitats are vulnerable to invasive plant species, including the European beach grass (*Ammophila arenaria*) that outcompetes native plants (Mooney & Zavaleta 2016), while coastal estuaries and wetlands are threatened by cordgrass (*Spartina* spp.) and canary grass (*Phalaris canariensis*) (CDFW 2015). Coastal rivers such as the Klamath and Eel support salmon and steelhead populations, river otters, beavers, amphibians, and birds. Key protected areas include the Humboldt Bay National Wildlife Refuge, South Cape Mendocino State Marine Reserve (SMR), South Humboldt Bay State Marine Recreational Management Area (SMRMA), Samoa State Marine Conservation Area (SMCA), Reading Rock SMR/SMCA, Pyramid Point SMCA, National Park lands, and a variety of California State Parks.

Climate Change and Sea Level Rise

Warming global and regional air temperatures are driving increases in global and regional sea levels by accelerating terrestrial ice melt, which increases freshwater input to oceans, and causing thermal expansion of seawater, which increases ocean volume. From 1993–2010, ice loss from glaciers and the Antarctica and Greenland ice sheets contributed to observed global sea level rise on the order of 0.05 in (0.13 cm) per year, while thermal seawater expansion contributed 0.04 in (0.1 cm) per year of observed global sea level rise during the same time period (Church et al. 2013).

> **Relative sea level** is the height of the ocean surface at a given location relative to Earth's surface. **Mean sea level** is the temporal average sea level for a given location, while global mean sea level change can be calculated by comparing relative sea levels over time across the entire ocean area. An increase in volumetric ocean water, or an increase in the height of the ocean surface, is referred to as global sea level rise. Although a global phenomenon, sea level rise manifests differently and has variable impacts at regional and local scales (NRC 2012; Church et al. 2013).

The rate and magnitude of sea level rise varies along the coast of the Pacific Northwest and northern California because regional factors influence sea level dynamics (NRC 2012):

- *Shifts in the Pacific Decadal Oscillation (PDO) and El Niño Southern Oscillation (ENSO):* Shifts in PDO and ENSO phases, which occur on decadal and sub-decadal cycles, respectively, alter wind and ocean circulation patterns, which contribute to altered sea levels. Cool PDO and ENSO phases (La Niña) lower regional sea levels, while warm PDO and ENSO phases (El Niño) can significantly raise regional ocean levels, sometimes increasing relative sea level up to 12 inches during winter (Ruggiero et al. 2010; Komar et al. 2011; NRC 2012). El Niño phases also alter the direction of storm tracks and waves reaching the outer coast, combining with sea level rise to accelerate erosion (Ruggiero et al. 2010, 2013).
- *Vertical land movement:* Vertical land movement influences relative rates of sea level rise and can occur through several mechanisms.
    - *Tectonic activity:* The Pacific Northwest and northern California (i.e. north of Cape Mendocino) experience significant tectonic activity due to the Cascadia Subduction Zone. This tectonic activity manifests as upward land movement (uplift) in some areas (e.g., Neah Bay, WA and Crescent City, CA) and downward land movement (subsidence) in other areas (e.g., Puget Sound, WA and Humboldt Bay, CA) on the order of several millimeters per year. Uplift areas experience reduced rates of sea level rise or sea level fall, while subsiding areas experience increased rates of sea level rise (NRC 2012; Russell & Griggs 2012).
    - *Sediment compaction and subsurface fluid extraction:* Land subsidence can also occur through sediment compaction, which is a reduction of sediment volume due to subsurface fluid extraction (i.e. groundwater, gas, oil), extensive drainage from recently established agricultural areas, or heavy loads. Compaction rates

vary by sediment type, and although exact compaction rates for the study region are not known, it is likely that the study region will experience compaction due to the predominance of peat- and mud-rich habitats. In some cases, sediment compaction can be slowed or halted by increasing subsurface fluid inputs (e.g., groundwater recharge), but typically subsurface fluid removal activities result in some degree of irreversible compaction (NRC 2012).

  - *Isostatic rebound/glacial isostatic adjustment:* Isostatic rebound can also drive vertical land movement; isostatic rebound is a process where land elevation adjusts to the loss of gravitational pressure from melting glacial ice, increasing in areas previously covered by glaciers (e.g., northern Washington) and decreasing in other areas (e.g., Oregon, northern California, and the remainder of Washington; NRC 2012).

- *Altered accretion potential:* Coastal ecosystems receive and accumulate (accrete) sediment through three natural mechanisms: (1) longshore sediment transport in marine waters along the coast; (2) eroding sediments from backshore sources; and (3) riverine systems draining sediment from coastal watersheds (Reeder et al. 2013; Thorne et al. 2018). Human-made structures such as dams, jetties, dikes, and seawalls can disrupt or reduce sediment delivery, which undermines sediment accretion in coastal systems and prevents them from keeping pace with sea level rise (Reeder et al. 2013). Additionally, some coastal systems, such as beaches in northern Oregon, are experiencing accelerated erosion as a result of the redistribution of sediment during past El Niño events and storm cycles; reduced sand supply causes erosion to outpace accretion in these systems, leaving them increasingly vulnerable to sea level rise and accelerated erosion rates (Ruggiero et al. 2010; Reeder et al. 2013). Invasive species can also reduce accretion; for example, non-native European beach grass reduces sand accumulation in dune systems, making dunes more vulnerable to overtopping from storm surge and gradual sea level rise (Reeder et al. 2013). Wetland accretion also consists of organic matter accumulation in the soils, which can be affected by plant species presence, salinity, precipitation, and tidal inundation tolerance.
- *Loss of coastal habitats and vegetation:* Loss of coastal habitats and vegetation facilitates inland penetration of storm surge and extreme tides, which may exacerbate sea level rise and storm impacts in some locations (Glick et al. 2007; Reeder et al. 2013).
- *Earthquake events:* Earthquakes and associated drastic shifts in land elevation can significantly raise sea levels on the outer coasts, and to a lesser extent in Puget Sound (Mauger et al. 2015). Extreme events could cause changes as great as 3.3–6.6 ft (1–2 m) of sea level rise in some areas, exceeding end-of-the-century projections in a single event (NRC 2012).

Sea Level Rise Trends and Projections

Global mean sea level rose by about eight inches since 1900 and is projected to continue rising at accelerated rates through the end of the 21st century (Table 1; Sweet et al. 2017). Regional and sub-regional sea level changes are variable and fairly uncertain due to the different factors described in the previous section (Komar et al. 2011; NRC 2012). Regional sea levels (i.e. from Cape Mendocino, CA north to the Canadian border) rose at slightly lower rates than global averages during the 20th century due to tectonic uplift (Table 1; NRC 2012). Regional sea levels are projected to rise through the end of the 21st century, but there could be slight decreases in sea level in the shorter-term (i.e. 2030–2050) due to tectonic uplift and gravitational and deformational effects described above (NRC 2012).

Sub-regionally, tide gauges indicate that several areas (e.g., Puget Sound, central Oregon coast, and Humboldt Bay) mirror global trends: sea levels have been rising, in some cases (e.g., Puget Sound, Humboldt Bay) at a faster rate than global averages (Table 1), and are projected to continue rising in the future (Komar et al. 2011; NRC 2012; Russell & Griggs 2012; Mauger et al. 2015). Comparatively, some sub-regions (e.g., Neah Bay in the Strait of Juan de Fuca and Crescent City, CA) have experienced lower rates of sea level rise and/or decreases in sea level due to tectonic uplift (Komar et al. 2011; NRC 2012; Russell & Griggs 2012; CDFW 2015; Mauger et al. 2015; Petersen et al. 2015). However, accelerated rates of global and regional sea level rise are projected to outpace rates of tectonic uplift in the future, resulting in rising sea levels for most locations in the Pacific Northwest and northern California (Ruggiero et al. 2010; NRC 2012; Petersen et al. 2015).

Table 1. Global, regional, and sub-regional sea level rise trends and projections. Sourced from [A] Sweet et al. 2017, [B] Church et al. 2013, [C] NRC 2012, [D] Mauger et al. 2015, [E] Reeder et al. 2014, [F] Komar et al. 2011, and [G] CDFW 2015.

Location	Trends	Projections
Global	• Sea levels rose 0.067 in (0.17 cm) per year from 1901–2010, increasing a total of 7–8 in (16–21 cm) [A] • Sea level rise rates are accelerating; sea levels rose 3 in (~7 cm) since 1993 [A, B]	• Depending on greenhouse gas emissions scenarios, mean sea levels likely to rise [A]: o 0.3–0.6 ft (0.09–0.18 m) by 2030 o 0.5–1.2 ft (0.15–0.36 m) by 2050 o 1.0–4.3 ft (0.3–1.3 m) by 2100 • A rise in sea levels over 8 ft (2.4 m) by 2100 is possible given Antarctic ice sheet collapse [A]
Regional[1]	• Sea levels rose 0.063 in (0.16 cm) per year during the 20th century [C]	• Sea levels may rise 3.9–56.3 in (9.9–143 cm) by 2100 [C]

[1] Defined as north of Cape Mendocino, CA to the Canadian border

Location	Trends	Projections
Sub-Regional - Washington	• *Puget Sound*[2]: Sea levels rose 0.08 in (0.2 cm) per year from 1900–2008 [C] • *Western Strait of Juan de Fuca*[3]: Sea levels fell 0.07 in (0.17 cm) per year from 1934–2008 [C] • *Outer Coast*[4]: Sea levels rose 0.06 in (0.15 cm) per year from 1968–2009[5] [D]	• *Puget Sound*: Sea levels may rise 14–54 in (35.5–137 cm) by 2100 [C, D] • *Strait of Juan de Fuca*[3]**:** Sea levels may rise 3.6–56.3 in (9.1–143 cm) by 2100 [C][E] • *Outer Coast***:** Same as regional trend [C]
- Oregon	• *Columbia River Mouth*: Sea levels fell 0.01 in (0.03 cm) per year from 1925–2008 [C] • *Central North Coast*[6]: Sea levels rose 0.05 in (0.13 cm) per year from 1967–2009[5] [F] • *Central-South Coast*[7]: Sea levels rose in 0.06 in (0.15 cm) per year from 1970–2009[5] [F]	• Same as regional trend [C]; no sub-regional projections available
- Northern California	• *Crescent City***:** Sea levels fell 0.03 in (0.08 cm) per year from 1938–2008 [C] • *Humboldt Bay*: Sea levels rose 0.21 in (0.53 cm) per year from 1977–2010[5] [F]	• Same as regional trend [B] • *North of Cape Mendocino*: Sea levels may rise 4–56 in (10–142 cm) [G]

Sea Level Rise Impacts

Sea level rise threatens human communities, native ecosystems, infrastructure, and other resources of value in the Pacific Northwest and northern California (Komar et al. 2011; NRC 2012; Russell & Griggs 2012; Reeder et al. 2013; Snover et al. 2013; Mauger et al. 2015). Potential impacts of sea level rise include:

- *Enhanced coastal flooding and impacts of coastal storms:* Higher sea levels will increase the frequency, duration, and depth of coastal flooding events, particularly in low-lying and subsiding areas, potentially leading to permanent inundation of some zones (Mauger et al. 2015). Sea level rise enhances freshwater flood risk by reducing drainage capacity of low-lying coastal areas, and enhances saltwater flood risk by increasing the

[2] Based on tide gauge from Seattle, WA
[3] Based on tide gauge from Neah Bay, WA
[4] Based on tide gauge from Willapa Bay, WA
[5] Based on summer mean sea levels due to shorter length of gauge record; further explanation given in Komar et al. 2011
[6] Based on tide gauge in Yaquina Bay, OR
[7] Based on tide gauge from Coos Bay, OR; areas south of Coos Bay, OR to Crescent City, CA experienced statistically insignificant decreases in mean sea level over a similar time period (Komar et al. 2011)

penetration and reach of storm surge, large waves, and high tides (Mauger et al. 2015). Although beyond the scope of this study, it is important to note that storm frequency and intensity and wave direction and height may also be affected by climate change; continued changes in these factors will interact with rising sea levels to increase flood and erosion risk along Pacific Northwest and northern California coastlines (Ruggiero et al. 2010; Reeder et al. 2013).

- *Enhanced coastal erosion and shoreline retreat:* Sea level rise will likely increase erosion of bluffs, dunes, and beaches in most areas. Shoreline armoring may reduce retreat potential locally, but will increase habitat loss and raise potential for infrastructure damage over the long term (Reeder et al. 2013).
- *Loss and change in coastal ecosystems and habitat availability:* By increasing erosion and inundation frequency, depth, and duration, sea level rise will likely contribute to the loss or reduction in area of some coastal ecosystems, including outer coast and estuarine beaches, coastal freshwater wetlands, brackish and tidal marsh, tidal flats, and tidal swamps (Ruggiero et al. 2010; Mauger et al. 2015). Impacts will be particularly acute for systems that have limited opportunities to migrate inland because they are backed by coastal infrastructure, steep slopes and topography, or natural bluffs (Mauger et al. 2015). Sea level rise will cause shifts in overall habitat distribution, in some cases transitioning to and/or expanding certain habitat types such as eelgrass, saltwater and transitional marsh, and potentially tidal flats, by inundating new areas (Reeder et al. 2013; Mauger et al. 2015). Sea level rise can also alter coastal habitats by changing biophysical characteristics of the habitat, such as surface water, groundwater, and soil salinity (Ruggiero et al. 2010; Reeder et al. 2013). Salinity changes may reduce habitat extent for some species and/or facilitate invasive species establishment (Reeder et al. 2013). Similar to salinity changes, sea level rise can also cause shifts in water temperature and the penetration of nutrient rich and low dissolved oxygen water into regional marshes and estuaries (Ruggiero et al. 2010), altering habitat suitability and species composition. Additionally, greater water depth will affect light penetration, affecting benthic communities and submerged aquatic vegetation (Environmental Protection Agency [EPA] 2014). Overall, alterations to coastal ecosystems are likely to affect critical ecosystem services, such as flood protection, recreation opportunities, and commercial fisheries (Mauger et al. 2015). Shifting coastal habitat availability will also alter available habitat for species of conservation, aesthetic, and economic concern, such as salmonids, pinnipeds, and migratory birds (Ruggiero et al. 2010; Reeder et al. 2013).
- *Decreased water quality:* Sea level rise increases the likelihood of saltwater intrusion in coastal aquifers, particularly if co-occurring with increased rates of groundwater withdrawal. Aquifer saltwater intrusion is already occurring in San Juan and Island Counties in Washington (Mauger et al. 2015). Sea level rise also increases salinity intrusion upstream in regional rivers and estuaries. Saltwater intrusion in both surface and groundwater sources degrades water quality and will likely increase drinking water treatment costs for regional communities (EPA 2015a). Additionally, tidal flooding in

new areas as a result of sea level rise could increase exposure to new or additional contaminant sources (EPA 2014).

- *Increased costal infrastructure damage/loss and economic impacts:* Increased coastal flooding, storm exposure, and erosion as a result of sea level rise will likely increase damage to regional industrial, commercial, transportation, utility, flood and erosion protection, and residential infrastructure (Ruggiero et al. 2010). For example, many hard armoring structures along the Oregon coast are vulnerable to inundation from sea level rise, which can enhance the vulnerability of land uses behind those structures (e.g., private homes, agriculture; Ruggiero et al. 2010). Sea level rise may also contribute to the degradation or loss of recreational and tourism areas and culturally important sites, including burial grounds and traditional fishing and shellfish gathering areas (Ruggiero et al. 2010; Lynn et al. 2013; Mauger et al. 2015). Infrastructure damage, combined with the alteration and loss of many coastal habitats, is likely to cause significant economic impacts on coastal economies in the Pacific Northwest (Reeder et al. 2013).
- *Impaired coastal utility functioning:* Higher sea levels may also impair the functioning of regional wastewater, stormwater, and drinking water utilities. Wastewater treatments plants are likely at risk for inundation due to their location at the lowest point of the watershed. For both wastewater and stormwater systems, sea level rise and saltwater intrusion and infiltration into outfall segments may increase pumping costs, cause unsanitary backflows, reduce the effectiveness of gravity-based drainage systems, and cause corrosive damage (Ruggiero et al. 2010; EPA 2014). Drinking water systems are typically less vulnerable due to their higher elevation (EPA 2015a), but may become vulnerable if salt fronts expand far enough upstream to affect intake sites or groundwater sources experience saltwater intrusion (EPA 2014). Additionally, existing desalination plants would likely be vulnerable as a result of their lower elevation and position next to the coastline (EPA 2015a).

2. Sea Level Rise Adaptation

The wide-ranging effects of sea level rise on ecosystems, ecosystem services, and human communities throughout the Pacific Northwest and northern California create major conservation and management challenges, forcing a paradigm shift in decision-making. Decisions are compounded at local-to-subregional scales because coastal communities and ecosystems have been subject to varied land use and ownership histories and management objectives, which may influence vulnerability to current and projected sea level rise and related coastal hazards. Management decisions are further compounded by different planning horizons, as action must be taken to deal with immediate- or near-term stressors (e.g., El Niño events, king tides) whilst simultaneously planning for and reducing vulnerability to long-term stressors (e.g., sea level rise; Ruggiero et al. 2010; Gregg et al. 2011; Russell & Griggs 2012; Snover et al. 2013; Gregg et al. 2016).

The purpose of this phase was to achieve a better understanding of the range of climate adaptation actions available to coastal managers and to identify which actions are being prioritized and implemented on the ground in response to sea level rise along the coasts of Washington, Oregon, and northern California.

Identifying Sea Level Rise Adaptation Actions

There are many adaptation approaches proposed and being taken by coastal managers in response to sea level rise in both the Pacific Northwest and broader United States (Huppert et al. 2009; Grannis 2011; Gregg et al. 2011; Russell & Griggs 2012; Farstad et al. 2013; Bridges et al. 2015). These approaches include:

- *Natural approaches:* utilization of existing features that are formed and change over time in response to natural forcing processes (e.g., coastal habitats);
- *Nature-based approaches*: engineered systems that mimic natural approaches but may include engineered features;
- *Structural approaches:* engineered structures designed to minimize flooding and erosion; and
- *Policy, planning, and regulatory approaches:* land-use planning, management, and regulatory tools that either prevent human activities in at-risk areas or modify how activities or projects are implemented to reduce risk to sea level rise and related damage.

Adaptation options can also be categorized based on their purpose: *protect* against sea level rise, *accommodate* sea level rise, *retreat* in the face of sea level rise, and *avoid* the impacts of sea level rise (Huppert et al. 2009; Farstad et al. 2013; Systems Approach to Geomorphic Engineering [SAGE] 2015).

- *Protect:* Actions that minimize sea level rise impacts by preventing seawater from reaching resources of interest or intruding in coastal areas. Protection strategies may utilize natural and nature-based solutions, structural solutions, or hybrid approaches.
- *Accommodate*: Actions that maintain continued occupation of coastal areas but modify coastal landscapes, infrastructure, and activities to accommodate higher water levels and occasional flooding.
- *Retreat:* Actions that accept and anticipate loss of sites vulnerable to sea level rise and/or exacerbated coastal hazards and that actively abandon, withdraw, or relocate assets to less vulnerable locations.
- *Avoid:* Actions that intentionally avoid sea level rise impacts by preventing or restricting development and other projects in current and projected coastal hazard zones. Avoidance actions are typically comprised of a variety of regulatory, planning, and policy tools in coastal floodplains and flood-prone areas.
- *Other:* Any climate adaptation actions that do not clearly fit within the *protect*, *accommodate*, *retreat*, *avoid* framework (e.g., minimize non-climate stressors that can exacerbate sea level rise impacts).

Based on management goals (i.e. protect, accommodate, retreat, avoid), there is a variety of different sea level rise climate adaptation actions and associated implementation tactics available to and in use by coastal managers (Table 2; Huppert et al. 2009; Grannis 2011; Gregg et al. 2011; Russell & Griggs 2012).

Table 2. Sea level rise actions and implementation tactics according to different management goals. NNBAs are italicized.

Management Goal	Sea Level Rise Adaptation Actions	Implementation Tactics
PROTECT	Protect/restore natural habitat areas such as: • *Dunes* • *Beaches (sand, gravel, cobble)* • *Spits (natural or man-made)* • *Rocky coastlines* • *Wetlands* • *Tidal marshes* • *Forested and scrub-shrub tidal wetlands* • *Maritime forests/shrubs* • *Oyster reefs* • *Seagrass beds* • *Kelp* • *Bluffs* • *Upland/inland/transitional habitat* • *Offshore islands*	• *Maintain habitat gradients and linked habitats (e.g., mudflat/wetland complexes)* • *Integrate sea level rise into restoration and protection plans* • Utilize tax or financial incentives for protecting/restoring natural habitats

Management Goal	Sea Level Rise Adaptation Actions	Implementation Tactics
	Protect/restore natural tidal connectivity and hydrologic regimes	• *Preserve systems with intact floodplains* • *Restore natural vegetation* • *Restore tidal channel systems* • *Reconnect tributary streams* • *Remove dams* • *Remove dikes/levees* • *Remove tide gates* • *Remove restrictive culverts* • *Remove bulkheads* • *Remove barriers to subsurface flows*
	Protect/restore natural sediment regime (i.e. sediment introduction, retention, accretion)	• *Beach/dune nourishment* • *Dune revegetation* • *Sand fencing* • *Protect/promote feeder bluffs* • Ensure human activities and development do not disrupt vital sediment supply
	Protect/restore system engineers that structure/maintain habitat	• *Increase beaver populations in upland areas* • *Protect seagrass beds to support wave attenuation and sediment trapping* • *Revegetate tidal habitats (i.e. marsh and dunes) with native vegetation for sediment retention or trapping*
	Utilize living shorelines	• *Vegetative buffers* • *Edging* • *Sills* • *Large wood placement* • *Live staking* • *Beaver dam analogs*
	Identify and protect sea level	• *Cliffs with slower erosion rates*

Management Goal	Sea Level Rise Adaptation Actions	Implementation Tactics
	rise refugia	• *Tidal wetlands projected to keep pace with sea level rise* • *Tidal wetlands backed by suitable landward migration areas (low gradient topography and open space)*
	Construct/maintain protective barriers	• Breakwaters • Groins • Revetments/riprap • Bulkheads • Seawalls • Levees/dikes • Tide gates and restrictive culverts • Berms
ACCOMMODATE	Protect space for upland/inland habitat migration	• *Conservation easements/Open space designations* • *Plant salt- or flood-tolerant species* • Rolling easements • Minimum development buffers • Land acquisition • Tax or financial incentives
	Retrofit coastal infrastructure	• Elevate infrastructure • Raise site grades • Convert to floating infrastructure • Convert to mobile infrastructure • Move critical uses to higher floors • Modify outfalls to reduce saltwater intrusion
	Utilize green infrastructure/floodable development	• *Rain gardens* • *Bioswales* • *Floodplains* • Permeable pavement • Watertight doors/windows/pump casings • Submersible pumps

Management Goal	Sea Level Rise Adaptation Actions	Implementation Tactics
		• Lined pipes • Backflow prevention devices • Flap gates • Gasketed/bolted manhole lids and sealed manholes
	Increase/enhance flood warning systems and preparedness education	• Integrate sea level rise, storm surges, and flooding into emergency management and hazard mitigation plans • Conduct education/outreach to vulnerable property owners • Invest in/utilize flood prediction/forecasting system
RETREAT	Managed retreat/realignment	• Inland/upland relocation of facilities, transportation infrastructure, armoring, or other development • Practice climate-informed site relocations • Remove barriers to upland habitat migration (i.e. levees)
	Abandon coastal infrastructure	• Leave infrastructure in place • Structure purchase and demolition
AVOID	Limit development in vulnerable areas	• Update floodplain maps (e.g., replace 100-year with 500-year floodplain) • Downzoning • Zoning overlay • Moratorium on development
	Transfer development rights	• Buyouts/Acquisition in fee • Tax incentives • Transferable development credits • Defeasible estates
	Incorporate sea level rise into coastal land-use policy and management	• Incorporate sea level rise into existing and new policies, plans, and projects (e.g., Comprehensive Plans, Shoreline Management Plans, design and development codes and siting, capital improvement projects) • Require setbacks and buffers • Building/rebuilding restrictions (e.g., raise freeboard requirements)

Management Goal	Sea Level Rise Adaptation Actions	Implementation Tactics
		• Sea level rise exactions (i.e. development permits that include resilience and retreat requirements) • Utilize incentive programs that promote sea level rise resilience • Remove incentive programs that promote vulnerable development • Enhanced flood insurance requirements • Require sea level rise real estate disclosures
OTHER	Reduce non-climate stressors that exacerbate sea level rise impacts or reduce resilience	• Minimize oil and groundwater extraction • Remove armoring that increases erosion, accretion, and/or limits habitat upland migration • Restrict land uses that damage or impair ecosystem processes and functions • Increase enforcement of current armoring rules and regulations

Many of these actions are already in use by coastal managers across the Pacific Northwest and northern California to meet different management goals and objectives. However, these actions can also be leveraged to enhance overall coastal resilience to sea level rise. Additionally, managers may choose to alter the implementation or application of existing management actions to adapt to changing conditions, or develop novel management actions to respond to emerging sea level rise challenges (Figure 1).

Continue Existing Management Action	***Alter Implementation of Existing Management Action***	***Create Novel Management Action***
Protect and restore coastal wetland habitat	Prioritize protection and restoration of coastal wetland sites with room to migrate inland as sea levels rise (i.e. sea level rise refugia)	Purchase inland/upland land to create new opportunities for coastal wetland migration as sea levels rise

Figure 1. Example continuum of sea level rise adaptation actions.

Sea Level Rise Adaptation Approaches

Given the variety of sea level rise adaptation actions available to and in use by coastal managers (Table 2), and the utilization of many of these actions for other resource objectives, managers may want to consider how each action and associated implementation tactics can be leveraged to minimize sea level rise vulnerability. Additionally, managers should consider known implementation strengths and weaknesses, such as cost, long-term viability and maintenance requirements, vulnerability to other climate change impacts, and whether an implemented action can meet multiple management objectives.

Although the literature divides sea level rise adaptation actions into different categories, as discussed below, many sea level rise adaptation actions are interrelated and can achieve multiple management objectives. For example, avoidance strategies, which are typically focused on keeping human communities out of harm's way by preventing development in vulnerable areas, can also garner significant ecological benefits by protecting and maintaining ecosystems and ecosystem processes that support sea level rise resilience, and by providing space to accommodate higher water levels (Grannis 2011). Specific examples include:

- Use of development setbacks along eroding bluffs: Setbacks protect human life and property by reducing risk of structure loss to erosion and reduce economic costs by limiting the need for shoreline armoring or structure relocation. However, setbacks also allow natural bluff erosion processes that provide critical sediment and help other nearshore habitats keep pace with sea level rise (Shipman et al. 2014).
- Preventing floodplain development: Preventing floodplain development, especially in areas that will act as sea level rise refugia, can protect valued tidal wetland and floodplain habitats, and also provide areas for these habitats to migrate in response to rising sea levels. In return, tidal wetland and floodplain habitats provide critical ecosystem services that can buffer human communities from rising water levels. Additionally, preventing human development in low-lying areas significantly reduces

flood risk and associated economic costs for recovery, repair, and relocation (Gregg et al. 2011; Brophy & Ewald 2017).

Protection Strategies

Protect or restore natural habitat areas

Natural habitat areas are created and maintained by natural physical, biological, geologic, and chemical processes, and include a variety of coastal habitats (e.g., wetlands, oyster reefs, seagrass beds, beaches, dunes, marshes). In the context of sea level rise, protecting and restoring natural habitat areas helps to maintain or create a continuum between the water and land that accommodates dynamic water conditions while helping diminish wave energy, moderate extreme water flows (e.g., by slowing inland water transfer and/or storing water), promote groundwater infiltration, and stabilize the shoreline. Functioning, healthy natural habitats may be able to keep pace with sea level rise, requiring no further investment, but natural areas may become vulnerable to inundation if they are deprived of sediment supply and/or if they are unable to migrate inland (U.S. Army Corps of Engineers [USACE] 2013; SAGE 2015; Brophy & Ewald 2017). Additionally, natural habitats may be vulnerable to other climatic changes, such as increasing air and water temperatures and altered salinity and ocean pH (USACE 2013; SAGE 2015).

Adaptation in Action: Dune Restoration in Humboldt and Del Norte Counties, California

The U.S. Fish and Wildlife Service (USFWS) and other partners are restoring native sand dunes in Humboldt and Del Norte Counties in northern California by removing invasive vegetation and re-planting native vegetation. Removal of invasive vegetation prevents dune over-stabilization, restoring dynamic sand processes to which native dune species are adapted. Dynamic native-dominated dunes are more resilient to changing sea levels, as they are able to naturally migrate and move in response to changes in sea level and erosion. Dynamic dunes maintain critical habitat for endangered coastal species, such as the western snowy plover, and also maintain flood and erosion buffering services for human communities (National Park Service [NPS] 2018; USFWS 2018a).

Protect or restore natural tidal connectivity and hydrologic regimes

Protecting or restoring tidal connectivity and hydrological regimes promotes natural dynamic processes than can enhance resilience to sea level rise by promoting sediment accretion and flood water storage, and by creating space for inland/upland migration. Implementation tactics largely fall into two categories:

- <u>Protection and restoration of floodplains and tidal channels</u>: Protecting intact floodplain systems and restoring rivers and tidal channels that were historically cut off or straightened increases water storage potential and complex and transitional habitat areas that may provide sea level rise refugia (USFWS 2018b). Restored natural habitats with intact tidal and hydrological regimes may be able to keep pace with sea level rise, requiring no further investment. However, these habitats may also be exposed to other climatic changes that alter ecosystem function or persistence (e.g., air temperature increases, altered freshwater flooding regimes; USACE 2013; SAGE 2015). Additionally, restoration and protection efforts typically require significant collaboration amongst diverse partners (USFWS 2018b).

- <u>Removal of man-made hydrological barriers (dams, levees, bulkheads, tide gates, restrictive culverts, subsurface flow barriers)</u>: These tactics involve the demolition and complete removal of man-made structures, or significant modification of structures to allow water passage (e.g., breaching levees, modifying tide gates). Removal of man-made barriers to tidal and hydrological connectivity garners many sea level rise adaptation benefits, including increased sediment delivery and accretion, and increased access to upland/inland habitat migration areas. Removing man-made hydrologic barriers may minimize long-term costs associated with maintaining aging infrastructure in the face of sea level rise and other climatic changes. However, structure removal projects may conflict with existing human land uses and/or human safety by increasing flood and erosion risk. Additionally, many barrier removal tactics can be costly, require significant collaboration amongst stakeholders, and can cause short-term impacts on nearshore and coastal ecosystems until hydrologic and sediment regimes stabilize (Czuba et al. 2011; Johannessen et al. 2014; Parsons & Allen 2015; USFWS 2018b).

Adaptation in Action: Restoring Hydrologic and Tidal Connectivity

Salmon Creek Delta, California
In northern California, the Humboldt Bay National Wildlife Refuge is using a combination of approaches to restore estuarine and floodplain hydrologic connectivity in the Salmon Creek delta. Hydrologic and tidal connectivity in the estuary has been restored by modifying and replacing tide gates with updated designs that allow constant flow exchange and fish passage. Tidal channels that were historically straightened or filled have also been excavated and given more sinuosity, restoring access to off-channel rearing habitat and increasing channel water storage capacity. Excavation material was used to raise the site elevation of an adjacent salt marsh, which was slowly transitioning to mudflat as a result of subsidence. Combined, these actions create a more resilient landscape by promoting water storage and tidal exchange, and restored a subsiding salt marsh by providing critical sediment (USFWS 2018b).

Nisqually River Delta, Washington
At the Nisqually National Wildlife Refuge in Puget Sound, four miles (6.4 km) of dike were removed in 2009 to return tidal flow to a degraded delta area. Paired with tidal marsh and surge plain forest restoration, this effort has resulted in the reconnection and restoration of over 21.7 miles (35 km) of tidal slough, and increased salt marsh habitat in southern Puget Sound by 55%. These restored habitats have an enhanced capacity to buffer sea level rise and storm surges (Feifel and Gregg 2015).

Protect or restore natural sediment regimes

Protecting and restoring natural sediment regimes helps existing coastal habitats keep pace with sea level rise by promoting accretion through stabilizing existing sediment and promoting additional sediment capture and retention. Implementation tactics include:

- Beach and dune nourishment: Adding externally-sourced material (sand, cobble) to eroding beaches and dunes in order to widen and elevate the habitat and push the shoreline seaward (Johannessen et al. 2014). Beach nourishment helps minimize wave attack, offset erosion, and reduce water penetration in backshore and upper beach zones, and can also supply sediment to down-drift beaches. Although introducing sediment can help maintain eroding systems, artificial sediment addition may alter regional sediment transport patterns, cause burial or mortality of current beach organisms and alteration of existing ecological processes, or introduce external contaminants with unintentional consequences. Additionally, artificial sediment additions typically must continue in perpetuity to continue to combat sea level rise, which can be costly and/or generate sediment supply challenges (Zhu et al. 2010).
- Dune revegetation: Planting native vegetation in dune systems to help capture and anchor sand (Zhu et al. 2010; USACE 2013). Seedlings accumulate wind-blown sediment around stems, promoting dune growth. Native plantings can be sourced from nurseries or adjacent dune systems. Dune rehabilitation offsets coastal erosion and helps dunes keep pace with sea level rise by capturing sediment, which maintains the many ecosystem services they provide (e.g., wave and flood protection for upland and inland areas, sediment source for fronting beaches). Although this alternative is fairly easy and inexpensive to implement, native vegetation may be vulnerable to additional climatic changes (e.g., shifts in temperature and precipitation). Additionally, maintaining dunes requires a large land footprint, which can compete with coastal development objectives (Zhu et al. 2010).
- Sand fencing: The placement of sand fencing on seaward slopes of existing dunes to stabilize existing bare sand and trap additional sediment (Zhu et al. 2010). Sand fencing is typically comprised of natural materials (e.g., branches, reed stakes) that eventually break down naturally. Similar to dune revegetation, sand fencing helps offset dune erosion and promotes the continuation of dunes and the services they provide in the face of sea level rise, but does require a larger areal footprint than some other adaptation measures (Zhu et al. 2010).
- Protect/restore feeder bluffs: Protection or restoration (e.g., via removal of bulkheads and coastal armoring) of feeder bluffs, which are eroding coastal bluffs that provide sediment to regional beaches. Feeder bluff protection and restoration helps offset beach loss to erosion by supplying critical backshore sediment. However, maintaining beach sediment supply from these bluffs may conflict with regional development and armoring objectives (Shipman et al. 2014).

Adaptation in Action: Feeder Bluff Restoration in Kitsap County, Washington

Kitsap County, Washington is attempting to restore natural feeder bluff dynamics to create resilient beach habitats. After a county-wide analysis that identified and prioritized potential restoration projects, the County completed a feeder bluff restoration demonstration project at Anna Smith Park. The demonstration project removed 650 feet of an old bulkhead, along with associated riprap and pilings, reconnecting the feeder bluff to the beach and freeing impounded sediment (Kitsap County 2012; Shipman et al. 2014).

Protect or restore ecosystem engineers that structure or maintain habitat

Ecosystem engineers are species (e.g., beavers) or species assemblages (e.g., native marsh and dune vegetation) that create, maintain, or modify habitats and natural processes. In the context of sea level rise, protecting and restoring ecosystem engineers can help create healthy, natural habitats that may be more resilient to rising water levels, potentially reducing the need for further investment and management (Pollock et al. 2015; Reynolds 2018). However, as biologic entities, ecosystem engineers and the habitats they create may be vulnerable to additional climate changes, such drought, shifts in riverine flooding frequency, or ocean acidification (USACE 2013; SAGE 2015). Additionally, managers may have limited control of exactly where and how ecosystem engineers modify the landscape after initial placement (Pollock et al. 2015). Example ecosystem engineers include:

- <u>Beaver:</u> Beaver dams expand wetland area and increase floodplain connectivity, which may help accommodate rising water levels. Beaver dams also promote local aquifer recharge and higher water tables, which can combat saltwater intrusion (Pollock et al. 2015).
- <u>Seagrass beds:</u> Seagrass beds help attenuate wave energy and height by slowing water velocity through their canopy, which may help reduce coastal erosion and inland wave reach as sea levels rise (John et al. 2016). Seagrass beds also help capture sediment, promoting accretion (Reynolds 2018).
- <u>Native tidal vegetation:</u> Native vegetation in tidal habitats, including marshes and dunes, helps capture and anchor sediment, promoting accretion (Zhu et al. 2010; USACE 2013).

Utilize living shorelines

Living shorelines, often referred to as nature-based solutions, are areas designed and constructed by humans to mimic the coastal protection function of natural habitats. Living shorelines also benefit native habitats by providing a more permeable landscape for inland migration and helping trap and accrete sediment. Living shoreline footprints are comprised predominately of native material (e.g., plants) that may be integrated with natural or nature-based structural features (e.g., oyster shells, biologs, concrete reef balls, rock) (NOAA 2015; SAGE 2015). Native vegetation helps minimize erosion by stabilizing sediment with roots, promotes groundwater infiltration, and helps slow water and diminish wave energy, buffering upland areas from flooding. Although often cheaper than hard infrastructure solutions, living shorelines can require long-term maintenance (e.g., replanting post-storms, re-anchoring logs).

Additionally, many of these tactics are vulnerable to eventual inundation from sea level rise, and vegetation establishment and growth may be affected by other climate changes. Living shoreline implementation tactics include:

- Vegetative buffers: Planting native vegetation adjacent to water to buffer upland areas from small waves and to hold sediment in place via roots (SAGE 2015).
- Edging: Utilizing structures to hold the toe of existing vegetated slope in place to avoid erosion (SAGE 2015).
- Sills: Material (stone, sand breakwaters, living reef, rock gabion baskets) placed parallel to existing shoreline to reduce wave energy, minimize erosion, and promote shoreward deposition (Julius & West 2008; SAGE 2015). Sills typically require more land area than edging.
- Large wood placement: Anchoring or burying of large tree trunks with and without root wads on existing shoreline to slow shoreline erosion, increase habitat complexity, and promote backshore sediment capture and accretion. This tactic can be used in combination with other soft shoreline methods (e.g., beach nourishment, vegetated buffers). High-water events could mobilize logs if they are not properly anchored, and this approach may also require minor long-term maintenance (e.g., nourishment, re-anchoring logs; Johannessen et al. 2014).
- Live staking: Planting of dormant, woody plant cuttings that will eventually form roots and new branches and revegetate bank. The vegetation stabilizes sediment, reducing erosion (Natural Resource Conservation Service [NRCS] 2018).
- Beaver dam analogs: Artificial, channel-spanning structures made of natural, biodegradable materials (e.g., willow branches, sediment) that mimic or reinforce natural beaver dams (see benefits discussed under ecosystem engineers, above). These are temporary landscape features whose function is altered by water flow, sediment, and beaver activity. Beaver dam analogs modify both upstream and downstream landscapes, meaning that maintenance over time is required to maintain beaver dam analog presence and benefits (Pollock et al. 2015).

Adaptation in Action: Replacement of Hard Armoring with Soft Armoring on Bainbridge Island, Washington

On Bainbridge Island in Washington, failing bulkheads along a ¼ mile of private shoreline property were removed and replaced with native vegetative buffers expected to respond more dynamically to rising sea levels. Following armoring removal, there was a 163% increase in salt marsh and intertidal area fronting the property. The project team also enhanced 33,000 square feet of riparian habitat vegetation cover by removing invasive species and planting over 2,650 native shrubs, trees, and other plants. Overall, the restoration project cost less than repairing the failing bulkheads, and garners similar flood and erosion protection through use of natural vegetation that stabilizes soils and is aesthetically pleasing (West Sound Watersheds Council 2015).

Identify and protect sea level rise refugia

Refugia areas are locations where sea level rise impacts are less severe or are occurring at a slower rate. Example sea level rise refugia include: cliffs or bluffs with slower erosion rates; marshes and estuaries accumulating sediment at rates comparable with sea level rise; tidal wetlands or estuaries backed by open space that is low-lying and suitable for landward migration; upland/upriver wildlife migration corridors; unimpaired/unaltered floodplains; and healthy oyster reefs (Gregg et al. 2011; Thorne et al. 2015; Brophy & Ewald 2017). Protecting resilient areas (e.g., by limiting development, maintaining open space) theoretically results in less long-term management requirements, but there is the possibility that these areas will eventually become vulnerable to inundation or will be affected by other climatic impacts (Gregg et al. 2011).

Adaptation in Action: Identification of Tidal Marsh Landward Migration Zones in Oregon

If tidal marshes cannot accrete enough sediment to keep pace with sea level rise, vegetation will need to migrate landward to survive. A recent modeling effort has mapped landward migration zones (i.e. areas that could host future tidal wetlands) for 23 Oregon estuaries south of the Columbia River. Landward migration zones were mapped for each estuary under six different sea level rise scenarios that could occur between the present and 2160. The study also demonstrated how landward migration zones can be prioritized for protection and restoration using a series of criteria, including available landward migration zone area under a given sea level rise scenario, available migration area under additional increases in sea level, land ownership, zoning, and development status. The results of this study can inform landscape-scale refugia planning; for example, the resultant maps can be used as a communication tool to engage with willing landowners and land-use planning agencies in order to promote habitat restoration and the retention of existing open space that could function as critical habitat in the future (Brophy & Ewald 2017).

Construct or maintain protective barriers

Sometimes referred to as “hard shoreline stabilization”, “armoring”, or “gray infrastructure”, structural protective barriers create a buffer between the water and land to protect vulnerable coastal resources and infrastructure from storms, wave action, and coastal erosion by keeping seawater and waves at bay (NOAA 2015). Although successful at reducing short-term coastal vulnerability to erosion and wave damage, protective barriers may be less effective at dealing with sea level rise-related flooding over the long-term. Additionally, protective barriers are often costly to install and maintain (SAGE 2015), and can degrade adjacent ecosystems by disrupting water and sediment delivery along-shore and between the upland and nearshore (Reeder et al. 2013), enhancing erosion of unreinforced systems, replacing native material and habitat, and introducing contaminants (SAGE 2015). Examples of protective barriers include:

- Breakwaters: Offshore structures parallel to shoreline, designed to break waves and promote sediment accretion. Can be floating/anchored, attached or detached from shore, and be continuous or segmented (SAGE 2015).
- Groins: Structures extending perpendicular from shoreline, designed to intercept along-shore sediment and water flow to prevent waves and beach erosion (SAGE 2015).
- Revetments or riprap: Materials laid over a shoreline slope, designed to protect underlying material from waves and erosion (SAGE 2015).
- Bulkheads: Vertical retaining walls installed parallel to the shoreline, designed to hold soil in place (SAGE 2015).
- Seawalls: Vertical or sloped walls installed parallel to shoreline, designed to absorb wave energy and redirect water away from land (SAGE 2015).
- Levees/dikes: Earthen, high volume, sloped structures with a watertight coating and backed by a drainage channel, placed between valuable resources and the water, designed to dampen wave energy and prevent overtopping to protect lowland areas from flooding (Zhu et al. 2010).
- Tide gates: Gates placed in levee walls, culverts, or pipe outflows designed to allow downstream flow of freshwater but prevent upstream movement of saline water (Giannico & Souder 2005).

Accommodation Strategies

Protect space for upland/inland habitat migration

Protecting upland and inland space behind natural systems allows them to migrate in response to rising sea levels, maintaining habitat availability and critical ecosystem service provisioning for adjacent human communities (Gregg et al. 2011; Brophy & Ewald 2017). In addition to accommodating higher water levels, many of the implementation tactics discussed below also function as avoidance strategies, keeping human communities out of harm's way (Grannis 2011; Gregg et al. 2011). These tactics tend to garner short- to mid-term sea level rise resilience, but may compete with development interests, reduce property values, and/or affect tax revenues for governmental agencies (Grannis 2011). Implementation tactics for protecting inland and upland migration space include:

- Conservation easements: Sometimes known as open space designations, conservation easements are legal agreements where landowners are prevented from developing vulnerable property areas or must adhere to very specific development rules, largely keeping property in its original state (Grannis 2011; Siders 2013). In exchange, property owners receive payment or tax benefits, and may be able to maintain some land uses (e.g., agriculture, forestry) if uses do not conflict with conservation goals. Conservation easements can protect natural habitat areas that buffer sea level rise impacts, and provide room for habitats to migrate inland and upland in response to rising water levels. Easements are a more cost-effective alternative for governments than land acquisitions, and easement terms apply in perpetuity (Grannis 2011).
- Plant salt- or flood-tolerant species: The planting of salt- and flood-tolerant native vegetation in upland or inland areas in anticipation of future sea level rise inundation

and/or wave exposure in order to protect future shoreline stability. Having native vegetation that is resilient to salinity exposure and flooding will help decrease erosion and allow habitats time to migrate as sea level rise, potentially requiring less long-term maintenance and management (Gregg et al. 2011). However, vegetation will still be vulnerable to other climatic changes (e.g., drought, air temperature increases) (SAGE 2015).

- Rolling easements: A legal agreement where certain types of conditional development are allowed to occur in the short-term on upland portion of the property to maximize economic value, but as sea levels rise and predefined boundaries move (e.g., mean high water line), infrastructure must be removed to maintain the natural shoreline, facilitate inland habitat migration, and allow human shoreline access. Rolling easements typically prevent armoring and shoreline protection, but relative to conservation easements, still allow some structural development that must eventually be removed (Grannis 2011; Titus 2011).
- Minimum development buffers: Building restrictions that require landowners to leave some property portions undeveloped in order to protect critical natural processes. Buffers leave space for natural, dynamic environmental processes that can be responsive to sea level rise and accommodate higher water levels, and provide opportunities for habitats to migrate inland as sea levels rise. However, buffers still allow some type of development, and in the long-term, sea level rise may inundate fronting habitats and/or require protective measures (Grannis 2011).
- Land acquisition: The purchase of land from private entities for conservation purposes, including maintaining native habitats and protecting land for inland/upland migration in the face of sea level rise. Land acquisition is often more expensive than easements or other land protection measures, but does ensure that acquired land can remain in natural condition in perpetuity (Grannis 2011).
- Tax and financial incentives: Tax and other financial incentives can be used to encourage development patterns that promote ample space for habitat function and migration, increasing resilience to sea level rise (Grannis 2011).

Adaptation in Action: Accommodating Space for Habitat Migration in Lopez Island, Washington

MacKaye Harbor, Lopez Island, was designated as a priority nearshore habitat region in San Juan County as it provides critical habitat for forage fish, salmonids, and eelgrass. A restoration project was designed to remove toxic creosote pilings and derelict infrastructure to improve eelgrass and wetland habitat, reduce erosion, and enhance nearshore water quality conditions. Accommodating space along the shoreline to enable potential landward migration may also facilitate habitat persistence in a changing climate (Johannessen & Williams 2009).

Retrofit coastal infrastructure

Retrofitting coastal infrastructure refers to making alterations to the structure or function of existing coastal infrastructure to accommodate higher sea levels and reduce the consequences of flooding. Implementation tactics include: elevating buildings, raising site grades, converting buildings to floating structures, moving critical uses to higher floors, converting permanent structures to mobile structures (e.g., moveable pumps), and modifying water outfalls to prevent saltwater intrusion. This approach often requires leadership and oversight from local and state governments, rather than federal regulation. Although this approach reduces flooding consequences, it does not reduce the likelihood of flooding, maintaining some level of societal vulnerability to damages (USACE 2013).

Install green infrastructure/floodable development

Green infrastructure utilizes engineered or natural systems to mimic natural processes that help control runoff, promote groundwater infiltration, and reduce water demand. In terms of adapting to sea level rise, green infrastructure helps promote stormwater infiltration into regional aquifers, which can help slow rates of subsidence and overall rates of relative sea level rise. Additionally, by reducing stormwater delivery to regional utilities, green infrastructure reduces the likelihood of backflows and overflows, which may become more likely as higher sea levels reduce drainage capacity (EPA 2015a). Example implementation tactics include:

- Rain gardens: A low point or depression area with planted vegetation designed to capture and store urban runoff during rain events (EPA 2015b).
- Bioswales: Vegetated, sloped areas that capture and direct runoff to larger storage areas (EPA 2015b).
- Floodplains: Low-lying, undeveloped areas adjacent to river or stream that occasionally flood. By accommodating high water levels, intact floodplains help prevent flooding in adjacent land areas and reduce pressure on man-made flood barriers (e.g., levees; The Nature Conservancy 2018).
- Permeable pavement: Porous paving materials that infiltrate, treat, and store rainwater (EPA 2015b).

Similar to green infrastructure, floodable development is designed to withstand floods, but typically does not have infiltration or runoff diversion benefits. Examples of floodable development include: installing watertight doors, windows, and pump casings, backflow prevention devices, flap gates, lined pipes, and using submersible pumps (EPA 2015a). Similar to retrofitting coastal infrastructure, floodable development reduces flooding consequences, but does not reduce the likelihood of flooding (USACE 2013).

Increase/enhance flood warning systems and preparedness education

Flood warning systems and flood preparedness education can help reduce societal risk to short-term flooding events (e.g., storms), as well as support long-term adaptation to chronic flooding risks associated with sea level rise. Example implementation tactics include integration of sea level rise, storm surges, and flooding into emergency management and hazard mitigation plans, conducting education/outreach to vulnerable property owners, and investing in and utilizing flood prediction or forecasting systems. Warning systems allow anticipation of extreme events, creating time for evacuation and emergency flood prevention measures (e.g., sandbags). Preparedness education and integration of sea level rise into emergency plans helps to ensure that government agencies, property owners, and citizens know the risks and appropriate responses under different conditions. Education can also support eventual policy change, such as moving development out of floodplains (Gregg et al. 2011).

Retreat Strategies

Managed retreat/realignment

Managed retreat involves proactive movement of infrastructure and communities out of flood-prone areas in anticipation of increasing costs, maintenance, and/or risk to human life as sea levels rise (Gregg et al. 2011). Managed realignment also includes intentional removal of upland migration barriers to accommodate dynamic habitat adaptation (French 2006). Managed retreat can be very effective at reducing vulnerability to flooding and erosion, particularly if combined with other adaptation actions (e.g., natural habitat restoration) and if relocation sites are selected based on their future climate resilience. However, managed retreat can be very expensive, and requires extensive collaboration amongst multiple stakeholders, which can prolong implementation timeframes (Gregg et al. 2011; Siders 2013).

Abandon coastal infrastructure

Sometimes, society must accept loss, rather than managed relocation, of coastal infrastructure. This typically occurs after severe flood damage, or if sea levels rise or erosion occurs too quickly or for an orderly, managed retreat. Infrastructure may be left in place and abandoned if it is too dangerous to remove, or governments may strategically buy and demolish vulnerable infrastructure to create open space and associated flood and erosion buffer benefits. This strategy generally includes significant financial costs (Grannis 2011; Siders 2013).

Adaptation in Action: Managed Retreat of Taholah Village, Washington

The coastal village of Taholah, one of two major population centers for the Quinault Indian Nation, is located at the confluence of the Quinault River and the Pacific Ocean. Taholah is experiencing increased flood risk and damages as a result of sea level rise, storm surge, and riverine flooding, which are only projected to get worse with climate change. The village also lies in the tsunami zone. In the face of these risks and failing protective infrastructure, the tribe decided to relocate the lower portion of the village to higher ground. To guide this relocation effort, the tribe began developing a Relocation Master Plan in 2014; this process involved an inventory of existing conditions as well as extensive community outreach and engagement. Published in 2017, the Relocation Master Plan identifies an upland relocation site, which varies in elevation from 26-164 feet above sea level. This site was selected by considering both the tsunami hazard zone and the Federal Emergency Management Agency (FEMA)'s 1-in-100-year flood zone, effectively providing protection from both sea level rise and tsunamis. The Relocation Master Plan also outlines how the relocated village will integrate low-impact development and green infrastructure to further enhance climate resilience (Quinault Indian Nation Community Development and Planning Department 2017).

Avoidance Strategies

Limit development in vulnerable areas

One way to mitigate future costs and consequences of sea level rise is to identify areas at risk from inundation and erosion and actively limit the placement of human infrastructure in those areas. Although effective at reducing sea level rise vulnerability, this action can conflict with development interests and other human land uses (USACE 2013). Implementation tactics include:

- <u>Updating floodplain maps</u>: Many hazard management guidance documents recommend updating maps to reflect the 500-year floodplain. Floodplain maps that show more extreme scenarios can inform climate-smart planning and development by anticipating worst-case scenarios (Gregg et al. 2011).
- <u>Downzoning</u>: Limiting uses and use intensity in flood- and erosion-prone areas to minimize development potential (Siders 2013).
- <u>Zoning overlay</u>: Creating an additional layer of zoning requirements for coastal hazard areas or other areas vulnerable to sea level rise impacts (Siders 2013).
- <u>Development moratoria:</u> Preventing issuance of any new building permits while regulators and policy makers update comprehensive plans and zoning rules to account for sea level rise (Siders 2013).

Transfer development rights

The transfer of development rights involves market-based mechanisms of concentrating development in resilient, urban areas while preserving open areas. In the context of sea level rise, transfer of development rights can help move development away from vulnerable shorelines (Siders 2013). Implementation tactics include:

- <u>Buyouts/Acquisition in fee</u>: The purchase of land in vulnerable areas to avoid emergency relief and rebuilding costs. Land buyouts provide the opportunity for conversion to open space, while providing property owners with the financial means to relocate (Grannis 2011; Siders 2013).
- <u>Tax incentives</u>: Base property tax assessments on current use value versus development value to increase the feasibility of maintaining undeveloped floodplain land (Siders 2013). If open space contributes to property value, property owners may be less likely to develop vulnerable areas (Grannis 2011).
- <u>Transferable development credits</u>: Dissociation of development rights with property ownership. Landowners in flood- and erosion-prone areas are able sell development rights to landowners in areas not vulnerable to sea level rise (e.g., upland areas) (Siders 2013).
- <u>Defeasible estates</u>: The transfer of land titles at an agreed upon point/state in time (e.g., when sea levels rise a certain amount). Defeasible estates lay the foundation for eventual transition to open space, and may de-incentivize use of shoreline armoring by property owners since properties will typically be transferred to public management when erosion or flooding impacts become unavoidable (Titus 2011).

Incorporate sea level rise into floodplain policy and management

To avoid the potential impacts of sea level rise, managers must explicitly incorporate sea level rise projections and potential impacts into floodplain policy and management decisions. By planning for future conditions, managers can help avoid sea level rise-related flooding and erosion impacts by precluding development that is or will become vulnerable to sea level rise and/or by ensuring that existing development has the financial means to recover from flooding events. Although this action increases long-term resilience, it can cause short-term conflicts with development interests (Grannis 2011; Titus 2011; Siders 2013). Implementation tactics include:

- Incorporating sea level rise considerations into existing plans: Explicit consideration of sea level rise impacts in Coastal Zone Management Plans, Shoreline Management Plans, Municipal Plans, Comprehensive Plans, and Hazard Mitigation Plans. If necessary, governments can use a moratorium on building until plans are updated (Siders 2013).
- Require setbacks and buffers: Siting/building restrictions that do not allow property owners to build or expand structures within a given distance of the shoreline, eroding areas, or another defined boundary; as a siting restriction, this does not grant public access to the undeveloped area (compare to easements, above) (Siders 2013). Setbacks and buffers can prevent development in areas vulnerable to sea level rise in the short-term, and in the long-term if setback distances intentionally accommodate sea level rise and erosion projections (Grannis 2011).
- Building and rebuilding restrictions: Building codes and standards, particularly for flood-prone areas, that ensure buildings are constructed in a manner to avoid flood impacts. These codes can also include strict regulations on the number or extent of rebuilds, and conditions for condemning a house as unfit for habituation due to proximity to shoreline and associated vulnerability (Siders 2013).
- Sea level rise exactions: Development permits that include retreat requirements and accommodate dynamic conditions (e.g., prevents shoreline armoring, requires rolling easement) (Siders 2013).
- Incentive programs: Tax and other financial incentives can be used to encourage development patterns that keep human communities out of harm’s way and that promote retention of open space that can buffer flooding and erosion (Grannis 2011).
- Flood insurance: Require that all properties in flood-prone areas have flood insurance to protect individual property owners and local governments from financial recovery burden (Siders 2013).
- Real estate disclosures: During property sales, property owners must disclose property risk from sea level rise and erosion to ensure buyers are fully aware of future risk. Although disclosures may not prevent continued occupation of hazard zones, they may help build education and support for emerging sea level rise management policies (Siders 2013).

Adaptation in Action: Managing Coastal Erosion and Flooding in Neskowin, Oregon

Neskowin is a small community in Tillamook County, Oregon, that experiences chronic coastal flooding and erosion, conditions that will likely only get worse with climate change and sea level rise. In response to these coastal hazards, the Neskowin Coastal Hazards Committee was formed and tasked with identifying short- and long-term strategies to protect the beach and adjacent human communities. The resultant Neskowin Coastal Erosion Adaptation Plan, ratified in 2014, includes recommendations to direct development away from hazard-prone areas using zoning overlays and setback requirements. The plan also recommends retrofits to existing protective infrastructure, and lays the foundation for more extreme actions should they become necessary in the future, such as managed retreat and purchase or transfer of development rights (Tillamook County 2013). Tillamook County is now attempting to scale Neskowin successes from the local to county level via the Tillamook County Coast Futures Project (Ruggiero et al. 2017).

Other Strategies

Reduce non-climate stressors that exacerbate sea level rise impacts or reduce resilience

Many non-climate stressors have the potential to interact with sea level rise to create more severe impacts, or to impair the ability of coastal areas to accommodate rising water levels. By identifying and reducing theses stressors, managers can promote resilience by reducing overall stress on coastal systems and habitats (Gregg et al. 2011). However, these actions usually are not as effective as more targeted climate adaptation actions (EPA 2015a). Implementation tactics include:

- Reducing local oil, gas, and groundwater extraction, which can accelerate local relative sea level rise from land subsidence.
- Restricting recreational uses to reduce trampling of native vegetation.
- Reducing the use of and removing seawalls (where feasible) in order to allow natural shoreline retreat and maintain natural sediment supply.
- Reducing pollution that can impair water quality and affect estuarine and nearshore habitat structure and function.

Gray Literature Content Analysis

After defining the range of adaptation approaches available to coastal managers, the next step was to better understand what actions are in use in the project area by identifying what actions are referenced in regional management literature (hereafter “gray literature”). The project team gathered relevant gray literature documents from Washington, Oregon, northern California, and the broader west coast (e.g., central and southern California, British Columbia). Additionally, national-scale documents were collected if they were directly referenced from a Pacific Northwest document or webpage. Documents were sourced from over 105 different agency, county/municipal, and organizational websites, as well as from Google web and Google

Scholar searches. All items were initially screened to ensure some reference to sea level rise, coastal flooding, or climate change adaptation. In total, we located and reviewed 121 documents of relevance (Table 3) from 2006–2016 (Figure 2). All documents were cataloged with relevant bibliographic information, search terms used in discovery, and regional relevance (e.g., state, sub-geographic region, agency relevance; Appendix A).

Table 3. Categories and types of relevant gray literature found.

Categories and types	**Number of documents** (n=121)
Guidance, reports, and analyses	*Total: 74*
- Adaptation guidance documents	- 37
- Climate impact and vulnerability assessment reports	- 33
- Analyses (e.g., law or policy analyses)	- 4
Plans and policies	*Total: 38*
- Climate change adaptation or action plans	- 23
- Comprehensive, general, municipal, or management plans	- 8
- Hazard mitigation plans	- 7
Other resources	*Total: 9*
- Project documents	- 8
- Student theses	- 1

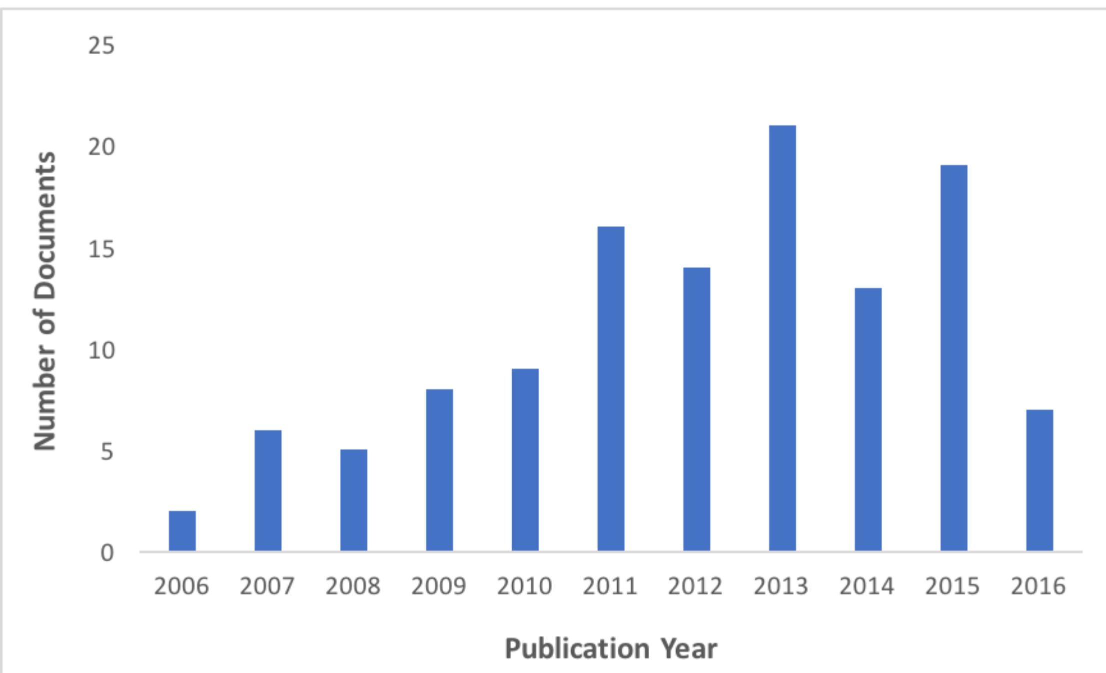

Figure 2. Publication year of relevant gray literature documents reviewed in Phase 2.

We created a coding system to review and catalog how sea level rise adaptation actions appear in the gathered gray literature. Many adaptation actions are already being used in coastal areas to address a variety of stressors (e.g., storm surge, king tides), so we designed a coding system to clarify whether actions were being proposed directly in response to sea level rise (e.g., to reduce vulnerability and/or enhance resilience), or whether actions were being suggested to address broader coastal zone management issues (e.g., erosion, "coastal flooding"). Additionally, we designed the coding system to help differentiate between documents focused explicitly on climate adaptation and documents that only briefly consider or mention climate adaptation. The rationale behind this additional layer of coding was to better understand how climate adaptation actions are discussed in different contexts.

Each document was evaluated on a scale of 0 to 2 with 0.5 increments in order to best codify the broad usage of these actions in coastal areas. Where possible, details on specific action methods were also recorded (e.g., types of hard protective structures or living shoreline tactics). Scoring occurred as follows:

- 0 – *no presence* of adaptation action(s) within document
- 0.5 – *presence* of adaptation action(s), but only in context of broader coastal management or coastal flooding
- 1 – *presence* of adaptation action(s), specifically linked with sea level rise
- 1.5 – *presence and greater emphasis* on adaptation action(s) specifically linked with sea level rise (e.g., if there is a climate adaptation section within a larger document)
- 2 – Adaptation action(s) are *focus of document*

Findings

Incorporating sea level rise into floodplain policy and management was the most cited sea level rise adaptation actions in the gray literature, followed by managed retreat of coastal infrastructure, and protect/restore natural coastal habitats (Table 4). This order did not change when national level documents and documents outside the specific project geography were excluded from analysis.

Table 4. Top 10 sea level rise adaptation actions appearing in the gray literature. NNBAs are italicized.

Sea Level Rise Adaptation Actions	Score
Incorporate sea level rise into floodplain policy and management	135.5
Managed retreat/realignment	125
Protect/restore natural habitat areas	121
Construct/maintain protective barriers	105.5
Retrofit coastal infrastructure	102
Identify and limit development in vulnerable areas	100.5
Protect space for inland/upland habitat migration	96
Install green infrastructure/floodable development solutions	78
Promote/restore natural sediment regimes	66
Reduce non-climate stressors that exacerbate sea level rise impacts or reduce resilience	58

The literature cataloging exercise revealed some other trends in the regional gray literature which may be important to regional managers and decision-makers addressing sea level rise. Although analyzing these trends is outside the scope of this project, they are noted below for future reference and further thought.

- The term "managed retreat" is used in a variety of contexts, which could potentially cause confusion. For this project, we defined managed retreat as a relocation strategy related to moving infrastructure and human communities. However, in regional gray literature, "managed retreat" is also commonly used to describe actions taken to protect inland space for eventual coastal habitat migration.
- Constructing protective barriers (e.g., bulkheads, levees, seawalls) was the fourth most cited action, but a number of regional resources were also dedicated to describing the potential negative ecological consequences of these structures, indicating their use should be carefully considered.
- A single action may fall in to multiple categories; for example, retrofitting coastal infrastructure may involve altering existing structures to incorporate green infrastructure components and/or transitioning them to be more flood-resilient (e.g., installing tide gates to prevent sewer system backflow). Similarly, policies may be used in a variety of ways (e.g., to protect coastal lands from development, to promote conservation easements that accommodate rising levels).
- Many documents cited the same examples of implementation (e.g., managed retreat at Surfer's Beach, CA). Implementation examples in each document were not systematically recorded, but this would be useful in future ASAP iterations.

Coastal Managers' Interviews

Results from the literature catalog were then compared with the adaptation actions regional managers are currently using on the ground within the project geography. Manager actions were discerned using phone interviews with a representative set of coastal managers in Washington, Oregon, and northern California. This interview process utilized an interview guide and followed all guidelines and approvals of the Oregon State University Internal Review Board for human subjects' research.

Interview questions were designed to gather responses that were consistent and comparable. Additionally, interview questions were designed to help differentiate between a manager's *intent* to act and the *implementation* of an action itself. Questions were also designed to identify factors that facilitate or act as barriers to action implementation (e.g., funding, sociopolitical factors, etc.).

Resource Manager Interview Questions:

1. What types of resources do you manage?
2. Have you thought about how sea level rise may affect the resources you manage?
3. What sea level rise adaptation actions have you utilized? (Managers were presented with Table 2 to facilitate standardized answers)

4. Why are you using these actions (i.e. part of existing management goals and activities, new application/implementation of existing management action in response to sea level rise, novel strategy developed in response to sea level rise challenges)?
5. If you are taking action, is action voluntary or mandated?
6. Are there any actions you are not currently using that you hope to use in the future? What has prevented you from using these actions in the past, and what implementation barriers to do you foresee in the future?
7. Where do you get your sea level rise science (i.e. literature, peers, conferences)? Do you have specific articles or reports you think we should review?
8. What types of sea level rise adaptation resources would you be interested in?

Forty-five individuals were contacted with a request for a phone interview, and nine responded (20% response rate). Respondents represented all states and sub-regions within the project boundaries, represented broad affiliations (e.g., federal, state, tribal), and represented a diversity of management focus areas (Table 5).

Table 5. State, sub-region, affiliation, and management focus areas of interviewed regional managers.

	Number of respondents
State and Sub-Region	
CA - Northern California	2
OR - Outer Oregon Coast	1
WA - Outer Washington Coast	2
WA - Puget Sound	3
WA - Strait of Juan de Fuca	1
Manager Affiliation	
Federal	2
State	3
County/City	1
Tribal	2
NGO	1
Management Focus Area	
Natural Resources	4
Human Communities	1
Cultural Resources	1
Recreation	1
Planning/Climate Adaptation	2

Findings
Protecting and/or restoring natural habitat was the most common sea level rise adaptation action being used by regional coastal managers, followed by protecting and restoring natural tidal connectivity and hydrologic regimes, and identifying and limiting development in vulnerable areas (Table 6).

Table 6. Sea level rise adaptation actions being implemented by coastal managers. NNBAs are italicized.

Sea Level Rise Adaptation Actions	**Number of Managers** (n=9)
Protect/restore natural habitat areas	7
Protect/restore natural tidal connectivity and hydrologic regimes	5
Identify and limit development in vulnerable areas	4
Promote/restore natural sediment regimes	3
Protect space for upland/inland habitat migration	3
Incorporate sea level rise into floodplain policy and management	3
Utilize living shorelines	2
Identify and protect sea level rise refugia	2
Managed retreat/realignment	1
Install green infrastructure/floodable development	1
Construct/maintain protective barriers	1

When asked to characterize current activities, managers indicated that in many cases, adaptation actions represent existing management actions (e.g., restoration) that have additional benefits when considered in the context of sea level rise (e.g., healthy, functioning habitats are better able to accommodate rising sea levels). Some adaptation actions are new applications of existing management strategies (e.g., restoration) with the intention of specifically enhancing resilience to sea level rise (e.g., prioritizing more resilient sites for restoration, such as marshes with room for inland migration). Finally, some adaptation actions represent novel approaches for the agency in question, and they are being implemented directly in response to sea level rise (e.g., facility relocation, species manipulation projects).

Although 55% of interviewed managers said they implemented adaptation actions in response to some form of mandate (e.g., from federal/state agency, tribal council, city council), 100% of managers indicated that implementation is also voluntary. This is largely due to management and public concern about the observed and projected impacts of sea level rise on regional coastal ecosystems, human communities, and infrastructure.

Of the sea level rise adaptation actions not currently in use, managers were asked to identify which they would be most interested in using in the future. Protecting space for upland/inland habitat migration, retrofitting coastal infrastructure, and managed retreat were the actions associated with the most interest for future implementation (Table 7). Managers listed several barriers that prevent current use of these actions, including funding, regulations, internal and external politics, scaling and translating regional climate information and adaptation to the project- or site-level, and private landownership (specifically the effectiveness of taking an action on a public land parcel [i.e. restoration] if adjacent private land parcels are taking no action or conflicting action [i.e. shoreline hardening]).

Table 7. Sea level rise adaptation actions not currently in use that managers are most interested in using in the future. NNBAs are italicized.

Adaptation Action	**Number of Managers** (n=9)
Protect space for upland/inland habitat migration	4
Retrofit coastal infrastructure	4
Managed retreat/realignment	4
Utilize living shorelines	3
Incorporate sea level rise into floodplain policy and management	3
Reduce non-climate stressors that exacerbate sea level rise impacts	3
Promote/restore natural sediment regimes	2
Identify and limit development in vulnerable areas	1
Protect/restore natural habitat areas	1
Identify and protect sea level rise refugia	1
Protect/restore natural tidal connectivity and hydrologic regimes	1
Install green infrastructure/floodable development	1
Increase flood warning systems and preparedness education	1

Comparison: Gray Literature and Interview Findings

The top sea level rise adaptation actions in use by and of interest to managers (Tables 6 and 7) were cross-referenced with the top actions discussed in the regional management literature catalog (Table 4) to identify similarities and differences (Table 8) and to inform which actions should be carried forward into the systematic mapping phase.

Table 8. Top five sea level rise adaptation actions referenced in the gray literature, currently in use by managers, and of future interest for implementation by managers. NNBAs are italicized.

Gray Literature (n=121)	**Current Actions** (n=9)	**Potential Future Actions** (n=9)
Incorporate sea level rise into floodplain policy and management	*Protect/restore natural habitat areas*	*Protect space for upland/inland habitat migration*
Managed retreat/realignment	*Protect/restore natural tidal connectivity and hydrologic regimes*	Retrofit coastal infrastructure
Protect/restore natural habitat areas	Identify and limit development in vulnerable areas	Managed retreat/realignment
Construct/maintain protective barriers	*Promote/restore natural sediment regimes*	*Utilize living shorelines*
Retrofit coastal infrastructure	*Protect space for upland/inland habitat migration*	Incorporate sea level rise into floodplain policy and management

Discussion

NNBAs are the sea level rise adaptation actions most commonly being implemented by managers. Managers also indicated that existing NNBAs will continue to be used in the future, and additional NNBAs will be incorporated where possible (e.g., protecting upland/inland space, utilizing living shorelines). The gray literature also promotes protecting/restoring natural habitat areas as top mentioned adaptation action. High current implementation and continued future interest in implementation made NNBAs good candidates for this project's systematic mapping process: high current implementation increases the likelihood of finding scientific evidence about appropriate implementation conditions, timeframes, and scales, while high interest in future implementation increases the likelihood that project findings will be relevant and utilized.

Structural adaptation actions have variable reference when comparing the gray literature with actual manager implementation. Specifically, protective structures (e.g., seawalls) were highly referenced in the literature, but are experiencing limited and declining use by interviewed managers, largely due to their cost, lifetime, and the potential for negative ecological impacts. Because of these issues, the project team determined that structural climate adaptation actions should not be a priority for the systematic mapping process.

Policy, regulatory, and planning adaptation actions represent areas of future adaptation growth. They were some of the top referenced actions in the gray literature, and although not currently being implemented by many managers, are of high interest for future implementation. Despite the high interest, several factors led the project team to determine that these adaptation actions would be difficult to carry through the systematic review process. First, these actions are generally complex from a sociopolitical perspective, which may limit evidence available for analysis and/or generate evidence that is too complex to analyze within the systematic review boundaries. Second, policy, regulatory, and planning action implementation occurs over much longer timeframes than NNBAs; with low current implementation by interviewed managers and very few examples of existing implementation in the gray literature, it was unlikely that there would be enough evidence from which to draw conclusions useful to regional managers.

Ultimately, the project team elected to prioritize NNBAs for the systematic review process because these actions are:

1. Currently being implemented on the ground. With funding and manager time and capacity currently being allocated to these actions, it is important to evaluate if science supports their continued use, and to identify if there are management alterations that could be made in order to improve action efficacy over the long-term;
2. Suitable for scientific evaluation, an important criterion for the systematic review process; and
3. Within the scope of expertise of the project team and the Scientific Expert Panel, ensuring that project team conversations and discussions with managers were robust.

Coastal management is a dynamic process, involving complex interactions between native ecosystems, human communities, and natural hazards. Sea level rise adds another layer of complexity to this management landscape, making it difficult to discuss NNBAs in isolation from policy, planning, regulatory, and structural actions. To accommodate this reality, the project team decided to note evidence for these other actions where possible in subsequent project phases, despite policy and structural actions not being chosen for specific analysis in the systematic review phase.

Conclusion

Phase 2 helped identify the sea level rise adaptation actions most commonly referenced in the gray literature and by regional coastal managers. A comparison of the gray literature and manager interviews identified that NNBAs are management actions being applied across the project geography and that will likely continue to be applied in the future. In order to incorporate sea level rise considerations into coastal management, managers need to know when, where, and how NNBAs could or should be implemented.

3. Systematic Mapping

Based on the manager interviews and gray literature findings from Phase 2, and in order to identify evidence from the scientific literature on the use of sea level rise NNBAs, we relied on a systematic review approach. Systematic review is a process originally developed in the late 1980s in the field of clinical medicine to find, analyze, and synthesize all relevant information on a particular medical intervention (e.g., a drug or surgical procedure). With growing awareness of how systematic review can add focus, objectivity and transparency to science synthesis, the process has been adapted for use in other fields, including environmental conservation and management (Burnett et al. 2006; Pullin & Stewart 2006). Compared to clinical medicine, evidence in ecology and environmental management tends to be limited and much more diverse in methodology, applicability, rigor, and in the ways and places it is catalogued (Behan et al. 2006; Doerr et al. 2015). This can make finding all available evidence and assessing its relevance considerably more difficult. But despite such challenges, use of systematic review methods in these fields continues to grow, in response to ongoing needs for objective ways to identify and package "best available science" and "actionable science" for use by practitioners.

In the context of environmental conservation, systematic review methods are most useful for narrowly targeted questions regarding the effectiveness of a specific action taken for environmental protection or restoration, or on behalf of a particular species. Given our experience on the pilot ASAP focused on fire (Gregg et al. 2016), we chose to rely on a systematic mapping approach for this project. Systematic mapping follows the same process and rigor of systematic reviews, but does not attempt to synthesize the scientific evidence in order to answer the question(s). Instead it illustrates the current state and trajectory of knowledge around a particular area of interest. In any kind of science review and synthesis, it is prudent to be as efficient, objective, and transparent as possible. The steps in a systematic protocol have proven very helpful in this regard, especially in refining review questions and documenting the process (Appendix B).

Systematic Literature Search Protocol

Literature that is relevant to this topic spans a number of disciplines and is not limited to that which discusses sea level rise explicitly. The scope, extent and sources of relevant literature vary depending on the specific type of action being considered. Therefore, a narrower focus on a particular climate adaptation action, or closely related set of actions, would be necessary for a comprehensive systematic review to be feasible.

Our goal for initial searching was a broad-brush survey and mapping of literature explicitly linking sea level rise and NNBAs. We primarily focused on peer-reviewed and gray literature published since 2000. This year was selected to reflect the rapid advances in climate modeling and scientific literature published on sea level rise and coastal change over the last 15+ years. We used the following questions to guide our preliminary literature search:

- Are the conditions, time frames, and geographic areas for use of existing nature-based tactics for restoring and maintaining coastal ecosystems and ecological functions changing in response to sea level rise? If so, how?

- Are there any new nature-based tools or tactics being developed for restoring and maintaining coastal ecosystems and ecological functions specifically in response to sea level rise? If so, under what conditions, time frames and geographic areas would these actions may be most effective for resource managers?
- As they incorporate sea level rise into planning and use of nature-based methods for restoring and maintaining coastal ecosystems and ecological functions, what additional science information should managers consider?

These questions are relatively broad in that they do not focus on a single, specific adaptation action but rather on a suite of actions. We elected to focus on a suite of NNBAs based on our results from Phase 1, which indicated that these adaptation actions are in use and of interest to coastal managers in the Pacific Northwest and northern California, both for protecting and restoring natural ecosystems and coastal processes and for protecting human life, infrastructure and values.

The first step of our initial search involved appraising sets of search returns for relevance to the review questions, termed “coarse filtering”. We used different combinations of search terms, and all searches were conducted using Google Scholar. The first 50 returns (or “hits”) for each search were examined. When fewer than 50 returns resulted, all were examined. Due to the large number of results for the search strings “sea level rise” “ecosystem-based adaptation”, and “sea level rise” “ecological engineering”, we examined more than 50 results, proceeding until high numbers of duplicates were encountered or further searching appeared unproductive. We augmented the systematic search with limited searching using traditional methods, such as searching bibliographies, conference abstracts, and contacting authors of highly relevant papers. From this initial search, about 38 references were provisionally deemed relevant (Table 9) as each included some substantive discussion of using natural or nature-based actions to adapt to sea level rise. Relevant references included mostly peer-reviewed papers, but also non-peer reviewed reports.

Table 9. Systematic search sources, number of search hits, and number of reviewed articles deemed relevant to the study questions.

<table>
<tr><th colspan="2">Source</th><th>Number of search “hits”</th><th>Number of relevant articles</th></tr>
<tr><td rowspan="4">Google Scholar Search String</td><td>“sea level rise” “nature-based adaptation”</td><td>42</td><td>9</td></tr>
<tr><td>“sea level rise” “ecosystem-based adaptation”</td><td>822</td><td>9</td></tr>
<tr><td>“storm surge” “ecosystem-based adaptation”</td><td>244</td><td>2</td></tr>
<tr><td>“sea level rise” “ecological engineering”</td><td>333</td><td>6</td></tr>
<tr><td rowspan="3">Traditional Search</td><td colspan="2">Bibliographies</td><td>5</td></tr>
<tr><td colspan="2">Conference abstracts</td><td>3</td></tr>
<tr><td colspan="2">Researcher recommendations</td><td>4</td></tr>
<tr><td colspan="3">Total number of relevant articles</td><td>38</td></tr>
</table>

This initial list of 38 relevant references was presented to the Scientific Expert Panel to serve as a basis for discussion and to solicit feedback in an iterative process of knowledge generation.

Scientific Expert Panel Workshop

To complement the systematic mapping process, we convened a Scientific Expert Panel to solicit input on science related to the use of NNBAs to respond to sea level rise. This approach builds on successful past efforts, including the initial ASAP pilot project (Gregg et al. 2016). Similarly, Beier et al. (2017) describe a process of iterative collaboration between scientists and managers in the co-production of practical and useful science to support natural resource decisions associated with climate adaptation. Berrang-Ford et al. (2015) also suggest that a combination of search approaches and an iterative process of systematically searching for science information, supplemented with input from experts, may be most appropriate for identifying knowledge related to climate adaptation.

Identifying, selecting, and recruiting science experts

Successful systematic mapping processes rely on qualified science advisors; ideally, scientists in the field under which the review question falls and those who do not have a vested interest in the review outcomes (INR 2008). The project team used a selection process to identify, prioritize, and invite a diverse group of scientists considered to be experts to serve on the panel (Figure 3).

Individual Candidates

- The candidate should reside in Oregon, Washington, or northern California, or have expertise in the review topic and experience with systematic reviews.
- The candidate should have expertise in one of the following areas: sea level rise, coastal storm impacts, nearshore ecosystems and processes, coastal hazards, coastal wetland restoration and conservation, coastal erosion, geologic hazards, beach restoration, and the environmental impacts of shoreline modification, coastal geology, or climate change.
- The candidate should not have any conflicts of interest that might prevent a candid and thorough review.

Composition of the Review Team

- In addition to expertise, there should be diversity with respect to geographic distribution, professional workplace (scientists within academia and non-academic settings), gender, race and/or ethnicity of the review team.

Figure 3. Scientific Expert Panel selection criteria.

In consultation with the Northwest Climate Adaptation Science Center, 11 potential candidates were identified from the region. We secured six advisors to serve on the Scientific Expert Panel:

- Karen Thorne, USGS Western Ecological Research Station
- Hugh Shipman, Washington Department of Ecology
- Laura Brophy, Oregon State University Institute of Applied Ecology
- Eric Grossman, USGS Pacific Coastal and Marine Science Center
- Peter Ruggiero, Oregon State University College of Earth, Ocean, and Atmospheric Sciences
- Nate Wood, USGS Western Geographic Science Center

Using scientific expertise to frame the systematic review exercise

Our strategy was to make the participation of the Scientific Expert Panel as efficient as possible considering the value of their time and efforts, and the short timeframe of the project. In November 2016, we convened a kickoff meeting with panelists to discuss the intent of the project, describe systematic review and mapping processes, and solicit their input on literature and topical considerations. Discussion focused on the following:

- What science question(s) regarding sea level rise adaptation would be of most interest to managers and policymakers?
- For which sea level rise adaptation actions are we likely to find the most scientific literature?
- How should we delineate the scope of “relevant” literature?
- What keywords or search strings are likely to be most productive? Please consider both ecological and sociopolitical factors.
- Which databases or other sources of literature are likely to be most helpful?

The information provided by the panel helped to shape the literature search protocol, initial “broad brush” systematic search of literature on NNBAs, and identification of literature themes. We then hosted an in-person workshop in March 2017 to have experts comment on the findings of our systematic mapping efforts, suggest additional studies to include in the review, and discuss knowledge gaps and future research needs.

Discussions at the workshop focused on a review of the initial search findings, and the benefits, risks, and uncertainties associated with nature-based techniques under current and future conditions. The panel largely concurred that the literature mapping characterized all of the major categories associated with coastal adaptation (e.g., habitat protection and restoration, hybrid approaches, and maintenance of natural sediment and hydrologic regimes). The search results also aligned with the panel’s early input that few studies about implementation or empirical monitoring data were likely to be found.

In a general discussion about the literature search and sea level rise adaptation actions, the scientific experts stressed that the values at risk frequently dictate the action(s) taken. For instance, actions may differ if managers are working to protect a habitat from sea level rise as compared to protecting a habitat to protect human communities, infrastructure, or ecosystem services from sea level rise. Although many NNBAs are being used to protect infrastructure and human communities, there is often a disconnect in temporal and spatial effectiveness in achieving adaptation goals; for example, the ability to implement specific actions does not always transfer from place to place as ecological conditions, institutional capacity, and management parameters can differ on a site-by-site basis.

Supplementary Searching

Panel members suggested relevant literature from their personal archives and professional networks, and potential avenues for supplementary searching. Our subsequent phase of searching utilized non-systematic (i.e. traditional) methods to augment the literature review, primarily iterative searches of closely related terms. Specific search results (i.e. titles of each result) were not documented due to time constraints and high numbers of duplicate hits.

To test the assumption that targeted searching would be more productive, and to supply an additional window into the scope and extent of relevant literature, we conducted a series of supplementary searches in Google Scholar, using a range of search terms focused on specific adaptation actions. For comparison, we also repeated searches that were conducted prior to the Scientific Expert Panel workshop. Percentages of the total number of results dating since 2010 for each search are provided as a window into the trend in interest and research focus on each topic (Table 10). Higher percentages suggest that interest in this topic may be increasing. It should be noted that there is likely considerable overlap in results from these searches, with similar search terms likely returning many of the same references. In other words, the numbers do not reflect the total number of studies for all topics combined. Figure 4 summarizes the years in which all documents considered in the systematic mapping were published (available in Appendix C).

Table 10. Search results for terms related to sea level rise adaptation actions.

Search Terms (Google Scholar)	**Results – Anytime**	**Results – Time Limited**	**Percent since 2010**
“living shorelines” “sea level rise”	698	584 since 2010	84%
“living shorelines” “climate change”	608	517 since 2010	85%
“estuary restoration” “sea level rise”	402	248 since 2010 378 since 2000	62%
“estuary restoration” “flooding”	555	292 since 2010	53%
"estuary restoration" "erosion"	654	328 since 2010	50%
“estuary restoration” “storm surge”	117	62 since 2010	53%
“coastal marsh” “storm surge”	1,300	754 since 2010 207 since 2016	58%
“salt marsh” “estuary restoration”	541	269 since 2010	50%
“coastal marsh” “estuary restoration”	88	50 since 2010	41%
“climate change” “estuary restoration”	522	346 since 2010	66%
"salt marsh" "sea level rise"	16,200	8,560 since 2010	53%
"coastal vegetation" "sea level rise"	3,440	2,190 since	64%

Search Terms (Google Scholar)	**Results – Anytime**	**Results – Time Limited**	**Percent since 2010**
		2010 569 since 2016	
"coastal marsh" "sea level rise"	3,470	1,810 since 2010 495 since 2016	52%
"adaptation actions" "sea level rise"	4,490	3,750 since 2010 849 since 2016	84%
"sea level rise" "estuary protection"	95	39 since 2010	41%
"marsh restoration" "sea level rise"	2,110	1,310 since 2010	62%
"beach nourishment" "sea level rise"	6,460	3,480 since 2010 699 since 2016	54%
"eco-engineering" "sea level rise"	246	198 since 2010	80%
"ecological engineering" "sea level rise"[1]	3,310	2,320 since 2010 684 since 2016	70%
"soft engineering" "sea level rise"	1,180	725 since 2010 180 since 2016	61%
"ecosystem engineers" "sea level rise"	1,100	871 since 2010	79%
"dune protection" "sea level rise"	350	181 since 2010	52%
"managed retreat" "sea level rise"	1,800	1,090 since 2010	61%
"managed realignment" "sea level rise"	1,630	960 since 2010	59%
"dune nourishment" "sea level rise"	173	101 since 2010	58%
"dune management" "sea level rise"	724	365 since 2010	50%
"dune management" "coastal protection"	427	216 since 2010	51%
"tidal marsh" "estuary restoration"	372	181 since 2010	48%
"tidal marsh" "sea level rise"	6,130	3,550 since 2010 951 since 2016	58%
"sea level rise" "nature-based adaptation"[1]	58	46 since 2010	79%
"sea level rise" "ecosystem-based adaptation"[1]	1,040	980 since 2010	94%
"storm surge" "ecosystem-based adaptation"[1]	399	364 since 2010	91%
"estuary restoration" "carbon sequestration"	102	83 since 2010	81%

[1]Repeat search of terms used to search prior to March 2017 scientist workshop. Results may differ from results obtained in February 2017.

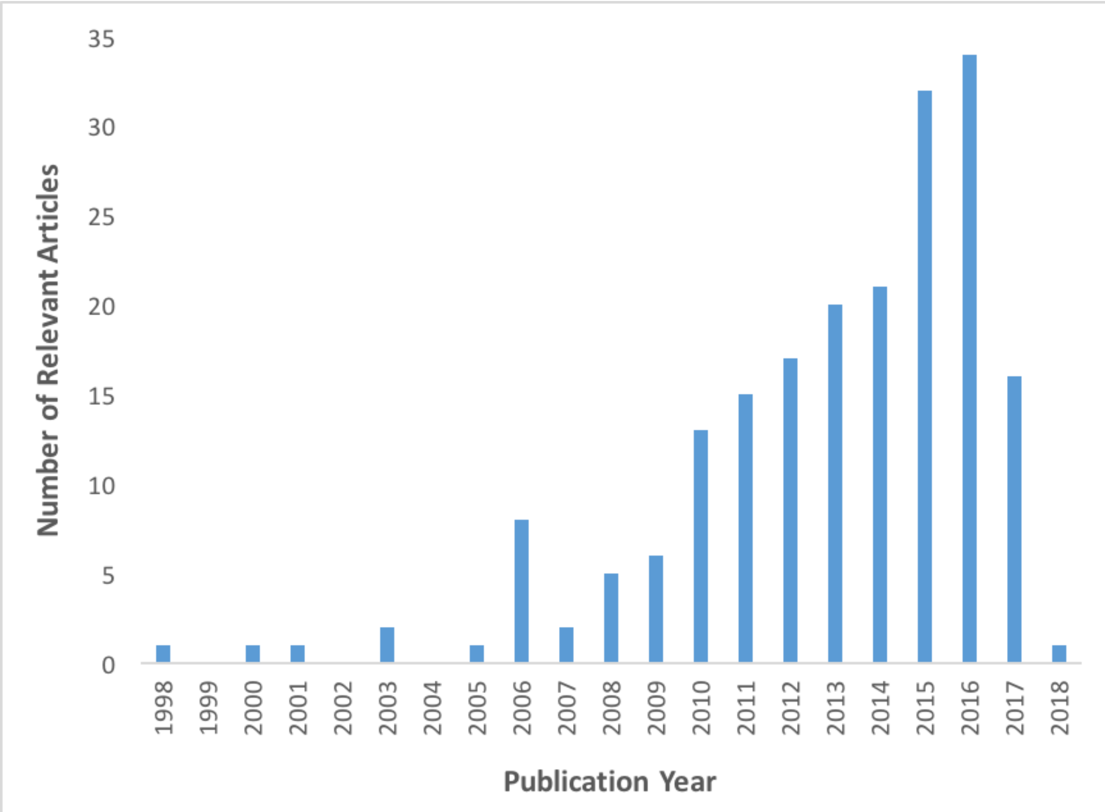

Figure 4. Publication year of relevant literature reviewed in Phase 3.

General outcomes

Owing to the broad nature of our review questions, relevant information was diffusely distributed among a range of academic disciplines. Relevant papers were found in a wide array of journals, including *Estuarine, Coastal & Shelf Science*, *Coastal Management*, *Ocean & Coastal Management*, *Coastal Engineering*, *Ecological Engineering*, *Ecological Applications*, *Nature Climate Change*, *Global Change Biology*, *Biological Conservation*, *Journal of Sea Research*, and *Estuaries and Coasts*. Ecological effects of sea level rise and primarily ecosystem-based actions to protect natural habitats were typically discussed in journals focused on the natural environment, whereas actions that fit along the hybrid continuum with some type of built component were typically discussed in journals with an engineering focus. We found much relevant information – perhaps the majority of it – in coastal and ecological engineering journals. Hotspots of activity and research were in places where sea level rise effects are already being felt, including Florida and the Gulf Coast, the Netherlands, California, and the northeastern U.S. seaboard. Significant efforts that encompass adaptation to sea level rise are also occurring in the Pacific Northwest, especially in the field of estuarine restoration.

As our search progressed, it became apparent that the term *ecosystem-based adaptation* is more commonly used than *nature-based adaptation*, based on the number of hits for each. Additionally, the screened literature revealed that sea level rise adaptation efforts are often integrated into broader coastal disaster preparedness and risk reduction efforts. This is because as a coastal risk factor, sea level rise is intertwined with ENSO events, increased frequency and intensity of storms and storm surges, and increased frequency and larger size of waves (Ruggiero 2008; NRC 2012; Barnard et al. 2015). Storm surges and flooding typically garner citizen and media attention to a much greater degree than incremental increases in mean sea level, and a result, sea level rise is often discussed and managed for in combination with other coastal risk factors rather than as a discrete threat.

Relatively few papers we found discussed specific adaptation actions in detail, likely due to the general nature of the search terms we used. But the number of such papers, and those that actually looked at the effectiveness of specific actions, appears to be increasing. Choosing a specific action (e.g., beach nourishment) and focusing searches on that specific action, would likely be more productive in identifying the extent of the knowledge base, and locating evidence regarding the merits and drawbacks of particular actions.

Overall, the high percentage of hits since 2010 (Table 10) indicate that ecosystem-based adaptation to sea level rise is a fast-moving and growing field of inquiry. As a result, the scientific literature base on relevant topics is rapidly expanding, making any literature search or assessment, including ours, a snapshot in time.

Responses to Review Questions

Responses to the questions that guided our literature search and review are provided below. These responses should be regarded as highly provisional, since they are based on small subset of relevant literature, not an exhaustive examination. Literature discussed includes references found using our systematic review protocol, references suggested by the Scientific Expert Panel, and references found in subsequent iterative searches.

Overarching Observations

As sea level rise progresses, the geographic range of coastlines subject to environmental impacts is likely to expand greatly. Impacts will not occur to the same degree at every location on the West Coast, but the geographic range and severity of impacts are expected to expand significantly, and areas previously not requiring adaptive measures will become exposed (NRC 2012). Thus, it is reasonable to conclude that use of existing NNBAs for restoring and maintaining coastal ecosystems and ecological functions will expand in geographic range as sea level rise progresses.

Additionally, sea level rise is also predicted to accelerate in coming decades (NRC 2012), resulting in more compressed time frames for managers to implement effective adaptation actions, and the urgency to respond rapidly will rise over time. Unless the availability of resources for coastal protection grows substantially, managers will increasingly find themselves in "triage" situations regarding where to focus restoration and adaptation efforts.

In general, the suite of sea level rise adaptation options available to managers in a given location will be highly influenced by local geomorphology, coastal assets at risk, the level of sea level rise protection deemed necessary, and other site-specific factors. The screened literature generally indicated that in each location, the viability of ecological alternatives to hard armoring will need to be carefully considered (e.g., by comparing costs and benefits of different adaptation approaches; Orton et al. 2016; Stein et al. 2016). In some cases, engineered protective measures may be the only adaptation option available in order to meet high flood safety standards (van der Nat et al. 2016). While the screened literature recognizes this reality, it also promotes making engineered approaches as "eco-friendly" as possible. For example, where hard armoring is deemed necessary, armored structures should be sited as high as possible along the shoreline to allow for habitat migration opportunities (Dethier et al. 2016a). Additionally, armoring should avoid impeding feeder bluff connectivity, which is critical for maintaining sandy sediment supply in natural systems (Dethier et al. 2016a). Another example of "eco-friendly" engineering is the use of "eco-levees" in marsh restoration (as has occurred in Humboldt Bay, California). These levees feature 10-to-1 slopes on the water-facing side of the levee, creating the opportunity for gradation between different marsh types and gradual habitat transitions as sea levels rise (Laird 2015).

Specific Responses

The screened literature yielded some examples of how existing use of NNBAs for restoring and maintaining coastal ecosystems and ecological functions is being adjusted in response to sea level rise. These linkages were not always clear, and relevant evidence often had to be deduced from other study findings. Specific and tangential evidence of changing management practices in response to sea level rise, or the lack thereof, are discussed below for several NNBAs identified in Phase 2. Where relevant, we also summarize emerging information and research needs, as well as any emerging management techniques in response to sea level rise challenges.

Protect and restore natural habitat areas

The screened literature generally recognizes the role natural habitat areas can play in buffering flooding and erosion from sea level rise, as well as from other coastal stressors, such as storm surge (Needelman et al. 2012; Cereghino 2015). For example, the Scientific Expert Panel discussed the ability of salt marshes to respond to rising water levels – depending on sediment availability and space – and attenuate wave energy (e.g., Port Susan Bay has an offshore drowned marsh that still provides coastal protection). Spalding et al. (2014) likewise note that coastal ecosystems play a critical role in reducing the vulnerability of coastal communities to rising seas and coastal hazards through their multiple roles in wave attenuation, sediment capture, vertical accretion, erosion reduction and the mitigation of storm surge and debris movement, and growing understanding of factors that affect the strength or efficacy of these ecosystem services in different locations. The literature discussed several ways in which natural habitat area protection and restoration efforts are being adjusted in response to sea level rise. Findings were largely related to a few habitat types, including salt marshes, estuaries, coastal wetlands, and floodplains. Specific adjustments include:

- **The explicit integration of sea level rise into restoration and management planning** to maintain restoration benefits into the future, including both ecological benefits and the maintenance of flood and erosion control ecosystem services. In estuaries, tidal marshes, and coastal wetlands, this has been accomplished by running sea level rise and/or hydrodynamic modeling scenarios to prioritize project locations, compare project alternatives, or revise project design to maximize landscape adaptation benefits, maintain habitat connectivity, and promote natural dynamic processes that increase long-term resilience (Crooks 2012; Shumway et al. 2012; Hamman et al. 2016; Whiting et al. 2017).

- **Exploring site conditions under which natural habitats yield the greatest flood and erosion protection benefits** (Shepard et al. 2011; Smolders et al. 2015, 2016; Stark et al. 2015, 2016). In a systematic review of coastal marsh ecosystem service management, Shepard et al. (2011) found that high vegetation density, high biomass production, and large marsh size were the factors linked with highest wave attenuation and shoreline stabilization benefits. They also found evidence that marsh processes, such as wave attenuation, sediment deposition and elevation building, can contribute to long term maintenance of coastlines. Evidence regarding the role of coastal marshes in floodwater attenuation was not as strong but studies they did find indicated that natural marshes drain more efficiently than altered marshes and that coastal wetland alteration increases flooding on a regional scale. There is a long history of wetland alteration and habitat conversion in the Pacific Northwest and northern California (Good 2000; Schlosser and Eicher 2012; Washington Department of Ecology 2017), diminishing the adaptive capacity of these areas. Results from individual studies screened in our search yielded similar results, but with more nuanced outcomes; for example, Smolders et al. (2015) found that for spring and storm tides in the Netherlands, a larger wetland surface area results in better attenuation up to a threshold wetland size, above which larger wetlands do not further contribute to more attenuation. Smolders et al. (2015) also found that wetland location matters; a wetland of the same size and elevation but located further upstream in the estuary can store more local flood volume and therefore has a larger attenuating effect on upstream high water levels. Screened literature also emphasized the role of maintaining diverse marsh elevations to achieve flood protection. For example, both Stark et al. (2015) and Smolders et al. (2015) demonstrated that both low and high elevation marsh is needed to effectively buffer flooding from both lower flood waves and regular tides and high flood waves and severe storm surges.

A consistent theme across a number of reviewed papers was the importance of understanding site-specific geomorphological, hydrological, and ecological factors and relationships that may affect project success (e.g., realizing coastal protection objectives) over different spatial areas and temporal timeframes, and the need for more research and modeling to better understand these dynamics (Bouma et al. 2014; Hill 2015). For example, the screened literature discussed the need for enhanced quantitative accounting of long-term spatial and temporal ecosystem dynamics, as this information will improve the predictability and reliability of using natural ecosystems in coastal protection efforts (Bouma et al. 2014). Additionally, managers could benefit from enhanced modeling that demonstrates wave height and wave energy reduction properties of marsh vegetation species native to the West Coast; it is generally believed marsh vegetation achieves flood and erosion risk reduction benefits, but it has not been specifically demonstrated for many West Coast species (NRC 2012).

Use of hydrodynamic modeling to analyze restoration scenarios and potential effects of land modifications is fairly widespread and rising. These models are becoming more sophisticated but rely on available bathymetric and geomorphic data to build, validate and calibrate and test them. Bathymetric data is not readily available for many smaller estuaries but will likely be needed in the future, as will information on how proposed land use modifications may alter coastal hydrodynamic and hydrologic processes (Whiting et al. 2017).

Several screened literature sources also discussed how new rationales for natural habitat restoration are emerging, which may provide new funding streams or societal encouragement for implementation. For example, the benefits of estuarine and marsh restoration for ecological purposes (e.g., creation and maintenance of nursery habitat and fish passage) are well established, but recent projects are also demonstrating the importance of marshes, wetlands, floodplains, and estuaries in flood buffering and erosion control (Needelman et al. 2012; Crooks et al. 2014; Cereghino 2015; FEMA 2015; Laird 2015; McLean 2017; Oregon Solutions 2017).

Similarly, several references discussed how oyster beds and reefs can buffer coasts from waves and retain sediment in shallow areas (Cheong et al. 2013; Reguero et al. 2014). This action shows enough promise to have been tested in some areas where researchers are introducing oysters onto artificial reef structures (e.g., mesh bags filled with shells, reef balls) with the expectation that these could become self-sustaining populations, including North Carolina (Rodriguez et al. 2014), Massachusetts (Gregg 2010c), Alabama (Gregg 2010d), and the Netherlands (Walles et al. 2015; de Paiva et al. 2016; Walles et al. 2016). Despite their apparent promise in other areas, our searches did not produce any documents explicitly discussing use of human-initiated oyster beds to buffer sea level rise impacts in the Pacific Northwest.[8]

Native Olympia oyster (*Ostreola lurida*) populations in the region have declined since the late 1800s due to overharvesting and pollution (Kirby 2004), making way for the establishment of the non-native Pacific oyster (*Crassostrea gigas*), which competes with the Olympia oyster for food and space. Although several native oyster restoration efforts are underway (e.g., Coos Bay and Netarts Bay, OR; Puget Sound, WA), the project goals are focused on improving water quality and creating habitat for species, rather than protecting shorelines from sea level rise (Blake & Bradbury 2012; Pritchard et al. 2015). Restoration of Olympia oyster populations may only yield minor wave attenuation benefits for coastlines as the species is much smaller in size than the Pacific oyster, and does not appear to create the tall three-dimensional structures that *C. virginica* does on the East Coast (Beck et al. 2009). Allowing space for both native and non-

[8] During a webinar, participants noted that Coast Salish Tribes and First Nations are constructing clam gardens along the coasts of Washington and British Columbia to support local food security, preserve tribal culture, and buffer the effects of climate change. The rock walls created in intertidal and subtidal zones to provide habitat structure for clams as well as protection for crustaceans and other species also trap and capture sediment, helping to buffer wave activity. Visit the Clam Garden Network for more information at https://clamgarden.com.

native oysters to build complex reef structures may be needed to achieve coastal protection goals.

An additional emerging rationale for coastal habitat restoration is the role that these ecosystems play in carbon sequestration. By storing carbon, intact and restored tidal marshes may help slow the rate of climate change and subsequent risk of sea level rise (McLeod et al. 2011; Fourqurean et al. 2012; Duarte et al. 2013). The screened literature discusses how carbon sequestration benefits can potentially be used to fund or encourage marsh restoration projects (e.g., carbon offset projects), garnering both climate adaptation and mitigation benefits (Restore America's Estuaries 2014; Sutton-Grier & Moore 2016). Additional research on exact greenhouse gas benefits will be needed (Sutton-Grier & Moore 2016), but efforts are underway (Crooks et al. 2014; Laird 2015; Sutton-Grier & Moore 2016). However, Thorne et al. (2018) caution that the ability of wetlands to store carbon long term declines as sea levels rise, particularly as wetlands drown and carbon is released back into the ecosystem.

Protect space for inland habitat migration

Another significant change to coastal habitat management and restoration in response to sea level rise evident in the screened literature is increased recognition of the importance of maintaining or creating open space for inland habitat migration. Primary evidence for this occurred in literature related to tidal and coastal wetlands (Kennish 2002; Shepard et al. 2011; Schile et al. 2014; Field et al. 2016; Brophy & Ewald 2017; Thorne et al. 2018) and dunes (Elko et al. 2016). For example, Oregon's tidal wetlands may not be able to persist in their current locations under projected sea level rise and therefore shift to higher-elevation areas; these potential future sites are known as "landward migration zones" or LMZs. Brophy & Ewald (2017) identified LMZs in a study of 23 Oregon estuaries; the maps produced through this project overlay areas of inundation with LMZs, land ownership, and land use information. The products can be used to inform and prioritize current and future protection and restoration of tidal wetlands, including avoiding development in high priority LMZs. However, steep topographical features and urban development along many areas of the region's shorelines may limit future migration potential, and opportunities for the use of NNBAs may only be applicable in the near-term before managers turn to hard engineering solutions or, ultimately, acceptance of habitat loss (Thorne et al. 2018).

The screened literature also discussed many factors that managers may need to consider when planning for inland habitat migration. For example, managers will need to consider not only the rate of coastal ecosystem retreat, but the rate of retreat in backing ecosystems such as forests. A study in the Northeast found a mismatch in rates of ecosystem change in tidal marsh and backing coastal forest in response to sea level rise, resulting in a projected loss of high-elevation marsh despite having space to retreat (Field et al. 2016).

Other considerations will become critical with attempting to protect inland habitat migration opportunities, including geomorphology and soil chemistry. Successful maintenance of coastal wetlands as sea levels rise is unlikely unless there are adjacent low gradient inland areas to which they can migrate (Schile et al. 2014). The extent to which such areas are available in relation to existing coastal wetlands varies widely, along with the potential for maintaining the functions and services of these ecosystems. In other areas, pollution or soil compaction associated with previous industrial or intensive agricultural uses may inhibit the ability of coastal wetland species to colonize further inland (Kennish 2002). Information on these topics will be relevant to decision makers charged with choosing where to target active management interventions intended to maintain coastal wetlands in light of sea level rise.

Protect and restore natural tidal connectivity and hydrologic regimes

Our search revealed significant regional literature discussing the ecological and ecosystem service benefits of restoring historically diked and drained tidelands (Ellingson & Ellis-Sugai 2014). The most obvious alteration in these activities specifically in response to sea level rise in increasing emphasis on identifying and utilizing opportunities to restore degraded estuarine and marsh area while maintaining flood protection for human communities and infrastructure (Needelman et al. 2012; Cereghino 2015; Laird 2015). There are several regional examples where setback levees are being used in combination with restoration of previously diked marshes and freshwater marshes through levee breaching, tidal channel restoration, and vegetation planting, including in Tillamook Bay, OR (FEMA 2015; Oregon Solutions 2017), the Snohomish River Estuary, WA (Crooks et al. 2014), and Humboldt Bay, CA (Laird 2015).The restored marshes provide additional buffering capacity for rising water levels, and the construction of new setback levees provides a final level of flood protection for human communities and infrastructure. Several of these projects have ongoing monitoring efforts, which will continue to yield important lessons learned about sea level rise resilience and other ecological outcomes over time, facilitating adaptive management (Shepard et al. 2011; Crooks et al. 2014; FEMA 2015; Laird 2015; Brown et al. 2016; McLean 2017; Oregon Solutions 2017; Whiting et al. 2017).

Protect and restore natural sediment regimes

Several screened papers discussed lessons learned from existing beach nourishment treatments. Notably most of the screened literature discussed nourishment of sandy ecosystems (Berry et al. 2013; Hanley et al. 2014; Stive et al. 2014; Yoshida et al. 2014; Dean & Houston 2016) and study geographies were generally well outside the project geography, such as the Netherlands (Stive et al. 2013), Japan (Yoshida et al. 2014), Europe (Hanley et al. 2014), and Florida (Dean & Houston 2016). Findings largely focus on the importance of site-level considerations in sandy beach nourishment project design and implementation, treatment scale, and implementation timeframes:

- Sediment size sourced and applied in nourishment treatment needs to match host beach sediment size in order to avoid substantial sediment loss through regular wave action (Speybroeck et al. 2006; Hanley et al. 2014).
- In the face of sea level rise, examining and prioritizing beach nourishment projects at a regional scale may be most effective; suggested methods include taking a “sandshed management” approach (i.e. applying a watershed management framework to shoreline

management; Revell et al. 2007) and/or using models that accommodate all factors that influence shoreline dynamics. This latter method was successfully applied in Florida to show that beach nourishment advanced shorelines seaward and could provide a positive return on investment in the face of sea level rise (Dean & Houston 2016).

- Treatment scale depends on local goals. Yoshida et al. (2014) developed a framework for considering beach nourishment volumes and costs. After projecting future shoreline changes and beach widths as a result of sea level rise, practitioners can identify beach widths needed based on goals (e.g., disaster prevention [>32 ft, >10 m], ecosystem conservation [>65 ft, >20 m] and recreation [>98 ft, >30 m]); these widths can be compared to projected beach widths to identify vulnerable areas, and then used to more accurately predict nourishment volume needed and associated costs.
- Beach nourishment needs to be timed to minimize negative near-, mid-, and long-term ecological impacts, and integrate multidimensional aspects of sandy beach ecosystems into project design (e.g., longitudinal, transverse, and vertical relationships of fauna and sediment movement; Speybroeck et al. 2006; Berry et al. 2013). Specifically:
    - In a review of beach nourishment practices, Speybroeck et al. (2006) propose that although managers should always consider local conditions, winter is typically an ideal time to implement beach nourishment projects to avoid impacts on nesting birds and epibenthic and benthic organisms while allowing rapid beach recovery.
    - Implementing several small projects is preferred to one large project to minimize ecological impacts (Spebroeck et al. 2006).
    - Ploughing by heavy machinery after nourishment should be avoided. Associated compaction has ecological consequences (e.g., steeper beach faces and greater reflection of waves can reduce coastal species richness and abundance) and may reduce resilience of adjacent systems as more compacted sand is less erosive, which reduces the supply of sand for longshore accretion (Speybroeck et al. 2006; Berry et al. 2013).
- Beach nourishment may function best as a near-term adaptation option; it can be part of a staged response to sea level rise to "buy time" to facilitate managed retreat, which in the long-term, may enable sandy beaches to maintain structure and function, increasing ecological resilience and allowing ecosystem service provisioning to continue (Berry et al. 2013).

Comparatively, we found little information on rocky shoreline nourishment with the exception of Shipman (2002), which evaluated how geologic setting affected project design and success of roughly thirty beach nourishment projects on Puget Sound. Shipman (2002) acknowledges that rocky shoreline nourishment can be used for erosion control but may be more vulnerable to damage from large storm and tide events than equivalent hard structures. The Scientific Expert Panel likewise noted that cobble beaches dissipate wave energy, reduce erosion, and are fairly adapted to dynamic conditions (e.g., cobble berm at Cape Lookout State Park [Komar & Allan 2010]). Given the abundance of rocky coastline in the study region, the effectiveness of rocky shoreline nourishment projects in responding to sea level rise represents an important area for future research. Key research and information needs identified by Shipman (2002) include engineering and regulatory guidance for nourishment use, systematic monitoring of implemented projects, and increased knowledge of the geomorphologic processes acting on individual sites to inform effective design.

The screened literature also yielded significant information about how dune management and restoration is evolving in the face of sea level rise. Several screened papers discuss how invasive vegetation removal practices in dune systems of the Pacific Northwest may need to be modified in light of sea level rise risk. Specific outcomes include:

- **Increased need to consider multi-resource objectives in restoration projects**. For example, there is significant regional activity focused on restoring habitat for the ESA-listed snowy plover (*Charadrius nivosus*) by removing invasive dune vegetation. However, in restoration areas close to human development, managers may need to consider maintaining invasive *Ammophila* spp. in foredunes in order to maintain established flooding buffers for human communities. Within the project site, areas less critical for flood control can be restored using lower-intensity techniques (e.g., herbicides, hand-pulling) that best restore native vegetation, natural dune processes and topography, and plover habitat. This combined approach effectively meets both habitat restoration and ecosystem service provisioning objectives (Zarnetske et al. 2010).
- **Prioritizing removal of *A. breviligulata* over *A. arenaria***. Relative to areas invaded by *A. arenaria*, *A. breviligulata* results in wider and shorter foredunes, effectively reducing flood protection from both storms and eventual sea level rise. *A. breviligulata* is expanding south and replacing *A. arenaria*, effectively increasing flood risk along the coast (Hacker et al. 2011; Seabloom et al. 2013). Removal of *A. breviligulata* may be particularly important in areas of high sand supply, as lower shoot density and sand capture efficiency result in enhanced horizontal, rather than vertical, dune growth (Zarnetske et al. 2015).

The other major category of screened dune-related literature focuses on restoring the dynamic processes of native dune systems, as dynamic dunes are more responsive to rising water levels than stabilized dunes. These papers largely attempt to address the scale, siting, and size of treatments needed in order to create resilient dune systems. Specific outcomes include:

- **Being strategic in the siting and scale of mechanical vegetation removal treatments**. A study in British Columbia, Canada, recommends that the spatial extent of vegetation removed should allow for a complete transport corridor into the foredune and, if applicable, to landward transgressive dunes. Additionally, the direction of dominant transporting winds should be explicitly considered. If vegetation cannot be removed over extensive, continuous stretches of foredune, the most strategic location should be identified to maximize sediment delivery into the transgressive system (Darke et al. 2013).
- **Selecting appropriate sand fencing size and placement**. Sand fences work by reducing wind speed, allowing sand accumulation and eventual colonization by early successional dune plant species. Sand fences are inexpensive, easy to construct, and relatively unobtrusive especially once sand accretion begins. According to a model developed by

Hanley et al. (2014), which focuses on European dunes, fencing is most effective when beach width is at least 115 ft (35 m) and dune base elevation above the sea level exceeds the 100-year return storm surge period. Fences should be in straight-line segments 3.3–9.8 ft (1–3 m) from the dune base with 30% of their height buried into the sand. This model was developed for meso-tidal (6.5–13 ft [2–4 m]) coasts in Europe, but the developers indicate it is applicable elsewhere.

- **Promoting the use of native vegetation** in dune restoration efforts to avoid dune stabilization issues associated with exotic species (*Ammophila* spp.); dominant native grasses promote dune building, and extensive root systems allow continued growth despite sand burial (Hanley et al. 2014). Encouraging the creation and maintenance of these more dynamic dunes may also yield more erosion-resilient systems as they can gradually migrate landward or seaward under aeolian processes (Darke et al. 2013).
- **Acknowledging and managing for both short- and long-term dune processes**, such as the ability to dunes to adapt over the long-term to changes in physical forcing (Elko et al. 2016). The Scientific Expert Panel noted that while dunes in the region have been able to keep pace with historical rates of sea level rise, the ecological processes of dune building may not naturally be able to keep pace as the availability and rate of sediment accretion may lag behind accelerating rates of sea level rise.

The screened literature identified several areas of future research that will help inform the use of sediment-related NNBAs:

- **Increased understanding of the potential impacts of beach nourishment** in the near-, mid-, and long-term, including direct, indirect, and cumulative ecological effects (Speybroeck et al. 2006) on beach microfauna, plants, terrestrial arthropods, and birds (Berry et al. 2013). For example, the Scientific Expert Panel noted that the sourcing and extraction of sediment to replenish dunes is complicated by the region's topography (e.g., hard to access offshore sources due to dangerous seas, locating adequate grain size).
- **Increased transdisciplinary research and communication of findings**. Under climate change, species invasions, sand supply, sea level rise, and changes in storminess are likely to interact in ways that make coastal protection uncertain, especially across different spatial and temporal scales. More transdisciplinary research can help address knowledge gaps in how natural features can function in coastal protection (Seabloom et al. 2013; Hanley et al. 2014; Zarnetske et al. 2015) and increased communication and collaboration between sectors can advance the field and create new research directions (Elko et al. 2016).
- **Exploration of how different sediment management actions can be paired to achieve more significant results**. For example, Hanley et al. (2014) indicate there could be great potential to combine their strategic modelling approach for locating sand fences with a better understanding of sediment dynamics and thus a way to predict where sand accretion and erosion are stable enough to allow native seedlings to establish and so facilitate dune revegetation efforts.

- **Accurate monitoring and continued adaptive management in response to emerging scientific knowledge on coastal dune processes**. Elko et al. (2016), which synthesizes information about dune management on developed coasts, identifies major needed research areas to accomplish this goal, including: (1) improving numerical models of dune formation, growth, and erosion to cross spatial and temporal scale; (2) expanding observations of beach-dune morphodynamics and sediment budgets over greater spatial and temporal scales; (3) developing systems-based management approaches by integrating hydrodynamics, geomorphology, ecology, and coastal management; (4) identifying success factors and incorporate into dune designs and management plans; and (5) quantifying and conveying social and economic benefits to a coupled natural/human dune system. The Scientific Expert Panel noted that a comprehensive status update on the stability of Northwest dunes is needed in order to identify which systems are most vulnerable. Allowing the space for dunes to be built naturally and then enhanced by restoration efforts may yield the strongest and most resilient dunes, but research is lacking on optimal design guidance.[9] Likewise, one of the objectives of Humboldt Coastal Dune Vulnerability and Adaptation Climate Ready Project is to identify areas of the Eureka littoral cell that have sediment deficits and adequate/surplus supply in order to better ascertain vulnerable areas and most appropriate adaptation responses (Judge et al. 2017).

Protect and restore system engineers that structure/maintain habitat

The screened literature revealed supporting evidence that planting tidal vegetation helps promote sediment accretion, enhancing resilience to sea level rise. In an experimental study, Baustian et al. (2012) found than unplanted tidal flat area decreased in elevation while planted areas increased. Future research on where tidal plantings are likely to be most successful, which species work best, and other specifics would be beneficial.

Our literature searches yielded limited references that address the use of marine plants (e.g., seagrass, kelp beds) for adaptation, aside from mentioning their ecological function and recommendations to protect these habitats where they exist. For example, Barbier et al. (2011) note that seagrass beds can dissipate wave energy and minimize erosion depending on bed size and distance from shore, seagrass species and density, and wave height and length. Using more specific search terms, such as "eelgrass" or "kelp" would likely have been more productive. Similarly, our literature searches did not reveal any information about using beavers in adapting to sea level rise. The Scientific Expert Panel, however, noted that the presence and function of these species do contribute to overall system resilience (e.g., kelp provides benefits for wave and sediment attenuation, beavers by provide platforms for vegetation to establish and promote accretion by slowing sediment).

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[9] See New Jersey's Dune Manual (http://njseagrant.org/wp-content/uploads/2016/07/Dune-Manual-Pgs-compressed.pdf).

Utilize living shorelines

The screened literature generally supported the use of hybrid approaches such as living shorelines, where possible, in lieu of or in combination with hard armoring. Living shorelines can maintain erosion and flood protection services for human communities while supporting native habitats (Sutton-Grier et al. 2015). After Hurricane Katrina, van Heerden (2007) found that levee areas protected by wetlands were less likely to breach than areas with standalone levees in New Orleans. Bilkovic et al. (2017) compiles, synthesizes, and interprets current knowledge on the science and practice of nature-based shoreline protections, including management, policy, and design considerations and guidance (including knowledge gaps). While a complete review of this book was outside the scope of this project, practitioners may find it useful to review as they design and implement their own living shoreline projects.

One major evolution in the use of living shorelines is enhancing designs to specifically bolster ecological conditions (Sutton-Grier et al. 2015). For example, Gittman et al. (2016) quantified the effectiveness of (1) sills with landward marsh, (2) natural salt marsh shorelines (control marshes), and (3) unvegetated bulkheaded shores in providing habitat for fish and crustaceans. Sills supported higher fish abundance and species diversity than unvegetated habitat adjacent to bulkheads, and even control marshes. Sills also supported higher cover of filter-feeding bivalves than bulkheads or control marshes. These ecosystem-service enhancements were detected on shores with sills 3+ years after construction, but not before. Sills provide added structure and may provide better refuges from predation and greater opportunity to use available food resources for fish and crustaceans than unvegetated bulkheaded shores or control marshes. Gittman et al. (2016) showed that rock sills can be used to enhance the biologic integrity of adjacent marsh habitats to a higher level than natural-state marshes, thereby providing sea level rise protection but also supporting biodiversity and ecological integrity.

Overall, the screened literature emphasized that increased information on the use of living shorelines is needed, including:

1. The level of protection provided by different types of natural infrastructure, how that protection varies across different regions and through time, and under what conditions natural infrastructure is likely to fail;
2. How protection varies with different types of storms, and with surrounding coastal landscape parameters including bathymetry, topography, and shelf width; and
3. Best practices for restoring or constructing natural and hybrid infrastructure that combine knowledge of the state of engineering and ecological science of coastal ecosystems, with a focus on how to design systems for hazards and disaster reduction (Sutton-Grier et al. 2015).

Policy considerations

The screened literature discussed several ways in which policy can support the use of NNBAs. For example, while not technically a NNBA, relocation or managed retreat allows for the enhancement of natural processes (i.e. sediment movement, occasional flooding) by moving infrastructure inland (e.g., Deer Harbor Road on Orcas Island, WA [Johannessen et al. 2014]), but is restricted in some places by permitting and policy decisions. Policy can be used to discourage or avoid building human infrastructure in "at risk" coastal areas that would then require costly, highly engineered protection measures, or that would impede ecological functions that help maintain coastal ecosystems (California Coastal Commission 2015). Where adaptive measures are needed, policy can be used to support the use of NNBAs (Dethier et al. 2016b). Loring (2014) discusses several federal, state, and local policies that may be used to authorize the use of NNBAs for sea level rise and other coastal impacts.

Conclusion

We used a combination of systematic mapping, input from a Scientific Expert Panel, and additional targeted searching to identify and distill management-relevant information from peer-reviewed and gray literature related to natural- and nature-based adaptation to sea level rise. The screened literature revealed some supporting evidence about when, where, and how NNBAs could or should be implemented in the future to prepare for and respond to sea level rise. The screened literature also identified key research gaps and information needs that can support future implementation of natural and nature-based adaptation efforts. Information generated from this phase was presented and expanded upon at a subsequent workshop series with regional managers and scientists.

4. Collaborative Scientists-Managers' Workshops

In January 2018, EcoAdapt and the Institute for Natural Resources held two workshops in Seattle, WA and Newport, OR to culminate the project, and to bring managers and scientists together for broader discussions regarding NNBAs in the context of climate change. The workshops were hosted in collaboration with the North Pacific Landscape Conservation Cooperative. Thirty-three participants from 22 organizations attended the workshops, including representatives from federal, tribal, state, county, and city agencies, non-profit organizations, and private consulting groups (Appendix D).

Goals and Objectives

The workshops were convened to share the results of the science synthesis and discuss future management directions that may require additional scientific efforts. Objectives included:

- Documenting how coastal management is changing in response to climate change;
- Discussing regional plans, priorities, and activities for managing sea level rise, with a focus on NNBAs;
- Identifying knowledge gaps around sea level rise adaptation efforts and describe the intended management application of desired future science products; and
- Developing partnerships between scientists and managers to ensure future research is addressing specific coastal management needs.

Discussion 1. Sea Level Rise Adaptation Scientific Consensus

The first discussion focused on participants' reflections on the ASAP methods and how the scientific literature findings correlated to managers' experiences on the ground.

Participant comments included:

- **The systematic mapping yielded a lot of information that was more relevant to certain areas of the Northwest coast than others**. Some of the NNBAs and associated literature were relevant to specific types of coastline; for example, beach nourishment is an activity that primarily occurs on the outer coasts rather than the Puget Sound region. Other strategies (i.e. sand fencing) are not widely practiced in the Northwest, although that may change should evidence emerge regarding their applicability and effectiveness. The coasts of Washington, Oregon, and northern California vary in terms of topography, tidal exchange, and energy gradients, so it is challenging to detect evidence that would prove consistent and applicable across the region.
- **The inherent interconnectedness of coastal watershed systems makes it challenging to compartmentalize or isolate climate-driven changes (and adaptation actions) from one another.** For example, areas such as the Skagit Delta in which tidal flooding and rain-on-snow events combine to cause massive floods may be more vulnerable to sea level rise. This likely complicates comprehensive or systematic literature searches as the breadth of literature relevant to a research question on sea level rise may also include

resources on storm surge, king tides, ocean circulation changes, wave and flood attenuation, shoreline stabilization, and more.

- **Alternative pools of literature may have yielded additional resources relevant to the research questions.** These include those focused on coastal engineering and coastal policy and regulatory analyses.

Managers were also asked to reflect specifically on how the literature findings compared to their personal experiences. Participant comments included:

- **There is a strong need for the integration of climate and environmental science into planning and permitting.** As regional population and development pressures increase over time, there will be more intensive use of coastal areas. Information on how these changes, combined with sea level rise and other climate-driven changes, may affect coastal environments should be incorporated into land-use planning and permitting; however, the evolution of these planning and permitting processes is typically resistant to change and lags behind emerging science. There are some opportunities to get science into the hands of jurisdictions that are updating coastal regulations (i.e. Washington State Shoreline Master Programs, updates of Oregon foredune management plans, county comprehensive plan updates), and to encourage policy makers to enable flexibility in the interpretation of "on the book" regulations to support coastal planning and management that is capable of responding to dynamic and changing conditions.
- **There are several long-term coastal restoration projects in the region, many of which did not explicitly incorporate sea level rise projections into project design.** There is some confidence that these projects will garner benefits in light of climate change, but intentionally integrating sea level rise projections and/or comparing restoration monitoring data with observed sea level rise to see if and how these projects are adaptive would be beneficial.
- **There is a high degree of spatial and temporal variability in managing for sea level rise.** Participants noted that ecological and sociopolitical characteristics influence the effects of and management options for sea level rise at any particular site. For example, certain sections of shoreline may be more vulnerable than others (e.g., outer coast vs. embayments), and existing land ownership, values at risk, and regulations guiding land use dictate which actions are feasible for implementation. In many cases, participants noted that it is much easier to permit a seawall or other type of hard armoring structure than natural or hybrid approaches. In other areas, there is an incentive to replace hard shorelines with soft approaches, but associated loss and narrowing of the marine buffer allows structures to be built even closer to the shoreline, enhancing risk. Part of the spatial variability also includes public perception of and support for NNBAs; in Oregon, for example, there is some stakeholder pressure to reduce dune heights to enhance aesthetic views (i.e. view grading) despite dunes' ability to buffer wind and wave action.
- **NNBAs need to be acknowledged as one tool in a larger toolbox for coastal management in a changing climate.** Participants cautioned that NNBAs should not be considered a "cure-all" for sea level rise. NNBAs should be paired with other approaches (i.e. setbacks, relocation) in order to maximize their use and longevity. For example, in

some areas relocation may not be feasible (i.e. septic systems in the San Juan Islands) and may need to be protected (if not decommissioned) with hard and soft engineering. Participants also expressed increasing need for and interest in phased approaches to adaptation. For example, jurisdictions can use existing regulations that support climate-informed development (i.e. restrictions on siting of new development) while exploring options for larger-scale adaptation (i.e. managed retreat).

Discussion 2. Sea Level Rise Planning and Management

The second discussion focused on if and how sea level rise is being integrated into coastal planning and management, as well as the implementation conditions behind the use of NNBAs in a changing climate. This included discussions of the benefits, risks, and uncertainties associated with their application, as well as the most and least suitable conditions for successful implementation.

Participants noted various ways in which sea level rise projections and impacts have motivated the modification of management practices in the Northwest. These include:

- Using FEMA flood maps to help educate the public on sea level rise risk and managed retreat and relocation;
- Incorporating sea level rise and other climate projections and impacts into county comprehensive planning;
- Accounting for the "worst case" scenarios in designing engineering projects;
- Elevating infrastructure (i.e. San Juan Islands);
- Incorporating sea level rise analyses as part of California Environmental Quality Act (CEQA) project impact assessments;
- Identifying infrastructure and habitats that may be affected over time;
- Adopting coastal hazard erosion overlay zones that incorporate sea level rise to guide oceanfront development (i.e. Neskowin, Tillamook County); and
- Relocating infrastructure out of vulnerable areas.

NNBAs being used by practitioners include:

- Removing invasive grasses from dunes and allowing space for inland dune migration;
- Acquiring land to create floodable space (i.e. Tillamook Bay);
- Designing hybrid infrastructure in Oregon parks that can be easily moved or replaced;
- Restoration of dune, salt marsh, tidal wetland, and estuarine habitats;
- Restoration of natural processes (e.g., tidal exchange, feeder bluff connectivity) via hard infrastructure removal or modification;
- Beach nourishment (sand, gravel);
- Riparian plantings to expand buffer width; and
- Woody debris and wrack placement and maintenance on beaches.

Participants then selected specific actions for evaluation, discussing the strengths and limitations of, and opportunities for, their use in response to sea level rise; these comments are presented below (Table 11).

Table 11. Participant evaluations of the strengths, limitations, and opportunities for the use of sea level rise adaptation actions.

Management Action	Strengths/Benefits	Weaknesses/Limitations	Opportunities
Cobble/gravel beach nourishment	- Jumpstarts recovery at site level (post removal of fill) - Adds natural material to a site so it does not look out of place - Dynamic approach, which allows for natural response - Can be raised in response to changing conditions - Lends itself to an adaptive management approach as material can be added incrementally - Likelihood of failure is lower than structural options - Yields multiple benefits (i.e. forage fish habitat) - Improves and maintains beach access and allows management of access in broader context of habitat restoration	- No guarantee of a permanent fix as success depends on the energy of the system and placement location (very site-specific) - Use in certain areas may have higher cost - Lack of design guidance - Design parameters for long-term maintenance may not align with existing habitat needs - May require supplementation in perpetuity - Not sufficient for a single parcel scale approach; not seen as viable option for homeowners, especially in comparison to hard armoring - Requires significant outreach to explain that system is supposed to change over time - Availability and sourcing of material is inconsistent - Lack long-term monitoring projects that demonstrate success; study outcomes very site-specific	- Explore whether this action can be used to buffer the negative impacts of hardened structures - Explore how to use available material (e.g., remove material that falls on railroad tracks and repurpose for nourishment, rather than trucking away)
Cobble berms/dynamic revetments	- Adds natural material to the site so it does not look out of place - Can be maintained and supplemented when necessary - Flexible, adaptable, dynamic approach that can move according to seasonal dynamics - More acceptable to the public and an environmentally-friendly approach - Relatively inexpensive	- Not as effective as shoreline hardening in some places; some limitations depending on location - Vulnerable to damage and deterioration in higher energy environments - May decrease recreational opportunities (e.g., walking, horseback riding) - May seem unnatural in some areas (e.g., beaches lacking cobble, but pulling cobble from adjacent areas [i.e. Cape Lookout])	- Develop guidance to determine best site placement from coastal geologists - Need to monitor performance as it is a fairly new technique, however, it may be more able to adapt to changing conditions (i.e. more flexible than fixed riprap)

Management Action	Strengths/Benefits	Weaknesses/Limitations	Opportunities
		- Understanding of impacts on surrounding habitats and species is not clear (e.g., cobbles tend to move laterally, not vertically, with wave energy), although effects are likely to be minimal	
Dune restoration	- Provides flood protection and long-term erosion protection by allowing for dynamic movement - More adaptable than hard infrastructure (e.g., fairly easy to manipulate dune height and width) - Highly valued scenic/aesthetic qualities - Protects infrastructure from sand inundation - Can yield multiple benefits (e.g., restore native plants and create habitat)	- May be competing objectives when looking at benefits for human communities vs. natural habitats (i.e. "view grading"/restoring ocean views vs. restoring habitat) - Can be expensive and requires heavy equipment - Requires ongoing maintenance (i.e. in Northern California, invasive species are pervasive along the coast outside treatment areas) - Public misperception regarding stabilization; dune still moves and vegetation helps to capture sediment for its growth - Public perception that dunes may not be effective in controlling erosion	- Identify the correct balance of stabilized dunes and natural habitat on specific coastlines - Critical to continue as so many communities depend on dunes for flood protection
Oyster reefs (i.e. oyster shell deposit sites, reef balls with live oysters)	- Benefits largely unknown because this action is not commonly used in the region - May be best suited in lower energy environments (i.e. estuaries, river mouths)	- May cause ecological and biological impacts, especially depending on oyster species used (i.e. non-native vs. native species) - May prove unsuccessful with ocean acidification	- Need to integrate monitoring to test longevity and durability with changing ocean conditions - Study impacts of oyster reefs on sediment dynamics, especially reefs composed of live oysters - Unclear if it would be allowed in different management units and what agency would provide review and permitting

Management Action	**Strengths/Benefits**	**Weaknesses/Limitations**	**Opportunities**
Relocation	- Creates adequate space to accommodate uncertainty in rate and magnitude of coastal change - Proactive approach to avoid damage to infrastructure - Offsets continual maintenance costs of soft and hard shoreline approaches - Moving hard structures out of the way allows for natural processes to return to a system, which in turn then can protect relocated structures - Lack of structures right on the shoreline allows habitats to move inland/upland as needed while maintaining natural angles and functions (assuming that there is a reliable sediment supply and habitats can keep pace/accommodate accelerating rate of change)	- Best implementation conditions tend to be very location-specific (i.e. many developed shorelines do not have enough space to move) - Some concern about upfront costs - May not be feasible in certain situations (i.e. moving tribal reservations or abandoning cultural use areas) - Permitting processes are not typically amenable to this approach, especially when compared to other actions - Raising elevations of structures can conflict with height restrictions in local codes - Lack of public understanding about relocation feasibility - Many counties cannot buy land but also cannot say its "unbuildable" as that constitutes a regulatory taking - Difficult to prove the value of structure movement to property owners - Pressure and incentive to armor to maintain property values can trump relocation options	- Conditional use permits may provide a workaround to permitting issues - Likely that investments in most vulnerable locations will decline in the face of eventual loss - Communicate benefits and risks to the public (i.e. use photo documentation and stories combined with projections) - Real estate disclosures about benefits and risks should be encouraged - Identify and share examples to demonstrate costs and benefits - Study impacts on site-specific sediment transport and impacts on geomorphology
Land acquisition and managed retreat	- Removes pressure/need for hard armoring - Keeps people out of harm's way - As it is currently voluntary, it is less socio-politically tense - Allows for restoration of natural habitats - Serves as an alternative to hard shorelines in permitting: permittee has to prove that managed retreat is more costly than hard armoring	- Typically very expensive - Landowner expectations of property values are often higher than appraisal prices; hard to find middle ground for purchase price - Expenses of tradeoffs are mostly unclear (e.g., will more infrastructure be built further inland as a result?) - Can be difficult to manage public expectations with change (e.g., loss of coastal views from campsites) - Because it is voluntary, agencies cannot	- Need options beyond acquisitions (e.g., allow some continued occupation of sites [e.g., flood easements]) - Positive impacts of retreat need to be better communicated to help shift public opinion - Need some restrictions or guidance on zoning changes to guide use of land once retreat

Management Action	Strengths/Benefits	Weaknesses/Limitations	Opportunities
		require people to move, which limits larger scale coordination - Differences in public opinion and palatability of different options (e.g., concerns about opening up space for flooding)	occurs - Develop access rules for land post-retreat - Need for technical information on how to best move infrastructure (e.g., older houses)
Conservation easements	- Can be applied at multiple scales - Flexible tool - Typically cheaper than acquisition - Some financial incentives for property owners (i.e. tax reductions for shoreline easements backed by upland development) - May pave the way for future acquisitions if land value is decreased by giving up development rights	- Requires monitoring to ensure easements are in compliance (i.e. on-site maintenance, no illegal dumping) - Ease of implementation depends on what is being protected (i.e. agriculture, forestry, natural habitats) - Can be challenging to maintain relationships across generational changes in ownership - Public perception of re-sale value may be negative (i.e. easements can reduce property value if development rights are ceded) - Size uncertainties: do not know how much area to protect, and how to market this option to funders - May result in a parcel patchwork approach to habitat protection; would likely be more effective at larger scale	- Increase education on how easements (i.e. green space) can help raise property value for surrounding neighborhood - Explore new incentives for landowners to use this tool - Explore ways to prove long-term economic benefits - Explore ways to implement at larger scale

Discussion 3. Critical Research and Management Questions

The last discussion focused on management needs and the co-generation of critical research. The following topics emerged:

- Site-specific cost-benefit analyses comparing hard and soft approaches (i.e. installation and maintenance over time, cost of outcomes with and without action implementation, ecosystem services valuation);
- Experimental projects to examine habitat restoration success in light of sea level rise;
- Research on potential coastal vegetation changes with increasing carbon dioxide levels;
- Longevity of existing and new infrastructure;
- Community responses to or preferences for new and emerging adaptation actions;
- Mechanisms by which to overcome social resistance to managed retreat (i.e. methods of engagement with and effective incentives for different stakeholders [agricultural producers, private landowners]);
- More general incorporation of climate change into planning and policy, and coordination across different levels of government;
- Sea level rise projections and vulnerability assessment results compared with catastrophic Cascadia earthquake, and how this information could be used in planning and permitting (i.e. is planning for tsunamis equivalent to planning for sea level rise?); and
- Monitoring of sea level rise impacts and management effectiveness across different shoreline types (i.e. high vs. low energy, natural vs. developed vs. working waterfronts).

Finally, participants discussed common barriers to communication between scientists and managers that can constrain effective science delivery and climate-informed decision making, as well as potential opportunities for improvement. These included:

- Access to actionable information: There is a lot of science available to inform management, but several barriers to its meaningful integration in decision making. For example, there is a noted lack of a shared vernacular across the scientist-manager-policymaker-public spectrum. It can also be difficult to sort through the sheer volume of resources (i.e. "information tsunami") to find relevant, high-quality science. Managers noted that shorter, more digestible fact sheets or other resources would be useful (i.e. email digests with brief summaries of the best peer-reviewed, vetted science), as well as more availability of open access articles.
- Constrained operations: Coastal planners and managers operate within a "culture of maintenance," wherein a lot of activity is focused on protection of infrastructure. Planning staff also expressed a lack of capacity to address longer-term planning projects in light of climate change.
- Integration of management perspectives into science: Participants noted that a lot of research can occur in a science "vacuum" wherein on-the-ground planning and management experiences are not reflected. Opportunities include requiring the integration of managers throughout a research project's lifetime (i.e. convening an advisory committee), and requiring management-relevant deliverables (as defined by managers) for stakeholders in the project's study area.

5. Concluding Thoughts

The purpose of this report is to describe and highlight salient features and results of this ASAP. The results are meant to stimulate discussion, and are not considered to be definitive or prescriptive in nature. The approach used in this project successfully helped us identify the range of sea level rise adaptation actions recommended in management plans and policies and implemented on the ground by resource managers, and an overall picture of the science behind NNBAs that address sea level rise. However, there are some limitations:

- Sea level rise itself is difficult to isolate from other coastal changes, such as storm surge and king tides;
- The factors that influence how vulnerable a location is to sea level rise and coastal change (e.g., topography, geology, sediment supply, etc.) also influence the effectiveness of NNBAs;
- NNBAs are not an option for all coastal areas (e.g., hard structures may be the only option for eroding cliffs), and in some cases, hybrid gray-green adaptation approaches may be necessary in order to provide adequate protection. For example, the Multiple Lines of Defense Strategy[10] was created by Louisiana's Lake Pontchartrain Basin Foundation to integrate coastal habitat protection and engineered flood protection measures, while strategically implementing both natural and built features that help buffer the coast from flooding and erosion (e.g., rock armoring, beach nourishment, oyster reefs, marsh revegetation [Gregg et al. 2017]);
- Some of the science identified through the systematic mapping was relevant to specific types of coastlines in the region (e.g., outer coasts vs. Puget Sound) or outside of the project geography (e.g., the Netherlands), so identifying evidence that is consistent and applicable at a regional scale was challenging; and
- Alternative pools of literature (e.g., engineering journals) may have yielded additional resources relevant to the research questions that to date have not been rigorously synthesized.

This project also revealed some overarching considerations that could inform future adaptation-related systematic review efforts:

- Our review questions were relatively broad in that they did not focus on a single, specific adaptation action but rather on a suite of actions. This wider focus in review questions was useful in getting a general impression of the scope of and sources for current scientific literature, but reduced the specificity with which we were able to define, or bound the scope of which references were relevant and which were not. Choosing and focusing systematic searching on a specific action (e.g., beach nourishment) could be more productive in identifying the extent of the knowledge base, and locating evidence regarding the merits and drawbacks of a particular action. However, given that managers have multiple sea level rise adaptation tools to choose

[10] Multiple Lines of Defense Strategy: http://saveourlake.org/lpbf-programs/coastal/multiple-lines-of-defense-strategy

from, the project team found it more useful to cover a portfolio of actions rather than a deeper diver into a single action.

- The search engines used in systematic reviews may require higher scrutiny. While Google Scholar is a very powerful search tool, and generally the most productive, the algorithms that it uses to generate returns are proprietary and not transparent, and Google may modify its search algorithms from time to time. This can preclude the ability to replicate search results from Google Scholar, especially if some time has passed. This could hinder efforts to build upon existing reviews such as this project, and would likely require some effort duplication in finding and screening relevant literature.
- A key lesson learned in both this project and the initial ASAP pilot project (Gregg et al. 2016) is the value of complementing a systematic literature search with workshops to elicit feedback, additional knowledge, and sources of literature from scientists and managers. This could be adopted as standard operating procedure, especially with forward-looking issues such as climate change where science can be diffuse, incomplete, and rapidly emerging (Berrang-Ford et al. 2015).

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Appendix A. Catalog of Gray Literature from Phase 2

Please see the link to the data record on ScienceBase: http://bit.ly/ASAPSLR

Appendix B. Systematic Review Methods and Search Protocol

Systematic Review

Systematic review is a process originally developed in the late 1980s in the field of clinical medicine to find, analyze, and synthesize all relevant information on a particular medical intervention (e.g., a drug or surgical procedure). A medical systematic review addresses the basic question "is the [drug or procedure] effective?" But in order to clearly define the scope of relevant scientific literature, the review question is usually framed more precisely by specifying the population under study, any comparators (e.g., a different intervention, or no intervention), and outcome measures used to assess effectiveness. For example: "In middle aged men, does Rogaine reduce male pattern baldness compared to a placebo?"

Use of systematic review in medicine expanded exponentially through the 1990s and 2000s. With growing awareness of how systematic review can add focus, objectivity, and transparency to science synthesis, the process was adapted for use in other fields, including environmental conservation and management (Burnett et al. 2006; Pullin & Stewart 2006). Compared to clinical medicine, evidence in ecology and environmental management tends to be limited and much more diverse in methodology, applicability, rigor, and in the ways and places it is catalogued (Behan et al. 2006; Doerr et al. 2015). This can make finding all available evidence and assessing its relevance considerably more difficult. Despite such challenges, use of systematic review methods in these fields continues to grow in response to ongoing needs for objective ways to identify and package "best available science" and "actionable science" for use by policymakers and practitioners.

In the context of environmental conservation, systematic review methods are most useful for narrowly targeted questions regarding the effectiveness of a specific action taken for environmental protection or restoration, or on behalf of a particular species. In our experiences with applying systematic review in such contexts, we have found one component of a systematic review to be particularly useful: the review protocol. The protocol is a short document drafted early in the process that lays out details of the review including:

- A paragraph or two discussing background, the issues at hand, and sometimes, a "problem" statement. This section explains why the review is needed and being done.
- The review question, or small set of closely related questions, which are (ideally) specific and tightly focused. The questions should be management and policy relevant, but clearly about science. Review questions are discussed and refined with stakeholders, experts and users of the information before the review begins, to ensure that the questions are as focused as possible on the issues at hand, and that all interested parties are in agreement about this.
- Keywords, search strings, search engines and databases, and other sources that will be searched.
- Criteria for including or excluding each reference found. The more focused and narrow the review questions are, the easier it is to specify and apply inclusion and exclusion criteria.

Depending on the issues at hand, the protocol may also specify how evidence quality will be assessed. In environmental conservation, this typically means assessing study sample sizes, replications, duration, and appropriateness of statistics used, etc. More often than not, the protocol evolves over the course of a review as additional or better keywords emerge, new databases or other sources of information come to light, or resources are recommended by partners or other subject experts.

Literature Search Protocol

The overall goal of the Available Science Assessment Process is to synthesize and evaluate the body of scientific knowledge on specific, on-the-ground climate adaptation actions to determine the conditions, time frames, and geographic areas where these actions may be most effective for resource managers. A systematic literature search will be conducted to identify scientific literature relevant to a subset of climate adaptation actions taken to address sea level rise.

Focus and purpose

Actions that managers may choose to take in response to sea level rise may vary depending on the environmental and/or social values they are trying to protect. For example, actions taken to protect human infrastructure in highly developed urban areas will generally differ from actions taken to protect ecological functions in less intensively developed tidal wetlands. This literature search focuses on nature-based techniques for restoring and maintaining coastal ecosystems and ecological functions as sea levels rise. Highly engineered structures (e.g., seawalls) are not the primary focus.

Rather than a systematic *review* on a narrow, targeted question regarding the effectiveness of a specific management action, this exercise will provide a systematic literature *map.* Systematic mapping focuses on the current state and trajectory of knowledge around a broad, open-ended question or a particular area of interest. In this case, the purpose of the systematic literature map is to provide a basis for discussion by regional scientists and managers with expertise on sea level rise and associated adaptation responses.

Review Questions

Are the conditions, time frames, and geographic areas for use of existing nature-based techniques for restoring and maintaining coastal ecosystems and ecological functions changing in response to sea level rise? If so, how?

Are there any new nature-based tools or techniques being developed for restoring and maintaining coastal ecosystems and ecological functions specifically in response to sea level rise? If so, under what conditions, time frames, and geographic areas may these actions be most effective for resource managers?

As they incorporate sea level rise into planning and use of nature-based methods for restoring and maintaining coastal ecosystems and ecological functions, what additional science information should managers consider?

Methods

Depending on the review/synthesis goal, and the nature of the review question(s), systematic review and systematic mapping generally involve some trade-offs between a tightly focused and deep search, and a search that is wider but not as in-depth. We are focusing on a fairly wide search (i.e. higher number of search terms, more open-ended questions), but using a more limited list of potential information sources.

Scope of search

We will conduct a systematic search of academic databases for peer-reviewed and gray literature published since 2000. This year was selected to reflect the rapid advances in climate modeling and scientific literature published on sea level rise and coastal change over the last 15+ years. Search methods are described below, including databases to be searched, search terms, and literature inclusion criteria. These methods may be modified and refined as the search progresses. Search parameters, along with any modifications made and their rationale, will be documented in the final project report. The systematic search may be supplemented with searches of bibliographies of particularly relevant or seminal papers and solicitation of relevant literature from subject matter experts and agency personnel.

For the academic database searches, search terms will be tested with preliminary searches and potentially augmented with additional terms based on initial findings.

Academic databases to be searched:

- Google Scholar

As time allows, these additional databases may be searched:

- AGRICOLA
- Academic Search Premier
- CAB Abstracts
- Environmental Sciences and Pollution Management
- Web of Science

Leads regarding where to find relevant literature provided by subject matter experts will be investigated (e.g., the following organizations, documents, and portals):

- San Francisco Bayland Goals rewrite for climate change: http://baylandsgoals.org
- Tijuana National Estuarine Research Reserve Climate Understanding and Resilience in the River Valley (CURRV) project: http://trnerr.org/currv/
- NASA Sea Level Change Portal: https://sealevel.nasa.gov

- Washington State Department of Ecology climate change reports and publications: https://ecology.wa.gov/Research-Data/Scientific-reports/Climate-change-reports-and-monitoring-data
- Climate Ready Communities: https://www.oregon.gov/lcd/docs/publications/climate_ready_communities.pdf
- Regional Framework for Climate Adaptation, Clatsop and Tillamook Counties: https://www.oregon.gov/LCD/OCMP/docs/Publications/Regional_Framework_Adapt_Clat_Till.pdf

Search terms

Because the focus is on recent literature specific to sea level rise adaptation, and in order to limit the volume of "hits" that will need to be reviewed, initial search strings will include the term *sea level rise*, or a similar term. We recognize that there may be relevant literature that will not be caught by this search strategy. Search terms and search strings may include:

- sea level + rise/rising/higher
- ocean level + rise/rising/higher
- coastal flooding/coastal inundation
- climate change planning
- sea level rise adaptation
- coastal adaptation
- coastal erosion
- bluff erosion
- storm surge
- managed retreat
- coastal realignment
- transition zone
- setback/set back
- upland space
- inland migration
- open space
- rolling/conservation + easement
- protect/restore + natural + shoreline/buffer/ecosystem/system/habitat/feature
- living shoreline
- soft/green + shoreline/armoring
- coastal protection
- ecosystem-based adaptation

Literature inclusion/exclusion criteria and assessment of relevance

For each database search, we will assess the first 50 "hits" for potential inclusion in the review/synthesis based on a hierarchical assessment of relevance by scanning article titles, followed by reading the abstract of articles with relevant titles and keywords, followed by reading the full-text of articles with relevant titles and abstracts. Studies will be deemed relevant based on the following criteria:

- Includes substantive discussion of nature-based methods for restoring and maintaining coastal ecosystems and ecological functions changing in response to sea level rise.
- Is focused on Oregon, Washington, Northern California, and southern British Columbia.

Literature on these topics with study sites along North America's eastern seaboard or Gulf Coast, or other coastal areas worldwide may be relevant and will be considered on a case-by-case basis.

For the purposes of this review, it is assumed that (1) there will be some degree of sea level rise resulting from human-induced climate change; (2) rising sea levels will impact ecological and social values; and (3) that managers will be faced with the need to respond in some fashion to protect or mitigate impacts on these values. Therefore, studies that discuss the effects of sea level rise, but do not include discussion of responses or management actions, will be excluded. Exceptions to this exclusion criterion may be made on a case-by-case basis.

Recognized limitations

The approach in this review protocol has a few known limitations:

- We are operating under a constrained timeline.
- We may have to approach the assessment of the literature, though systematically, in a way that varies from the traditional systematic review approach.

Potential Conflicts of Interest and Sources of Support

The ASAP team and panelists declare that they have no competing conflicts of interest. This review is funded by the Department of the Interior's Northwest Climate Adaptation Science Center.

Appendix C. Catalog of Literature Reviewed in Systematic Mapping

Please see the link to the data record on ScienceBase: http://bit.ly/ASAPSLR

Appendix D. Scientists-Managers' Workshop Participant Lists

Seattle, Washington

Name	Affiliation
Lance Bailey	City of Port Townsend
Don Benson	No affiliation identified
Rich Carlson	USFWS Puget Sound Coastal Program
Ann Edwards	PNW Landscape Conservation Design Technical Committee
Bill Gerken	Moffat & Nichol
Cindy Jayne	Jefferson County Climate Action Committee
Lisa Kaufman	Northwest Straits Foundation
Jordan Macke	Fain Environmental
Mary Mahaffey	North Pacific Landscape Conservation Cooperative
Younes Nouri	Moffat & Nichol
Dawn Pucci	Island County Department of Natural Resources
Cynthia Rossi	Point No Point Treaty Council
Hugh Shipman	Washington Department of Ecology
Judy Surber	City of Port Townsend
Anna Toledo	Island County Department of Natural Resources
Tina Whitman	Friends of the San Juans
Fletcher Wilkinson	Samish Indian Nation
Todd Woddard	Samish Indian Nation
Janet Wright	Island County Planning Department

Newport, Oregon

Name	Affiliation
Margaret Corvi	Confederated Tribes of Coos, Lower Umpqua, and Siuslaw Indians
Amanda Craig	Confederated Tribes of Coos, Lower Umpqua, and Siuslaw Indians
Nicole DeCrappeo	USGS/Alaska Climate Science Center
Laurel Hillmann	Oregon Parks and Recreation Department
Adrienne Kirk	Confederated Tribes of Coos, Lower Umpqua, and Siuslaw Indians
Denise Lofman	Columbia River Estuary Taskforce
Meg Reed	Oregon Coastal Management Program
Hui Rodomsky	Lincoln County Department of Planning and Development
Ashley Russell	Confederated Tribes of Coos, Lower Umpqua, and Siuslaw Indians
John Schaefer	Confederated Tribes of Coos, Lower Umpqua, and Siuslaw Indians
Jay Sennewald	Oregon Parks and Recreation Department
Patty Snow	Oregon Coastal Management Program
Trevor Taylor	Oregon Parks and Recreation Department
Patrick Vaughan	California State Parks