Puget Sound National Estuary Program

Marine Vegetation State of Knowledge Report

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EXECUTIVE SUMMARY

This document provides technical support for the Marine Vegetation Implementation Strategy by synthesizing the existing state of knowledge on eelgrass (*Zostera marina*) and kelp (canopy-forming, floating species and understory species) in Puget Sound, including the impacts of pressures and stressors on marine vegetation and considerations for executing the Implementation Strategy's five recovery strategies. The strategies collectively aim to advance eelgrass and kelp recovery in Puget Sound, as defined in the Beaches and Marine Vegetation Vital Sign, by coordinating regional opportunities, priorities, and funding in: 1) Research and Monitoring, 2) Regulation, 3) Protected Areas, 4) Restoration, and 5) Community Connections.

Recovery is needed for marine vegetation in Puget Sound because the current extent of these foundation habitats is significantly reduced from their historical distributions and they support many important ecosystem functions and services. Both eelgrass and canopy kelp (primarily *Nereocystis luetkeana*) naturally exhibit high inter-annual variability, however, persistent reduction in abundances observed at many locations in Puget Sound indicates that observed declines are not due to natural variation. **The likely drivers of observed declines are climate change and human modifications, which can cause detrimental changes in water quality, physical disturbance, excess nutrient and sediment loading, and altered food web dynamics.** Changes in the abundance of understory kelps cannot be assessed at present due to the lack of monitoring information.

Research over the last five or 15 years since prior recovery plans were written for kelp and eelgrass, respectively, has yielded substantial advances in understanding the key pressures and stressors for marine vegetation. While the identities of the major stressors in Puget Sound are generally known, more information is needed to understand stressor intensity, the cumulative impact of multiple stressors, and differentiation of stressor impacts by scale and species. The body of literature on eelgrass stressors is generally more robust than for kelp and the knowledge of understory kelps represents the largest gap. **Water quality features, especially temperature, nutrients, and clarity, and the availability and stability of appropriate substrate are perhaps the primary drivers of marine vegetation.** Biological stressors (e.g., disease, competition, grazing, invasive species), physical disturbance (e.g., vessel activity, shellfish aquaculture), and other water and substrate quality aspects (e.g., salinity, contaminants, hydrogen sulfide) may contribute to changes in marine vegetation but are less commonly identified as the primary or singular driver. Stressors are often found to overlap and interact, and **it is very likely that the cumulative impact of multiple stressors ultimately determines the trajectory of marine vegetation beds.**

Many external forces associated with climate change have and will continue to impact our ability to recover marine vegetation in Puget Sound. Temperature rise is a primary concern for marine vegetation and Washington state has limited management or regulatory tools to reduce water temperature. Future changes in sea level, storm intensity, and salinity may also contribute to the future abundance of marine vegetation, but predicting or controlling the ultimate impact

of those threats is challenging. Existing management and regulation may be able to more easily reduce other stressors, including those known to interact in deleterious ways with climate change. For example, reducing excess nutrient, sediment, and contaminant loads from in-water and terrestrial sources may increase the resilience of marine vegetation to climate stressors.

There are many considerations relevant for executing the Implementation Strategy, based on information related to scale, design, effectiveness, and other factors. Stressor identification is a key element of the **Research and Monitoring Strategy** because understanding the relevant stressors at site- and region-level scales will help determine appropriate management actions. All monitoring and research activities within the strategy would benefit from a) the expansion of Tribal capacity and collaboration to incorporate Indigenous Scientific Knowledge, and b) the co-development of research with managers to improve the useability of scientific information. In addition to considerations discussed in another Implementation Strategy appendix, the *Base Program Analysis*, implementation of the **Regulatory Strategy** would be strengthened by research on how regulated activities affect eelgrass and kelp, and on the effectiveness of regulatory programs. The establishment of new protected areas as part of the **Protected Areas Strategy** should consider spatial design principles related to protected area size, location, shape, proximity to other managed areas, distribution, connectivity, management measures, and other concepts. Before-after-control-impact studies should be used to assess whether protected areas effectively reduce region- and site-specific stressors on marine vegetation and generate associated ecological and socioeconomic benefits. The **Restoration Strategy** should aim to improve on existing tools to determine site suitability for restoration by incorporating the most crucial biophysical conditions (informed by stressor research). Restoration techniques and the effectiveness of restoration for social and ecological outcomes are areas where additional information is needed. Community engagement as part of the **Community Connections Strategy** can increase environmental stewardship, though more research is needed to understand existing marine vegetation stewardship in Puget Sound. Citizen/community science projects should consider a) engaging participants in research activities beyond only data collection and b) intentionally measuring project effectiveness, among other principles. Research on outdoor recreation and harvest of marine vegetation is needed to identify actions that support these human connections to eelgrass and kelp.

Examples where marine vegetation abundance has increased as a direct result of management actions are limited in Puget Sound and the Pacific Northwest region. Climate change and other stressors that can be beyond the control of practitioners, including algal competition (related to nutrients) and sediment dynamics, have often impeded recovery efforts. Notwithstanding uncertainty about the extent to which marine vegetation recovery can be achieved, actions to minimize stressors associated with coastal development (e.g., changes to hydrology and loading of nutrients, sediments, and contaminants), marine activities (e.g., disturbances associated with vessel traffic and shellfish aquaculture), and climate change (primarily temperature) can benefit the ecosystem as a whole, including potential benefits to human health and well-being via improved aesthetics and recreation opportunities.

Contents

Tables, Figures, and Uncertainty Tables

Acronyms and Abbreviations

AUV	Autonomous underwater vehicles
BACI	Before-After-Control-Impact
CoSMoS	Coastal Storm Modeling System
eDNA	Environmental DNA
MLLW	Mean Lower Low Water
MPA	Marine Protected Area
NOAA	National Oceanic and Atmospheric Administration
PNNL	Pacific Northwest National Laboratory
PSRF	Puget Sound Restoration Fund
PSU	Practical salinity unit
ROV	Remotely operated vehicle
SAV	Submerged aquatic vegetation
SLR	Sea level rise
SVMP	Submerged Vegetation Monitoring Program
UAS	Unoccupied aerial systems
UAV	Unmanned aerial vehicles
WA DNR	Washington Department of Natural Resources
WDFW	Washington Department of Fish and Wildlife

1 INTRODUCTION

This State of Knowledge Report is meant to provide a scientific and technical foundation to the Marine Vegetation Implementation Strategy (hereafter "Implementation Strategy"). Briefly, the Implementation Strategy describes the regional outcomes necessary to accelerate habitat recovery progress as measured by the Puget Sound Vital Sign indicators for kelp and eelgrass. It serves as a road map for aligning opportunities across agencies, programs, projects, and funding and highlights the areas requiring the most attention to sustain and accelerate the progress achieved to date. While "marine vegetation" can refer to any plant or algae that inhabits marine waters, the Implementation Strategy is focused on seagrasses and kelps due to the unique and complex habitat supporting structure they provide. Seagrasses are rooted, flowering plants and there are six species present in the Puget Sound region, including native eelgrass (*Zostera marina*), non-native dwarf eelgrass (*Nanozostera japonica*, according to current taxonomic classification, formerly *Zostera japonica*), several species of surfgrass (*Phyllospadix sp*.), and widgeon grass (*Ruppia maritima*). While the Implementation Strategy is inclusive of all five native seagrass species, eelgrass (*Z. marina*) is the primary seagrass focus of this State of Knowledge Report because it is the predominant native seagrass in Puget Sound and is the principal species of interest for regulatory programs. Kelps are large brown seaweeds, including canopy and understory species. In the Puget Sound region (i.e., the Washington state waters of the Salish Sea), there are two canopy-forming species (giant kelp, *Macrocystis pyrifera*, and bull kelp, *Nereocystis luetkeana*) and roughly 20 species of understory kelps. The Implementation Strategy and this State of Knowledge Report are inclusive of all kelp species in Puget Sound.

The Implementation Strategy and its five component strategies and strategy approaches are described in the Implementation Strategy Narrative document. This State of Knowledge Report is one of several technical appendices to the narrative: the others are the *Base Program Analysis* (Implementation Strategy *Appendix II.b*), which describes the regulatory policies and programs within which eelgrass and kelp can currently be managed in Puget Sound; *Ecosystem Services Values Supported by Marine Vegetation in Puget Sound* (Implementation Strategy *Appendix II.c*), which quantifies the services provided by eelgrass and kelp to the broader environment (including humans); and *Marine Vegetation Research Priorities* (Implementation Strategy *Appendix I.*e) and *Marine Vegetation Research Priorities Process Spreadsheet* (Implementation Strategy *Appendix I.f*), both described below.

The State of Knowledge Report begins by introducing the status of eelgrass and kelp populations in Puget Sound and the current recovery targets which are the primary aim of the Implementation Strategy (Section 2). The strategies within the Implementation Strategy are summarized in Section 3. The context (life history and ecology) of eelgrass and kelp are presented in Section 4, followed by a summary of information about threats to marine vegetation (Section 5). Section 6 describes various considerations necessary for recovery planning and actions within the Implementation Strategy, discussed in the context of specific strategies. Finally, existing models and other tools available to support decision-making for eelgrass and kelp recovery are discussed (Section 7).

While the authors acknowledge the value of Indigenous Scientific Knowledge about eelgrass and kelp in Puget Sound, this type of information was not actively sought in the production of this report beyond what was available in published sources (e.g., Appendix B of the Puget Sound Kelp Conservation and Recovery Plan (Calloway et al., 2020)). Section 6.1.4 discusses recommendations about the incorporation of Indigenous Scientific Knowledge in implementation of approaches and activities within the Implementation Strategy.

Finally, while this document describes current scientific knowledge about eelgrass and kelp in Puget Sound, there are many topics for which more research is needed to understand eelgrass and kelp threats and therefore the most appropriate and effective recovery actions. As part of the development of the Implementation Strategy, research needs (scientific uncertainties that are barriers to marine vegetation recovery) were identified and prioritized. Throughout this State of Knowledge Report document, Uncertainty Tables highlight those research needs/uncertainties that relate to the information discussed in a section (for example, Uncertainty Table A). The priority level of each uncertainty (top, high, medium, low, or no priority) is provided and underlining is added to text to emphasize where uncertainties (or parts of them) are only about eelgrass or kelp (rather than both).[1] Uncertainty identification numbers (MV ###) align with the presentation of research needs in Implementation Strategy *Appendices I.e: Marine Vegetation Research Priorities* and *I.f: Marine Vegetation Research Priorities Process Spreadsheet*; Implementation Strategy *Appendix I.e* provides more information about the process to develop and prioritize the uncertainties and Implementation Strategy *Appendix I.f* is a Microsoft Excel spreadsheet that presents the list of uncertainties at each step of collation, refinement, and prioritization. *Appendices I.e* and *I.f* also include details about the sources of research needs and the identification and prioritization process. Sources include Calloway et al. (2020), the Puget Sound Kelp Conservation and Recovery Plan: Status Update (Whitty & Oster, 2023), Kelp Policy Recommendations - Recommendations To Advance Effectiveness of Kelp Policy in Washington (Kelp Policy Advisory Group et al., 2023), the Puget Sound Eelgrass (*Zostera marina*) Recovery Strategy [WA DNR (2015), sometimes citing Short (2014) and Thom et al. (2011)], the Statewide Kelp Forest and Eelgrass Meadow Health and Conservation Monitoring and Prioritization Plans (WA DNR, 2023a, 2023b), Beheshti and Ward (2021), Heady et al. (2022), Hollarsmith et al. (2022), Lambert et al. (2023), National Marine Fisheries Service (2017), Pacific Birds Habitat Joint Venture (2024), San Juan County Marine Resources Committee and San Juan County Environmental Stewardship (2024), Sherman and DeBruyckere (2018), Stormwater Strategic Initiative (2021), and The Tulalip Tribes (2021), as well as additional non-report sources.

[1] Priority levels were assigned to uncertainties based on the results of expert/practitioner review and an expert/practitioner voting exercise. Top priorities are the 11 uncertainties that received the most votes (a "Top 10" list with one additional uncertainty due to a tie). Generally, the remaining uncertainties were split roughly into thirds around the cutoffs of ten and five votes to assign high, medium, and low priority. Uncertainties with "no priority" are those that were not included in the prioritization voting exercise (they are more specific sub-questions of broader uncertainties). Implementation Strategy *Appendix I.e: Marine Vegetation Research Priorities* and *Appendix I.f: Marine Vegetation Research Priorities Process Spreadsheet* (Microsoft Excel spreadsheet) describe the full process of generating research priorities.

Uncertainty Table A. Example research need/uncertainty

ID	Uncertainty	Priority Level
MV 007	Identify contributing factors responsible for observed site-specific losses of marine vegetation (i.e., why has marine vegetation disappeared at a site?).	**Top**

2 BACKGROUND

This section presents a summary of the status and trends of marine vegetation, the Marine Vegetation Vital Sign indicators, and data sources. Greater detail can be found in the Implementation Strategy Narrative and on the various websites linked throughout this section.

2.1 Marine Vegetation Vital Sign Indicators

The Beaches and Marine Vegetation Vital Sign is focused on nearshore habitat, including kelp forests and eelgrass beds. There are four indicators used to track the conditions of these habitats and the impacts of restoration and protection efforts. These indicators were developed with regional scientists and stakeholders.

- *Eelgrass area*: sound-wide acreage of native eelgrass meant to track its overall health in greater Puget Sound. There is currently no target for this indicator. The previous target set in 2011 by the Puget Sound Partnership, 20% increase in eelgrass area by 2020, was not met (Christiaen et al., 2022a).
- *Short and long-term change at eelgrass sites*: the number of eelgrass sites that are increasing, decreasing, stable, or absent, calculated from the most recent six years (short term) and all years (long term) of the 20+ years of data. This indicator captures change in eelgrass at local scales which may not be detected by the *Eelgrass area* indicator. Currently, this indicator has two targets:
    1. No net loss: by 2030, see no significant difference between the number of sites with increases and declines in eelgrass area in each of three sub-regions of Puget Sound (San Juan Islands and Strait of Juan de Fuca, Northern Puget Sound and Saratoga and Whidbey Basins, and Central Puget Sound and Hood Canal).
    2. Net gain: by 2050, sites with long term increases in eelgrass area significantly outnumber sites with declines in each of three sub-regions of Puget Sound.
- *Floating kelp bed area*: long-term trend in the extent of canopy-forming kelp (bull kelp and giant kelp) at sampling locations throughout Washington state, as measured by the area of kelp present at the water surface. Trends are synthesized for 11 sub-basins, including South Coast, North Coast, Western Strait, Eastern Strait, San Juan Islands, North Puget Sound, Saratoga and Whidbey Basins, Admiralty Inlet, Hood Canal, Central Puget Sound, and South Puget Sound. There is currently no target for this indicator.

- *Understory kelp abundance and condition*: this indicator and any associated target(s) have not been developed at the time of writing, but are intended to report on the distribution, community composition, and trends of understory (non-canopy forming) kelp species, which are more abundant and diverse than canopy kelps in Puget Sound.

More detail on and justification for the indicators, indicator targets, and methods for data collection and analysis are available on the Vital Sign indicator webpages linked above.

Separate from the Vital Sign indicators and targets, Washington State directed Washington Department of Natural Resources (WA DNR) to create a Statewide Kelp and Eelgrass Health and Conservation Plan (Senate Bill 5619, signed into law March 2022, RCW 79.135.440) (WA DNR 2023a, 2023b). The target of this complementary plan is to conserve and restore at least 10,000 acres of kelp forest and eelgrass meadow habitat in Washington state waters by 2040 by advancing strategies identified in the existing eelgrass and kelp conservation and recovery plans (WA DNR, 2015; Calloway et al., 2020, respectively). Three pilot areas have been identified, including two in Puget Sound: Eastern Strait of Juan de Fuca and South Puget Sound. WA DNR is currently working with local partners in those areas to identify priority kelp and eelgrass beds for conservation and restoration.

2.2 Marine Vegetation Status and Trends

The status and trends for eelgrass and kelp in Puget Sound are presented according to recently published literature and the most recent reporting for the Vital Sign indicators. While historically abundant and broadly distributed, it is thought that there have been substantial declines in marine vegetation across Puget Sound over the last two centuries. Both eelgrass and kelp naturally exhibit high inter-annual variability, however, the significant and persistent reduction in abundances indicate that these long-term declines are not due to natural variation. Kelp and eelgrass differ in the magnitude and locations of observed declines and changes in marine vegetation at individual sites do not necessarily reflect broader basin-scale trends. The Implementation Strategy is a Puget Sound-wide strategy and is not intended to capture site-specific variation; therefore, we focus on the status of eelgrass and kelp relevant to this regional perspective and do not attempt to discuss all site-level trends. This approach is not meant to devalue the impact of local variation in marine vegetation abundance. Individual sites experiencing declines may hold distinct ecological, recreational, and cultural value, which underscores the importance of understanding local factors influencing status within the broader regional context.

Evaluating decadal scale trends between 1972 and 2012, eelgrass was stable at a sound-wide scale, but trends at smaller scales were spatially asynchronous with individual locations exhibiting complete loss, declines, and increases (Shelton et al., 2017). Divergent trends were observed even at adjacent sites. At present, Puget Sound has approximately 51,700 acres of eelgrass, based on a pooled 3-year average from 2021-2023. The *Eelgrass area* indicator generally increased between 2004 and 2016 but there has been a declining trend in the total acreage since 2016, although changes are relatively small compared to the total amount of

eelgrass (approximately 10%). The *short and long-term change at eelgrass sites* indicator shows that while eelgrass in some areas of Puget Sound is stable (Northern Puget Sound, Saratoga and Whidbey Basins, Central Puget Sound, and Hood Canal), other areas are experiencing declines (San Juan Islands, Strait of Juan de Fuca, Skagit Bay, and other small embayments and terminal inlets).

The occurrence of canopy kelp along most of Puget Sound's shorelines has decreased over the last century or more, although the magnitude of loss varies by location. In South Puget Sound, bull kelp (*N. luetkeana*) extent in 2017 was 63% lower than the earliest baseline in 1878, with up to 96% loss in some areas (Berry et al., 2021). In contrast to much of the rest of the Puget Sound region, canopy kelp abundance along the Western Strait of Juan de Fuca and outer coast has remained stable over the last century despite high interannual variability (Pfister et al., 2018). Recent trends in canopy-forming kelps vary by location in Washington state, according to the *floating kelp bed area* indicator. In the Strait of Juan de Fuca, canopy kelp populations have been stable over the past couple of decades, despite high inter-annual variability. Protection Island in the Eastern Strait is one exception, where total loss of kelp has occurred along some shorelines in the last 10-25 years. Declines have also been observed in Central and South Puget Sound, including total loss at some sites – areas of Possession Sound, for example. Limited data availability in Admiralty Inlet, North Puget Sound, and the San Juan Islands make it difficult to assess trends in those subbasins. The limited number of monitoring sites available in Admiralty Inlet and North Puget Sound do not indicate major concerns in those subbasins, however, there is concern that canopy kelp has declined in the San Juan Islands based on Indigenous knowledge and other sources of information. Although approximately one-half to one-third of canopy kelp locations in Washington are classified as stable, there is growing concern that site-specific declines may become more pervasive due to the cumulative impact of multiple stressors. Due to the lack of information about understory kelp species, changes in abundance, composition, and distribution cannot be assessed.

Uncertainty Table B. Status and trends monitoring uncertainties

ID	Uncertainty	Priority Level
MV 002	Conduct "status and trends [monitoring] of kelp and eelgrass" "species' distributions and changes through time [(including historical distribution)] in Puget Sound", including through incorporation of traditional ecological knowledge (quoted material from Calloway et al. (2020, p. C-1); WA DNR (2023a, p. 11)).	**Top**
MV 012	Generate standardized methods for monitoring understory kelp.	**High**

2.3 Marine Vegetation Indicator Considerations

Several key uncertainties and limitations exist with respect to the Marine Vegetation Vital Sign indicators described above. The indicators focus primarily on the spatial distribution and areal coverage of kelp and eelgrass, but do not contain information about habitat condition (i.e., health of the plants) or structure of the habitat, such as the density of plants or total biomass (Uncertainty Table C). Habitat condition and structural features influence the functioning of the habitats in ways that impact their ecosystem services and can have implications for persistence of the eelgrass meadow or kelp forest. For eelgrass, structural characteristics including shoot density within an area, blade length, root and rhizome depth, lateral extension, and belowground biomass all have important relationships to the functioning of the habitat, services provided, and ability of the plants to withstand stressors (Livingston, 1984; Namba et al., 2018; Schmidt et al., 2011). For kelp, structural characteristics such as stipe length, number or size of blades, and density of stipes within an area may be important for functions, services, and resilience (Gundersen et al., 2021). Other features of the plant condition, such as presence of disease, epiphytes, and bryozoans, may also impact the ability of marine vegetation habitats to function properly and deliver expected services (Graham et al., 2021).

As mentioned above, the indicators are intended to describe Puget Sound-wide trends in areal extent of eelgrass meadows and kelp forests. As such, the indicators do not capture important aspects of within-site variability, such as a reduction in total biomass resulting from structural changes including thinning or increased patchiness. Such changes may be a precursor to a reduction in extent and, if detected, could serve as an indicator of impending decline. For example, Magel et al. (2023) observed an increase in the coefficient of variation of percent cover and shoot density in a declining eelgrass bed, which preceded measured changes in aboveground biomass. Kelp and eelgrass monitoring in Puget Sound at the spatial and temporal scales required for this level of detail remains limited and is challenging from a capacity perspective.

Uncertainty Table C. Marine vegetation health uncertainty

ID	Uncertainty	Priority Level
MV 039	Identify healthy and unhealthy kelp and eelgrass sites. How does the status of kelp in places like Elliott Bay compare to kelp in reserves/"undisturbed" areas? (Quoted material from Whitty and Oster (2023, p. 12).)	**Medium**

2.4 Regional Marine Vegetation Data

WA DNR's Nearshore Habitat Program monitors seagrass through the Submerged Vegetation Monitoring Program, which uses towed underwater videography to generate estimates of seagrass area and depth distribution. Seagrass monitoring data is made available via annual monitoring reports and as a GIS database which are linked on WA DNR's Nearshore Habitat Eelgrass Monitoring page. The seagrass monitoring program was designed to be logistically

feasible and statistically robust and uses a rotating panel design that is resampled during summer at 3-year intervals using towed underwater videography (Dowty, 2005, 2017; Dowty et al., 2017). Other regular monitoring of seagrass with higher temporal frequency occurs at the DNR-led Dumas Bay SeagrassNet site and at the Padilla Bay National Estuarine Research Reserve, which utilizes the National Estuarine Research Reserve's System-Wide Monitoring Program.

Kelp monitoring in Washington represents a unique collaboration, called The Kelp Forest Monitoring Alliance of Washington State, which includes a diverse group of organizations and individuals, including state agencies, Tribes, community science, and non-governmental organizations. Currently, information sources used in the *floating kelp bed area* indicator include kelp monitoring by WA DNR, Northwest Straits Commission-supported Marine Resources Committees, and Samish Indian Nation. The monitoring program design and assessment protocols were designed as part of The Kelp Forest Monitoring Alliance of Washington State and included recommendations for future program enhancements (Berry et al., 2023). Recently, WA DNR released a new spatial kelp linear extent product that integrates multiple data sources to identify where canopy kelp are documented along one kilometer segments of shoreline, using all available monitoring data sources and types, including aerial imagery data, kayak surveys, and boat surveys (McKenna & Claar, 2026). The spatial extent includes all areas of the state where canopy kelp is present. More details on existing marine vegetation monitoring programs, including limitations and challenges, are discussed in Implementation Strategy *Appendix II.b: Base Program Analysis* (see Section 2.1).

Uncertainty Table D. Regional monitoring uncertainty

ID	Uncertainty	Priority Level
MV 011	What does community monitoring of marine vegetation look like in the region? Who is involved? What are the impacts of that community-based monitoring? How might that monitoring be more strategically used to have more diverse impacts? How might more diverse people be included in that monitoring work?	**Top**

3 Strategies for Improving the Vital Signs

The Implementation Strategy includes five strategies which collectively aim to advance eelgrass and kelp recovery in Puget Sound, as defined in the Beaches and Marine Vegetation Vital Signs, by coordinating regional activities. The strategies, and interactions among them, are summarized below. The Implementation Strategy Narrative provides more detail about each strategy.

3.1 Research and Monitoring Strategy

The Research and Monitoring Strategy is to "Implement targeted research and monitoring initiatives to understand the factors driving changes in marine vegetation, with consideration of ecological and community benefits" (Implementation Strategy Narrative, Section 3.3).

This strategy aims to improve understanding about eelgrass and kelp given the many scientific uncertainties about marine vegetation in Puget Sound. It focuses on three core areas of research: monitoring of eelgrass and kelp distribution in space and time, threats to eelgrass and kelp, and ecosystem services (the latter organized following Millennium Ecosystem Assessment (2003)). Research to study other basic biophysical aspects of marine vegetation (e.g., dispersal and connectivity) is also part of the Research and Monitoring Strategy. In addition, this strategy includes approaches to a) improve enabling conditions for marine vegetation research in the region (e.g., capacity, funding, monitoring protocols, community science coordination, community engagement in identifying research priorities, interdisciplinarity) and b) to strengthen exchange of scientific information among researchers, practitioners, and decision-makers.

Improved understanding about eelgrass and kelp in Puget Sound, resulting from actions in this strategy, will inform and enable planning in the other four strategies.

3.2 Regulatory Strategy

The Regulatory Strategy is to "Evaluate and improve implementation of existing shoreline, nearshore, water quality, and land use regulations, programs and policies to enhance protections for marine vegetation" (Implementation Strategy Narrative, Section 3.4).

This strategy aims to utilize and strengthen existing regulatory programs and policies to better protect marine vegetation from threats. To do this, the strategy includes; a) increasing staff capacity of tribes and other agencies and programs; b) developing recommendations for regulatory improvements (following marine vegetation-specific analysis of policy/program effectiveness); and c) applying recommendations to reduce barriers to regulatory implementation (as necessary), including by facilitating exchange of scientific information about eelgrass and kelp to practitioners and regulators.

3.3 Protected Areas Strategy

The Protected Areas Strategy is to "Protect marine vegetation in existing and new reserves, refuges, and other protected areas that respect Tribal treaty and sovereign rights" (Implementation Strategy Narrative, Section 3.5).

This strategy aims to protect marine vegetation from threats in Puget Sound by creating new protected areas and improving management within new and extant protected areas. To do this, the strategy includes a) fostering conditions to enable protected area development and management (including tribal and community engagement, coordination throughout Puget Sound, goal establishment, governance design, etc.); b) analyzing/synthesizing information to

inform design of protected areas; c) establishing protected areas; and d) enabling long-term protected area implementation through partnerships, outreach, and funding.

3.4 Restoration Strategy

The Restoration Strategy is to "Use effective restoration methods to accelerate recolonization and expansion of marine vegetation at sites shown to possess suitable ecological and sociocultural conditions" (Implementation Strategy Narrative, Section 3.6).

This strategy aims to supplement protective efforts (Regulatory and Protected Areas strategies) with active (planting of eelgrass and kelp) and passive (removal of threats from a site) restoration (Beheshti & Ward, 2021). It includes conducting pilot restoration projects designed based on improving understanding of threats (through the Research and Monitoring Strategy) and restoration methods; resolving restoration capacity barriers; and measuring effectiveness of pilot projects. The strategy also includes assessing the potential for restoration to be designed for multiple benefits (in addition to direct eelgrass and kelp outcomes) and for eelgrass and kelp to be part of (currently separate) process-based restoration of nearshore habitats.

Successful marine vegetation restoration in Puget Sound depends on stressor reduction through the Regulatory and Protected Areas strategies.

3.5 Community Connections Strategy

The Community Connections Strategy is to "Expand and promote responsible stewardship, local food harvest, and outdoor recreation to better connect communities with marine vegetation and support human wellbeing while upholding Tribal treaty and sovereign rights" (Implementation Strategy Narrative, Section 3.7).

This strategy aims to promote human wellbeing from, and community relationships with, eelgrass and kelp in Puget Sound. It does this by a) researching current interactions (or lack thereof) of Puget Sound residents and eelgrass/kelp (including recreation, stewardship, etc.); b) improving capacity and funding of Tribes for stewardship and other marine vegetation activities; c) facilitating community outreach and science efforts; d) developing and communicating best practices and locations for harvesting marine vegetation and other species in marine vegetation habitats; and e) understanding and increasing responsible outdoor recreation.

This strategy is meant to intersect with human wellbeing in the other four strategies.

4 CONTEXT

4.1 Ecology and Life History of Marine Vegetation

This section provides a very brief overview of the life history, ecology, and ecosystem functioning of kelp and eelgrass focused on context most relevant to the following two sections of this document, which discuss marine vegetation pressures/stressors and considerations for

implementing the Implementation Strategy recovery strategies. Extensive documentation of the ecology and life history of seagrasses and kelps can be found throughout the published literature. More detailed accounts of Puget Sound ecology and life history are also available for eelgrass (Short, 2014; Thom et al., 2011; WA DNR, 2015) and kelp (Calloway et al., 2020; Hollarsmith et al., 2022). The following information was synthesized from these documents and the references therein.

4.1.1 Eelgrass (*Zostera marina*)

Seagrasses are rooted, flowering plants that grow intertidally and subtidally in the soft sediments of marine and estuarine environments. There are six species of seagrass found in Washington state waters, however the most widespread are native eelgrass (*Zostera marina*) and non-native dwarf eelgrass (*Nanozostera japonica*, according to current taxonomic classification, formerly *Zostera japonica*). While the Implementation Strategy is inclusive of all five native seagrass species, native eelgrass (*Z. marina*) is the focus of this State of Knowledge Report because it is the most widespread in Puget Sound and the primary species of interest for regulatory programs. Eelgrass spreads via sexual reproduction (flowering and seed dispersal) and asexual reproduction (lateral spreading via roots and rhizomes) (Figure 1). In Puget Sound, eelgrass is typically perennial although biomass fluctuates within and between years. Aboveground biomass increases throughout the growing season (approximately April through August) and typically peaks in mid-late summer.

Eelgrass in Puget Sound grows on sandy and muddy substrates between 1.4 meters and -12.5 meters relative to the low tide line (mean lower low water, MLLW), but the majority occurs between 0 and -4 meters relative to MLLW. Approximately half of the eelgrass in Puget Sound is found on large tidal flats, such as the river deltas of Padilla Bay, Samish Bay, and Skagit Bay (this bed type is more common in Northern Puget Sound and the Saratoga and Whidbey Basins). The other half grows in many narrower fringing beds along steeper shorelines (this bed type is more common in Central Puget Sound, Hood Canal, San Juan Islands, and Strait of Juan de Fuca).

In addition to appropriate soft substrate, the primary biophysical requirements of eelgrass are adequate light and nutrients. The deeper edge of eelgrass beds is primarily determined by sufficient light availability, and the shallower edge is limited by exposure/desiccation stress. Biotic interactions (e.g., grazers, destructive foragers) and other physical conditions (e.g., shear stress, wave energy) can also influence the edges of eelgrass beds. Eelgrass tolerates a wide range of salinities and is generally not impacted except at persistently low salinity (less than 5 PSU). Eelgrass generally prefers cold water with moderate nutrient concentration. Eelgrass has been found to tolerate water temperature up to 30°C globally, however in the Pacific Northwest eelgrass shows signs of physiological stress above 15°C and may be locally adapted to lower temperature in this region (Thom et al., 2003). Sublethal temperature stress may make plants more susceptible to other disturbances. Eelgrass has high uptake efficiency of nutrients from both the sediment and water column. Very high nutrient levels can result in eelgrass decline primarily due to light limitation by epiphyte overgrowth, smothering by macroalgae, and increased concentration of hydrogen sulfide in sediments. Other eelgrass stressors include, but

are not limited to, water turbidity, sedimentation and substrate changes, and grazers such as waterfowl and invertebrates.

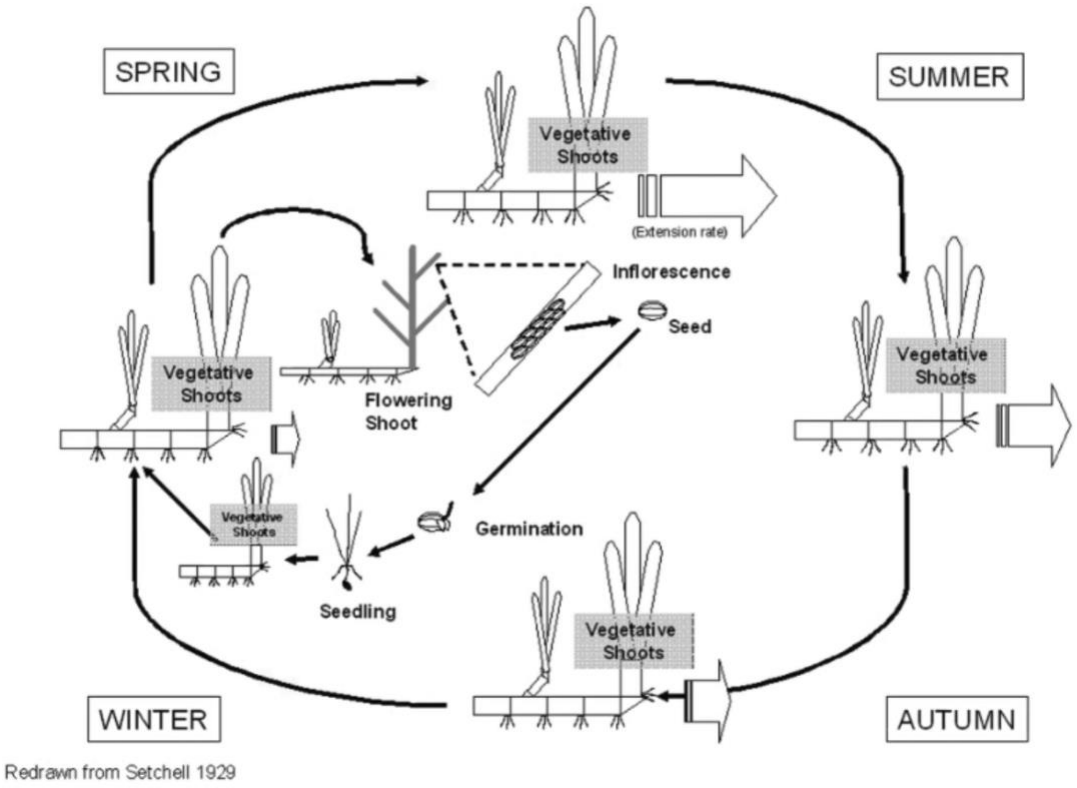

Figure 1. Stylized life history of perennial eelgrass. Image from Fonseca and Uhrin (2009).

4.1.2 Kelp

Kelps, a type of brown algae, occur throughout Puget Sound in rocky, high energy, nearshore environments in areas less than 30 meters depth (relative to MLLW). Washington has over 20 species of kelp, including understory (prostrate and stipitate) and canopy kelps (Table 1). Canopy forming kelp in Puget Sound are primarily two iconic species — *Nereocystis luetkeana* (bull kelp, most common inside Puget Sound) and *Macrocystis pyrifera* (giant kelp, more common in the western Strait of Juan de Fuca and Outer Coast). Canopy kelps occur subtidally and have gas-filled pneumatocysts that suspend them at the top water column where they create large surface canopies. Most of the remaining species of kelp in Puget Sound are understory species, including stipitate (erect midcanopy kelps that do not reach the surface) and prostrate (kelp lacking rigid or gas-filled structures), which can occur in intertidal and subtidal areas. Prostrate kelps are the most widely distributed in Puget Sound.

All kelps alternate between two phases—sporophyte (macroscopic, asexual form) and gametophyte (microscopic, sexual form) (Figure 2). Mature sporophytes release spores into the water column which drift to the seafloor within several meters of the parent plant. Kelps require solid substrate (rock, gravel, cobble, etc.) and, once attached, spores germinate into

gametophytes that reproduce sexually to produce new sporophytes. Sporophytes grow rapidly throughout the growing season (spring and early summer) and biomass typically peaks in mid-summer. Kelp can be annual or perennial depending on the species. Kelps exhibit high natural year-to-year variability in abundance often due to fluctuations in water conditions, such as nutrients and temperature.

Table 1. Species of kelp in Puget Sound (common name, if used). List adapted from Calloway et al. (2020): Appendix A – Kelp Knowledge Review, wherein additional taxonomic details are provided.

Canopy (i.e., floating) kelps	
Nereocystis luetkeana (bull kelp)	*Macrocystis pyrifera* (giant kelp)
Egregia menziesii (feather boa kelp)	
Understory kelps (prostrate form, unless noted)	
Agarum clathratum	*Laminaria sinclairii*
Alaria marginata	*Neoagarum fimbriatum*
Costaria costata	*Pleurophycus gardneri*
Cymathaere triplicata	*Saccharina latissima* (sugar kelp)
Dictyoneurum californicum	*Saccharina complanata*
Dictyoneurum reticulatum	*Laminaria setchellii* – stipitate
Hedophyllum nigripes	*Lessoniopsis littoralis* – stipitate
Hedophyllum sessile (sea cabbage)	*Postelsia palmaeformis* (sea palm) – stipitate
Laminaria ephemera	*Pterygophora californica* – stipitate
Laminaria longipes	

Both the micro- and macroscopic phases of kelp are susceptible to stressors and disturbance. As with eelgrass, kelps require adequate nutrients and light, in addition to appropriate hard substrate. Kelp species tend to be “shade-tolerant”, making them well adapted to lower-light environments, but still require enough light so that photosynthesis exceeds respiration. As such, the deeper edge of kelp forests is primarily determined by light availability and the shallower edge by exposure/desiccation. Biotic interactions (e.g., grazers, destructive foragers) and other physical conditions (e.g., shear stress, wave energy) can also influence the edges of kelp forests. Like most marine autotrophs, kelps are nitrogen limited. Nutrients that are both too high and too low, high temperature, and low salinity are thought to influence kelp distribution, community composition, and productivity. Individual kelp species and life stages have unique optimal temperature, nutrient, and salinity ranges, but most species perform best in cold water with high nutrients and salinity. Describing temperature and nutrient optima is made further difficult by local adaptation and acclimation. Physiological pathways may allow kelp to augment their performance outside of optimal temperature ranges given sufficient nutrient availability, although two recent lab studies of bull kelp did not find support for this (Fales et al., 2023; Weigel et al., 2023). Temperature stress may make plants more susceptible to other disturbances. Other kelp stressors include, but are not limited to, water turbidity, sedimentation and substrate changes, and grazers such as sea urchins, kelp crabs, and snails.

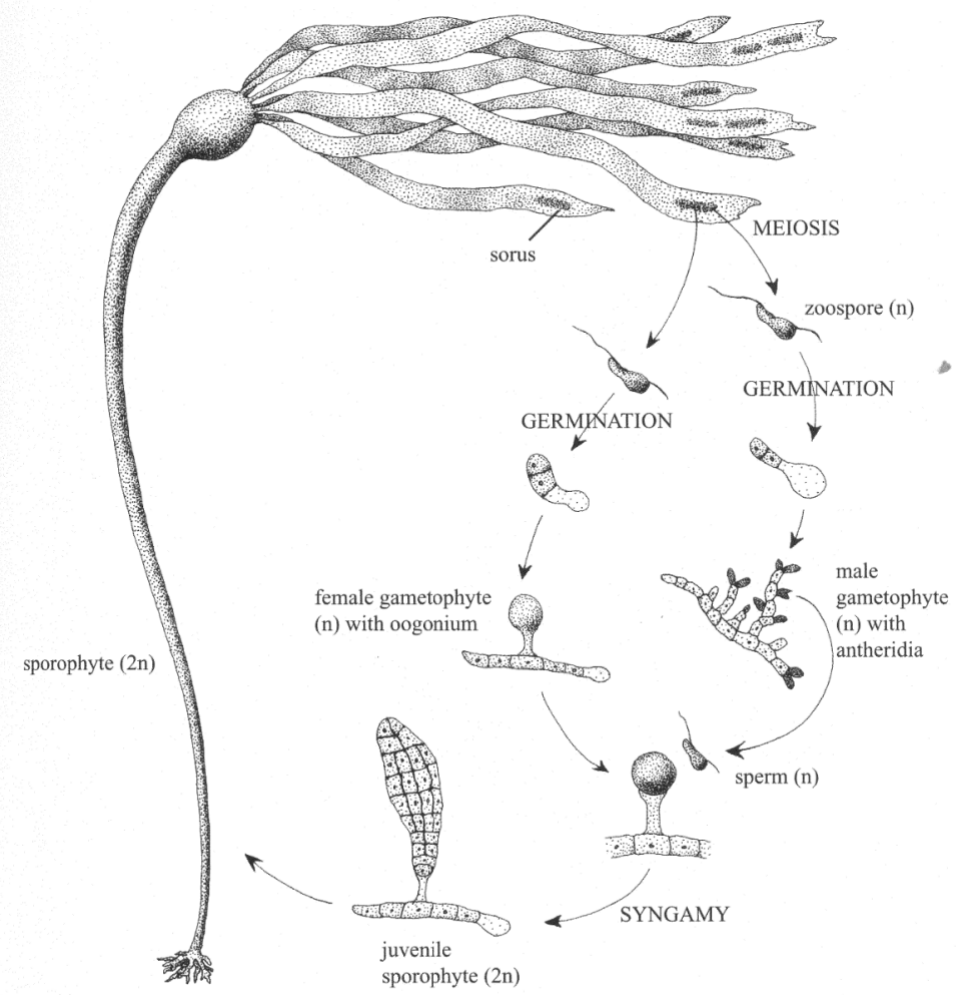

Figure 2. Diagram of kelp life stages. Image from Mondragon and Mondragon (2003).

Uncertainty Table E. Marine vegetation life history/ecology uncertainties

ID	Uncertainty	Priority Level
MV 013	Investigate kelp and eelgrass genetic structure (diversity, population dynamics, dispersal, connectivity).	**High**
MV 017	"Understand environmental thresholds of microscopic life stages [of kelp] and dispersal distances of spores in Puget Sound." What factors impact kelp recruitment? (Quoted material from Calloway et al. (2020, p. C-1).)	**High**
MV 018	What is the relationship between understory kelp distribution and canopy kelp distribution? How does understory kelp community health affect bull kelp populations?	**High**

4.1.3 Key differences between taxa

Although kelp and eelgrass share some similar attributes, sensitivities, and basic requirements, there are a few key differences between the two taxa which determine their distribution and productivity. Their substrate requirement is a primary difference — eelgrasses require soft substrate for roots and kelps require hard substrate to which the holdfasts attach. Related, eelgrass benefits from small to moderate amounts of sediment accretion which help beds maintain an appropriate depth in the water column whereas kelps are negatively impacted by sedimentation, which can cover essential hard substrate or directly smother the kelp. Furthermore, eelgrasses prefer shallower, lower energy areas, tolerate a wide salinity range, and require higher light availability whereas kelps perform better in higher energy, high salinity, and tolerate lower light environments.

4.2 Marine Vegetation Ecosystem Functions and Services

Ecosystem functions are the natural processes and ecosystem interactions occurring because of the presence of eelgrass or kelp. These include both physical functions that depend on structural characteristics of marine vegetation and biochemical functions that are related to biological processes. Broadly, physical functions include the dampening of wave motion/energy (wave attenuation), which can decrease erosion and stabilize sediments. The roots and rhizomes of eelgrass further contribute to the stabilization of the sediment in which they grow. Slowing of currents and wave attenuation by marine vegetation allows sediments to more easily fall out of the water column, which increases water clarity, and slows the residence time of water allowing for more efficient nutrient uptake by marine vegetation. The physical structure of marine vegetation enhances the complexity of nearshore areas and provides shade, cover, and refugia for a wide array of marine life, including forage fish, rockfish, abalone, and salmon. By providing habitat (physical) and through primary production (biochemical), kelp and eelgrass support healthy and vibrant food webs. Biochemical functions of marine vegetation relate to their roles in nutrient, carbon, and dissolved oxygen cycling, and the removal of contaminants.

Ecosystem services are the human benefits, including economic, social, and cultural dimensions, arising from ecosystem functions. Ecosystem services are often categorized as provisioning (e.g., food, raw materials), regulating (e.g., water purification, carbon sequestration, flood protection), supporting (e.g., nutrient cycling, primary production), and cultural (e.g., recreation, heritage) (Millennium Ecosystem Assessment, 2003). Kelp and seagrass ecosystems are associated, directly and indirectly, with several important services:

- Habitat for ecologically and commercially important species that increase biodiversity;
- Food web support (e.g., primary production, forage and nursery habitat);
- Cultural value to Indigenous and Tribal communities and other non-tribal communities;
- Recreation opportunities for harvest, fishing, and water sports;
- Coastal protection by acting as natural breakwaters to slow currents and reduce wave heights; and

- Potential local water quality improvements through carbon, nutrient, and contaminant uptake and reduction in suspended sediment loads.

Seagrasses and kelps are used as biological indicators of marine and estuarine health throughout the world because of their widespread distribution and quick response to disturbance and changes in water quality. Declines in eelgrass and kelp populations have resulted in losses to nearshore biodiversity, changes in water quality conditions, and negative impacts to fisheries, tourism and coastal health (Graham, 2004; Bertocci et al., 2015; Unsworth et al., 2019; O'Leary et al., 2021b; Magel et al., 2023).

For Implementation Strategy *Appendix II.c: Ecosystem Services Values Supported by Marine Vegetation in Puget Sound*, the authors produced a conceptual model of the ecosystem services associated with marine vegetation in Washington state based on stakeholder workshops and reviews of planning documents and published literature. In the conceptual model (Figure 3), ecosystem functions are linked to services and human wellbeing outcomes. Additional details on these ecosystem services and human wellbeing connections of marine vegetation in Puget Sound can be found within Implementation Strategy *Appendix II.c*, WA DNR (2015), and Calloway et al. (2020), including Appendices A and B. Sherman and DeBruyckere (2018) present a comprehensive review and state of the knowledge of the ecosystem services provided by eelgrass habitats on the U.S. West Coast.

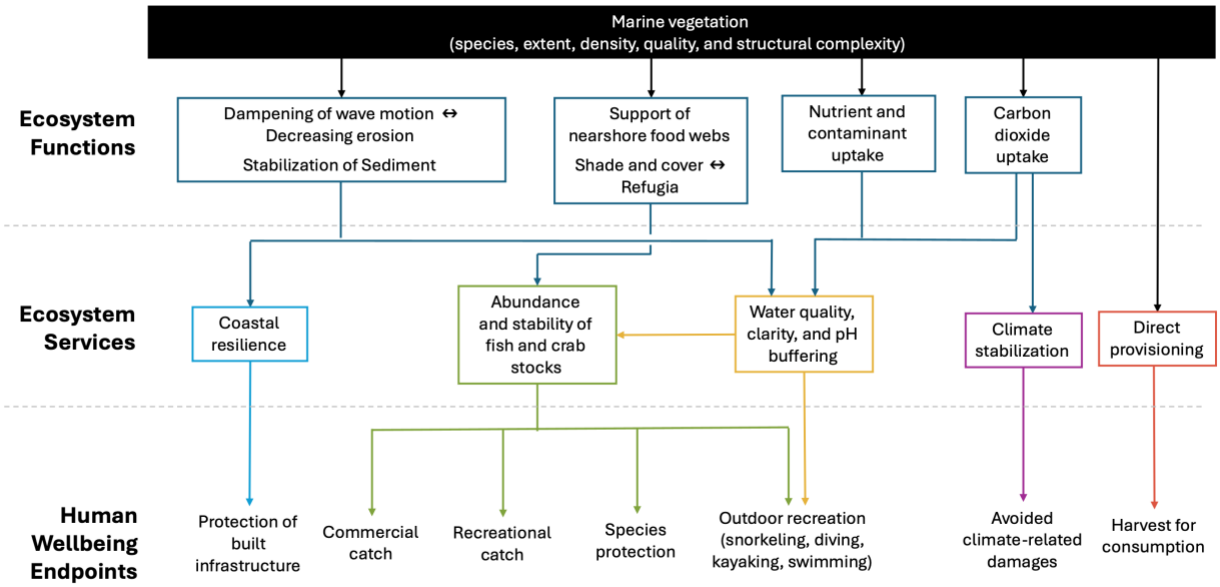

Figure 3. Conceptual model of ecosystem services provided by marine vegetation in Puget Sound. Reproduced from Implementation Strategy *Appendix II.c: Ecosystem Services Values Supported by Marine Vegetation in Puget Sound*.

Scientific uncertainties about the ecosystem services provided by marine vegetation are listed in Uncertainty Table F. All but three uncertainties about ecosystem services were crafted following the Millennium Ecosystem Assessment (2003) framework (supporting, regulating, cultural, and

provisioning services) which includes ecosystem functions within "services"; this differs from the functions/services framework used in Implementation Strategy *Appendix II.c* and discussed in this State of Knowledge Report. The three other ecosystem services uncertainties (MV 019, MV 026, and MV 033) were identified during the development of Implementation Strategy *Appendix II.c: Ecosystem Services Values Supported by Marine Vegetation in Puget Sound*. Additional data gaps identified in *Appendix II.c* are a) the amount of marine vegetation harvested by users in Puget Sound and b) access barriers for eelgrass users in Puget Sound.

Uncertainty Table F. Ecosystem services uncertainties

ID	Uncertainty	Priority Level
MV 009	Understand the supporting ecosystem services provided by kelp and eelgrass in Puget Sound. Ecosystem supporting services include primary production, food web support, and "habitat and nursery grounds for marine invertebrates [(e.g., Dungeness crab, sunflower star)], salmon, rockfish...forage fish[, and marine birds]" (quoted material from Calloway et al. (2020, p. C-1)).	**Top**
MV 014	Understand the ecosystem regulating services provided by kelp and eelgrass in Puget Sound, and the potential of these services to help mitigate and adapt to climate change. Ecosystem regulating services include nutrient attenuation, wave dissipation, sediment stabilization, acoustic attenuation, carbon sequestration, and ocean acidification buffering.	**High**
MV 019	How do quantitative and qualitative changes in marine vegetation translate to changes in the abundance, stability, and/or extinction risk of species that are important commercially, recreationally, or culturally?	**High**
MV 026	How do changes in marine vegetation translate to changes in coastal processes (e.g., wave energy and erosion)?	**Medium**
MV 032	How do the cumulative effects of stressors on kelp and eelgrass impact the regulating, supporting, provisioning, and cultural ecosystem services provided by kelp and eelgrass at regional and local scales? How are regulating and supporting services a driver of provisioning services?	**Medium**

ID	Uncertainty	Priority Level
MV 033	How are coastal human communities vulnerable (economically, physically, and culturally) to loss of marine vegetation and its ecosystem services? Aspects of vulnerability may include food insecurity, livelihood impacts, loss of access to traditional foods and cultural practices, or increased vulnerability to storms. How can vulnerability be reduced?	**Medium**
MV 034	What is the spatial distribution of the ecosystem services provided by kelp and eelgrass? "Are there kelp and eelgrass habitats that represent an unusual or distinct ecological community?" Are there kelp and eelgrass habitats that represent distinct cultural, food, recreation, or economic use? (Quoted material from WA DNR (2023a, p. 11).)	**Medium**
MV 037	How does marine vegetation contribute to regional sense of place and the unique place-based character of Puget Sound? What might marine vegetation decline mean for residents' regional sense of place and character of Puget Sound? How does marine vegetation contribute to humans' source of meaning/purpose and sense of belonging/community?	**Medium**
MV 041	Quantify the dollar value of tangible ecosystem services provided by kelp and eelgrass.	**Medium**
MV 042	Understand the cultural ecosystem services provided by kelp and eelgrass in Puget Sound. Ecosystem cultural services include recreation, local foods, cultural heritage, spiritual enrichment, sense of place, artistic inspiration, stewardship activities, and community building.	**Low**
MV 043	Understand the provisioning ecosystem services provided by kelp and eelgrass in Puget Sound. Ecosystem provisioning services include: current and historical recreational, commercial, cultural, and subsistence harvest and use of marine vegetation, as well as maintenance of recreational, subsistence, and commercial fisheries (including shellfish).	**Low**

5 Pressures and Stressors Affecting Marine Vegetation

As nearshore habitats, eelgrass and kelp are at risk from a wide variety of terrestrial and ocean-based stressors that impact marine vegetation distribution, community composition, and productivity within Puget Sound. The sources of these stressors are primarily climate change and human development, which result in changes to water quality, physical disturbance, nutrient and sediment loading, and food web dynamics that are well documented in scientific

literature, synthesis documents, and existing recovery plans. While the identities of the major stressors to marine vegetation are generally known, more information is needed to understand the cumulative impact of stressors, stressor intensity, and differentiation of stressor impacts at the regional and local scales. Basic research and thoughtfully designed stressor monitoring are needed to fill these information gaps. Marine Vegetation Implementation Strategy workshop participants highlighted the importance of collecting stressor data along with habitat monitoring data to contribute to stressor-response research.

The primary focus of this section is a discussion of the pressures and stressors (Section 5.2) affecting marine vegetation in Puget Sound. In addition, several potential resilience attributes are also discussed (Section 5.3). Note that according to the nomenclature of Puget Sound Partnership, *pressures* are human actions that are the source of stressors on the ecosystem and *stressors* are the proximate cause of ecosystem changes. However, other sources of information may use alternative words (such as drivers, threats) and alternative definitions; we do not attempt to reconcile differences in this terminology.

Uncertainty Table G. Pressure and stressor uncertainties

ID	Uncertainty	Priority Level
MV 001	Better understand the human activities that are sources of stress to kelp and eelgrass at regional and local scales. Potential drivers of change include nearshore development (e.g., overwater structures, shoreline armoring, outfalls, dredging, etc.), upland development, fisheries, boating, and climate change. Where are these human activities located, and at what densities/intensities? How (and on what timescale) are they exerting stress on marine vegetation individually and cumulatively? What is the relative importance of activities at different sites?	**Top**
MV 005	Better understand "how...stressors impact [the] reproduction, growth, and survival/mortality" of different species of individual kelp gametophytes and sporophytes at regional and local scales. Stressors may be physical (e.g., "temperature, light availability, suspended sediment, sediment deposition and erosion, nutrient availability, and hydrodynamics") or biological (e.g., "competition with other seaweeds, grazing impacts...disease, and microbiome") (quoted material from Calloway et al. (2020, p. C-1)).	**Top**

ID	Uncertainty	Priority Level
MV 010	Better understand "how...stressors impact [the] reproduction, growth, and survival/mortality" of individual eelgrass plants at regional and local scales. Stressors may be biological (e.g., disease, invasive species), chemical (e.g., anthropogenic nitrogen, contaminants, and porewater hydrogen sulfide), or physical (e.g., "temperature, light availability") (quoted material from Calloway et al. (2020, p. C-1)).	**Top**
MV 006	What are the relationships between and cumulative effects of multiple stressors at specific sites? How do interactions among different stressors combine to affect kelp and eelgrass, and does their relative importance vary by site? On what spatial and time (e.g., gradual change versus extreme events) scales and at what intensity do stressors cause harm? "How do natural variables such as current strength, substrates..., or geographic region influence measured effects of [stressors]?" (Quoted material from Lambert et al. (2023, p. 13).)	**Top**
MV 007	Identify contributing factors responsible for observed site-specific losses of marine vegetation (i.e., why has marine vegetation disappeared at a site?).	**Top**
MV 016	How do stressors impact the quantity, quality, composition, structure, and resilience of kelp and eelgrass populations at specific sites and region-wide?	**High**

5.1 Previous Syntheses

Previous efforts have synthesized the threats to eelgrass and kelp in Puget Sound, which included extensive literature review and expert elicitation efforts. Here we list and briefly describe those sources of information. The remainder of Section 5 focuses primarily on recent information about marine vegetation pressures and stressors since these foundational documents were written.

5.1.1 Eelgrass stressor syntheses

*Thom et al. (2011) "Eelgrass Stressors (*Zostera marina *L.) in Puget Sound"*

- Technical summary and comprehensive rating of individual stressors, including a conceptual model summarizing how individual stressors impact eelgrass structure and health (Figure 4).
- Main findings:

- Many eelgrass stressors interact making it difficult to attribute declines to individual stressors and the effects of environmental change may be hard to predict.
- Stressors are likely to vary considerably around Puget Sound due to spatial differences in human population, agriculture, and other pressures.
- In available case studies from Puget Sound and nearby areas, stressors observed to have the greatest impact on eelgrass were those directly affecting substrate (e.g., construction, boat activity), shading from overwater structures, and macroalgal blooms.
- The rating exercise resulted in four categories of stressors associated with prioritization for research and management (Table 2): high threat with high knowledge (priorities for management), high threat with low knowledge (priorities for management and research), lower threat with low knowledge (less pressing research priority), and lower threat with high knowledge.

- *Note*: Epiphytes were not explicitly mentioned as a stressor in the Thom et al. (2011) conceptual model, although epiphytes were discussed in relation to nitrogen over enrichment in Short (2014). This has been identified as a gap in the Thom et al. (2011) conceptual model.

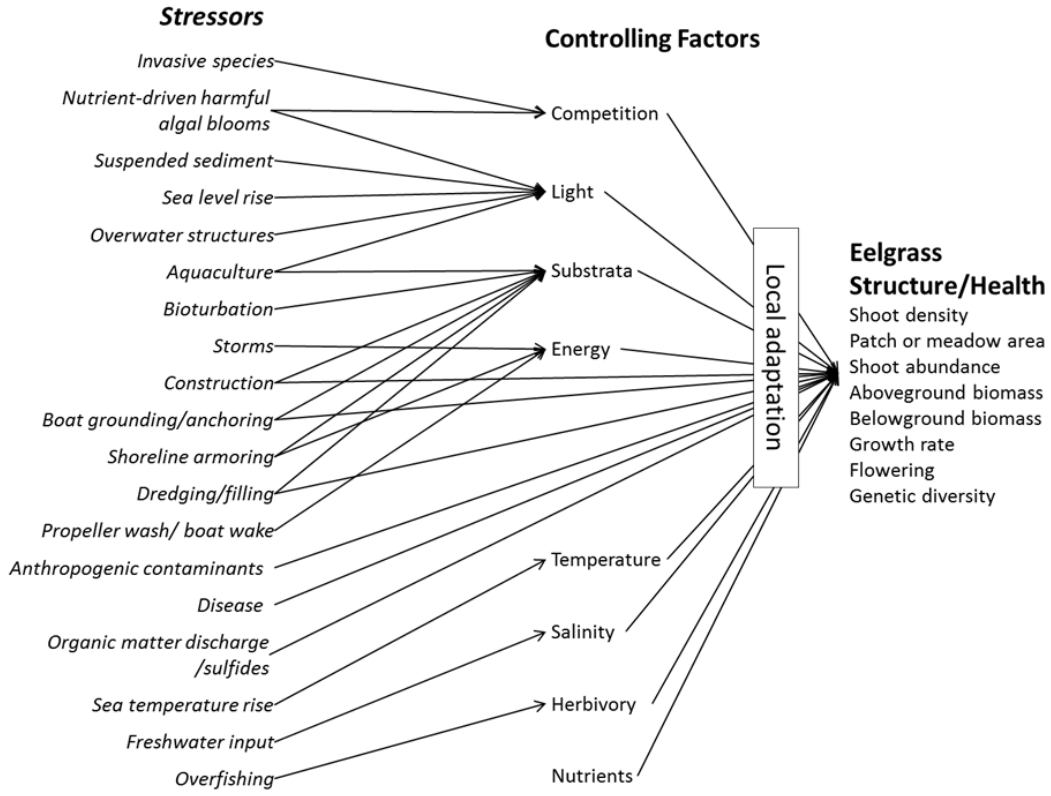

Figure 4. Thom et al. (2011) conceptual model of eelgrass stressors.

Table 2. Categorization of eelgrass stressors by threat and knowledge rankings from Thom et al. (2011). Within categories, stressors are listed from high to low threat scores.

		Knowledge Score	
		Low (<2)	High (>= 2)
Threat Score	High (>2)	Sea level rise, sea temperature rise, suspended sediment, shoreline armoring, nutrient-driven harmful algal blooms, anthropogenic contaminants, disease, freshwater input	Overwater structures, dredging/filling, construction
	Moderate to low (<= 2)	Invasive species, aquaculture, storms, organic matter input/sulfides, boat grounding/anchoring, propeller wash/boat wake, overfishing, bioturbation	None

Short (2014) "Nitrogen as an Eelgrass Stressor in Puget Sound"

- In-depth review and evaluation of nitrogen loading as a regionally important environmental stressor in Puget Sound, including a brief discussion of eelgrass stressors that interact with nitrogen [Appendix A in Short (2014)].
- Main findings:
    - Increasing nitrate concentrations have been found throughout Puget Sound and increases have been more rapid in the Sound than in the Strait of Juan de Fuca. Watersheds – and human activities occurring within them - are the presumed sources of that nitrogen.
    - Nitrogen is an indirect stressor on eelgrass because it promotes the growth of phytoplankton, nuisance macroalgae, and epiphytes.
    - Eelgrass in South Puget Sound and Hood Canal have shown typical symptoms of nitrogen over-enrichment.
    - Short recommends that Sound-wide nitrogen loading should be reduced to maintain and expand eelgrass.

Sherman and DeBruyckere (2018) "Eelgrass habitats on the U.S. West Coast: State of the Knowledge of Eelgrass Ecosystem Services and Eelgrass Extent"

- Report describing the presence and extent of eelgrass along the U.S. West Coast, ecosystem services provided by eelgrass habitats, threats to eelgrass, and knowledge and data gaps. Information was compiled from over 500 peer-reviewed articles and reports and subsequently reviewed by eelgrass experts.
- Main findings:
    - Numerous reports document the existing and emerging threats to eelgrass. Authors found literature on 19 threats for the U.S. West Coast, four of which were documented in all of the ecoregions considered: increased sedimentation, coastal development, sea level rise, and sea temperature change. Thom et al. (2011) was the primary reference for threats in the Salish Sea, so threats described by Sherman and DeBruyckere for this region mirror those in Figure 2.

    - Threats identified for other ecoregions, but not identified in the Salish Sea, included tectonic changes and lack of awareness.
    - Produced a geodatabase on the current and historical extent of eelgrass in 444 estuaries of the U.S. West Coast. Eelgrass occurs in at least 36% of the 444 estuaries.

Magel et al. (2025a) "Distribution of current and future risk to eelgrass and canopy kelp in Puget Sound".

- A spatially explicit risk assessment of threats to eelgrass and canopy kelp habitats was used to evaluate the distribution of cumulative habitat risk in Puget Sound, including the Eastern Strait of Juan de Fuca and San Juan Islands. Expert ratings from Raymond et al. (2026) and Thom et al. (2011) were used to adjust the exposure and consequence scores in the calculation of risk from each threat.
- Main findings:
    - Spatial data were identified and synthesized to describe potential threats eelgrass and kelp from temperature, nutrients, salinity, terrestrial human activities, and marine human activities. These data were overlaid with spatial maps of the habitats in a cumulative risk assessment framework.
    - Cumulative risk to eelgrass differed spatially among subregions of Puget Sound. On average, Hood Canal and North Puget Sound had the highest risk and San Juan Islands had the lowest risk for eelgrass, although there were several high-risk outliers.
    - The relative importance of individual threats also differed among subregions. Shoreline armor, river flow magnitude, industrial land use, and impervious surface coverage of watersheds were commonly in the top five threats out of 15 total to eelgrass for each region.
    - The final report and link to a webtool that allows users to explore the risk assessment results are available at www.pugetsoundinstitute.org/kelp-eelgrass-risk-assessment

5.1.2 Kelp stressor syntheses

Calloway et al. (2020) "Puget Sound Kelp Conservation and Recovery Plan" and "Appendix A: Kelp Knowledge Review"

- Recovery plan outlining an adaptive management approach to conserve and restore kelp in Puget Sound. "Appendix A: Kelp Knowledge Review" summarizes the available knowledge on kelp life history, ecology, ecosystem functions, and stressors. A 2023 update highlights progress made towards goals of the 2020 recovery plan (Whitty & Oster, 2023).
- Main findings:
    - Anecdotal observations and research suggest that Puget Sound kelp is declining.
    - Water quality degradation, urbanization/development, invasive species, altered food webs, and warming ocean temperatures are likely driving regional declines

in kelp, and these stressors are likely to increase with continued population growth and climate change.
    - Current knowledge on kelp stressors is extensively reviewed in Appendix A.

Hollarsmith et al. (2022) "Toward a conceptual framework for managing and conserving marine habitats: A case study of kelp forests in the Salish Sea".

- Salish Sea kelp experts identified perceived direct and indirect pressures to kelp and produced a conceptual model. The authors conducted a comprehensive literature review to assess the level of support for pathways identified by the experts.
- Main findings:
    - Kelps are declining in the Salish Sea (a hotspot for kelp diversity). Data and monitoring gaps have limited the ability to identify and manage specific drivers of decline despite urgency to protect kelp habitats.
    - Experts produced a conceptual model of direct and indirect pathways by which drivers and pressures impact bull kelp in the Salish Sea (Figure 5).
    - The literature review revealed major gaps in our understanding with very few studies on bull kelp in Puget Sound. However, broader coastal and global studies better support the experts' conceptual model. The compiled list of literature is available in the paper's supplementary material.

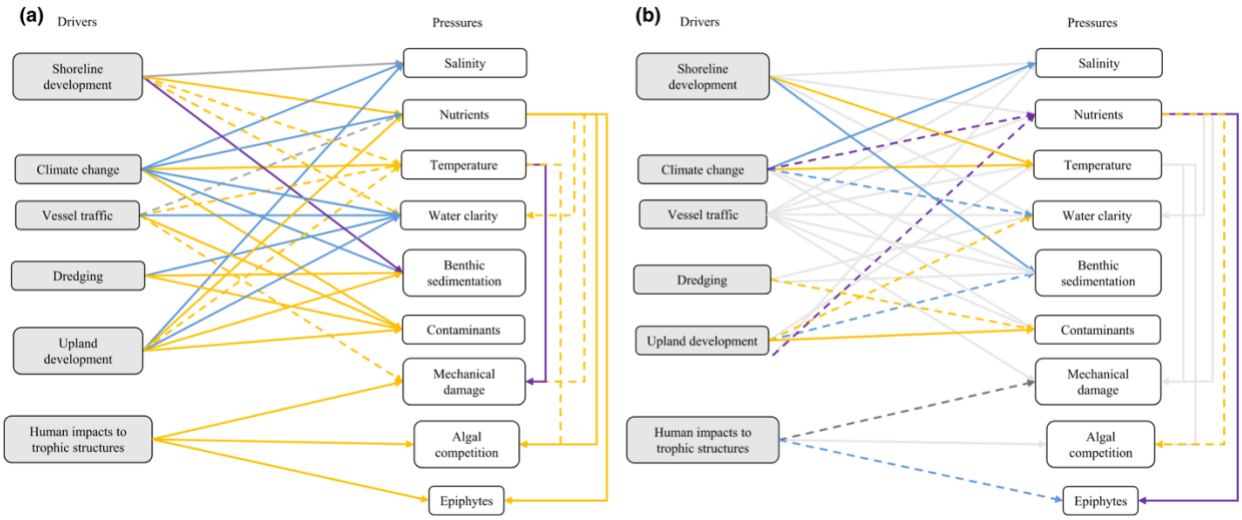

Figure 5. *Simplified* expert conceptual model from Hollarsmith et al. (2022) describing threats to bull kelp in the Salish Sea and support for the relationships identified in published literature from (a) the broader coast and (b) Salish Sea. Line color indicates the direction of the relationship (blue = negative, dark gray = neutral, orange = positive, purple = no consensus, and light gray = no literature). Line texture indicates the number of studies identified (dashed = two or fewer studies; solid = greater than two studies).

Raymond et al. (2026) "Severity and certainty metric for kelp stressors: A tool for research, management, and conservation".

- Expert rating of the relative importance and certainty of kelp stressors identified by Hollarsmith et al. (2022) for three kelp taxa (*Macrocystis*, *Nereocystis*, and understory kelps), over macroscopic and microscopic phases, in Washington state waters.
- Main findings:
    - An updated, comprehensive literature search for recently published literature (2021-2023) was performed for kelp following the search criteria of Hollarsmith et al. (2022). The compiled list of literature is available in the report's supplementary material.
    - Experts identified temperature and substrate change to be the greatest stressors across all taxa and life phases with a relatively high degree of certainty. High nutrient levels received the lowest stress score, but certainty was low.
    - Low certainty scores highlight the need for more research on understory kelps and on gametophyte life stages of both understory and canopy kelps.
    - Expert stressor severity and certainty ratings were compared between kelp sporophytes (this study) and eelgrass (Thom et al., 2011) (Figure 6).

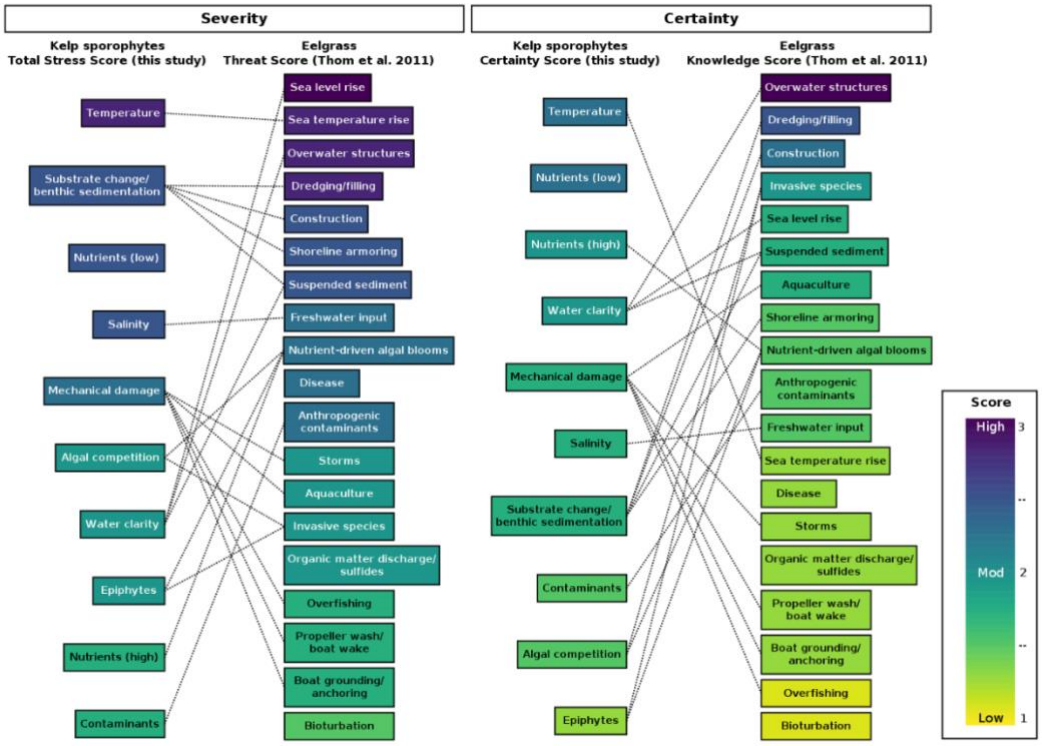

Figure 6. Raymond et al. (2026) comparison between the kelp threat severity and certainty scores (averaged across taxa for the sporophyte phase) and eelgrass threat and knowledge scores from Thom et al. (2011), listed and colored from high to low. Dashed lines link stressors/threats with the same or similar underlying drivers.

Magel et al. (2025a) "Distribution of current and future risk to eelgrass and canopy kelp in Puget Sound".

- A spatially explicit risk assessment of threats to eelgrass and canopy kelp habitats was used to evaluate the distribution of cumulative habitat risk in Puget Sound, including the Eastern Strait of Juan de Fuca and San Juan Islands. Expert ratings from Raymond et al. (2026) and Thom et al. (2011) were used to adjust the exposure and consequence scores in the calculation of risk from each threat.
- Main findings:
    - Spatial data were identified and synthesized to describe potential threats eelgrass and kelp from temperature, nutrients, salinity, terrestrial human activities, and marine human activities. These data were overlaid with spatial maps of the habitats in a cumulative risk assessment framework.
    - Cumulative risk to kelp differed spatially among subregions of Puget Sound. On average, South Puget Sound, Central Puget Sound, and Saratoga and Whidbey Basins had the highest risk and San Juan Islands had the lowest risk for kelp, although there were several high-risk outliers in the San Juan Islands.
    - The relative importance of individual threats also differed among subregions. High and low nutrients, vessel traffic, industrial land use, and impervious surface coverage of watersheds were commonly in the top five threats out of 14 total to kelp for each region.
    - The final report and link to a webtool that allows users to explore the risk assessment results are available at www.pugetsoundinstitute.org/kelp-eelgrass-risk-assessment

5.2 Pressures and Stressors

The primary pressures identified in previous syntheses broadly included human development and structures (upland and shoreline), terrestrial human activities (forestry, agriculture), marine human activities (boating, dredging, shellfish harvest, overfishing), and climate change. Marine vegetation stressors associated with those pressures (Hollarsmith et al., 2022) can be broadly categorized into water and substrate quality stressors, biological stressors, direct impacts of human activity (e.g., physical disturbance), and climate stressors (e.g., temperature and sea level rise). This section presents a non-exhaustive overview of recent literature [*since the publication of WA DNR (2015) and Calloway et al. (2020)*] on the relationships between stressors and marine vegetation, which are grouped into tables below by these broad categories. Available literature from Puget Sound and Salish Sea is prioritized, but evidence from other regions is presented when local studies were lacking. The body of literature surrounding eelgrass stressors is generally more robust than the body of work available for kelp. However, important uncertainties remain for both. Because many stressors are shared between eelgrass and kelp, we address habitats together and present citations for both taxa, when available. Colors (eelgrass – yellow; kelp – blue) are used in the tables following to help readers identify citations pertinent to a given taxa. The order in which stressors or citations are presented is not indicative of their importance (see Figure 6 for expert "severity" ratings of stressors).

Marine nearshore areas are highly dynamic with environmental conditions that are impacted by terrestrial, marine, atmospheric, and anthropogenic forces operating over a wide variety of

spatial and temporal scales. This dynamism is thought to simultaneously increase the resilience and susceptibility of nearshore habitats, including marine vegetation (Boyd et al., 2016). However, it also complicates our ability to observe the stressors experienced by those habitats and understand which factors are driving habitat variability. Furthermore, stressors commonly co-occur and co-vary in the environment, therefore it remains challenging to isolate the impacts of any single stressor on marine vegetation. Studies of marine vegetation often present results on one stressor in the context of one or multiple other stressors. For these reasons, citations may be listed more than once in the tables below if they address multiple stressors and brief descriptions highlight the interactions or dependencies between the stressors evaluated.

Uncertainty Table H. Additional pressure uncertainty

ID	Uncertainty	Priority Level
MV 040	How are the "impacts and benefits of" nearshore development (that degrades marine vegetation) distributed across "different human communities"? (Quoted material from Lambert et al. (2023, p. 13).)	**Medium**

5.2.1 Water quality and substrate quality stressors

Human development along the shoreline and within catchments that drain to Puget Sound has fundamentally changed terrestrial-nearshore linkages by impacting the ability of the landscape to retain water, sediments, and nutrients (Pearson et al., 2018). Of particular concern is the potential for land use changes to increase contaminants (Hahn et al., 2022) and alter sediment delivery to the nearshore (Rubin et al., 2023). Aligned with the findings of prior syntheses, recent publications confirm that water and substrate/sediment quality are primary drivers of marine vegetation, particularly the availability of light (Krumhansl et al., 2021; Pontier et al., 2024), nutrients (Weigel et al., 2023; Pontier et al., 2024), and appropriate substrate (Rubin et al., 2023; Davis et al., 2024) (

Table 3). Temperature and salinity, which are presented below in Table 6 (“Climate stressors”), are also key components of water quality. Temperature is known to interact with other stressors, including nutrients and light availability (e.g., Berry et al., 2021; Krumhansl et al., 2021; Spiecker and Menge, 2022). The role of nutrients, including those derived from terrestrial or wastewater treatment plant sources, in the losses or declines of Puget Sound marine vegetation remains difficult to wholly assess, however recent research focused on kelp suggests that marine vegetation in some areas of Puget Sound may be more susceptible to high (and low) nutrients than others and identified interactions with temperature, water movement (upwelling, currents, etc.), and light. While hydrogen sulfide toxicity has been implicated in seagrass declines globally, recent research in Puget Sound found that eelgrass was not negatively impacted by hydrogen sulfide unless multiple stressors were present (Simpson et al., 2018). While Hahn et al. (2022) found that kelp in the Salish Sea accumulated anthropogenic contaminants, the impact of contaminants on marine vegetation (e.g., changes to productivity,

reproduction, persistence, etc.) remains highly uncertain and there is a paucity of research on this topic, particularly within the Puget Sound region.

Table 3. Selected publications for water and substrate quality stressors on marine vegetation.

Stressor	Reference(s)	Key Findings
Contaminants	(Fonseca et al., 2017)	Eelgrass; US West Coast – Evaluation of *Z. marina* following an oil spill in San Francisco Bay found no relationship between oil exposure and shoot density or rhizome growth. Study highlights significant uncertainty in seagrass response to oil exposure, based on existing literature.
	(Qiao et al., 2022)	Eelgrass; NW Pacific Ocean – Mesocosm study of *Z. marina* in China found toxic effects of copper and cadmium at individual, subcellular, physiological, and molecular levels. However, damage caused by short term exposure stress was reversible.
	(Hahn et al., 2022)	Kelp; Salish Sea – Assessment of metals, persistent organic pollutants, and polycyclic aromatic hydrocarbons in edible seaweeds found that contaminants in seaweed may pose risk to human health. Research did not quantify impact of contaminants to kelp but demonstrates that kelps absorb various contaminants from the environment.
Hydrogen sulfide (*eelgrass only*)	(Simpson et al., 2018); Washington Sea Grant Project # R-HCE-7 to PI D. Schull	Eelgrass; Puget Sound – Field studies found a complex relationship between *Z. marina* and hydrogen sulfide in the sediment – eelgrass simultaneously increased and decreased hydrogen sulfide and generally low concentrations were observed around the root zone. Eelgrass growth and photosynthetic efficiency was reduced in the presence of high hydrogen sulfide, but eelgrass was not negatively impacted unless multiple stressors were present.
Light availability / water clarity	(Krumhansl et al., 2021)	Eelgrass; Atlantic Coast of Canada – Field study found that *Z. marina* at warmer, shallower, low water motion sites had lower productivity and resilience relative to beds in deeper, cooler, well flushed areas, and that higher temperatures lowered eelgrass tolerance to low-light conditions.
	(Spiecker & Menge, 2022)	Kelp; US West Coast (OR) – Field manipulation study found differing responses of understory kelp *H. sessile* to herbivory and light availability depending on geographic setting (intermittent versus persistent upwelling and thus nutrient availability). The persistent upwelling site had stronger grazing pressure which reduced the overall kelp population, although remaining individuals were longer potentially due a reduction in surrounding competitors. At the intermittent upwelling site, effects of grazing and light were negligible.
	(Pontier et al., 2024)	Kelp; Salish Sea (BC) – Field study found optimal growth rates for *Nereocystis* sporophytes occurred in a narrow range of conditions with decreased growth at temperatures > 10°C , below 1 µm/L nitrate concentration, and surface light availability reduced blade growth at both low and high levels.

Stressor	Reference(s)	Key Findings
Nutrients	(Supratya & Martone, 2024)	Kelp; Salish Sea – Lab study aimed at establishing best practices for culturing *Nereocystis* sporophytes in recirculating culture. While not aimed at understanding stressors, authors observed that sporophyte condition degraded rapidly under excessively high or low nutrient levels, stagnant flow, and temperature fluctuations due to power outages. Larger sporophytes seemed less sensitive than smaller sporophytes.
	(Fales et al., 2023)	Kelp; Salish Sea – Lab study compared various physiological responses of canopy, *Nereocystis*, and understory, *S. latissima*, sporophytes to the interactive effects of short-term exposure to different temperature (low, moderate, and warm) and nitrogen concentration (low vs. high). Both species responded negatively to the warmest temperature (21°C) at both nitrogen levels. Results suggested that high nutrients may reduce kelp performance at supra-optimal temperatures.
	(Berry et al., 2021)	Kelp; Puget Sound – *Nereocystis* losses in over century scale have occurred in areas with elevated temperature, lower nutrients, and lower current velocities (high currents are presumed to exclude grazers).
	(Weigel et al., 2023)	Kelp; Puget Sound – Lab study examined temperature x nutrient impacts on microscopic *Nereocystis* gametophytes and sporophytes from seven Puget Sound populations. Thermal tolerance was similar across microscopic life stage and populations (best performance occurred ~10-16°C) and high temperature (>18°C) was more stressful than low nitrogen. Higher nitrogen did not improve survival at high temperatures.
	(García-Reyes et al., 2022)	Kelp; US West Coast (CA) – Observational study of *Nereocystis* canopy cover found that wintertime ocean conditions (temperature) were a good predictor of summer canopy cover. Authors attribute the relationship to the effects of decreased winter upwelling and/or warmer (but not lethal) water temperature on decreased nutrient availability.
	(Pontier et al., 2024)	Kelp; Salish Sea (BC) – Field study found optimal growth rates for *Nereocystis* sporophytes occurred in a narrow range of conditions with decreased growth at temperatures > 10°C, below 1 µm/L nitrate concentration, and surface light availability reduced blade growth at both low and high levels.
	(Menge et al., 2020)	Kelp and seagrass; US West Coast (OR/WA) – Field study observed spatiotemporal variability in intertidal species of kelp *H. sessile* and surfgrass *P. scouleri* and unexpectedly found that growth rates of both were higher with warmer water temperature and increased nutrients. However, authors note that increasing temperature with climate change will likely reach thresholds for both species beyond which growth will decrease. Further, *H. sessile* growth decreased with dense phytoplankton blooms and *P. scouleri* growth decreased with increasing air temperature.

Stressor	Reference(s)	Key Findings
Sedimentation / substrate change	(Poppe & Rybczyk, 2022)	Eelgrass; Puget Sound – Hybrid model calibrated using Padilla Bay NERR field data found that the current suspended sediment concentration in Padilla Bay is insufficient for the entire eelgrass meadow to keep pace with projected SLR over 100 years. The predicted sediment load required to maintain eelgrass would likely prevent sufficient light availability for eelgrass.
	(Davis et al., 2024)	Eelgrass; Puget Sound – Evaluation of elevation data found that different rates of elevation change among habitats type and five estuaries. Eelgrass sites exhibited negative elevation change, although most were located in the "sediment starved" Padilla Bay estuary.
	(Rubin et al., 2023)	Kelp; Eastern Strait of Juan de Fuca – Sedimentation following removal of the Elwha dam reduced kelp abundance, including canopy and understory kelps. Some areas rapidly recovered if they received temporary sediment plumes, but not persistent deposition.
	(Farrugia Drakard et al., 2025b)	Kelp; US West Coast (AK) – Gametophyte densities and growth of *Nereocystis* cultured in the lab were lower under combinations of high sediment load, high temperature, and low salinity conditions, selected to mimic glacial melt, terrestrial runoff, and climate conditions.

5.2.2 Biological stressors on marine vegetation

The influence of biological stressors on marine vegetation is challenging to disentangle as they can be hard to experimentally control or manipulate. Recent work has continued to explore the potential role of trophic structure, competition, disease, grazing, and invasive species and some important advancements have been made (Table 4). A common theme is that biological stressors are unlikely to act alone and that marine vegetation can be resilient to these stressors in the absence of other physical or chemical stressors. In cases where other stressors are present, biological stressors can be important. Seagrass wasting disease, caused by the globally distributed protist *Labyrinthula zosterae*, is common in eelgrass meadows along the west coast of North America, but disease prevalence was highest at warm and shallow sites (Aoki et al., 2022; Graham et al., 2023) and where invertebrate grazer abundance was high (Aoki et al., 2025). Urchin overgrazing of kelp was more likely following a marine heatwave in California (Cavanaugh et al., 2025), but was not observed following the same marine heatwave on the Washington coast (Tolimieri et al., 2023). Non-native *Sargassum horneri* seaweed decreases recruitment of *Macrocystis,* but researchers suggest that *S. horneri* thrives in disturbed ecosystems rather than being the driver of change (Sullaway & Edwards, 2020). Non-native dwarf eelgrass (*N. japonica*) is typically found higher in the intertidal zone than native eelgrass – although they can co-occur in the middle of their depth ranges – and may facilitate future migration of eelgrass under sea-level rise (Sherman & DeBruyckere, 2018). Although *N. japonica* and native eelgrass may compete for space and resources in some places where they co-occur,

Boardman and Ruesink (2022) found no statistically significant change in native eelgrass biomass or shoot count when *N. japonica* was removed.

Table 4. Selected publications for biological stressors on marine vegetation.

Stressor	Reference(s)	Key Findings
Changes to trophic structure	(Hughes et al., 2013; Raymond et al., 2021)	Eelgrass; US West Coast – AK study did not find support for the trophic cascade observed in CA where expansion of sea otter populations resulted in seagrass recovery.
Competition (epiphytes, algal overgrowth)	(Ruesink, 2016)	Eelgrass; US West Coast (WA) – Field manipulation study found that removal of epiphytes did not accelerate growth of *Z. marina* as expected indicating that eelgrass tolerates seasonally-abundant epiphytes coinciding with rapid leaf emergence, thus producing fresh leaves free from microalgal competition.
	(Menge et al., 2020)	Kelp and seagrass; US West Coast (OR/WA) – Field study observed spatiotemporal variability in intertidal species of kelp *H. sessile* and surfgrass *P. scouleri* and unexpectedly found that growth rates of both were higher with warmer water temperature and increased nutrients. However, authors note that increasing temperature with climate change will likely reach thresholds for both species beyond which growth will decrease. Further, *H. sessile* growth decreased with dense phytoplankton blooms and *P. scouleri* growth decreased with increasing air temperature.
	(Beckley & Edwards, 2021)	Kelp; US West Coast (CA) – Field manipulation study examining the relative importance of shade, scour, and organismal effects from understory macroalgae *D. herbacea* on the recruitment, survival, and growth of *Macrocystis* early life stages found that scour had the strongest negative effect on survival of microscopic stages and recruitment, but that both shade and scour affected survival and growth of larger sporophytes.
	(Whalen et al., 2023)	Kelp; Canada (BC) – Eight-year field study of rocky intertidal community dynamics observed major shifts in zonation and abundance causing community-level reorganization during a multiyear marine heatwave. Primary production shifted away from upper elevations via declines in seaweed cover, including kelps. At low elevations, seaweeds remained stable or rapidly recovered. Rather than shifting the community uniformly, the heatwave restructured dominance and reduced ecosystem habitability via changes in stress, grazing, and competition.
Disease	(Aoki et al., 2022)	Eelgrass; US West Coast, including Puget Sound – Survey of *Z. marina* across latitudes (CA to AK), found between 11 and 99% of plants infected with wasting disease in individual meadows and that disease prevalence was 3x higher in locations with warm temperature anomalies in summer.

Stressor	Reference(s)	Key Findings
	(Aoki et al., 2025)4/20/2026 5:08:00 PM	Eelgrass; US West Coast, including Puget Sound – Survey of *Z. marina* across latitudes (CA to AK), found that grazing by small invertebrates was associated with a 29% increase in the prevalence of wasting disease suggesting that grazing may facilitate disease outbreaks. Both disease prevalence and lesion area increased with total epifauna abundance, although relationships differed among grazer taxa.
	(Graham et al., 2023; Graham et al., 2024)	Eelgrass; Pacific Northwest, including Puget Sound – Survey of *Z. marina* across latitudes (WA to AK), found high prevalence of wasting disease across sites. The occurrence of disease was lower at subtidal sites compared to intertidal sites and was lower in colder sites than warmer sites regardless of depth.
	(Graham et al., 2021)	Eelgrass; Puget Sound – Field study found more seagrass wasting disease reduced eelgrass growth and disease reduced belowground carbon accumulation.
Grazing / Disturbance	(Hughes et al., 2018)	Eelgrass; US West Coast (CA) – Mesocosm study found that despite CO_2 driven changes in grazer biomass and an increase in macroalgal and epiphyte biomass, *Z. marina* was resilient to acidification impacts on community composition even when coupled with nutrient loading.
	(Castorani et al., 2021)	Kelp; US West Coast (CA) – Field manipulation study found that regular, long-term removal of canopy kelp *Macrocystis* depresses ecosystem productivity and that the ability of understory kelps to compensate for canopy kelp losses are mediated by herbivore density and substrate suitability.
	(Berry et al., 2021)	Kelp; Puget Sound – *Nereocystis* losses over the past century have occurred in areas with elevated temperature, lower nutrients, and lower current velocities (high currents are presumed to exclude grazers).
	(Spiecker & Menge, 2022)	Kelp; US West Coast (OR) – Field manipulation study found differing responses of understory kelp *H. sessile* to herbivory and light availability depending on geographic setting (intermittent versus persistent upwelling and thus nutrient availability). The persistent upwelling site had stronger grazing pressure which reduced the overall kelp population, although remaining individuals were longer potentially due a reduction in surrounding competitors. At the intermittent upwelling site, effects of grazing and light were negligible.
	(Cavanaugh et al., 2025)	Kelp; US West Coast (CA) – A severe marine heatwave caused dramatic declines in *Nereocystis* due to high temperatures and decreased nutrient concentrations. Persistence was more likely in areas where water remained cooler due to seascape features that promote upwelling. However, urchin overgrazing increased after the heatwave and replaced temperature as the dominant driver.

Stressor	Reference(s)	Key Findings
	(Tolimieri et al., 2023)	Kelp; US West Coast (WA) – Six years of field observations from kelp forest communities showed a ~50% loss of *Macrocystis* and *Nereocystis* canopy during the 2013-2014 marine heatwave but the canopy recovered quickly, within two years. Site explained most of the variation in community assemblage structure rather than year. Although urchin *S. purpuratus* density increased starting in 2017, no top-down effects of urchins on kelp were observed.
	(Whalen et al., 2023)	Kelp; Canada (BC) – Eight-year field study of rocky intertidal community dynamics observed major shifts in zonation and abundance causing community-level reorganization during a multiyear marine heatwave. Primary production shifted away from upper elevations via declines in seaweed cover, including kelps. At low elevations, seaweeds remained stable or rapidly recovered. Rather than shifting the community uniformly, the heatwave restructured dominance and reduced ecosystem habitability via changes in stress, grazing, and competition.
Invasive species	(Howard et al., 2019)	Eelgrass; British Columbia, Canada – Eelgrass shoot density loss was increased 73-81% in Barkley Sound field enclosures with high densities of non-native European green crab (*C. maenas*) and eelgrass was detected in crab stomach contents. Findings were similar to observations of green crab disruption of eelgrass on the Atlantic coast.
	(Sherman & DeBruyckere, 2018)	Eelgrass; US West Coast (CA, OR, WA) – Literature review discusses that non-native eelgrass *N. japonica* is typically found higher in the intertidal zone than *Z. marina* although they can co-occur, such as in Willapa Bay, and that *N. japonica* may actually "reserve" space for future migration of *Z. marina* as habitats shift under sea level rise.
	(Boardman & Ruesink, 2022)	Seagrass; US West Coast (WA) – Field study in a rare multispecies seagrass bed in Willapa Bay found that non-native *N. japonica* reached an end-of-summer biomass an order of magnitude greater than either native seagrass (*Z. marina* and *R. maritima*). Experimentally removing *N. japonica* revealed stronger competition on *R. maritima* than *Z. marina*.
	(Sullaway & Edwards, 2020)	Kelp; US West Coast (CA) – Field manipulation study found that recruitment of *Macrocystis* and adult stipe density increased by 4-fold and 9-fold, respectively, in plots where non-native *S. horneri* was removed but there was no difference in net community production. Authors suggest that *S. horneri* thrives in disturbed ecosystems rather than driving ecosystem change.
	(Korabik et al., 2024)	Kelp; US West Coast (CA) – Lab culturing experiment on the growth and survival of *Macrocystis* gametophytes to temperature, salinity, and presence of non-native *S. muticum* found that increasing temperature had a larger effect than decreasing salinity. Competition from *S. muticum* had an additive, but not interactive, negative impact when combined with increasing temperature.

Uncertainty Table I. Additional biological stressor uncertainties

ID	Uncertainty	Priority Level
MV 005.1	Where are invasive macroalgae (e.g., *Undaria pinnatifida*, *Sargassum muticum*) found? How do invasive macroalgae affect the local environment? What methods can be used to control invasive macroalgae? What are the ecological outcomes of grazing and/or removal of *Sargassum*?	**No priority**
MV 010.1	What effect will non-native species or excessive amounts of native species have on native seagrass?	**No priority**
MV 010.2	What are the "risk factors [and mortality outcomes] associated" with outbreaks of eelgrass wasting disease? (Quoted material from WA DNR (2015, p. 22 (citing Thom et al. (2011))).)	**No priority**

5.2.3 Human activity stressors on marine vegetation

Human activity has fundamentally changed the shorelines and nearshore of Puget Sound, including altered structure and function and the movement and harvest of resources (Pearson et al., 2018). Evidence for the impact of these activities on marine vegetation is mixed, with more available studies for eelgrass than kelp (Table 5). The shading from docks has a well-documented negative impact on seagrasses globally (Eriander et al., 2017; Lambert et al., 2023), although only one prior study has focused on Puget Sound – specifically the impact of large commercial docks present at marine terminals (Simenstad et al., 1997). Shoreline armor impacts are less clear, with one unpublished study finding a small effect of armor on the shallow edge of eelgrass beds (Christiaen et al., 2022b) and no studies for kelp. One might expect that understory kelps in the shallow subtidal are more exposed to impacts from shoreline structures (i.e., armor, docks) than canopy kelps further offshore, however studies are lacking. Shoreline development could impact the ability of habitats, particularly eelgrass, to migrate with sea level rise as discussed in the next section. Vessel activity impacts, including disturbance from anchoring and moorings, also have better documentation in seagrass literature. Few studies have been conducted in Puget Sound, however, there is evidence of spatial overlap between vessels and eelgrass habitat in San Juan County (Jefferson et al., 2024). While there are impacts of shellfish aquaculture on eelgrass, they are not always negative (Howarth et al., 2022) and, in some cases, negative impacts can be mitigated by adjusting the timing of activities (Boardman & Ruesink, 2025). Kelp harvest, a potential physical disturbance pathway, is discussed in Implementation Strategy *Appendix II.b: Base Program Analysis* (see section 7.3).

Table 5. Selected publications for human activity stressors on marine vegetation.

Stressor	Reference(s)	Key Findings
Shoreline development, incl. overwater structures, armor	(Lambert et al., 2023)	Eelgrass and Kelp; global – Review of evidence for the marine impact of small overwater structures on seagrass, macroalgae, and fish found relatively little research on the topic aside from well-documented negative impacts on seagrasses in multiple parts of the world by reducing light availability. Evidence of impacts on macroalgae and fish was inconclusive.
	(Nahirnick et al., 2020)	Eelgrass; British Columbia – Shoreline activities (boats, docks, log booms, and armoring) and residential housing density were correlated with changes in *Z. marina* area coverage and meadow shape index in three estuaries, suggesting an overall deterioration of ecosystem health that is deleterious for eelgrass.
	(Eriander et al., 2017)	Eelgrass; Sweden – Field surveys at 14 docks and 4 marinas found 42–64% less *Z. marina* coverage within 6 meters from elevated docks and that floating docks affected larger areas and caused up to 100% reduction in eelgrass coverage. Light was measured and effects were attributed to shading.
	(Christiaen et al., 2022b)	Eelgrass; Puget Sound – *Z. marina* transects compared between armored and unarmored shorelines showed small effect on the location of the shallow edge of eelgrass beds, which were 0.25 meters higher at sites without armor. Authors note that other stressors may be more detrimental to eelgrass in Puget Sound.
Shellfish aquaculture (*eelgrass only*)	(Howarth et al., 2022)	Eelgrass; global – Review of impacts of aquaculture on *Z. marina* found positive, neutral, and negative effects. Negative responses of eelgrass are most commonly report and can be caused by shading and sedimentation. Positive responses are possible due to improvement in water clarify and reduced epiphytes from filter feeding and nutrients from biodeposits.
	(Boardman & Ruesink, 2025)	Eelgrass; US West Coast (WA) – Field surveys in oyster aquaculture beds found higher *Z. marina* recovery when mechanical harvest occurred during the early growing season versus the late growing season with higher contribution of new shoots from seedlings following early growing season disturbance.
	(Ruesink et al., 2023)	Eelgrass; US West Coast (WA) – Field surveys in aquaculture beds found that Pacific oysters (*M. gigas*) meat, shell growth, and survival were essentially the same regardless of eelgrass density (no eelgrass, sparse, or dense). Rather, grow out techniques were strongly influential of oyster survival and condition. Importantly, eelgrass density in "dense" aquaculture beds was half that of nearby unfarmed eelgrass beds.

Stressor	Reference(s)	Key Findings
	(Stote et al., 2023) and references therein	Eelgrass; US West Coast (WA) – Synthesis of the scientific literature related to biology, ecology, and interactions between ecosystem engineers in Willapa Bay and Grays Harbor: shellfish, eelgrass, and burrowing shrimp. Ecological interactions and their effect vary by species, location, estuary conditions, and shellfish growing practices, but interactions can include spatial competition, biological effects, and physical effects. Eelgrass generally recovers from shellfish aquaculture disturbance because impacts are periodic (pulse) rather than long-term (press), however cumulative effects from multiple stressors can cause irreparable damage to eelgrass.
Vessel activity (boating and moorage)	(Jefferson et al., 2024)	Eelgrass; Puget Sound – Aerial surveys of vessel use during 2024 found an average of ~ 2,000 vessels in the nearshore areas of San Juan County on summer weekends. While the study goal was not to identify eelgrass impacts, spatial analysis showed a moderate to strong level of overlap between vessel hotspots and eelgrass areas of Sucia, Stuart, Waldron, San Juan, Shaw, and Lopez islands.
	(Kelly et al., 2019)	Eelgrass; US West Coast (CA) – Aerial images and GIS analyses found that boats damage up to 41% of *Z. marina* beds from illegal anchor outs in San Francisco Bay and that each boat may cause up to 0.3 hectares of damage.

5.2.4 Climate stressors on marine vegetation

Climate-related stressors are a primary concern for marine vegetation and temperature impacts have received the most attention, motivated by recent high-impact marine heatwaves in the region (Table 6). Elevated temperatures directly affect productivity and respiration, and ongoing research continues to refine optimum temperature ranges and extreme tolerances for both eelgrass and kelp (Magel et al., 2022; Pontier et al., 2024; Weigel et al., 2023) and the interaction of temperature with other stressors, including nutrients, algal blooms, and light availability (Berry et al., 2021; Krumhansl et al., 2021; Spiecker & Menge, 2022). Sea level rise has not been identified as a primary concern for kelp (Hollarsmith et al., 2022) but is frequently discussed in eelgrass literature (Poppe & Rybczyk, 2022; Smith & Liedtke, 2022). Eelgrass occurs in a narrower depth range than kelp in Puget Sound and altered sediment dynamics and shoreline development may prevent eelgrass from keeping pace with sea level rise or adjusting their distributions landward [“coastal squeeze” (Thorne et al., 2025)] or, in some cases, seaward [“ejection effect” (Shaughnessy et al., 2012)]. Other climate impacts less commonly addressed in the literature, include ocean acidification, changes to freshwater input, and increased storm intensity. Ocean acidification is unlikely to directly negatively impact marine vegetation, which may stand to benefit from increased carbon availability (Hollarsmith et al., 2020; Korabik et al., 2023; Zimmerman et al., 2017). However, a recent global meta-analysis found that the impact of acidification on kelps is expected to differ between the sporophyte and gametophyte life phases and thus the overall impact on kelp is more likely to be neutral (Roethler et al., 2025). Indirect impacts through trophic interactions are possible, however, there is limited evidence in the literature (Hughes et al., 2018). Low salinity has been shown to be stressful for some species

and life phases of kelp (Farrugia Drakard et al., 2025b, 2025a). Eelgrass tolerates a wider salinity range; however long periods of low salinity have been associated with eelgrass declines and outbreaks of eelgrass wasting disease elsewhere (WA DNR, 2015). The relationship between storm intensity and marine vegetation may be positive or negative and is difficult to disentangle. Although storms are known to dislodge kelp and eelgrass, the habitats can recover and storms may offer additional benefits such as delivery of nutrients through mixing and reducing grazing pressure (Hamilton et al., 2020).

Table 6. Selected publications for climate stressors on marine vegetation.

Stressor	Reference(s)	Key Findings
Acidification	(Hughes et al., 2018)	Eelgrass; US West Coast (CA) – Mesocosm study found that despite CO_2 driven changes in grazer biomass and an increase in macroalgal and epiphyte biomass, *Z. marina* was resilient to acidification impacts on community composition even when coupled with nutrient loading.
	(Hollarsmith et al., 2020)	Kelp; US West Coast (CA) and Chile – *Macrocystis* gametophytes were exposed to current and projected temperature and pH combinations in a common garden lab experiment. High temperature resistance was observed in this early life stage and egg production was elevated under low pH. Authors note that both donor populations considered regularly experience low pH events associated with upwelling.
	(Korabik et al., 2023)	Kelp; US West Coast (CA) – *Nereocystis* gametophytes were exposed to current and projected temperature and pH combinations in a common garden lab experiment. Increased temperature decreased gametophyte survival and offspring production and altered reproductive timing, regardless of pH. Decreased pH increased survival and offspring production but with less effect than temperature.
	(Bell et al., 2024)	Kelp; US West Coast (AK) – Lab experiment examined separate and combined impacts of acidification and warming on growth and nutritional value of one canopy (*Macrocystis*) and two understory (*H. nigripes* and *N. fimbriatum*) kelp species in summer and winter. Although poleward populations of *Macrocystis* were resilient to both warming and acidification in this experiment, the two understory kelps had lower biomass and nutritional quality under warmer conditions in both seasons. Acidification had only a marginally significant negative impact on *H. nigripes* biomass during winter when combined with warming.
	(Roethler et al., 2025)	Kelp; Global – Meta-analysis of data from 143 experimental studies of true kelps (order Laminariales) showed that warming had a strong negative impact on kelps at all life stages with impacts to growth, reproduction, and survival. Ocean acidification generally had no effect due to the relative impact on sporophytes (expected to be positive) versus gametophytes (may be negative). Warming and acidification together acted synergistically.

Stressor	Reference(s)	Key Findings
Freshwater input / Salinity	(Farrugia Drakard et al., 2025b)	Kelp; US West Coast (AK) – Gametophyte densities and growth of *Nereocystis* cultured in the lab were lower under combinations of high sediment load, high temperature, and low salinity conditions, selected to mimic glacial melt, terrestrial runoff, and climate conditions.
	(Farrugia Drakard et al., 2025a)	Kelp; US West Coast (AK) – Comparison of ideal salinities for cultivation of kelp gametophytes, including *Nereocystis* and *A. marginata*. *Nereocystis* gametophytes grew fastest at a salinity of 32 and *A. marginata* grew fastest between 20-32 PSU, depending on where the specimens were collected.
	(Korabik et al., 2024)	Kelp; US West Coast (CA) – Lab culturing experiment on the growth and survival of *Macrocystis* gametophytes to temperature, salinity, and presence of non-native *S. muticum* found that increasing temperature had a larger effect than decreasing salinity. Competition from *S. muticum* had an additive, but not interactive, negative impact when combined with increasing temperature.
Sea level rise (SLR)	(Smith & Liedtke, 2022)	Eelgrass; Puget Sound – Model of Bainbridge Island WA predicted an increase in *Z. marina* habitat in response to SLR; however the model did not account for possible changes in sediment resuspension, storm surge, or wave energy and the compounding interaction with shoreline development, which could reduce habitat suitability for eelgrass under SLR.
	(Poppe & Rybczyk, 2022)	Eelgrass; Puget Sound – Hybrid model calibrated using Padilla Bay NERR field data found that the current suspended sediment concentration in Padilla Bay is insufficient for the *Z. marina* meadow to keep pace with projected SLR over 100 years. The predicted sediment load required to maintain eelgrass would likely prevent sufficient light availability for eelgrass.
	(Davis et al., 2024)	Eelgrass; Puget Sound – Evaluation of elevation data found that different rates of elevation change among habitats type and five estuaries. *Z. marina* sites exhibited negative elevation change, although most were located in the “sediment starved” Padilla Bay estuary.
Storm intensity	(Hamilton et al., 2020)	Kelp; US West Coast (OR) – 35-yr time series of *Nereocystis* found a strong positive relationship between canopy area and winter wave height, indicating a difference from *Macrocystis*. Authors hypothesize this unexpected finding could be due indirect controls on competition or predation and a difference in life history (*Nereocystis is* an annual species, whereas *Macrocystis is* perennial).

Stressor	Reference(s)	Key Findings
	(Mora-Soto et al., 2024a)	Kelp; Salish Sea (BC) – Changes in percent cover of *Nereocystis* from satellite imagery was compared to in global climate metrics (ONI and PDO) and local-scale environmental conditions (temperature, heatwaves, and wind) to understand patterns of resilience. The coldest and most exposed (high currents and fetch) areas had a constant presence of kelp since 1972, indicating the most favorable conditions even during suboptimal climate periods. Warmer and more sheltered areas had more variable cover but may have benefited from wind-wave forcing that increased resilience during one suboptimal climate period (2014-2019 marine heatwave).
Temperature	(Krumhansl et al., 2021)	Eelgrass; Atlantic Coast of Canada – Field study found that *Z. marina* at warmer, shallower, low water motion sites had lower productivity and resilience relative to beds in deeper, cooler, well flushed areas, and that higher temperatures lowered eelgrass tolerance to low-light conditions.
	(Magel et al., 2022)	Eelgrass; US West Coast (OR and WA) – *Z. marina* beds responded differently in four coastal estuaries to a marine heatwave, with typically colder/deeper estuaries experiencing increases in eelgrass and typically warmer/shallower estuaries experiencing decreases in eelgrass. Findings indicate that temperature thresholds were exceeded during the heatwave in some estuaries, depending on underlying estuary conditions.
	(Magel et al., 2023; Marin Jarrin et al., 2022)	Eelgrass; US West Coast (OR) – Two studies identified temperature increases from a marine heatwave as the likely cause of extensive *Z. marina* declines in Coos Bay estuary.
	(Claar et al., 2025)	Kelp; US West Coast (WA) and Salish Sea – *Nereocystis* and *Macrocystis* observations spanning a large marine heatwave showed relationships between multiple temperature metrics and canopy abundance at 6 subregions, which declined 36–85% during the heatwave. Temperature metrics were generally a weak predictor, and authors emphasize the importance of multiple interacting drivers. The best predictor metric and recovery trajectory differed among subregions, indicating uncertainty about resistance and recovery mechanisms.
	(Weigel et al., 2023)	Kelp; Puget Sound – Lab study examined the combination of temperature and nutrient impacts on microscopic *Nereocystis* gametophytes and sporophytes from seven Puget Sound populations. Thermal tolerance was similar across microscopic life stage and populations (best performance occurred ~10-16^{o}C) and high temperature (>18^{o}C) was more stressful than low nitrogen. Higher nitrogen did not improve survival at high temperatures.
	(García-Reyes et al., 2022)	Kelp; US West Coast (CA) – Observational study of *Nereocystis* canopy cover found that wintertime ocean conditions (temperature) were a good predictor of summer canopy cover. Authors attribute the relationship to the effects of decreased winter upwelling and/or warmer (but not lethal) water temperature on decreased nutrient availability.

Stressor	Reference(s)	Key Findings
	(Korabik et al., 2023)	Kelp; US West Coast (CA) – *Nereocystis* gametophytes were exposed to current and projected temperature and pH combinations in a common garden lab experiment. Increased temperature decreased gametophyte survival and offspring production and altered reproductive timing, regardless of pH. Decreased pH increased survival and offspring production but with less effect than temperature.
	(Cavanaugh et al., 2025)	Kelp; US West Coast (CA) – A severe marine heatwave caused dramatic declines in *Nereocystis* due to high temperatures and decreased nutrient concentrations. Persistence was more likely in areas where water remained cooler due to seascape features that promote upwelling. However, urchin overgrazing increased after the heatwave and replaced temperature as the dominant driver.
	(Pontier et al., 2024)	Kelp; Salish Sea (BC) – Field study found optimal growth rates for *Nereocystis* sporophytes occurred in a narrow range of conditions with decreased growth at temperatures > 10^{o}C, below 1 µm/L nitrate concentration, and surface light availability reduced blade growth at both low and high levels.
	(Korabik et al., 2024)	Kelp; US West Coast (CA) – Lab culturing experiment on the growth and survival of *Macrocystis* gametophytes to temperature, salinity, and presence of non-native *S. muticum* found that increasing temperature had a larger effect than decreasing salinity. Competition from *S. muticum* had an additive, but not interactive, negative impact when combined with increasing temperature.
	(Mora-Soto et al., 2024a)	Kelp; Salish Sea (BC) – Changes in percent cover of *Nereocystis* from satellite imagery was compared to in global climate metrics (ONI and PDO) and local-scale environmental conditions (temperature, heatwaves, and wind) to understand patterns of resilience. The coldest and most exposed (high currents and fetch) areas had a constant presence of kelp since 1972, indicating the most favorable conditions even during suboptimal climate periods. Warmer and more sheltered areas had more variable cover but may have benefited from wind-wave forcing that increased resilience during one suboptimal climate period (2014-2019 marine heatwave).
	(Kurman & terHorst, 2023)	Kelp; US West Coast (CA) – Field collected *Macrocystis* spores from 3 populations were exposed to three temperatures in the lab. At higher temperatures, individuals from all sites had lower settlement and maturation success, however the magnitude of decrease varied among populations. Survival increased in two populations but decreased in one population. There was little genetic variation in temperature responses among individuals within sites, but dispersal among populations could allow for adaptation in early life history traits (i.e., evolutionary rescue).

Stressor	Reference(s)	Key Findings
	(Tolimieri et al., 2023)	Kelp; US West Coast (WA) – Six years of field observations from kelp forest communities showed a ~50% loss of *Macrocystis* and *Nereocystis* canopy during the 2013-2014 marine heatwave but the canopy recovered quickly, within two years. Site explained most of the variation in community assemblage structure rather than year. Although urchin *S. purpuratus* density increased starting in 2017, no top-down effects of urchins on kelp were observed.
	(Whalen et al., 2023)	Kelp; British Columbia, Canada – Eight-year field study of rocky intertidal community dynamics observed major shifts in zonation and abundance causing community-level reorganization during a multiyear marine heatwave. Primary production shifted away from upper elevations via declines in seaweed cover, including kelps. At low elevations, seaweeds remained stable or rapidly recovered. Rather than shifting the community uniformly, the heatwave restructured dominance and reduced ecosystem habitability via changes in stress, grazing, and competition.
	(Bell et al., 2024)	Kelp; US West Coast (AK) – Lab experiment examined separate and combined impacts of acidification and warming on growth and nutritional value of one canopy (*Macrocystis*) and two understory (*H. nigripes* and *N. fimbriatum*) kelp species in summer and winter. Although poleward populations of *Macrocystis* were resilient to both warming and acidification in this experiment, the two understory kelps had lower biomass and nutritional quality under warmer conditions in both seasons. Acidification had only a marginally significant negative impact on *H. nigripes* biomass during winter when combined with warming.
	(Roethler et al., 2025)	Kelp; Global – Meta-analysis of data from 143 experimental studies of true kelps (order Laminariales) showed that warming had a strong negative impact on kelps at all life stages with impacts to growth, reproduction, and survival. Ocean acidification generally had no effect due to the relative impact on sporophytes (expected to be positive) versus gametophytes (may be negative). Warming and acidification together acted synergistically.
	(Menge et al., 2020)	Kelp and seagrass; US West Coast (OR/WA) – Field study observed spatiotemporal variability in intertidal species of understory kelp *H. sessile* and surfgrass *P. scouleri* and unexpectedly found that growth rates of both were higher with warmer water temperature and increased nutrients. However, authors note that increasing temperature with climate change will likely reach thresholds for both species beyond which growth will decrease. Further, *H. sessile* growth decreased with dense phytoplankton blooms and *P. scouleri* growth decreased with increasing air temperature.

5.3 Stressor Reversibility

Kelp and eelgrass in Puget Sound are likely responding to a combination of multiple (potentially interacting) stressors; however, some stressors are more or less feasible to reverse or mitigate. Furthermore, existing policies and programs likely only address a subset of stressors (see Implementation Strategy *Appendix II.b: Base Program Analysis* for further consideration of the management landscape). Conservation and restoration planning should consider not only the relative importance of each stressor for the taxa, but also the ability to reverse or mitigate damage through management actions and which stressors are targeted by existing management levers. For example, whereas some coastal development impacts could be addressed at the local level by existing policies and programs, widespread impacts from climate change (e.g., temperature and sea level rise) may be more challenging to reverse and do not have state or local programs through which they can be addressed but, in some cases, impacts could be mitigated. An analysis by Green et al. (2021) found that nonpoint source nutrient controls were successful at reducing water column nutrients in two out of three U.S. estuaries considered in the study and that these controls may have helped to facilitate seagrass restoration in one estuary. Green et al. (2021) hypothesized that eelgrass restoration was possible in Newport Bay, CA because management controls successfully addressed a high priority eelgrass stressor (nutrients and associated eutrophication) via the primary pathways by which excess nutrients were entering the system. In Peconic Estuary, NY, nonpoint source nutrient controls were not successful at reversing ongoing water quality and habitat deterioration because management pathways did not address the primary sources of nutrients to the estuary (atmospheric deposition and groundwater with long residence time), due to the technical challenges of addressing these sources.

Recognizing the importance of reversibility, expert surveys by Thom et al. (2011) and Raymond et al. (2026) rated the relative reversibility of each stressor to eelgrass and kelp, respectively, and the level of scientific certainty about reversibility. In both cases, reversibility scores were included in the final calculation of the relative importance of each stressor. High reversibility means that the stressor can be easily stopped or removed (such as using existing technology at relatively low effort), and the habitat will again be suitable for marine vegetation. Low reversibility means that it is not practically possible to reverse the stressor, or changes would require extensive remediation (for example, the technology to remove the stressor at the scale needed does not currently exist). Note that 'reversibility' in these reports did not consider mitigation (i.e., the ability to reduce the intensity or lessen the ultimate impact of the stressor) – this distinction is discussed more below. While most eelgrass stressors were rated as medium reversibility, Thom et al. (2011) highlighted three stressors that experts believed had high relative reversibility (storms, boat ground/anchoring, and propeller wash/boat wake) and four stressors that had low reversibility (sea level rise, overwater structures, anthropogenic contaminants, and sea temperature rise). Most kelp stressors were also rated as medium reversibility, but Raymond et al. (2026) rated three kelp stressors as having high relative reversibility (contaminants, low nutrients, and mechanical damage) and three as low reversibility (epiphytes, salinity, and temperature). In some cases, however, the experts' level of certainty for these ratings was low and a more definitive assessment would require additional

information. For example, Thom et al. (2011) and Raymond et al. (2026) had opposite scores for the reversibility of contaminants for eelgrass (low) and kelp (high), respectively, but both groups of experts noted low scientific certainty in their rating of contaminant reversibility indicating that additional information is needed about the ability to remove existing and prevent new contaminants from impacting marine vegetation.

Even if a stressor is not reversible, opportunities may exist to reduce the intensity of the stressor or lessen its ultimate impact on marine vegetation via adaptation (for brevity, "mitigation"). In many cases, stressor mitigation could have a meaningful influence on the persistence of marine vegetation. For instance, Thom et al. (2011) recognized this distinction for sea level rise and noted that although the stressor itself cannot be easily reversed, that some mitigation may be possible. Barrier removal to allow for the landward migration of eelgrass – avoiding "coastal squeeze" – and ensuring adequate sediment supply would not reverse sea level rise but could provide an adaptation pathway allowing eelgrass to persist despite sea level rise (as discussed in Section 5.2.4). Proposed updates to the Shoreline Management Act rules seek to encourage this type of sea level rise adaptation (see Implementation Strategy *Appendix II.b: Base Program Analysis* Section 3.1.1). Similarly, the removal of existing overwater structures may not be possible or practical, however management actions are available to reduce the impacts of shading caused by overwater structures such as the incorporation of grating and other measures to increase light penetration (see Implementation Strategy *Appendix II.b: Base Program Analysis* Section 3), which could reduce associated impacts to marine vegetation (Fresh et al., 2006; Gladstone & Courtenay, 2014). One important exception is temperature, a high priority stressor for marine vegetation that is thought to interact with other stressors, for which little practical opportunity currently exists for reversal or mitigation at the Puget Sound-wide scale.

In prioritizing stressors for management action, primary considerations should include the relative importance of the stressor to the marine vegetation taxa of interest, spatial and temporal scale required for an action to have an impact, magnitude of change required (complete or partial removal of the stressor), and other complementary actions that would help mitigate impacts, increase resilience, or facilitate adaptation (see Section 5.4 for examples). It may also be helpful to consider the interactions between stressors in prioritizing management action. For example, temperature has been shown, in some cases, to interact with other stressors over which we may have more control, such as nutrients and light availability. By managing for adequate nutrients and light, marine vegetation may be able to better withstand temperature impacts.

5.4 Resilience Attributes

Marine vegetation may respond differently to stressors within a region. For example, eelgrass responded both positively and negatively to a widespread marine heatwave depending on the estuary (Magel et al., 2022). Oregon and California kelp populations also showed disparate responses to the same marine heatwave (Hamilton et al., 2020). These differences may be due to attributes that confer resilience by mitigating the impact of stressors or improving

adaptability to impacts. Examples of potential resilience attributes include, but are not limited to, depth, genetics, nearby source populations or suitable habitat, residence time or flow, and microbiome. Table 7 presents a non-exhaustive list of recent publications where these attributes were discussed in relation to marine vegetation persistence.

Table 7. Selected publications for factors that may contribute to marine vegetation stressor resilience.

Stressor	Reference(s)	Key Findings
Depth	(Aoki et al., 2020)	Eelgrass; US East Coast (VA) – Field study of restored *Z. marina* beds found that depth was a critical determinant of restoration success and marine heatwave resilience, with best success at intermediate depths, excluding the shallowest and deepest portions of habitable depth.
	(Magel et al., 2022, 2023)	Eelgrass; US West Coast (OR and WA) – Two studies of coastal estuaries identified site depth as a potential mitigating factor in determining the response of *Z. marina* beds to environmental change, with deeper beds showing less change compared to shallower beds.
	(Graham et al., 2023; Graham et al., 2024)	Eelgrass; Pacific Northwest, including Puget Sound – Survey of *Z. marina* across latitudes (WA to AK), found that the occurrence of seagrass wasting disease was 16% lower at subtidal sites compared to intertidal sites and was lower in colder subtidal and intertidal sites. Findings highlight the importance of subtidal and colder locations for eelgrass resilience and indicate that disease presence can serve as a proxy for resilience.
	(Cavanaugh et al., 2025)	Kelp; US West Coast (CA) – *Nereocystis* were more likely to persist during a marine heatwave at shallower sites due to stronger delivery of cold, nutrient rich upwelled waters in shallow areas.
Genetics	(Pazzaglia et al., 2021)	Seagrass; global – Review of the genetic components and considerations for improving success of seagrass restoration, which include diversity, resistant strains, local adaption, and possibly epigenetics.
	(DuBois et al., 2022)	Eelgrass; US West Coast (CA) – Field transplantation experiment found strong "home-site" advantage in growth and survival indicating that local-scale environmental mosaics (temperature, light, grazing pressure) can increase phenotypic variation, potentially increasing resilience to future global change.
	(Dykman et al., 2025)	Kelp; British Columbia, Canada – Field transplantation experiment of *Macrocystis* between warm and cool microclimates found inconsistent evidence for local adaptation and possible maladaptation in kelp from the warmer site. The more diverse population from the cooler site survived better and grew larger regardless of outplant site. Kelp cultures from a larger number of parents (10 vs. 2) had reduced self-fertilization rates but, surprisingly, lower short-term survivorship.

Stressor	Reference(s)	Key Findings
	(Harden et al., 2024)	Kelp; US West Coast (CA) – Study indicates a genetic component of heat stress tolerance that is predictive between the gametophyte and sporophyte stages of *Macrocystis*, indicating the potential for selecting temperature resilient strains for restoration. However, heat stress resilient kelps had reduced genetic variation underscoring the importance of integrating heat tolerance genes into a broader genetic pool.
	(Kurman & terHorst, 2023)	Kelp; US West Coast (CA) – Field collected *Macrocystis* spores from 3 populations were exposed to three temperatures in the lab. At higher temperatures, individuals from all sites had lower settlement and maturation success, however the magnitude of decrease varied among populations. Survival increased in two populations but decreased in one population. There was little genetic variation in temperature responses among individuals within sites, but dispersal among populations could allow for adaptation in early life history traits (i.e., evolutionary rescue).
Population connectivity or alternative suitable habitat	(Munsch et al., 2023)	Eelgrass; US West Coast, including Puget Sound – Survey of *Z. marina* from CA to AK found that beds were universally dynamic and bed edges often shifted by tens of meters from the previous bed boundary but sometimes much further. Eelgrass often vacated and later recolonized the same area, indicating that protection of presently vacant areas for possible colonization – particularly nearby other meadows – may bolster resilience. Eelgrass beds in less modified areas were more stable, and authors hypothesized that eelgrass meadows change more under greater stress regimes.
	(Kendrick et al., 2017)	Seagrass; global – Review of the role genetic connectivity and consequences for dispersal and recruitment. Study calls for a more integrated understanding of the role of contemporary dispersal and recruitment in species persistence.
	(Bemmels et al., 2025)	Kelp; Salish Sea – Genomes of *Macrocystis* and *Nereocystis* identified 6-7 geographically and genetically distinct clusters of each species, which authors suggest could be used to define management units. Genetic health indicators (effective population size, genetic diversity, and inbreeding coefficients) varied widely among *Nereo* populations and were more uniform among *Macro* populations. Genetic diversity of *Nereo* was highest in northern BC and NW Vancouver Island and lowest in south Puget Sound (Squaxin Island).
	(Gierke et al., 2023)	Kelp; West Coast of North America (AK to CA) – Genetic structure of *Nereocystis* across its entire range was evaluated using microsatellite markers. Four co-ancestral groups were identified, including a separate group in inner Salish Sea that had the poorest diversity. Higher sampling density in the Salish Sea allowed authors to perform a seascape genetics approach to test isolation by transport and environment.
Residence time / flow	(Krumhansl et al., 2021)	Eelgrass; Atlantic Coast of Canada – Field study found that *Z. marina* at warmer, shallower, low water motion sites had lower productivity and resilience relative to beds in deeper, cooler, well flushed areas, and that higher temperatures lowered eelgrass tolerance to low-light conditions.

Stressor	Reference(s)	Key Findings
	(Supratya et al., 2020)	Kelp; Salish Sea – Lab study suggested that *Nereocystis* in sheltered habitats with lower flow may be more vulnerable to high temperature, where an inability to adjust blade morphology to local hydrodynamic conditions could drive declines even at sublethal levels of warming.
	(Berry et al., 2021)	Kelp; Puget Sound – *Nereocystis* losses in over century scale have occurred in areas with elevated temperature, lower nutrients, and lower current velocities (high currents are presumed to exclude grazers).
	(Mora-Soto et al., 2024a)	Kelp; Salish Sea (BC) – Changes in percent cover of *Nereocystis* from satellite imagery was compared to in global climate metrics (ONI and PDO) and local-scale environmental conditions (temperature, heatwaves, and wind) to understand patterns of resilience. The coldest and most exposed (high currents and fetch) areas had a constant presence of kelp since 1972, indicating the most favorable conditions even during suboptimal climate periods. Warmer and more sheltered areas had more variable cover but may have benefited from wind-wave forcing that increased resilience during one suboptimal climate period (2014-2019 marine heatwave).
Microbiome	(Kardish & Stachowicz, 2023)	Eelgrass; US West Coast (CA) – A field transplantation study tested the influence of host origin versus environment on *Z. marina* microbiome and found that local environmental differences create rapid shifts in associated microbial community composition with potential functional implications for rapid environmental acclimation.
	(Wang et al., 2021)	Eelgrass; US West Coast (OR) – A mesocosm transplantation study found that the belowground microbiome recovered quickly following transplantation whether or not the roots were washed. However, growth traits of the washed plants lagged behind intact sod transplants for the first week.
	(Weigel et al., 2022)	Kelp; Puget Sound – Metagenomic study of *Nereocystis* found that the genomes of kelp-associated bacteria carried carbon assimilation, polysaccharide degradation, nitrogen transformation, and vitamin biosynthesis genes that may be central to kelp-microbe interactions. The kelp microbiome is likely sensitive to climatic stressors and thus requires additional research to understand how kelp fitness will be impacted by changes in microbiome composition and functions.
	(Molnar et al., 2025)	Kelp; Puget Sound – Experimental study of the interactive effects of temperature and nutrients on the *Nereocystis* microbiome found that temperature had a larger effect than nutrients and microbial diversity increased with temperature, contrary to expectation.

6 Considerations in Implementing Recovery Strategies

The Implementation Strategy outlines many approaches in the five strategies (Section 3) to pursue recovery of eelgrass and kelp in Puget Sound. Importantly, there is uncertainty about the scale of effective management (generally) for marine vegetation in the region (MV 025,

Uncertainty Table J). This section summarizes technical information pertinent to management/implementation within each specific strategy. It discusses management considerations related to scale, design, effectiveness, collaboration, stressor identification, and multiple benefits (these terms, including synonyms, are underlined when used in this Section 6 for visual emphasis), presenting opportunities, barriers, and recommendations for each as applicable. Considerations related to cost of recovery actions are not discussed; Implementation Strategy Narrative *Section 6* describes such considerations and information about economic approaches that can be used for cost assessment.

Uncertainty Table J. General management uncertainty

ID	Uncertainty	Priority Level
MV 025	At what scale will kelp and eelgrass management be most effective? How much does management effectiveness vary by location?	**High**

6.1 Research and Monitoring Strategy Considerations

6.1.1 Marine vegetation monitoring

Monitoring of eelgrass and kelp distribution in Puget Sound is one research topic targeted by the Research and Monitoring Strategy. The *Base Program Analysis* (Implementation Strategy *Appendix II.b*) provides a list of existing monitoring programs in Puget Sound. As discussed in Section 2.4, the current frameworks for monitoring marine vegetation in Puget Sound comprise primarily of underwater towed video surveys for seagrass distribution (Christiaen et al., 2022a) and a combination of kayak and fixed-wing aerial surveys and Indigenous Scientific Knowledge from the Samish Indian Nation for canopy kelps (Berry et al., 2023; Claar et al., 2025). While the monitoring programs were thoughtfully designed to detect trends in marine vegetation at the Puget Sound-wide scale, there are spatial and temporal gaps in monitoring coverage (Christiaen et al. 2022a; Claar et al., 2025; Dowty et al., 2022 and sources cited therein). Technological developments may allow for improved or expanded marine vegetation monitoring in the future.

6.1.1.1 Monitoring kelp and eelgrass with aerial imagery

Various aerial imagery techniques (unoccupied aerial systems (UAS)/unmanned aerial vehicles (UAV)/drones; fixed-wing aircraft; and satellites such as Landsat, Sentinel, and Planet) (Berry & Cowdrey, 2021; Cavanaugh et al., 2021) have been touted as useful for kelp and seagrass monitoring in other places (Hamilton et al., 2020 and sources cited therein; sources cited in Orth & Heck, 2023) and have been used to varying extents in Puget Sound (Cowdrey & Claar, 2024; Gaeckle et al., 2022; Hitchner et al., 2022; NV5 Corvallis, 2022, 2023; e.g., Pfister et al., 2018).

Satellites capture broad spatial regions (Cavanaugh et al., 2021; Reshitnyk et al., 2023; Schroeder et al., 2019 as cited in Cavanaugh et al. 2021; Veettil et al., 2020) and therefore can

include unique locations (Orth & Heck, 2023). Hamilton et al. (2020) employed Landsat satellite imagery to measure bull kelp cover along the Oregon coast, and Douglas et al. (2025) mapped eelgrass area in Izembek Lagoon in Alaska in Sentinel-2 and Landsat satellite images. However, these free, lower resolution satellites do not work in all places (Hitchner et al., 2022; Nijland et al., 2019 as cited in Hamilton et al., 2020; Reshitnyk et al., 2023; Schroeder et al., 2019 as cited in Hamilton et al., 2020 and Cavanaugh et al., 2021) and the data frequency can depend on tides and cloud cover (Douglas et al., 2025; Hamilton et al., 2020) and how often specific satellites take images of an area (e.g., once every 16 days (Landsat), once every five days (Sentinel 2), up to twice a day for other satellites) (Douglas et al., 2025; Reshitnyk et al., 2023; Rowan & Kalacska, 2021 and sources cited therein). Use of Landsat and Sentinel satellites for bull kelp monitoring in Puget Sound so far has not worked; a NASA study attempting to monitor bull kelp in Puget Sound using these satellites found that areas with kelp could not be visually distinguished from areas without kelp, which may be due to currents, tides, kelp density, nutrients, wave action, or inaccurate classification of areas without kelp (Hitchner et al., 2022). The study also found that image criteria (tide level, season, and cloud cover) left few suitable satellite images for kelp monitoring. Given that eelgrass monitoring using these satellites requires similar image criteria (Douglas et al., 2025), the availability of Landsat and Sentinel images for eelgrass monitoring in Puget Sound may also be sparse. Despite the limitations identified in their study, Hitchner et al. (2022) suggest that Puget Sound satellite-based kelp monitoring could still be possible with additional research on techniques such as multiple endmember spectral mixture analysis per McPherson et al. (2021, as cited in Hitchner et al., 2022).

In contrast, despite regional visibility issues (Cavanaugh et al., 2021), higher-resolution satellites have been effectively used to monitor bull kelp in the Salish Sea in British Columbia (Mora-Soto et al., 2024b) and Gendall et al. (2025) generated a time series of canopy kelp in Haida Gwaii from 1973-2021 using a combination of satellites and aerial imagery with various resolutions. High-resolution is required for satellites to measure kelp beds that fringe the coastline (Gendall et al., 2023 as cited in Gendall et al., 2025; sources cited in Mora-Soto et al., 2024b; Reshitnyk et al., 2023), to measure smaller areas of vegetation (Heblinski et al., 2011 as cited in Rowan and Kalacska, 2021; Rowan & Kalacska, 2021), or to determine species of vegetation (Planet, n.d. as cited in Rowan & Kalacska, 2021; Reshitnyk et al., 2023; Satellite Imaging Corporation, n.d. as cited in Rowan & Kalacska, 2021; Silva et al., 2008 as cited in Rowan & Kalacska, 2021). High resolution satellite images (Reshitnyk et al., 2023) were recently found to be inferior to in-water measurements of eelgrass area in Massachusetts (Carr & Callaghan, 2024). Use of satellites with higher spatial resolution are more expensive (Cavanaugh et al., 2021; Klemas, 2011 as cited in Rowan & Kalacska, 2021; Reshitnyk et al., 2023; Schroeder et al., 2019 as cited in Cavanaugh et al., 2021).

While a number of remote sensing approaches can be complicated by the environmental conditions described above, and others such as topography shadowing (Cavanaugh et al., 2021; Yamazaki et al., 2009 as cited in Cavanaugh et al., 2021), ideal sampling conditions can be easier to access using UAS and fixed-wing airplanes (Cavanaugh et al., 2021 and sources cited therein). Fixed-wing airplanes have been used for aerial monitoring of canopy kelp in parts of Puget

Sound since 1989 (Kelp Forest Monitoring Alliance of Washington State, 2025; Pfister et al., 2018; Van Wagenen, 2015), and more areas were added to this monitoring approach in 2022 (WA DNR, 2024a). In addition, more recent UAS/UAV surveys now supplement airplane and kayak monitoring (Section 6.1.1.2) of kelp in Puget Sound (Berry & Cowdrey, 2021; Cowdrey, 2021; Cowdrey & Claar, 2024; Ledbetter & Berry, 2024). Both types of aircraft can yield high-resolution imagery that allows for the identification of canopy species (Reshitnyk et al., 2023). For example, Timmer et al. (2024) were able to spectrally delineate giant kelp fronds, bull kelp blades, and bull kelp pneumatocysts in multispectral UAV images collected on the British Columbia coast; the authors also quantified the effect of tidal height on the amount of kelp classified in UAV images, which can inform the design of future kelp monitoring using UAVs and other remote sensing technologies. However, fixed-wing aircraft and UAS/drones differ in the spatial scale for which they make sense (Cowdrey & Claar, 2024; Reshitnyk et al., 2023). In the context of yearly canopy kelp monitoring, Reshitnyk et al. (2023) provide a guide to choosing optical remote sensing technologies, including considerations related to price and scale of monitoring effort.

In other parts of the country (i.e., Massachusetts), fixed-wing airplanes conduct eelgrass monitoring (Carr & Callaghan, 2024). In addition, seagrass monitoring can employ drones/UAVs (Lønborg et al., 2022 as cited in Orth & Heck, 2023; sources reviewed in Veettil et al., 2020). While aerial imagery in general is not currently used for region-wide eelgrass distribution monitoring in the Submerged Vegetation Monitoring Program (SVMP) in Puget Sound (for reasons described in Section 6.1.1.2) (Christiaen et al., 2022a; Dowty et al., 2022), this technology could have site-specific management monitoring applications: UAVs have been employed for monitoring eelgrass restoration effectiveness at several sites in Puget Sound (Gaeckle et al., 2022). UAVs were used to monitor eelgrass area and snorkeling/diving monitored eelgrass shoot density (Gaeckle et al., 2022).

There are different methods for analyzing marine vegetation in aerial monitoring images (Cavanaugh et al., 2021; Rowan & Kalacska, 2021; Veettil et al., 2020). Current and future remote sensing could be improved by applying object-based classification and machine learning to process images (Orth & Heck, 2023 and sources cited therein). Progress has been made by the Hakai Institute through the creation of Kelp-O-Matic, a model that uses deep neural networks to analyze drone images and map polygons of canopy kelp presence (by species) (Denouden et al., n.d.; Denouden & Reshitnyk, 2023; HakaiInstitue, n.d.; Reshitnyk, 2023). This tool speeds up analysis of images (Fishman, 2022; Reshitnyk et al., 2023) and is actively used in kelp monitoring in British Columbia (Tula Foundation, n.d.), Alaska (Barnacle Foods, n.d.), and California (Fishman, 2022).

Remote sensing using aerial imagery is beneficial not just for future monitoring with new imagery but also retroactive monitoring via past imagery (Veettil et al., 2020 and sources cited therein) (e.g., G. McKenna et al., 2025); sources of untapped historical images may be explored for Puget Sound kelp monitoring (Berry & Cowdrey, 2021; Berry et al., 2023). Furthermore, the temporal trends captured in present-day marine vegetation monitoring were compared to spatial information recorded in historical maps such as those dating back to the mid- to late

1800s in studies of the Salish Sea in British Columbia (Mora-Soto et al., 2024b), Haida Gwaii (Gendall et al., 2025), and South Puget Sound (Berry et al., 2021).

6.1.1.2 Monitoring kelp and eelgrass with in-water approaches

Current Puget Sound bull kelp monitoring includes boat surveys (Berry, 2017; Berry et al., 2019) and kayak monitoring (e.g., Ledbetter & Berry, 2024; Northwest Straits Initiative, n.d.) in addition to aerial imagery (Berry et al., 2023; Claar et al., 2025; Cowdrey & Claar, 2024; NV5 Corvallis, 2023). Despite the promise of aerial imagery to monitor kelp distribution at broad scales (Berry et al., 2023; Cavanaugh et al., 2021; Reshitnyk et al., 2023; Schroeder et al., 2019, as cited in Cavanaugh et al., 2021), in-water methods have both logistical and analytical value. The kayak method, in particular, requires less work to analyze survey data, less "technological expertise", and fewer supplies while adding human wellbeing benefits of engagement of the local community and recreation for volunteer kayakers (Berry & Cowdrey, 2021, p. 43). Low-density, thin canopy kelp beds that prove difficult for measurement with aerial imagery can be measured by kayak, as can the depth distribution of kelp beds (Ledbetter & Berry, 2024). Furthermore, while some (but not all) optical remote sensing approaches can technically measure aspects of the health of canopy kelp (via carbon or nitrogen metrics), boating or underwater monitoring is recommended for characterization of the condition of kelp (not just its distribution, as discussed in Section 2.3) (Reshitnyk et al., 2023). Underwater methods may be particularly useful for monitoring understory kelps which cannot be monitored using optical remote sensing (Reshitnyk et al., 2023). Underwater kelp monitoring is taking place via dive surveys as part of a collaborative Eyes on Kelp project in Puget Sound (Puget Sound Restoration Fund, n.d.c).

In-water methods are also important for eelgrass monitoring; Carr and Callaghan (2024) recently found that neither aircraft nor drone imagery fully captured the extent of eelgrass that was documented by SCUBA surveys and underwater cameras in Massachusetts bays (for aircraft surveys, this was particularly true for the deep borders of eelgrass beds). Both aerial methods were also highly inaccurate in areas with "patchy" eelgrass (Carr & Callaghan, 2024, p. 13). Eelgrass beds in Puget Sound can occur in water depths (maximum depth -14.3 *meters* MLLW (Christiaen et al., 2022a)) greater than those studied by Carr and Callaghan (2024) (maximum depth -15 *feet* MLLW), and this added depth may prevent the effective use of aerial imagery techniques for seagrasses (Hossain et al., 2015 as cited in Veettil et al., 2020; Zimmerman & Dekker, 2006 as cited in Veettil et al., 2020) and submerged aquatic vegetation broadly (Rowan & Kalacska, 2021 and sources cited therein). Because subtidal eelgrass in Puget Sound is located outside the depth limits for aerial imagery, and in order to identify species (i.e., *N. japonica* vs. *Z. marina*), eelgrass-monitoring in Puget Sound's Submerged Vegetation Monitoring Program (SVMP) relies upon towed underwater videography rather than aerial imagery or acoustic methods (Christiaen et al., 2022a; Dowty et al., 2022 and sources cited therein).

However, single-beam sonar (WA DNR Aquatic Assessment and Monitoring Team) (WA DNR, n.d.) and side-scan sonar (WA DNR Aquatic Reserves) (e.g., Gaeckle, 2009), two types of

acoustic remote sensing [the following sources as cited in Rowan and Kalacska (2021): Abukawa et al. (2013); Bennett et al. (2020); Greene et al. (2018); Mizuno et al. (2018); Rotta et al. (2019); Stocks et al. (2019)], are employed for other seagrass distribution monitoring in Puget Sound. Additional studies have measured seagrasses with sonar methods [the following sources as cited in Veettil et al. (2020): Asada et al. (2005)[2]; Hamana & Komatsu (2016); Komatsu et al. (2003); Lefebvre et al. (2009)], and sonar are less impacted by depth and turbidity than visual types of remote sensing (Stocks et al., 2019 as cited in Rowan & Kalacska, 2021). An advantage of acoustic remote sensing is that it allows for seagrass distribution to be mapped more quickly over larger areas compared to towed videography (A. Greene, personal communication, October 15, 2025). However, eelgrass was more comprehensively mapped by SCUBA and underwater photographs than side-scan sonar (or other the aerial imagery methods discussed above) in a Massachusetts study (Carr & Callaghan, 2024). In addition, species identification is not possible with acoustic remote sensing (Rowan & Kalacska, 2021), and eelgrass occurring in patches is not identified clearly with side-scan sonar (Carr & Callaghan, 2024; Gaeckle, 2009) (though Carr and Callaghan (2024) also found this to be true for aerial imagery as well). The WA DNR Aquatic Reserves Program also currently assesses eelgrass distribution by utilizing side-scan sonar on Autonomous Surface Vessels (White, 2024; A. Greene, personal communication, October 15, 2025).

Underwater monitoring of seagrass could be aided generally by autonomous underwater vehicles (AUVs) (Lønborg et al., 2022, as cited in Orth & Heck, 2023). Remotely operated vehicles (ROVs) can enable underwater surveys in poor conditions (Chadwick, n.d. as cited in Rowan & Kalacska, 2021). The utility of AUVs and ROVs for underwater kelp monitoring are currently being examined in Puget Sound; the Eyes on Kelp project aims to explore the use of an AUV to improve kelp dive surveys (Puget Sound Restoration Fund, n.d.c), and the Seattle Aquarium and Reef Check are currently studying the performance of ROVs in relation to scuba divers for monitoring kelp in Puget Sound (Randell, n.d.).

Another technological innovation that could be explored for marine vegetation monitoring is environmental DNA (eDNA): kelp can be detected using this method, and recent work suggests that eDNA could perhaps be used to track the health condition of a *Macrocystis* population based on its zoospore output (Ward et al., 2025 and sources cited therein). However, additional research is needed to better understand kelp eDNA (Ward et al., 2025).

6.1.1.3 Integrating methodologies for marine vegetation monitoring

Specifically because of the limits of aerial imagery for monitoring kelp quality, Hamilton et al. (2020) recommend coupled underwater monitoring and aerial analysis for kelp monitoring. An integrated approach involving various kelp monitoring methodologies is currently being implemented by the Marine Plan Partnership in British Columbia (Cavanaugh et al., 2021). Veettill et al. (2020) also recommend that seagrass monitoring utilize both direct and remote sensing methodologies. However, work is needed to standardize remote sensing methods for

[2] Due to a language barrier, the citation for this paper in References could not be fully assessed for the accuracy of author names and journal name.

submerged aquatic vegetation (Rowan & Kalacska, 2021 and sources cited therein) and establish accepted methods by which to integrate monitoring data from disparate methodologies, which would improve prospects for integrating multiple methods in the future. Recent work by WA DNR to integrate statewide kelp monitoring demonstrates the challenges of bringing together data from multiple sources and provides one approach to this type of data synthesis, which could be applicable to other regions and species (McKenna & Claar, 2026).

For canopy kelps, utilizing multiple monitoring methods would allow for a) measurement of both kelp health and areal coverage (Cowdrey & Claar, 2024), and b) monitoring in other places (an issue with Washington canopy kelp monitoring) (Berry et al., 2023). In addition to recommending monitoring areas that currently lack canopy kelp information (e.g., North Puget Sound, Admiralty Inlet (D. Claar, 2025)) (Berry et al., 2023; Claar et al., 2025), the Kelp Forest Monitoring Alliance of Washington State recommends improving the Floating Kelp Monitoring Program by:

- developing an annual monitoring sampling plan and using developing technologies or other methods specifically suitable for individual places (Berry et al., 2023; Claar et al., 2025);
- evaluating older kelp data (Berry et al., 2023; Claar et al., 2025);
- monitoring additional kelp characteristics (Berry et al., 2023; Claar et al., 2025);
- including more local knowledge and community science (Berry et al., 2023);
- better connecting management to kelp monitoring data (Berry et al., 2023);
- including more Indigenous Scientific Knowledge (Berry et al., 2023); and
- following other recommendations (Berry et al., 2023).

6.1.2 Stressor identification

Stressor identification is one of the primary research topics that the Research and Monitoring Strategy (Section 3.1) aims to address. Though some information about pressures and stressors for eelgrass and kelp exists already (Section 5), there is still a need for greater understanding of the impacts of these stressors at the scale of Puget Sound and at specific sites (Uncertainty Table G). For example, until it is understood specifically which threats have led to reductions in eelgrass/kelp populations at a given site (MV 007, Uncertainty Table G), it will be difficult to determine which regulatory, protected area, and/or restoration actions are appropriate for recovery there. Conversely, the identification of relevant threats that operate on a larger spatial scale (region-wide or beyond) will determine whether those threats are manageable via existing local-, regional-, or state-level programs (described in Implementation Strategy *Appendix II.b: Base Program Analysis*). Stressor identification therefore has direct implications for planning and implementation within the other strategies in the Implementation Strategy. The level of information needed about stressors varies among marine vegetation type (eelgrass versus kelp) (Section 5.2), within type (i.e., understory versus canopy kelp), and within life phases of individual species (i.e., kelp gametophytes versus sporophytes) (Raymond et al., 2026). Concurrently measuring stressors and the distribution of marine vegetation (e.g., Berry et al., 2019) could reduce disconnect between these two types of data (e.g., disconnect between temperature and canopy kelp data observed by Pfister et al., 2018). Stressor monitoring is not a

component of the Floating Kelp Monitoring Program monitoring protocol in Puget Sound (Berry et al., 2023) (however, for some kelp monitoring sites, environmental variables are measured (D. Claar et al., 2025)).

6.1.3 Information sharing

Another approach within the Research and Monitoring Strategy is to strengthen information sharing among researchers and between researchers and managers in Puget Sound. An identified barrier to better regulatory implementation for kelp in Puget Sound is a lack of "local science" (Whitty & Oster, 2023, p. 9), which suggests that the effectiveness of the Research and Monitoring Strategy to inform and underpin the Regulatory Strategy requires consideration of the appropriate spatial scale of data collected and communicated to management audiences. Knowledge exchange between researchers and managers could be improved using bi-directional dialogue to co-produce research questions and projects at the outset to generate data that is useable in regulatory/management applications (Cvitanovic et al., 2016 and sources cited therein). Other recommendations for improving knowledge exchange between researchers and decision-makers include a) having a knowledge broker to facilitate dialogue between involved parties, b) planning time and approaches for eventual knowledge exchange at the beginning of research projects (including by determining all relevant stakeholders), and c) engaging with communities beyond decision-makers in research activities (e.g., via citizen science) (Cvitanovic et al., 2016). Facilitation by knowledge brokers can seek to intentionally build trust and connections between managers and researchers by coordinating engagement opportunities (Cvitanovic et al., 2025). Citizen science is discussed further in Section 6.5.3.

A list of current examples of research coordination in Puget Sound and information about a WDFW and NOAA pilot program ("Science Sprint") that aims to bridge the science-policy gap are provided in Section 2.3 of the *Base Program Analysis* (Implementation Strategy *Appendix II.b*).

6.1.4 Tribal capacity, knowledge, and collaboration

Another barrier that the Research and Monitoring Strategy seeks to remedy is the insufficient capacity of Tribes and local communities to participate in eelgrass and kelp research activities in Puget Sound (Tribal research and monitoring projects about eelgrass and kelp are listed in the *Base Program Analysis* (Implementation Strategy *Appendix II.b* Table 1 and Section 7.1)). The Implementation Strategy directly calls for the incorporation of Indigenous Scientific Knowledge in several approaches (e.g., Section 6.5.2 of this document) given the robust knowledge of marine vegetation by Tribes in the Pacific Northwest (Calloway et al., 2020 Appendix B). Including Tribal perspectives in Implementation Strategy research and activities also reflects a broader national and international recognition of the importance of Indigenous knowledge (Gazing Wolf et al., 2024 and sources cited therein; Hatch et al., 2023 and sources cited therein). However, Indigenous experts and communities own their knowledge, so it should be incorporated into Implementation Strategy activities only if led by these groups and as they deem appropriate (Carroll et al., 2022, as cited in Gazing Wolf et al., 2024; Gazing Wolf et al., 2024). Increasing funding for Tribally-led research can facilitate the inclusion in biodiversity

management of forms of knowledge and worldviews that have historically been excluded or exploited by the Western scientific enterprise (Hatch et al., 2023 and sources cited therein; Salomon et al., 2023). Furthermore, robust incorporation of Indigenous knowledge into environmental work necessitates fundamental reorganization of settler-colonial institutions (Gazing Wolf et al., 2024).

Collaboration of Tribes with researchers from other sectors is described in the Tribal Habitat Strategy of the treaty Tribes in western Washington as necessary to "elevate tribal science" (Northwest Indian Fisheries Commission, 2019, p. 4). Principles for effective collaborations among Tribes and "mainstream science" (Hatch et al., 2023, p. 9) include: projects are designed to be flexible and to include time for relationship-building, particularly before commencement; community members are paid; projects aim to answer questions generated by the local Indigenous community; mainstream scientists actively give power to Indigenous perspective and expertise; Indigenous community members contribute to grant writing; mainstream scientists formally request permissions and set up agreements with collaborators; and mainstream scientists mind the privacy and ownership of Indigenous data (Hatch et al. (2023) includes a full list of principles). Collaborations with Tribes would benefit from "boundary spanners" who can align goals of Tribal and non-Tribal partners to ensure fair and mutually beneficial outcomes that are not extractive (Hatch et al., 2023). These considerations for Indigenous Scientific Knowledge and Tribal capacity also apply to the research aspects of other strategies described below.

6.2 Regulatory Strategy Considerations

Regulatory considerations are primarily addressed in the *Base Program Analysis* (Implementation Strategy *Appendix II.b*), so this Section 6.2 points to some pertinent *Base Program Analysis* sections and highlights needed research to inform the Regulatory Strategy (Section 3.2).

6.2.1 Stressor identification and information sharing

Research on the specific impacts on eelgrass and kelp of regulated activities/projects in Puget Sound (MV 023, Uncertainty Table K) is needed to understand opportunities for regulatory improvement within the Regulatory Strategy, as is research to understand the suite of available actions for marine vegetation recovery (MV 015, Uncertainty Table K). Not all stressors can be managed by existing regulatory programs in Puget Sound (plus Section 5.3 discusses stressor reversibility).

Considerations about information sharing discussed for the Research and Monitoring Strategy (Section 6.1) also apply to the information sharing approach in the Regulatory Strategy.

Uncertainty Table K. Regulatory scope uncertainties

ID	Uncertainty	Priority Level
MV 023	"What project types or activities that require a permit, lease, or authorization under existing rules and regulations have the potential to adversely impact kelp or the ecosystem function it provides? Are those impacts temporary or permanent, and [how] can they be [avoided and/or minimized]?" What is the additive impact of a regulated activity on stressors that aren't (or can't be) regulated? (Quoted material from Kelp Policy Advisory Group et al. (2023, p. 6).)	**High**
MV 015	What actions could improve the management of marine vegetation stressors associated with regulated activities? What actions could address the effects of temperature and other pressures/stressors not associated with regulated activities (i.e., unmanageables)?	**High**

6.2.2 Regulatory effectiveness and training

Current understanding of, and recommendations for improved regulatory effectiveness in Puget Sound is synthesized in the *Base Program Analysis* (Implementation Strategy *Appendix II.b*). However, regulatory effectiveness for marine vegetation specifically remains a top research priority for the region (MV 008, Uncertainty Table L), and there are many other research needs related to regulations and regulated activities for marine vegetation in Puget Sound (Uncertainty Table L). The *Base Program Analysis* also discusses existing training resources and recommendations for improved regulator training which can support the approach on this topic in the Regulatory Strategy.

Uncertainty Table L. Uncertainties about regulatory effectiveness and design

ID	Uncertainty	Priority Level
MV 008	"Understand the effectiveness of current management policies relating to [protection] of kelp [and eelgrass] from [stressors associated with] construction, [water quality,] harvest, and other activities in Puget Sound" (quoted material from Calloway et al. (2020, p. C-1)).	**Top**
MV 020	What are the effects of kelp and eelgrass management frameworks on Tribal Treaty rights? What are the perspectives of Tribal co-managers on management options?	**High**

ID	Uncertainty	Priority Level
MV 048	What do property owners know about the "potential impacts" of nearshore development activities on kelp and eelgrass, both during construction and through the life of a structure? (Quoted material from Lambert et al. (2023, p. 13).)	**Low**
MV 049	How do design, operation, and other variables (e.g., age, ownership) affect "the potential impacts" of human infrastructure and activities "on marine vegetation"? (Quoted material from Lambert et al. (2023, p. 13).)	**Low**
MV 049.1	"What is the relative importance of [overwater structure] design elements (e.g. height, width, aspect, decking material) in minimising impacts on [marine] vegetation and fish use? How can these design elements be incorporated into future [overwater structure] permitting or modifications to [mitigate] potential...impacts? Are impacts of design elements additive or synergistic?" (Lambert et al., 2023, p. 13)	**No priority**
MV 051	What alternatives to private overwater structures exist, and how can they be incentivized?	**Low**
MV 052	Evaluate the additional damage caused by unpermitted structures that lack impact minimization measures (e.g., mooring buoys without approved anchoring systems, docks without grating).	**Low**
MV 056	How "have permitting and regulatory changes altered the willingness of private homeowners to build new [structures along their shoreline]?" (Quoted material from Lambert et al. (2023, p. 13).)	**Low**

6.3 Protected Areas Strategy Considerations

6.3.1 Protected area effectiveness

6.3.1.1 General protected area effectiveness

Marine protected areas (MPAs) are a management tool whereby specific areas of the ocean are designated as zones for conservation, typically restricting human activities in the area. Many MPAs are designated as “no-take” zones, meaning that no harvest may take place in the MPA (nor can other human activities which may cause physical damage to the habitat); however, other MPAs do not restrict all harvest or activity (Lester et al., 2009). MPAs have in large part been used in an effort to reduce the impacts of commercial and/or recreational fishing on marine organisms, hence the focus on harvest as the main restricted stressor in many MPAs (Filbee-Dexter et al., 2024). A meta-analysis found that no-take reserves of different sizes and geographic locations positively impacted biological outcomes (diversity, size, or biomass/abundance) for fish species, but not for algae density (based on the few studies of reserve effectiveness for algae at the time) (Lester et al., 2009). More recently, Cheng et al.

(2019) conducted a meta-analysis of MPA effectiveness in terms of biological processes (herbivory and predation), rather than common community structure metrics, and found that 1) predation was affected by MPAs, contingent on habitat type, temperature, and predator abundance, and 2) herbivory on seagrass/algae was not affected by MPAs. MPA effectiveness is predominantly (but not exclusively) measured based on ecological outcomes, and more research assessing social/economic/human wellbeing outcomes of MPAs is needed (Rasheed, 2020; O'Leary et al., 2021a; for example, Nowakowski et al., 2023) (which would increase understanding of potential multiple benefits of MPAs).

Stakeholder engagement in MPA management (including design and effectiveness evaluation) is frequently attributed to MPA effectiveness (Di Cintio et al., 2023). In one example of stakeholder engagement, co-production and leadership by resource users led to a more ambitious management plan than originally proposed for a National Marine Sanctuary in Florida (Boucek et al., 2024). Based on the history of MPA development in Puget Sound, Christie et al. (2018) recommend that any future establishment of new MPAs in Puget Sound should first and foremost follow Tribal leadership and also a) aim for socio-ecological co-benefits, and b) involve intentional efforts to engage and build trust with communities that would be impacted by MPAs.

6.3.1.2 Effectiveness of protected areas for marine vegetation

The Protected Areas Strategy (Section 3.3) aims to use protected areas as a tool for protecting marine vegetation in Puget Sound. Few MPAs globally have been established for the express purpose of protecting kelp (they usually focus on larger fauna, from which kelp can indirectly benefit), but doing so has been recommended (Eger et al., 2020 and sources cited therein) and there are examples of kelp-driven MPAs in Puget Sound (Section 6.3.1.3). Effectiveness of MPAs for kelp in various locations around the world is inconsistent. A 2014 global meta-analysis (of only five studies) found that kelp coverage did not statistically vary between MPAs and control sites (Gilby & Stevens, 2014). In areas that have been effective, MPA management of higher trophic level organisms was sufficient to positively impact kelp due to the absence of non-trophic stressors (Eger et al., 2020 and sources cited therein). In a New Zealand no-take MPA, kelp density increased in association with fewer turf algae and urchins and increased fish (Peleg et al., 2023). In California MPAs where restricted fishing is the main form of protection, kelp abundance showed more positive trends within some MPAs (North Coast) than outside them and algae diversity was higher in some MPAs (Northern Channel Islands) than outside them (Carr et al., 2021).

In Puget Sound, the primary stressors to kelp are thought to be sedimentation/change in substrate, competition with other algae, low nutrients, and temperature (Raymond et al., 2026), though more research on threats is needed (Uncertainty Table G) including at the scale of individual sites. Current evidence indicates MPAs are better able to protect kelp from impacts of direct or indirect harvest than from impacts of temperature or water quality (Filbee-Dexter et al., 2024 and sources cited therein). MPAs that restrict kelp harvesting directly have been successful in generating greater kelp biomass (Filbee-Dexter et al., 2024 and sources cited

therein). Similarly, MPAs are also not typically created with the express goal of seagrass protection or restoration (Douglass et al., 2018), though they are used (sources cited in Orth et al., 2010) including in Puget Sound (Section 6.3.1.3). MPAs may not fully protect eelgrass from all human impacts; human trampling in an MPA with public access but restricted take can still result in local reductions in *Z. marina* (Travaille et al., 2015).

6.3.1.3 Protected areas in Puget Sound

A 2009 inventory documented 109 MPAs in Puget Sound (Van Cleve et al., 2009). Van Cleve et al. (2009) and the Implementation Strategy *Appendix II.b: Base Program Analysis* (Table 5) provide lists of protected areas and their authorities. Resource managers have previously perceived protected area effectiveness to be mixed in Puget Sound, but also acknowledged significant capacity limitations for effectiveness monitoring (Masters, 2015). Some MPAs in Puget Sound involve protecting eelgrass and/or kelp, such as many of the Aquatic Reserves managed by WA DNR (WA DNR, 2007, 2010b, 2010a, 2011, 2014, 2019, 2024b). The management plans for all seven marine Aquatic Reserves describe eelgrass and/or kelp in conservation targets, management goals, and/or reasons for establishing the MPA (WA DNR, 2007, 2010b, 2010a, 2011, 2014, 2019, 2024b), and several Aquatic Reserves emphasize protection of noteworthy kelp or eelgrass habitats: Cherry Point Aquatic Reserve includes part of a substantial eelgrass habitat in Birch Bay (WA DNR, 2024c), Fidalgo Bay Aquatic Reserve is part of the southern Salish Sea's vastest eelgrass habitat (Fidalgo Bay—Guemes Channel—Padilla Bay) (WA DNR, 2019), and Smith and Minor Islands Aquatic Reserve aims to protect the most expansive bull kelp beds in the state (WA DNR, 2010b). Another local example of eelgrass-focused protected areas are Voluntary No-Anchor Zones, which aim to reduce the physical impacts of boat anchors (Northwest Straits Commission, n.d.). Furthermore, as part of the Statewide Kelp Forest and Eelgrass Meadow Health and Conservation Plan (WA DNR, 2023a, 2023b), WA DNR recently established the Squaxin Island Kelp Protection Zone which protects kelp habitat from commercial development (Vinson, 2025). However, full characterization of Puget Sound protected areas in terms of a) the extent to which they include marine vegetation habitat, b) whether they have the express goal of marine vegetation protection, c) the types of activities permitted/restricted in areas with marine vegetation, d) the extent to which restricted activities correspond with the primary stressors to marine vegetation at that location, and e) the effectiveness of those protected areas (for marine vegetation-related outcomes or other outcomes for which the protected areas were established), is beyond the scope of this State of Knowledge Report. Analysis of a), c), and d) are called for in one approach in the Protected Areas Strategy.

6.3.1.4 Considerations for measuring effectiveness in existing or new protected areas in Puget Sound

Because protected areas can in theory restrict some threats to marine vegetation (e.g., nearshore development, harvest, boating) but not necessarily others (e.g., climate change (Smith et al., 2023; Filbee-Dexter et al., 2024)), improved understanding of the major stressors to eelgrass and kelp both regionally and at specific locations (Uncertainty Table G) is critical for determining whether and how protected areas can be used to pursue marine vegetation

recovery goals. Furthermore, research on the effectiveness of protected areas in Puget Sound is needed to determine whether existing activities or restrictions in practice lead to desired outcomes (Uncertainty Table M).

Uncertainty Table M. Protected area effectiveness uncertainty

ID	Uncertainty	Priority Level
MV 029	How well are existing marine protection area authorities protecting kelp and eelgrass? What is the effectiveness of these authorities?	**Medium**

Effectiveness of MPAs can be measured in a variety of elements and using a variety of metrics (O'Leary et al., 2021a). Effectiveness may be measured not only based on outcomes of protection but also based on management metrics (how well the MPA is being implemented/run) and the adequacy of MPA spatial design (Rodrigues & Cazalis, 2020, as cited in O'Leary et al., 2021a). Outcome metrics can be ecological, social, or economic, though ecological outcomes are more commonly measured (O'Leary et al., 2021a). The design of effectiveness evaluations determines whether they can attribute causality to the measured outcomes; evaluations can also measure the value of MPAs (e.g., cost-effectiveness), but extremely limited examples of this were documented in a systematic map of effectiveness studies (O'Leary et al., 2021a). This systematic map database of published evidence on marine spatial management effectiveness studies in the U.S., Canada, Greenland, Europe, Australia, and New Zealand from 2009-2019 can be used as a tool to inform the design of future studies to evaluate MPA effectiveness (O'Leary et al., 2021a). For example, it found that only 10% (89) of studies used a before-after-control-impact (BACI) design to study MPA effectiveness (O'Leary et al., 2021a). BACI design is recommended for MPA effectiveness studies for controlling other factors that may contribute to measured patterns outside and within MPAs (Lester et al., 2009).

Understanding the effectiveness of existing MPAs is particularly important given the concerns of Tribes in Puget Sound about the creation of new protected areas in the region without appropriate justification (Van Cleve et al., 2009 Appendix 2).

6.3.2 Spatial design of new protected areas

Burns et al. (2023) reviewed MPA design guidelines from 56 publications and reports and produced a synthesized list of 24 guidelines which should be considered when designing new protected areas in Puget Sound. Marine vegetation-specific considerations related to select guidelines are discussed below.

"Prioritize areas where the main threats can be mitigated by an MPA and avoid areas where the main threats cannot be mitigated by an MPA" (Burns et al., 2023, p. 7).

- This guideline reiterates that the utility of protected areas as a tool for conserving marine vegetation in Puget Sound depends on which stressors are locally most important and whether protected areas can alleviate those stressors. That said,

protected areas can be beneficial in reducing cumulative stressor impacts even if they cannot alleviate all stressors (Filbee-Dexter et al., 2024).

Design large MPAs that are spaced to maximize coverage of the home range of target species throughout its life history, and support a viable population of the species and self-recruitment (Burns et al., 2023).

- These guidelines relate to selecting/designing MPA sites that are useful areas for the target species, and thus design of MPAs for marine vegetation should consider the timescales on which these species demonstrate variations in the habitats they occupy (e.g., seasonal growth patterns and inter-annual changes). The habitat conditions needed for marine vegetation (i.e., the right quantity/quality of nutrients, light, and substrate (Section 4.1)) should contribute to the design of protected areas aimed at protecting those species.

Design MPAs to cover the water column and other full "ecological units" (Burns et al., 2023, p. 6).

- This guideline is important for both eelgrass and kelp given their life histories. Adult canopy kelp in particular span the entire water column and so have the potential to be impacted by activities in both the benthic and pelagic realms. However, both eelgrass and kelp have free-floating life phases that utilize the water column for dispersal (sources and discussion is further below).

Choose locations for MPAs with different predicted climate conditions (Burns et al., 2023).

- This guideline is advisable for kelp; MPAs in other places have shown mixed effectiveness at increasing kelp resilience to temperature changes (Smith et al., 2023; Filbee-Dexter et al., 2024 and sources cited therein).

Consider ecological and economic trade-offs when choosing MPA sites; try to reduce effects experienced by fishers. Choose MPAs based on relevance to "non-extractive industries" (Burns et al., 2023, p. 7) and community prioritization.

- These guidelines suggest the importance of community engagement in the design and establishment of protected areas (Boucek et al., 2024 and sources cited therein; e.g., Masters, 2015), as discussed in Section 6.3.1. In the context of eelgrass and kelp in Puget Sound, considerations about fishers could be expanded to include other users of marine vegetation and the associated ecosystem, such as kelp harvesters, participants in outdoor recreation, and Tribal co-managers.

Choose MPA locations based on proximity to other areas that are monitored, managed, or used in ways that relate to the MPA (Burns et al., 2023).

- An opportunity to consider in relation to this guideline is to concurrently design and implement protected areas and restoration projects in connected or proximal areas so that they can be mutually beneficial (Eger et al., 2022). Implementing MPAs and restoration projects in the same places was specifically recommended for Puget Sound by resource managers interviewed by Masters (2015).

Compliance and management are easier when MPAs have basic shapes and are lower in number (bigger in size). Pursue spillover-related fishery benefits by designing MPAs to be higher in number (reduced in size) (Burns et al., 2023).

- These conflicting shape/size guidelines for MPAs depend on case-specific considerations about compliance and human wellbeing outcomes of MPAs. Kelp populations can spillover to outside the boundaries of an MPA (Castilla et al., 2007, as cited in Filbee-Dexter et al., 2024), so the smaller MPA guideline may apply to kelp and associated benefits. Again, considerations about fisheries could be expanded for Puget Sound to include other users of marine vegetation and the associated ecosystem.

Employ a buffer zone for minimizing MPA effects of outside stressors (Burns et al., 2023).

- The use of buffer zones around MPAs for eelgrass can be informed by the work of Donoghue et al. (2018) to measure the natural fluctuation in eelgrass edges year to year (they observed fluctuation of up to 34 meters in two years).

Create MPAs with no extraction allowed, and that are permanent. Enable some adaptive management in future by enacting both stationary and dynamic MPAs (Burns et al., 2023).

- Given that "extraction" of marine vegetation or higher level trophic organisms may not be the most important stressor on eelgrass or kelp at a site (Section 5.1), the guideline about extraction could either be expanded to exclude all human activity (i.e., to address all "manageable" threats in the MPA) or could be modified to prohibit the particular human activities that drive the most important stressors at the site. Permanence can guarantee long-term protection, though it may be helpful to keep management flexible enough to change in the future if conservation actions need to change (Filbee-Dexter et al., 2024). Dynamic MPAs might be relevant for eelgrass if distributions change under future sea level rise (Sherman & DeBruyckere, 2018 and sources cited therein).

Create three or more MPAs (no-take) per "bioregion" (Burns et al., 2023, p. 6), with three or more different habitats of each type. Anticipate spatially-limited disturbances by spreading out MPAs (Burns et al., 2023).

- This guideline more explicitly recommends establishing a network of MPAs, which is consistent with the Puget Sound MPA Work Group's recommendation for strategic design of MPAs as a network (Van Cleve et al., 2009). These recommendations suggest the value of region-scale MPA implementation in Puget Sound, though the selection of sites within a network will require consideration of site-scale conditions (per other guidelines from Burns et al. (2023)).

Account for inter- and intra-reserve connectivity of populations by opting for distances between and sizes of MPAs in a network based on species mobility, larval dispersal, and hydrodynamics (Burns et al., 2023).

- Eelgrass and kelp both have sessile and free floating life phases (Section 4.1). Dispersal distances for giant kelp are less than or equal to 10 kilometers (Reed et al., 2006, as cited in Eger et al., 2020). Bull kelp dispersal distances vary for this species' two different

spore dispersal approaches (dispersal from sori drifted to the bottom and blade-located sori at the top of the kelp canopy (Amsler & Neushul, 1989 as cited in Bemmels et al., 2025; Burnett et al., 2024 and sources cited therein)): a modeling study found that surface-released spores may travel as far as 20 kilometers, while benthic release of spores can travel over 10 kilometers but more commonly travel less than one meter (based on California flow data) (Burnett et al., 2024). In addition, if adult giant and bull kelp become detached, they can be productive and disperse spores (sources cited in Burnett et al., 2024). Rothäusler et al. (2011) calculated that giant kelp rafts in Chile may have traveled between 37 and 553 kilometers, which suggests that there may be kelp population connectivity on this scale. However, floating reproductive tissue is not as large a dispersal source as forests (sources cited in Burnett et al., 2024), so protected areas would be more likely to be biologically connected if established within 10-20 kilometers at most (for canopy kelp, depending on the species).

- For eelgrass, dispersal distances are <15 meters for pollen and ~<5 meters (mean 1.27 meters) for seeds (Ruckelshaus, 1996). However, other dispersal mechanisms may distribute seeds much further (Orth & Heck, 2023 and sources cited therein). For example, Chesapeake Bay research found that eelgrass seeds can germinate after predator organisms pass seeds through their guts (Sumoski & Orth, 2012). They calculated that the possible dispersal of eelgrass seeds via this biotic dispersal in bird species *Aytha affinis* (a species found in Puget Sound (Encyclopedia of Puget Sound, n.d.)) is between two and 19.5 kilometers (Sumoski & Orth, 2012). In addition, reproductive eelgrass ramets that break away from beds and float through the water could transport seeds 34 kilometers (Harwell & Orth, 2002 as cited in Crow et al., 2023). Despite these potential methods of seed dispersal, seed recruitment is thought to be less relevant for Puget Sound [Thom et al. (2014); Phillips et al. (1983) as cited in Borde et al. (2014)]; as a result, proximity of Puget Sound MPAs to existing eelgrass beds may matter more than pelagic connectivity.
- Further understanding of dispersal patterns for eelgrass and kelp is needed (Uncertainty Table E, MV 013) and can inform spatial design of marine vegetation-focused MPAs. The typical inter-annual changes in eelgrass and kelp coverage (Section 4.1) should also be considered when determining the necessary proximity of protected areas to ensure dispersal connectivity during years when populations have receded.

Choose habitats to be covered by protected areas with a target of 10-50% of each habitat type covered by an MPA/network (increase this where stressors (e.g., climate change) are greater) (Burns et al., 2023).

- If protected areas are established in Puget Sound for the purposes of habitat representation specifically (i.e., to preserve current habitat rather than to address stressors), the region should aim to cover at least 10% of eelgrass and kelp in protected areas.

Develop MPAs in 30% of the region being managed (Burns et al., 2023).

- Washington State as a whole had 26% coverage of MPAs as of 2009 (Van Cleve et al., 2009); determining the current statistic for Puget Sound specifically is beyond the scope of this State of Knowledge Report but could be calculated using spatial analysis.

Additional spatial design guidelines identified by Burns et al. (2023) are listed in Table 8. Ultimately, research is needed to understand how to best employ spatial design principles in protected areas for kelp in Puget Sound (Uncertainty Table N).

Table 8. Additional MPA design guidelines (adapted from Burns et al. (2023))

Goal	Guideline
Ecological connectivity	Location of MPA should be informed by the cross-ecosystem connectivity and other relationships between protected areas and surrounding environments.
Ecological connectivity	Situate MPAs based on gene flow. Currents can be used in the absence of genetic information.
Habitat representation	Choose MPA locations with novel or distant physical or biological features.
Habitat representation	Choose MPA locations that are "ecologically important" (Burns et al., 2023, p. 6) and biodiverse.
Persistence of species/population	Choose MPA locations with endangered, vulnerable, or otherwise significant species.
Manage or support human activities	Minimize fishing edge effects by designing MPAs in basic shapes.

Uncertainty Table N. Protected area design uncertainty

ID	Uncertainty	Priority Level
MV 038	What is the optimal spatial design (e.g., size, density, connectivity) for sugar and bull kelp protection?	**Medium**

The above design guidelines from Burns et al. (2023) specifically focus on achieving ecological MPA goals, and there are other drivers of MPA effectiveness which can be considered when setting up a new MPA (and subsequently evaluating its effectiveness) (Gallacher et al., 2016). These include governance elements (management organization, involvement of community organization, stakeholder-manager engagement, community awareness about MPA rules, stakeholder resource conflict, enforcement, management capacity (funding), stakeholder support of and involvement in MPA management, and established goals and management plans) and socioeconomic elements (economic context, existing human activities, human values

related to the habitats/species, and community awareness of stressors at the site) (Di Cintio et al., 2023; Gallacher et al., 2016). Published information on effectiveness of MPAs in terms of social and economic outcomes is much sparser than for ecological outcomes (O'Leary et al. 2021a), so there is likely still much to learn about best practices for MPA design to pursue those goals.

6.4 Restoration Strategy Considerations

6.4.1 Puget Sound restoration context

The Restoration Strategy (Section 3.4) in the Implementation Strategy outlines approaches for undertaking both passive and active restoration projects to increase the spatial distribution of eelgrass and kelp in Puget Sound. Active restoration is the seeding or planting of new eelgrass or kelp in an area, while passive restoration is the modification of an area (e.g., removal of stressors) to enable natural growth (Beheshti & Ward, 2021). On the U.S. West Coast, eelgrass restoration takes place at generally small scales and most eelgrass restoration has been completed as mitigation to counteract the impacts of development projects (Beheshti & Ward, 2021; Ward & Beheshti, 2023).

Eelgrass restoration in Puget Sound dates back at least to 1974, at which time restoration via transplantation in the Northwest was still being tested (Thom, 1990). Of the Puget Sound eelgrass restoration projects assessed (since 1996) in a review by Beheshti and Ward (2021), most Puget Sound projects were not completed for mitigation purposes, and all were active rather than passive (Ward & Beheshti, 2023). In addition, most of these projects (and earlier Puget Sound projects reviewed by Thom (1990)) used transplantation rather than seeding methods (Beheshti & Ward, 2021) (methods are discussed further in Section 6.4.3). A site selection model was developed (Borde et al., 2014; Thom et al., 2014, 2018) to inform eelgrass restoration in Puget Sound, and work remains needed to determine why restoration projects at many model-selected sites have not been effective (discussed further in Section 6.4.2). Recent and ongoing work aims to test eelgrass seeding methods in Puget Sound (Crow et al., 2023; McCloskey, n.d.; Price et al., 2023; San Juan Islands Conservation District, n.d.; Seacology, n.d.a, n.d.b, n.d.c; Wilmerding et al., 2022).

Kelp restoration activities in Puget Sound are more recent. Pre-2000, Elliot Bay Marina mitigation involved effective kelp restoration using long-lines (sources cited in Carney et al., 2005). However, despite some subsequent studies on artificial kelp planting and restoration methods in the region (Carney et al., 2005; e.g., Duggins et al., 2001 as cited in Carney et al. 2005), when the Puget Sound Restoration Fund's (PSRF) dedicated bull kelp restoration work started in 2010 Puget Sound kelp restoration was still in its early days (McKenna et al., 2022a; Puget Sound Restoration Fund, n.d.b). PSRF continues to work to test kelp restoration methods since the methods used so far have resulted in surface-level growth and some subsequent natural growth, but not enough of the latter for the kelp to be self-sustaining (Golonka, 2024; H. Hayford, personal communication, November 11, 2025; Pacific Salmon Foundation, 2025; Puget Sound Restoration Fund, n.d.a, n.d.b; Toft, 2023) (methods are discussed further in Section 6.4.3). In addition, the Vashon Kelp Forest project has been proposed to grow bull and

sugar kelp (*Saccharina latissima*) both for bull kelp restoration and harvest (Vashon Kelp Forest, n.d.a, n.d.b), though this project does not yet have a WA DNR lease (Brown, 2025). A site selection model was developed recently for bull kelp in Puget Sound (McKenna et al., 2022b) (discussed further in Section 6.4.2), but it is not clear to what extent the model has yet been used to choose locations for restoration activities.

A full list of existing Puget Sound restoration projects (past and present) was not produced for this State of Knowledge Report; however, eelgrass restoration projects from Puget Sound are reviewed by Ward and Beheshti (2023) and Tribal restoration work is described in Section 7.1 of the *Base Program Analysis* (Implementation Strategy *Appendix II.b*). In Puget Sound, Tribes are leading many efforts to restore eelgrass and kelp, demonstrating the local importance of Indigenous knowledge in restoration which has also been noted in the international seagrass context (Unsworth et al., 2025 and sources cited therein). Furthermore, the Washington Kelp Project Inventory aims to document kelp projects (including restoration projects) in the state.

In addition, the Pacific Salmon Foundation's Restoration Resource Hub is an upcoming Canadian resource for information about restoration projects to inform understanding of effectiveness in the wider Salish Sea (Pacific Salmon Foundation, n.d.), and the Kelp Forest Alliance is an international database of kelp restoration projects (Eger et al., 2022).

6.4.2 Site suitability

6.4.2.1 Modeling

Restoration projects require the selection of locations in which to plant eelgrass/kelp or directly remove a stressor. An approach recommended in a recent review of U.S. West Coast eelgrass restoration is to first model site suitability and then experiment at sites to test suitability on the ground (Beheshti & Ward, 2021; Ward & Beheshti, 2023). In Puget Sound, the Pacific Northwest National Laboratory (PNNL) modelled and mapped site suitability for eelgrass restoration by incorporating modelled biomass production, stakeholder feedback, historical and current eelgrass distribution, several stressors, and substrate (Thom et al., 2014, 2018). The resulting Eelgrass Restoration Site Prioritization Geodatabase (part of the Eelgrass Restoration Habitat Suitability Model discussed in Section 7.2) identified roughly 3,000 hectares of habitat that lacked eelgrass but was expected to be highly suitable, which was used to select nine test sites where eelgrass was transplanted to test restoration suitability (Thom et al., 2014, 2018). Eelgrass survived at four of those sites and three were identified as sites suitable for larger eelgrass planting (Thom et al., 2014, 2018). Further test transplants and larger plantings have shown mixed success; some of each type of planting failed to result in eelgrass survival, while robust shoot density was observed over time at a larger planting at Joemma Beach (Gaeckle, 2019; Shannon et al., 2018). These results demonstrate the importance of conducting additional assessment of model-selected sites, including continuous monitoring of water quality variables to understand short periods of extreme stress at a site, to improve the likelihood of effective restoration (Borde et al., 2014; Busch et al., 2010; Golden et al., 2010; Tanner et al., 2010; Unsworth et al., 2025). Section 6.4.2.2 discusses variables that could be added to site suitability modeling to improve its accuracy. Understanding precisely why restoration was

unsuccessful at many of the model-predicted sites in Puget Sound remains a research need for the region (MV 003.1, Uncertainty Table Q). Risk level of seagrass should inform restoration site choices (Unsworth et al., 2025), so site selection could be further informed in Puget Sound by a forthcoming spatial cumulative risk assessment for eelgrass and kelp (Magel et al., 2025a).

A Bull Kelp Restoration Site Selection Tool has also recently been developed for Puget Sound by University of Washington students in collaboration with PSRF (McKenna et al., 2022b) (Section 7). The tool models habitat suitability for bull kelp based on historical distribution and seven biophysical variables, and also maps regulatory information (such as ferry routes and jurisdictional information) to inform understanding of permitting implications of possible restoration sites (McKenna et al., 2022b). The Site Selection Tool may presumably inform the bull kelp restoration activities of PSRF and its partners in Puget Sound; however, McKenna et al. (2022b) highlight additional data, variables, and analyses that could improve the tool beyond its current status. Other University of Washington students, in collaboration with the Seattle Aquarium, produced a follow-up bull kelp habitat suitability model specifically for Elliott Bay (Randell et al., 2023b; Randell et al., 2025; Randell, n.d.; Williams et al., n.d.) which is also intended to be used for restoration planning (Habitat Strategic Initiative Lead, 2023; Randell et al., 2023a). The Elliott Bay model uses MaxEnt and is currently based on 1994-2000 kelp distribution and four benthic variables (Randell et al., 2025; M. Williams, personal communication, November 11, 2025; Williams et al., n.d.). In 2026, Seattle Aquarium will finish broadening the model to cover other nearby areas in central Puget Sound (e.g., eastern Bainbridge Island) (Randell et al., 2025; M. Williams, personal communication, November 11, 2025). They have also planned to examine environmental differences in these new areas and to add more data such as kelp habitat information from recent and upcoming ROV-based surveys (Randell, n.d.; Randell et al., 2025; M. Williams, personal communication, November 11, 2025).

6.4.2.2 Biophysical variables

Environmental conditions important for survival of eelgrass and kelp such as nutrients, light, and substrate (Section 4.1; Beheshti & Ward, 2021 and sources cited therein) could be included in site suitability models to predict sites that are amenable to marine vegetation; all three of these are included in the recent Bull Kelp Restoration Site Selection Tool (McKenna et al., 2022b) but nutrients are not a clear variable included in the PNNL eelgrass site suitability model (Thom et al., 2014). For eelgrass restoration, variables related to hydrodynamics, grazing species, algae, bioturbators, and climate resilience (Unsworth et al., 2025 and sources cited therein), as well as historical impacts (Beheshti & Ward, 2021 and sources cited therein) and wave exposure specifically (Tanner et al., 2010), could also be included in site suitability models. For the PNNL Puget Sound model, Thom et al. (2014) specifically suggest considering wave exposure in future site suitability assessments (as well as more information about eelgrass physiology and genetics (Backman, 1991 as cited in Thom et al., 2014; Wyllie-Echeverria et al., 2010 as cited in Thom et al., 2014)). For eelgrass restoration via seeding methods, sediment quality (including lugworm (*Abarenicola pacifica*) density and hydrogen sulfide (Crow et al., 2023; Price et al., 2023; Wilmerding et al., 2022)) could be assessed during site selection in addition to water quality (Spooner, 2025). Furthermore, Golden et al. (2010)

recommend that the amount of time that variables are above extreme levels (using more than one year of data) be included in site selection models (for eelgrass). McKenna et al. (2022b and sources cited therein) also suggested modeling wave exposure, as well as vessel traffic, contaminants, predator abundance, reef topography, native and non-native macroalgal competition, sedimentation, and grazing for bull kelp restoration site suitability since these variables are not included in the current version of their tool. The subsequent bull kelp habitat suitability model for Elliott Bay includes seafloor slope and aspect, but Seattle Aquarium data on kelp crabs and understory algae were pulled from the model because it was overfit with those data (Randell et al., 2025).

Furthermore, while the historic presence of seagrass can be included in site suitability models, historical distribution is not a guarantee of restoration success, particularly if stressors at the site are still occurring (Thom et al., 2014; Unsworth et al., 2025). The disconnect between historical distribution and current restoration effectiveness is demonstrated by the failure of eelgrass restoration at many sites chosen based on the PNNL site suitability approach (Section 6.4.2.1) which included historical eelgrass distribution as one model variable (Thom et al., 2014). On the other hand, the current distribution of kelp may be a useful variable to include in site suitability modeling, as kelp restoration can be effective when conducted on sites that still have some kelp left (Eger et al., 2022 and sources cited therein). The Bull Kelp Restoration Site Selection Tool for Puget Sound currently only includes historical (1911-1912) kelp distribution (McKenna et al., 2022b), while the bull kelp habitat suitability model for Elliott Bay includes "historic" bull kelp distribution from 1994-2000 (Randell et al., 2025, p. 21; Williams et al., n.d.); Seattle Aquarium plans to add more recent ROV and drone survey data to the Elliott Bay model (Randell et al., 2025).

6.4.2.3 Spatial design elements

Eger et al. (2022 and sources cited therein) suggest using spatial design principles from MPA literature to inform restoration planning (i.e., Section 6.3.2). For example, that global review of kelp restoration projects found that the most important factor for kelp restoration effectiveness is distance between extant kelp and the restoration site, suggesting that MPA network design guidelines for population connectivity may be relevant for choosing restoration sites (Eger et al., 2022). For example, an effective passive restoration project for *Macrocystis* in southern California utilized an artificial reef located 0.5-3.5 kilometers from an existing population (Reed et al., 2024). Distance to existing populations also contributed to restoration effectiveness for some Pacific Northwest eelgrass projects (Thom, 1990) and exemplars of seagrass and kelp restoration globally (sources cited in Saunders et al., 2020). Furthermore, a global meta-analysis of seagrass restoration (not specific to *Z. marina*, though half of the projects included that species) found that restoration occurring less than one kilometer from donor beds are more successful than projects further away (van Katwijk et al., 2016). Distances between a source population and a restored site might need to be species-specific given differences in spore dispersal (e.g., giant vs. bull kelp) (Bemmels et al., 2025 and sources cited therein). Specific information about dispersal for both eelgrass and kelp is discussed in Section 6.3.2. The importance of connectivity to existing marine vegetation indicates that restoration

site selection requires consideration of factors at local (e.g., site stressors) and regional (e.g., population distribution) scales. However, further research is needed to understand the implications of connectivity for eelgrass and kelp restoration design in Puget Sound (MV 022, Uncertainty Table O). Furthermore, Unsworth et al. (2025 and sources cited therein) recommend designing seagrass restoration within regional contexts so that synergistic benefits can be attempted, and Eger et al. (2022) suggest that kelp restoration and MPAs could be implemented concurrently.

Another spatial design consideration for restoration is the area of the site actively targeted for restoration. For example, a *Z. marina* restoration experiment using Dispenser Injection Seeding in the Dutch Wadden Sea found that larger area seeded (i.e., 400 square meters as opposed to four square meters) resulted in higher efficiency of seed recruitment and higher plant density (Gräfnings et al., 2023). In contrast, recruitment efficiency (but not overall density of surviving plants) was higher when the density of seed was reduced (Gräfnings et al., 2023). For kelp restoration, larger restoration site areas could help resist grazing (Eger et al., 2022).

Relatedly, the overall volume of vegetation used in an active restoration project may also matter for restoration design. For seagrass restoration, two dynamics result from using a larger amounts of plants (i.e., at least thousands): 1) denser populations can better facilitate their own growth and reproduction, and 2) a larger area improves the chance that environmental conditions (varying over small scales) will be suitable for at least part of the planted population (van Katwijk et al., 2016). In a successful eelgrass restoration project using seeding in Virginia's coastal bays, using a substantial amount of seeds and plots for distributing seeds was suspected to begin positive feedback cycles that fostered growth and subsequent survival of eelgrass, in addition to subsequent seeding (Orth et al., 2020). Other positive species interactions that may apply to restoration are discussed in Section 6.4.3.

Finally, Beheshti and Ward (2021) recommend thinking long-term about how the size of a restored eelgrass area could increase; suitable space around the planted area would allow for population expansion over time. The boundary of eelgrass populations in Washington (mostly Puget Sound) can naturally expand up to 34 meters in two years (Donoghue et al., 2018).

6.4.2.4 Social and economic variables

Several non-biophysical factors have also been recommended for consideration in site selection:

- Costs (Unsworth et al., 2025);
    - Seagrass restoration can cost $399,532 per hectare (Bayraktarov et al., 2016 as cited in Unsworth et al., 2025 (incorrectly cited as Elisa et al., 2016)).
    - Depending on the method, a global review of limited cost data indicates that kelp restoration can cost between $1,500 to $707,000 per hectare (Eger et al., 2022).
- Capacity/funding (Beheshti & Ward, 2021 and sources cited therein);

- "social and governance factors" (Ward & Beheshti, 2023, p. 13 and source cited therein) / opportunities and social attitudes (Unsworth et al., 2025).
    - Unsworth et al. (2025) recommends involving stakeholders in seagrass restoration site selection.

6.4.2.5 Additional site selection recommendations

Finally, other design elements should be considered when selecting restoration sites. Firstly, selection of eelgrass restoration sites should be accompanied by the selection of control (reference) sites that are an appropriate depth and distance from the restoration site, to use in the evaluation of restoration effectiveness (Section 6.4.5) (Thom et al., 2005 as cited in Beheshti & Ward, 2021). In addition, seagrass restoration site selection should include establishment of articulated goals (e.g., human engagement, communication, biodiversity, seagrass itself, etc.) for the restoration (Unsworth et al., 2025 and source cited therein).

In general, site suitability conditions for marine vegetation restoration in Puget Sound is a major research need (MV 004, Uncertainty Table O).

Uncertainty Table O. Restoration site suitability uncertainties

ID	Uncertainty	Priority Level
MV 004	What are the conditions (biophysical, social, and economic) that make a site suitable for kelp and eelgrass restoration? How do recent trends in the distribution of marine vegetation relate to the optimal locations for restoration? Where can volunteers and communities be engaged to support restoration, and how do volunteers and communities benefit from this engagement?	**Top**
MV 022	How does site connectivity affect kelp and eelgrass restoration? Study how to design ecosystem-scale approaches to restoration/management which increase connectivity.	**High**

6.4.3 Restoration methods

6.4.3.1 Eelgrass restoration methods

There are several existing techniques that can be used for restoration of eelgrass. On the U.S. West Coast, a common active restoration method is "bare root anchoring", but other methods include unanchored shoots, plugs, and seeding (Beheshti & Ward, 2021, p. 13; Ward & Beheshti, 2023, p. 7). Passive restoration methods for eelgrass include water quality remediation, removing debris, and hydrological restoration (Beheshti & Ward, 2021). Beheshti and Ward (2021, p. 16) characterize 10 eelgrass restoration techniques according to the following factors, which can be used to inform method selection for a given project:

- Level of impact to donor population from which eelgrass material is collected for transplant;

- Machinery requirements;
- Scale of anticipated benefits;
- Genetic diversity implications;
- Flow regime needed;
- Suitability for community science;
- Bioturbation implications;
- Diver requirements;
- Level of difficulty in "re-locating" sites;
- Intertidal suitability;
- Speed of planting;
- Speed of preparation;
- Ability of materials to biodegrade;
- Cost.

Seeding (active restoration) is not common on the West Coast (Beheshti & Ward, 2021) or in Puget Sound (Seacology, n.d.c), but it has been used in other places such as the Chesapeake Bay and nearby areas (e.g., Busch et al., 2010; Golden et al., 2010; Orth et al., 2020). Orth et al. (2020) present a noteworthy example of effective eelgrass restoration using seeding in four coastal bays in Virginia between 1999 and 2018. Eelgrass increased close to 3612 hectares through annual seeding which covered 536 plots and used 74.5 million seeds total, in part due to natural recruitment from initial restoration growth (Orth et al., 2020). A key factor in the effectiveness of this project was that environmental conditions were suitable for eelgrass – eelgrass had been disturbed by a storm and disease in the 1930s and seed recruitment was the biggest barrier to natural recovery (Orth et al., 2020). Indeed, temperature may explain the differing effectiveness of restoration in Chesapeake Bay (using primarily shoot transplantation methods) and the Virginia coastal bay restoration (Orth et al., 2010).

Orth et al. (2020) also attribute the effectiveness of eelgrass restoration in Virginia coastal bays to: a) monitoring on long timescales; b) use of restoration best practices; c) positive feedbacks (discussed further below); d) the morphology of the bays, which contributed to the retention of seeds; and e) collaboration, including with volunteers who completed seed gathering. The Virginia restoration involved collecting seeds in the spring and dispersing them in the fall after summer storage (Orth et al., 2020). A Chesapeake Bay comparison of a similar seeding method to buoy-deployed seeding (which involves collecting shoots in the spring and deploying the shoots in targeted areas for dispersal of seeds from shoots) found that both methods yielded similar shoot density (Golden et al., 2010) and both methods can be cost-effective in relation to shoot transplantation (Busch et al., 2010). However, each seeding approach has pros and cons: manual dispersal of seeds can occur temporally closer to natural germination (reducing risks of mortality), but costs are higher due to the laboratory facilities required to store seeds (Busch et al., 2010) (such facilities are a known barrier to seeding on the U.S. West Coast, as per van Katwick et al. (2021 as cited in Ward & Beheshti, 2023)). In contrast, buoy-deployed seeding does not require facilities for storing seeds, but dispersal may occur well in advance of germination (increasing risks of mortality) (Busch et al., 2010). Ultimately, the relative costs of

the two seeding methods varied depending on storage success and seed productivity (Busch et al., 2010), and research is needed on seed quality to improve use of seeding methodologies (Vanderklift et al., 2020).

Though Beheshti and Ward (2021) advise against seeding on the U.S. West Coast (except as a supplementary method) until more is understood about the technique, there is recent and ongoing research in and near Puget Sound on eelgrass seeding methodologies. Wilmerding et al. (2022) describe pilot studies to test and refine four seed dispersal methods in Westcott Bay and Blind Bay in the San Juan Islands: broadcast seeding (3,000 seeds at each site), seed buoys, hessian bags, and germinated seeds. All methods showed some survival in (short-term) monitoring after seed dispersal but the authors found that the germinated seed method (using burlap frames) had too many issues to be used in future (Wilmerding et al., 2022). They also concluded that broadcast seeding needs to use more seeds and that use of seed buoys needs to consider conflict with boat traffic in Puget Sound (Wilmerding et al., 2022). Two other ongoing projects in Puget Sound aim to transplant both eelgrass shoots and seeds at Decatur, Sucia, and Shaw Islands (Seacology, n.d.a, n.d.b; Tanner et al., 2025). In addition, based on recent seeding work in British Columbia, Spooner (2025) presents best practices for the use of buoy-deployed seeding on the West Coast and suggests that eelgrass restoration incorporate this method in addition to shoot transplantation.

Technological developments may also assist with eelgrass restoration methods. Both dispersal and harvest could be completed via autonomous vehicles (Vanderklift et al., 2020). Mechanical harvesters have been used to collect eelgrass seeds in Chesapeake Bay (Busch et al., 2010; Orth et al., 2012 as cited in Vanderklift et al., 2020), which was found to be much faster and allow for harvesting seeds at the magnitude needed for a large restoration project (Busch et al., 2010). However, it should be noted that seed collection using the harvesting machine was less selective, more complicated, and more expensive than harvesting by hand (Busch et al., 2010). Busch et al. (2010) also tried to use a machine for seed dispersal, but it did not save any time relative to manual dispersal. For planting eelgrass shoots, the Grasshopper robot by Reefgen is being tested in Puget Sound in collaboration with WA DNR (Stiffler, 2024) and is also being used in the current eelgrass restoration project in Decatur, Sucia, and Shaw Islands (Seacology, n.d.a). Grasshopper can also be used for seeds, and developers are working to create faster versions of the robot with more capacity (Stiffler, 2024).

6.4.3.2 Kelp restoration methods

For kelp, different restoration methods can be used at different scales (Eger et al., 2022). Active restoration methods used globally include seeding and transplantation of substrate or mesh (Eger et al., 2022). Locally, PSRF has been testing several methods for active bull kelp restoration in Puget Sound. Their early work transplanting sorus and juvenile sporophytes did not produce any adults (McKenna et al., 2022a; Golonka, 2024). While transplanting “green gravel” (gravel with kelp “seeds” on it) is being touted as a pioneering method in other areas of the Salish Sea (Cascadia Seaweed, n.d.; Techcouver Newsdesk, 2025) and elsewhere globally (Wood et al., 2024), PSRF’s 2012 attempt at this methodology in Puget Sound showed no bull

kelp growth (McKenna et al., 2022a). PSRF also determined that sporophytes are the preferred life stage of kelp to transplant (McKenna et al., 2022a). More recently, PSRF has been working on outplanting kelp via lines with seeds on them, deployed either on pyramid substrates or on straight lines deployed above the sediment (McKenna et al., 2022a; Puget Sound Restoration Fund, n.d.b). The latter has repeatedly yielded adult kelp growing the full water column (Golonka, 2024; Puget Sound Restoration Fund, n.d.b; Toft, 2023), with higher abundance than at a reference site (McKenna et al., 2022a); it also yielded "30+ wild recruits" beyond the transplanted lines in both 2024 and 2025, with at least one recruit itself reaching reproduction (H. Hayford, personal communication, November 11, 2025; Pacific Salmon Foundation, 2025; Puget Sound Restoration Fund, n.d.b). However, greater recruitment is needed for planted kelp to replenish itself (H. Hayford, personal communication, November 11, 2025; Puget Sound Restoration Fund, n.d.b). Much of PSRF's work is done in collaboration with Tribes in Puget Sound; PSRF's work began at Doe-Kag-Wats/Point Jefferson in collaboration with the Suquamish Tribe (Puget Sound Restoration Fund, n.d.b), they work with the Jamestown S'Klallam Tribe and other tribes and partners to maintain a bull kelp seed bank for restoration (Mesa, 2023; Puget Sound Restoration Fund, n.d.a), and they are collaborating with Port Gamble S'Klallam Tribe for restoration of bull kelp in the Port Townsend Shipping Canal (Royal, 2025). In addition, PSRF collaborates with the Squaxin Island Tribe on kelp restoration using gametophyte-covered lines at Squaxin Island (Ledbetter et al., 2025; Toft, n.d.). The 2024 deployment at Squaxin Island also included putting seeds on rocks and twine around the main lines, as well as kelp crab mitigation techniques. Kelp growth was not observed and kelp crabs were, so the 2025 deployment meant to experiment with gametophyte density (Toft, n.d.). Another method being tested by PSRF is "kelp gardening", which involves planting kelp on twine or other fibers attached to natural rocks (Hauser, 2025). The method has not been effective yet, but is meant to be a simpler restoration approach that does not need permits (Hauser, 2025). More details about kelp restoration methods can be found in PSRF's *Kelp Cultivation Handbook* (Puget Sound Restoration Fund, n.d.d). Furthermore, Seattle Aquarium and PSRF are experimenting with the use of ROVs for kelp restoration monitoring (Randell, n.d.).

Passive restoration methods for kelp include artificial reef installation and chemical and manual grazer removal (Eger et al., 2022). Reed et al. (2024) effectively restored *Macrocystis* on an artificial reef in southern California via natural recruitment from an existing population 0.5-3.5 kilometers away. Kelp grew to a greater biomass on the artificial reef than at existing populations, and showed greater survival than kelp seeded on lines that were also deployed at the reef (Reed et al., 2024). Passive restoration methods that have been utilized in conjunction with active methods in Puget Sound include efforts to improve water quality at Doe-Kag-Wats (Puget Sound Restoration Fund, n.d.b) and mitigate kelp crabs at Squaxin Island (Toft, n.d.).

6.4.3.3 Additional methodological design considerations

In addition to the specific techniques available for restoration, the design of a restoration project can consider additional elements:

- The timing of kelp restoration could be designed to account for grazing trends (Carney et al., 2005; Eger et al., 2022).
- Several types of positive species interactions in kelp have been identified that could be considered in the design/implementation of kelp restoration: intraspecific facilitation, interspecific facilitation, trophic cascades, kelp genetics, microbial relationships with kelp, and other human interventions (Eger et al., 2020). All of these require research to understand if and how they can increase the effectiveness of kelp restoration (Eger et al., 2020). For example, for intraspecific facilitation, small dispersal distances (*Macrocystis*: ≤10 kilometers) suggest that conducting kelp restoration at sites near existing kelp would promote connectivity to support long-term survival of kelp at the restored site (Eger et al., 2020 and sources cited therein). Furthermore, because adult kelp density affects the environment that supports juvenile kelp survival, kelp restoration approaches that involve transplanting multiple kelp life stages could improve the effectiveness of restoration (Eger et al., 2020 and sources cited therein). For trophic cascades, current work by the University of Washington and The Nature Conservancy California aims to culture and release *Pycnopodia* (sunflower star) to ultimately understand how doing so can impact kelp restoration (Eger et al., 2020 and sources cited therein; Taguchi & Urton, 2024).
- Positive species interactions might also improve seagrass restoration (Corinaldesi et al., 2023 and sources cited therein), based on ecological theory: biodiversity, facilitation cascades, benefits generated by other species further away, trophic control of seagrass grazing, microbial relationships, mutualistic relationships with other macroorganisms, and intraspecific density (Valdez et al., 2020). Using a greater density of seagrass can increase the effectiveness of restoration projects, in part by the seagrass facilitating its own expansion (Orth et al., 2020; van Katwijk et al., 2016 and sources cited therein). For interspecies interactions, Zhang et al. (2021) found that co-dispersal of juvenile clams alongside eelgrass had different impacts depending on the restoration method used. In addition, the microbes associated with *Z. marina* and other seagrass species may support the plants by mineralizing organic matter, solubilizing phosphorus, and fixing nitrogen (Tarquinio et al., 2019 as cited in Corinaldesi et al., 2023) and may improve seagrass' ability to tolerate stressors (Corinaldesi et al., 2023 and sources cited therein). Microbial interactions could be utilized in two possible ways for restoration (Corinaldesi et al., 2023): 1) selected microbes could be applied directly on species to improve their health, and 2) the microbiome could be used as a factor in choosing restoration source material (Jorissen et al., 2021 as cited in Corinaldesi et al., 2023). However, research is needed on how to use microbial interactions in seagrass restoration (Corinaldesi et al., 2023 and sources cited therein). Hardly any restoration projects in the U.S. (Zhang et al., 2021) or the West Coast specifically (Beheshti & Ward, 2021) use or measure positive species interactions in seagrass restoration.
- Genetics can be incorporated to inform which source populations to use and to design restoration for improved gene flow (Larson, 2025; Unsworth et al., 2025 and sources cited therein). For example, a recent study sequenced the genomes of giant and bull kelp from Washington and British Columbia, finding that populations within this region are genetically discrete but that there is gene flow between adjacent populations

(Bemmels et al., 2025). Bemmels et al. (2025) recommend 1) using these "genetic clusters" (p. 689) to develop a spatial strategy for acquiring sources for restoration [Massatti et al. (2020), Moritz (1994), Palsbøll et al. (2007), Ying and Yanchuk (2006), all as cited in Bemmels et al. (2025)], and 2) (pending more research) using larger populations as bull kelp restoration sources and reducing self-fertilization in those sources. For eelgrass, a recent study in Willapa Bay identified genetic clusters distinguished by whether eelgrass plants flowered and found that both environmental factors and genetics play a role in determining whether individual eelgrass will be perennial or annual (Briones Ortiz et al., 2025). The authors argue that local adaptation needs to be considered when determining source plants for eelgrass restoration [Hufford and Mazer (2003), van Katwijk et al. (2016), Unsworth et al. (2023), all as cited in Briones Ortiz et al. (2025)]. A new Washington Sea Grant study will soon conduct further research on eelgrass genetics for restoration applications (Larson, 2025).

- Other co-located nearshore restoration projects might also influence natural seagrass (re)colonization or restoration success. The Puget Sound Eelgrass Recovery Strategy (WA DNR, 2015) recognized the potential of other restoration projects, such as tidal wetland restoration of river deltas, to support eelgrass growth and expansion by restoring ecosystem processes and potential nearshore habitat. Notable increases in eelgrass area at three sites (200 acres gained, in total) occurred 4-6 years after delta restoration in the Skokomish River which removed dikes and restored tidal wetlands and distributary channels starting in 2006 (WA DNR, 2015). Following the 2009 removal of a 308 ha dike in the Nisqually River delta, there was a dramatic expansion of eelgrass at the front of the delta approximately 2 km from the project that persisted from 2012-2015 (WA DNR, 2015). However, monitoring at two eelgrass beds closer to the restoration site observed no change in the larger eelgrass bed and small negative impacts on the smaller bed in the 5 years following dike removal 4/20/2026 5:08:00 PM. These findings demonstrate the potential for interaction between restoration projects and adjacent habitats, highlighting the importance of research and monitoring to inform restoration project design that maximizes multiple ecosystem benefits.

6.4.3.4 Stressors and methodological effectiveness

Knowledge about the effectiveness of restoration methods for eelgrass across temporal and spatial scales (on the U.S. West Coast) and kelp (globally) is still preliminary (Beheshti & Ward, 2021; Eger et al., 2022; Ward & Beheshti, 2023), and questions related to method effectiveness have been identified as research needs for Puget Sound (Uncertainty Table P). However, for eelgrass restoration, environmental conditions matter more than methods for restoration effectiveness (Beheshti & Ward, 2021). Similarly, restoration method is not a driver of kelp restoration success globally (Eger et al., 2022). Given this, uncertainties (Uncertainty Table G; Uncertainty Table Q, MV 003) about the impacts of stressors appear to be important barriers to restoration implementation (Beheshti & Ward, 2021; Ward & Beheshti, 2023). For both kelp and eelgrass, local stressors at a site need to be understood and, if possible, addressed before conducting restoration (Allan et al., 2013 as cited in Orth et al., 2020; Beheshti & Ward, 2021; Eger et al., 2020; Gräfnings et al., 2023; McDonald et al., 2016 as cited in Vanderklift et al.,

2020; Orth et al., 2010, 2020; Thom, 1990; Thom et al., 2014; Vanderklift et al., 2020). Indeed, eelgrass restoration can be more effective if environmental threats are addressed before restoring eelgrass (Merkel & Associates, Inc., 1998 as cited in Beheshti & Ward, 2021; Thom et al., 2008). In other cases, if stressors are addressed marine vegetation may not need active restoration and could recover naturally (Reed et al., 2024 and sources cited therein). In general, restoration may be required in addition to reducing stressors to recover coastal habitats (Vanderklift et al., 2020).

Some stressors operate on different temporal scales than others (Eger et al., 2020 and source cited therein), which will have implications for the short- and long-term effectiveness of restoration. Factors suspected to contribute to eelgrass restoration failure or reduced survival in some Puget Sound projects include method, characteristics of donor plants, multiple impacts of algae, sediment changes, and benthic organisms, depending on the site (Gaeckle, 2019). Globally, fish and urchin grazing on kelp is the most frequent stressor contributing to kelp restoration failure (Eger et al., 2022). However, grazing is not thought to be one of the bigger threats to kelp in Puget Sound regionally (Raymond et al., 2026) (perhaps due to fewer urchins [Carson et al. (2016), H. Carson, personal communication, May 30, 2019, both as cited in Berry et al. (2019)]), though more research on kelp threats is needed at regional and local scales (Berry et al., 2019; Uncertainty Table G). Sea snail *Lacuna vincta* grazing might have reduced survival of transferred juvenile bull kelp at San Juan Island (Carney et al., 2005), and more recent physical observations of degraded kelp structures and kelp crab abundance have implied site-level differences in suspected grazing on bull kelp within South Puget Sound (Berry et al., 2019). Squaxin Island and Wing Point are sites with the most probable grazing (by kelp crabs) in South and Central Puget Sound, respectively, though other stressors are also expected in those locations (Ledbetter et al., 2025; Ledbetter & Berry, 2024; Pyle, 2023). Kelp crab grazing at the Squaxin Island restoration site is thought to be the result of reduced lingcod and rockfish (Toft, n.d.).

Uncertainty Table P. Restoration method uncertainties

ID	Uncertainty	Priority Level
MV 024	"Investigate [and develop] methods to enhance and restore persistent, floating kelp canopies that have documented declines, and understory beds if declines are documented in Puget Sound" (quoted material from Calloway et al. (2020, p. C-1)).	**High**
MV 030	What strains of eelgrass and kelp are most suitable for transplanting and restoration projects? Will this change as waters warm?	**Medium**
MV 045	What is the effectiveness of different techniques for transplanting eelgrass? What is the viability of seeds as a restoration technique?	**Low**

6.4.4 Implement restoration pilot projects

The Restoration Strategy calls for the use of pilot projects to test restoration techniques in Puget Sound. Pilot projects are a best practice for eelgrass restoration which complement site suitability modeling (Beheshti & Ward, 2021; Unsworth et al., 2025), as demonstrated by the Puget Sound PNNL pilots described above (Section 6.4.2.1), and can also be important for kelp restoration (Eger et al., 2020). Ward and Beheshti (2023) recommend that more than one method be studied during eelgrass restoration pilots, and that pilots last longer than one growing season; however, these added elements have implications for the cost and feasibility of pilot projects. More specifically, Golden et al. (2010) recommend transplanting adult eelgrass to sites to test restoration effectiveness before using seeding methods. However, because pilot projects may be too small to demonstrate the expected results of restoration projects on the order of kilometers (due to size-related considerations described above), Gräfnings et al. (2023) recommend also following pilot projects with follow-up studies on the relevant spatial design for a given site.

6.4.5 Measuring restoration effectiveness

The Restoration Strategy calls for evaluating the effectiveness of restoration projects (both pilot and at-scale). In their review of U.S. West Coast eelgrass restoration projects, Beheshti and Ward (2021) make recommendations related to effectiveness evaluations:

- Use standard methods for monitoring eelgrass restoration. Ideally, Washington restoration projects (both for mitigation and other restoration) should use similar requirements to those in the California Eelgrass Mitigation policy (monitor shoot density and areal coverage of eelgrass each year for at least five years);
- A "reference meadow" (Beheshti & Ward, 2021, p. v) should be used for effectiveness assessment (i.e., control-impact);
- Work with volunteers and communities to increase restoration capacity (and stewardship);
- Measure effectiveness in terms of habitat function over longer timescales;
- Make restoration monitoring/effectiveness data public, including in a database of restoration outcomes (Stamey, 2004 as cited in Beheshti & Ward, 2021; Thom et al., 2008 as cited in Beheshti & Ward, 2021);
- Improve communication fora for eelgrass restoration practitioners.

For kelp restoration, Eger et al. (2022) recommend articulated restoration objectives and BACI design for assessment of restoration impact.

Several restoration reviews have identified barriers to improved effectiveness evaluation:

- Appropriate effectiveness monitoring for eelgrass restoration can only take place if effectiveness metrics are established *a priori* (Ward & Beheshti, 2023);
- Goals of both eelgrass and kelp restoration projects can vary (Bayraktarov et al., 2019 as cited in Eger et al., 2022; Beheshti & Ward, 2021);
- Scale of eelgrass seed dispersal makes studying effectiveness difficult (Beheshti & Ward, 2021);

- Funding/capacity for monitoring past five years post-restoration (eelgrass) is uncommon but essential for measuring resilience of both reference and restored sites (Beheshti & Ward, 2021; Unsworth et al., 2025; Ward & Beheshti, 2023);
- Generally, effectiveness information presented by kelp restoration projects is inconsistent, precluding more detailed analyses of global patterns in restoration effectiveness (Eger et al., 2022);
- Mitigation practitioners do not have the same incentives to publish data as other researchers, and limited availability of data from mitigation practitioners precludes wider understanding of the effectiveness of those projects (Ward & Beheshti, 2023).

Uncertainty Table Q includes Puget Sound research needs about the effectiveness of marine vegetation restoration.

Uncertainty Table Q. Restoration effectiveness uncertainties

ID	Uncertainty	Priority Level
MV 003	How effective is restoration of eelgrass and kelp over time? What are the metrics for measuring restoration effectiveness (e.g., persistence, genetics, biomass, marine vegetation community benefits, other ecosystem services)? What stressors (biological, physical, chemical) affect the success or failure of eelgrass/kelp restoration at specific sites?	**Top**
MV 003.1	What are the causes of eelgrass transplantation failure at sites identified as potential by the PNNL transplant site selection model?	**No priority**
MV 053	How does kelp introduction (new strains) impact native kelp?	**Low**

6.4.6 Multi-benefit restoration

The Restoration Strategy includes an approach aiming to pursue the possibility of conducting marine vegetation restoration projects that could achieve ecosystem service benefits (Section 4.2) beyond the recovery of eelgrass and kelp populations. Measuring restoration effectiveness in terms of ecosystem services in addition to (or instead of) plant population outcomes is rare among U.S. West Coast eelgrass restoration projects (Beheshti & Ward, 2021; Ward & Beheshti, 2023), though Thom et al. (2008) identified biodiversity, carbon sequestration, and habitat function as some of the aims of eelgrass restoration projects in the Puget Sound or wider Salish Sea. Uncertainty about connections and directional impacts among ecosystem services is a barrier to designing and measuring effectiveness of seagrass restoration projects based on ecosystem services (Unsworth et al., 2025 and sources cited therein) (Uncertainty Tables F and Q contain relevant research needs for Puget Sound). The ecosystem services generated by

eelgrass restoration need to be studied by collecting specific data for those services rather than data on the recovery of eelgrass itself (Beheshti & Ward, 2021; Ward & Beheshti, 2023). For example, Orth et al. (2020) demonstrated the effectiveness of eelgrass restoration (via seeding) on the U.S. East Coast in terms of not just eelgrass area but also biomass of fish and invertebrates, sediment carbon and nitrogen, turbidity, and facilitation of separate restoration of bay scallops within the eelgrass habitat.

Smith et al. (2025) argue that ecosystem restoration (not specific to marine vegetation) may facilitate human wellbeing benefits, both via participation of individuals and communities in restoration activities and via the ecological change due to restoration; restoration may improve social networks, optimism, and sense of place, each of which contribute to community and psychosocial resilience (Smith et al., 2025 and sources cited therein). For seagrass, human wellbeing benefits like equality and social capital can result from community involvement in selecting restoration sites (Unsworth et al., 2025). However, human benefits of restoration generally need to be studied further (Martin & Lyons, 2018; Smith et al., 2025). Context-specific social indicators related to quality, beneficiaries, and access (Martin & Lyons, 2018) could be used to measure the human benefits generated by restoration of eelgrass and kelp in Puget Sound. Such indicators can be measured only if there are articulated goals of restoration projects (and ideally data collected before and after restoration) (Martin & Lyons, 2018).

Research is needed in Puget Sound on the impacts of marine vegetation restoration on ecosystem services and how to optimize restoration for those benefits (Uncertainty Table R, MV 059); however, this uncertainty was designated a low priority for the region given the more immediate research needs related to successful survival of eelgrass and kelp in restoration projects (i.e., Uncertainty Tables O, P, and Q) (Implementation Strategy *Appendix I.e: Marine Vegetation Research Priorities*). Research is also needed to consider how process-based restoration projects not focused on eelgrass or kelp could affect marine vegetation (Uncertainty Table S), which relates to a Restoration Strategy approach on this other field of restoration work.

Uncertainty Table R. Multi-benefit restoration uncertainties

ID	Uncertainty	Priority Level
MV 059	How do kelp and eelgrass restoration efforts impact the ecosystem services provided by these taxa (e.g., carbon storage in estuaries, associated species, etc.)? How and where can restoration efforts be adapted specifically to benefit ecosystem services?	**Low**
MV 054	What are potential markets for marine vegetation ecosystem services?	**Low**

Uncertainty Table S. Process-based restoration uncertainty

ID	Uncertainty	Priority Level
MV 031	How do ecosystem restoration projects aimed at restoring sediment dynamics and other aspects of landscape function and connectivity (e.g., fish barrier removal, piling removal, etc.) impact kelp and eelgrass?	**Medium**

6.5 Community Connections Strategy Considerations

6.5.1 Marine vegetation connections

The first approach in the Community Connections Strategy (Section 3.5) aims to foster research about the relationships of Puget Sound residents with marine vegetation. This research need is reflected in uncertainty MV 036 (Uncertainty Table T). Increased understanding of human relationships to marine vegetation can inform actions in other approaches within the Community Connections Strategy related to outdoor recreation, harvest, and stewardship.

Uncertainty Table T. Cultural connection uncertainty

ID	Uncertainty	Priority Level
MV 036	What are the cultural linkages and practices associated with kelp and eelgrass among diverse human populations in Puget Sound? What might their decline mean for those cultural linkages and practices?	**Medium**

6.5.2 Tribal capacity/funding

The second approach in the Community Connections Strategy is to improve capacity and funding of Tribes for eelgrass and kelp conservation, sustainable access, monitoring, restoration, and research. Section 7.1 of the *Base Program Analysis* (Implementation Strategy *Appendix II.b*) describes the marine vegetation work currently led by Tribes in Puget Sound. The discussion of Tribal capacity and funding consideration for the Research Strategy (Section 6.1.4 of this document) also applies to the Community Connections Strategy.

6.5.3 Community engagement/science/education

The third approach in the Community Connections Strategy is to foster stewardship of marine vegetation through place-based education, community science, and other public engagement activities.

There are multiple types of environmental education activities, including community/citizen monitoring and research projects (Ardoin et al., 2020). A systematic review found that generally environmental education has demonstrated positive outcomes, either directly (in terms of ecological metrics, actions in the environment, or observed behavior) or indirectly (in terms of

community capacity building, self-reported behavior, and attitudes and awareness about a topic), though review authors acknowledged possible publication bias in this field (Ardoin et al., 2020 and sources cited therein). Education can reduce the impacts of recreational activities (e.g., scuba diving) [Medio et al. (1997), Camp and Fraser (2012), both as cited in Ardoin et al. (2020)]. Environmental education can also be effective at generating partnership building, community learning, social capital, and community resilience as well as individual civic attitudes, motivation, and responsibility (Ardoin et al., 2023) which may relate to fostering stewardship (Dresner et al., 2015 as cited in Ardoin et al., 2023 (incorrectly cited as Dresner et al., 2014)).

Ardoin et al. (2020) recommend four principles for environmental education projects to be able to measure effectiveness based on direct metrics:

- Education projects should have local emphasis;
    - This can include local communities pointing to relevant issues to them.
- Education projects should involve collaboration across sectors to develop partnerships;
- Education projects should include action-based learning;
    - Examples include community engagement, active restoration, and citizen science.
- Education projects should be designed with evaluation in mind (ideally based on a clear aim of the project and co-producing effectiveness metrics).

Section 7.4.3 of the *Base Program Analysis* (Implementation Strategy *Appendix II.b*) provides a list of place-based education programs in Puget Sound.

Citizen or community science is a type of environmental education activity in which members of the public contribute (in varying degrees) to research (Ardoin et al., 2020; Jones et al., 2018 and sources cited therein; Suškevičs et al., 2024 and sources cited therein). Advantages of citizen science include that it can increase public awareness of scientific issues, be cost-effective, contribute to relationships, influence behavior, and incorporate traditional/local knowledge (Kelly et al., 2020 and sources cited therein). Known benefits of citizen science for participants include improved stewardship, social capital, and understanding about the environment (Kelly et al., 2020 and sources cited therein). The degree of involvement of participants in citizen science projects can range from contributory (participants gather data) to co-created (participants help design the project) (Suškevičs et al., 2024 and sources cited therein). A global survey of citizen science in marine conservation (which includes projects related to kelp and seagrass habitats) found that most projects are contributory rather than co-developed (Kelly et al., 2020). This was also found to be the case in a systematic review on how citizen science affects the governance of protected areas (marine and terrestrial) (Suškevičs et al., 2024).

Jones et al. (2018) suggest that citizen science is needed globally for conservation of seagrasses. Considerations for designing new citizen science projects include ten principles from the European Citizen Science Association (2015):

- Participants are actively involved in creating scientific information, at a minimum as a contributor;

- Science is achieved through the project;
- Projects benefit both the public participants and professional researchers;
- There are options for engagement beyond data collection contributions;
- Participants are provided feedback about the information generated;
- Caveats of citizen science methodology are scientifically addressed;
- Data are posted and published publicly;
- Participants receive credit in communications about projects;
- Effectiveness of citizen science is measured, using multiple metrics related to participant benefits, management outcomes, community outcomes, and generation of data;
- Environmental impact, ethical, and legal aspects of a project are managed by project coordinators.

With respect to effectiveness, Kelly et al. (2020) found that most citizen science projects in marine conservation fail to evaluate the outcomes for participants, suggesting more research is needed on participants' experiences on such projects. Research is also needed on citizen science power dynamics (Kelly et al., 2020).

The *Base Program Analysis* (Implementation Strategy *Appendix II.b*) discusses the status and prospects of community monitoring in Puget Sound. It notes that current community monitoring programs for eelgrass and kelp in Puget Sound primarily operate in the northern parts of Puget Sound.

Community engagement more broadly, including elements of community- and place-based conservation, has the potential to improve community support for protection or restoration actions and foster stewardship behavior by determining local priorities and ensuring that decision-making is done in partnership with communities (Jennings et al., 2024). Key research needs about marine vegetation stewardship in Puget Sound are highlighted in Uncertainty Table U. Research to address these uncertainties can increase understanding about how the above engagement activities are used for eelgrass and kelp in the region and the topics/contexts for which those activities might be useful for increasing stewardship.

Uncertainty Table U. Stewardship uncertainties

ID	Uncertainty	Priority Level
MV 027	To what extent do Puget Sound residents engage in stewardship activities associated with marine vegetation? What does this stewardship landscape look like? Who is involved in this work? Who is missing from this work? What is working and what isn't and where? How does this stewardship inform regional knowledge, awareness, and sense of place associated with Puget Sound and its social-ecological system?	**Medium**

ID	Uncertainty	Priority Level
MV 028	What does the public know about eelgrass and kelp? What does the public know about how and why eelgrass and kelp are managed in Puget Sound? What are their opinions? What are public perceptions of benefits received from interaction with eelgrass and kelp?	**Medium**

6.5.4 Recreational harvest

The fourth approach in the Community Connections Strategy is to improve access to eelgrass and kelp habitats for harvest (of marine vegetation and species living in those habitats). There are many uncertainties about direct harvest of marine vegetation in Puget Sound (Uncertainty Table V), and research to study these is an important first step for determining subsequent actions to improve harvest access. One study at Libbey Beach in the Smith and Minor Islands Aquatic Reserve in Puget Sound provides some information about kelp harvesting practices there: Kilgo et al. (2019) found that while most harvesters comply with state rules on the amount of kelp that can be harvested daily, many harvesters collected kelp using a cutting approach that is understood to be unsustainable and not recommended by WA DNR. They confirmed the negative impacts of that cutting approach on kelp growth, length, and density over time by conducting a kelp harvesting experiment in the field at this same site. In contrast, sustainable harvest practices showed neutral or positive impacts on those kelp outcomes. Kilgo et al. (2019) recommend research on kelp harvesting in Puget Sound on a larger spatial scale.

Uncertainty Table V. Harvest uncertainties

ID	Uncertainty	Priority Level
MV 035	What is the current status of health risks associated with kelp harvesting and consumption? What groups are at most risk from toxic exposure from marine vegetation harvesting and/or consumption? Do these risks and potential exposures geographically vary? How are these risks communicated? What is the current awareness of these risks to human health? Does marine vegetation make fish/shellfish safer to consume by reducing contaminants or pathogens?	**Medium**
MV 044	What are harvesters' knowledge and awareness about how marine vegetation harvest and consumption is managed? Where are there gaps in legal socialization and awareness associated with that governance and regulation? What is the effectiveness of outreach about methods and regulations for kelp harvest? Are there areas where outreach about foraging and harvesting are falling short? How equitably distributed are impacts of governance and regulations of harvest?	**Low**

ID	Uncertainty	Priority Level
MV 046	What types of marine vegetation are harvested by Puget Sound residents? Where are they harvested? Where is harvesting not taking place, and why? Why are they harvested? How do individuals and communities use kelp today (e.g., food, cosmetics, fertilizer) and how else could it be used? How is marine vegetation processed and consumed by Puget Sound residents?	**Low**
MV 047	What human communities depend or rely on marine vegetation harvest more than others? How might those communities be inequitably impacted by changes to regional marine vegetation?	**Low**
MV 055	Is marine vegetation being harvested, consumed, and/or sold illegally? What might that illegal use mean for harvesters and/or consumers? What might need to change within the marine vegetation governance or regulatory system in order to address this illegal activity (even if unintentional)?	**Low**

Eelgrass and kelp have both been traditionally consumed by Indigenous populations in the Puget Sound region (Calloway et al., 2020 Appendix B and sources cited therein; Tanner et al., 2025). An ongoing eelgrass restoration project in Picnic Cove on Shaw Island, a collaboration involving the Coast Salish Youth Coalition, began with a traditional meal made of the rhizome of eelgrass (Tanner et al., 2025). This project actively aims to increase understanding of the role of eelgrass in Northern Coast Salish culture and to increase first foods connections of young people (Tanner et al., 2025).

In addition, Kobluk et al. (2021) is a notable example (in British Columbia) of the value of research co-production with Indigenous experts specifically relevant to kelp harvest. The study examined the ecological impacts of traditional kelp harvest practices used by the Heiltsuk First Nation and was based on an expressed research question from a Heiltsuk kelp harvester. Productivity of kelp (*Egregia menziesii*, a species found in Puget Sound) did not vary between control and harvested kelp, indicating the sustainability of traditional practices. Furthermore, the study used both direct measurements of kelp and a survey of Heiltsuk experts to identify the variables that impacted re-growth of kelp after harvest: water temperature and starting size of kelp.

6.5.5 Outdoor recreation

The fifth approach in the Community Connections Strategy is to foster sustainable outdoor recreation. Environmental education aimed at scuba divers can be effective at reducing impacts to reef environments (Ardoin et al., 2020 and sources cited therein), so similar approaches may prove useful in Puget Sound recreational diving contexts. Research to address regional uncertainties about outdoor recreation as it pertains to marine vegetation (Uncertainty Table W) will clarify where and what types of interventions may be needed to address impacts on eelgrass/kelp and recreation access barriers.

Uncertainty Table W. Outdoor recreation uncertainties

ID	Uncertainty	Priority Level
MV 021	Which recreation areas "are...showing signs of overuse"? Which types of uses have the "biggest impacts" (e.g., kelp harvest, crab pots, mechanical damage from boats)? What are the spatial and temporal thresholds for recreational overuse? (Quoted material from The Tulalip Tribes (2021, p. 39) and 01.15.2025 HSIAT meeting (Implementation Strategy partner engagement).)	**High**
MV 050	Where do people recreate in and around marine vegetation communities in Puget Sound and how does the presence and quality of marine vegetation influence activity levels and participant experience?	**Low**
MV 057	How are recreational boats and boating infrastructure "potentially affecting tribal [fishing] access and opportunities"? (Quoted material from The Tulalip Tribes (2021, p. 40).)	**Low**
MV 058	Identify current and potential kelp user groups and their barriers to access for responsible recreation and harvest.	**Low**

For recreational boating specifically, mooring buoys are not uniformly distributed throughout Puget Sound (Robertson, 2022) so the strategy actions for this boating management tool will need to take place at a sub-regional scale (relevant jurisdictions are listed in the Implementation Strategy *Appendix II.b: Base Program Analysis*). La Manna et al. (2015) recommend that mooring management incorporate long-term monitoring to be able to measure effectiveness (i.e., including data from before establishment of new mooring systems); such monitoring could support the Regulatory Strategy approach aiming to improve implementation of mooring buoy regulation as well as the Community Connections Strategy approach to foster responsible outdoor recreation. Compliance monitoring (La Manna et al., 2015) would also provide data to inform improvements to mooring enforcement activities.

7 Decision Support Tools and Models

7.1 Research and Monitoring

The following web tools are sources of information on current and historical vegetation observations and can assist researchers and resource managers in studying, protecting and restoring marine vegetation in Puget Sound:

- WA DNR's Marine Vegetation Atlas
- WA DNR's Puget Sound Eelgrass Monitoring Data Viewer
- Marine Resources Committees Eelgrass and Kelp Monitoring on Northwest Straits Commission's SoundIQ

- WA DNR's Floating Kelp Indicator Interactive Map
- WA DNR's Washington Floating Kelp Linear Extent Data Viewer
- Samish Indian Nation's Kelp Monitoring StoryMap

The recently released Washington Kelp Project Inventory (an expansion of the 2020-2022 Puget Sound Kelp Project Inventory) is a resource to share and explore kelp related projects and track kelp conservation and recovery in Washington state.

7.2 Models

A number of models exist that may help elucidate the dynamics of eelgrass and kelp in Puget Sound in response to environmental changes, including restoration. Many of the following are complex, biophysical models which are best suited for use in research, but some have also been applied to inform management decisions.

Atlantis Model for Puget Sound: end-to-end ecosystem simulation model that integrates physical, chemical, ecological, and anthropogenic processes in a three-dimensional, spatially explicit domain. The model represents species of ecological and conservation concern and key exploited species at a level of detail necessary to evaluate anthropogenic impacts. Species from 73 functional groups are included in the model, including eelgrass and kelp (Morzaria-Luna et al., 2022).

Coastal Storm Modeling System (CoSMoS): dynamic modeling approach to provide detailed projections of coastal hazard exposure (e.g., flooding, coastal change, groundwater) due to both future sea level rise and storms. CoSMoS models all the relevant physics of a coastal storm (e.g., tides, waves, and storm surge), which produce local flood projections. Additional modules project long-term coastal evolution (i.e., beach changes and cliff retreat) and be used to describe changes to nearshore habitats. The CoSMoS model is being produced for Washington state (www.usgs.gov/centers/pcmsc/science/ps-cosmos-puget-sound-coastal-storm-modeling-system).

Magel-Francis Qualitative Network Model: conceptual model of the links among human stressors and ecosystem components across the terrestrial-freshwater-estuarine gradient of a generalized Puget Sound watershed. Eelgrass is included as a component of the conceptual model and the positive, neutral, or negative response of eelgrass can be evaluated in response to simulated management interventions or ecosystem changes. Magel and Francis (2022) evaluated multi-benefit outcomes of potential management interventions to address population growth and development.

Salish Sea Model: predictive three-dimensional coastal ocean model with comprehensive hydrodynamic and water quality simulation capabilities. It is used for estuarine research, restoration planning, water-quality management, as well as assessments of pollution, oil spill and sediment transport and climate change response (Khangaonkar et al., 2019, 2021). A linked Submerged Aquatic Vegetation (SAV) submodel is available that has been previously applied to

eelgrass in Dumas Bay, Puget Sound (Khangaonkar et al., 2021). A model using the same modeling framework as Salish Sea Model (FVCOM-ICM with SAV submodel) was recently used to explore eelgrass abundance scenarios and impacts on water quality in the Coos Bay estuary, Oregon (Magel et al., 2025b). Recent advances in model setup have eliminated the need for bathymetric smoothing which enhances capacity for increased nearshore resolution and improves performance of the model for predicting nearshore currents and temperature (Khangaonkar et al., 2026).

7.3 Tools

The following tools have been developed to inform restoration and mitigation for eelgrass and kelp in Puget Sound.

Bull Kelp Restoration Site Selection Tool: tools to identify sites with potential for bull kelp restoration projects in Puget Sound, which incorporate available biological, environmental, and political spatial data relevant to bull kelp restoration. The initial project was sponsored by the Puget Sound Restoration Fund and authors were students in the University of Washington GIS Certification Program. Documentation includes a report (McKenna et al., 2022b) and interactive web app. Working with the Seattle Aquarium, a subsequent cohort of GIS Certification Program students created a Bull Kelp Habitat Suitability model for Elliott Bay based on several physical variables and kelp distribution. The current version of the Elliott Bay model is available in a web map. The Seattle Aquarium plans to add more data and additional geographic locations within central Puget Sound to improve the model's utility for kelp restoration (Habitat Strategic Initiative Lead, 2023; Randell, n.d.; Randell et al., 2023a; Randell et al., 2023b; Randell et al., 2025; Williams et al., n.d.; M. Williams, personal communication, November 11, 2025).

Eelgrass Restoration Habitat Suitability Model: model that predicts eelgrass performance throughout Puget Sound under varying environmental conditions. The development process generated an eelgrass restoration model and geodatabase that prioritized sites suitable for eelgrass transplantation. The model and database provide a methodology for assessing effects of climate and land use changes on species distributions and identifying mitigation for these changes through stressor reduction and improved site selection. The modeling and follow-up test planting based on identified suitable sites identified fine-scale light data and improved physiological data, particularly regarding low-light conditions and phenotypic or genotypic adaptations, as critical information needs to improve this method of restoration planning (Thom et al., 2018).

Puget Sound Nearshore Habitat Conservation Calculator: a NOAA Fisheries-developed tool used to quantify impacts of nearshore projects for use in Endangered Species Act Section 7 and Clean Water Act Section 404 Permit consultations. The Calculator is used to calculate the loss of nearshore habitat functions and values for Endangered Species Act-listed species associated with proposed projects and has helped to create a new market for conservation credits and debits. The Calculator and its application to management are discussed in the Implementation Strategy *Appendix II.b: Base Program Analysis* (see Section 3.1.3 and Box 3). The scientific

strengths and weaknesses of the Calculator – and other similar kelp and seagrass habitat valuation tools used by NOAA – were evaluated by Hale et al. (2025).

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