

Building Capacity for Kelp (Laminariales) Mariculture in the Salish Sea: Ecological Considerations and Initial Farm Design Guidance

EMILY BUCKNER, NICOLE NAAR, GRACE ADAMS, JOTH DAVIS, SEAN MATSON, and DANIEL TONNES

Introduction

Kelp (Phylum Phaeophyta, Order Laminariales) are large brown seaweeds found in coastal temperate and polar waters around the world. As photosynthesizing organisms, brown seaweeds grow in the photic zone and create widespread marine “forests” that provide crucial habitat to near-shore fishes, invertebrates, and mammals (Steneck et al., 2002; Klinger, 2015). Kelp has a biphasic life history—the large sporophyte plants obligately alternate with a microscopic gametophyte (sexual) phase. Kelp forests are aptly named, as the sporophytes of different kelp species assume a diversity of structural roles; some grow to form a sea surface canopy, while others lie prostrate along the seafloor or grow into the water column to form an

“understory” (Wernberg and Filbee-Dexter, 2019).

Although many kelps are found in these subtidal, diverse, three-dimensional structures, they can also proliferate in small patches outside of kelp forests in areas such as the rocky intertidal zone. Sporophytes of different kelp species can live anywhere from a single growing season to several decades and demonstrate variations in successional establishment, making the habitat “hotspots” they form temporally dynamic and variable (Dayton, 1985; Reed et al., 2006; Springer et al., 2010).

In addition to providing habitat and refugia, kelp provide the marine environment with energy and nutrients via large amounts of organic material (whole plants, detritus, and dissolved organic material) that serve as the base of nearshore, deepwater, and terrestrial food webs (Steneck et al., 2002; Christie et al., 2009; von Biela et al., 2016; Elliott Smith and Fox, 2022). They also influence the water quality surrounding them, changing carbon chemistry, nitrogen, and other nutrients, metals, and chemicals (Klinger, 2015; Pfister et al., 2019). These ecosystem services, defined as the direct or indirect benefit to human society from the natural environment (Kumar,

2010), can be assigned a monetary value and may be considered in conservation or management decision-making.

Kelp mariculture has increased worldwide and the global scientific literature increasingly highlights local ecological benefits. This has captured the interest of many aspiring Washington kelp farmers who are eager to harness the ecological and economic benefits of cultivating kelp, even though the regulatory process for permitting kelp farming is still a work in progress. This paper is a response to the growing local interest and regulatory uncertainty in a kelp farming industry, and it was specifically developed to provide potential farmers, leasees of state-owned aquatic lands, and regulators with pertinent biological and ecological information that may assist those writing and assessing permit and lease applications. This paper was also developed for tribes that are considering seaweed farming and/or may review proposed farms for environmental effects or impacts to Usual and Accustomed fishing areas. Permitting for seaweed farms and similar activities are particularly complex in Washington state, where proposals require multiple local, state, and federal reviews as well as tribal reviews (Conroy et al., 2023). Here we consider the

Emily Buckner (emily@restorationfund.org) is with Puget Sound Restoration Fund, 8001 NE Day Rd W, Bainbridge Island, WA 98110. Nicole Naar is with Washington Sea Grant, College of the Environment, University of Washington, Seattle, WA 98105 and the NOAA, National Marine Fisheries Service, West Coast Region, 7600 Sand Point Way NE, Seattle, WA 98125. Grace Adams, Sean Matson, and Daniel Tonnes are also with the NOAA/NMFS West Coast Region in Seattle. Joth Davis is with Blue Dot Sea Farms, Bainbridge Island, Washington.

doi: <https://doi.org/10.7755/MFR.85.1-4.4>

ABSTRACT—As a new type of marine activity in an environmentally and socially complex region, one limitation of the development of seaweed farming within Washington State waters of the Salish Sea is a lack of information about how to best implement sustainable farming practices. In this paper we discuss the potential environmental benefits and risks posed by open-water native kelp (*Laminariales*) maricul-

ture in the Salish Sea, suggest initial farm design guidance to maximize ecosystem benefits and minimize ecological harms, and identify priority areas for future monitoring and research. We also emphasize the importance of conducting kelp farming in a way that accommodates tribal concerns and ensures access to treaty-protected fishing grounds. We suggest an adaptive management approach, using the best available

information to propose initial guidance followed by suggestions for data collection that would inform the efficacy of those considerations. Our goal is to provide regulatory and proprietary agencies, tribes, and potential sea farmers with the best available, locally-specific (where possible) information, making suggestions when appropriate, and identifying remaining knowledge gaps to inform future research.

global literature on the ecological impacts of kelp farming, paired with the regional ecological and social context in which local kelp mariculture could occur, and highlight the precautions and challenges potential farmers and marine resource managers should consider. We pay particular attention to any potential negative ecological impacts and marine spatial use conflicts, especially including treaty rights and related concerns from western Washington treaty tribes.¹ We are taking this approach in recognition of the social and ecological controversy associated with other forms of sea farming in the region (e.g., intensive fish farming), which has proven detrimental to their social acceptance, and which the emerging kelp farming in the U.S. portion of the Salish Sea should strive to avoid.

We provide farm design guidance for open-water native kelp cultivation, using an approach that considers two main dimensions: 1) potential ecological impacts associated with kelp cultivation, specifically within a regional context, and 2) the different aquatic stages of the kelp farming cycle, including site selection, cultivation, and harvest (the *ex situ* hatchery phase and post-harvest processes are not discussed). The relative newness of domestic kelp cultivation, especially on the U.S. west coast, presents both limitations and opportunities. Data relevant to local kelp species (emphasized in Hollarsmith et al., 2022, also see Table 1 and Table 2), environmental conditions, and impacts are generally lacking. Therefore, we have tried to fill information gaps by referring to published literature from other areas, relying on insights from local researchers, and emphasizing the need for adaptive management informed by future research and monitoring. As such, the majority of information provided pertains to sugar kelp, *Saccharina latissima*; however, the ini-

tial farm design guidance and ecological considerations presented are also applicable to other types of seaweed mariculture (e.g. other kelps, see Table 1), dulse, *Palmaria mollis* (Druehl and Clarkston, 2016); nori, *Pyropia/Porphyra* sp. (Bergdahl, 1990). Although we recognize that kelp cultivation can serve various purposes, including restoration, bioremediation, and mitigation, we focus here on commercial kelp cultivation. As the opportunities for kelp cultivation in the Salish Sea increase, these other important uses should be considered in more depth—either independently or in tandem with commercial cultivation (i.e. “restorative aquaculture” (Mizuta et al., 2022)).

Regional Description

Ecological Context

The Salish Sea is the marine area of the southern portion of British Columbia, Canada, and the northwestern portion of Washington. The major waterways that define it include the Strait of Georgia, the Strait of Juan de Fuca, and Puget Sound (Fig. 1). The Puget Sound portion of the Salish Sea has several interconnected basins or biogeographic regions that encompass contiguous, ecologically unique, and spatially isolated freshwater, estuarine, and marine habitats (Downing, 1983; Burns, 1985).

These natural conditions have contributed to the genetic differentiation of many species. A few examples, among better known native species that have been studied, include several rockfish species—yelloweye rockfish, *Sebastes ruberrimus*; copper rockfish, *Sebastes caurinus*; brown rockfish, *Sebastes auriculatus*; quillback rockfish, *Sebastes maliger*—and a roundfish, Pacific hake, *Merluccius productus*, within the various regions of the Salish Sea and between Puget Sound and the open ocean (Seeb, 1998; Buonaccorsi et al., 2002, 2005; Iwamoto et al., 2015; Andrews et al., 2018). Genetic differentiation has also been found among bull kelp, *Nereocystis luetkeana*, within the Strait of Juan de

Fuca, the San Juan Islands, and central and south Puget Sound (Gierke, 2019), but genetic analysis has not occurred for other kelp species in the study area. Evidence for limited genetic differentiation has been demonstrated in several native molluscan shellfish species within the Salish Sea, but generally more so between Puget Sound and locations along the outer coast, including the Olympia oyster, *Ostrea lurida* (Heare et al., 2017; Silliman, 2019), geoduck, *Panopea generosa* (Vadopalas et al., 2004, 2012); and basket cockle, *Clinocardium nuttali* (Dimond et al., 2022).

The region is also home to several species listed under the Endangered Species Act (ESA), including distinct populations of Chinook, *Oncorhynchus tshawytscha*, and chum, *Oncorhynchus keta*, salmon; bull trout, *Salvelinus confluentus*; green sturgeon, *Acipenser medirostris*; eulachon, *Thaleichthys pacificus*; yelloweye rockfish; and bocaccio, *Sebastes paucispinis*; in addition to southern resident killer whales, *Orcinus orca*; humpback whales, *Megaptera novaeangliae*; and marbled murrelet, *Brachyramphus marmoratus*; with designated critical habitat for a subset of these species within marine waters of the study area. Threatened invertebrates in the southern Salish Sea include the native Olympia oyster, *Ostrea lurida*, and the pinto abalone, *Haliotis kamschatkana*, which has seen a 97% decline since 1992 (Carson and Ulrich, 2019).

The nearshore of the region is generally defined as encompassing the marine shoreline, intertidal beach, and subtidal zone to the photic zone depth (about 30 m/98 ft deep). It hosts a rich variety of aquatic vegetation including canopy forming bull kelp, *Nereocystis luetkeana*; (regional distribution shown in Fig. 1) and eelgrass, *Zostera* sp. Eelgrass is a prolific type of submerged nearshore vascular vegetation that provides important ecosystem services including substrate for the spawn of Pacific herring, *Clupea pallasii*, and habitat for myriad fish and invertebrate species (Plummer et al., 2013).

¹Although the term “tribe” has largely fallen out of favor among academics, it is the term that local indigenous groups use in reference to themselves and their communities (e.g., Treaty Indian Tribes in Western Washington, 2011).

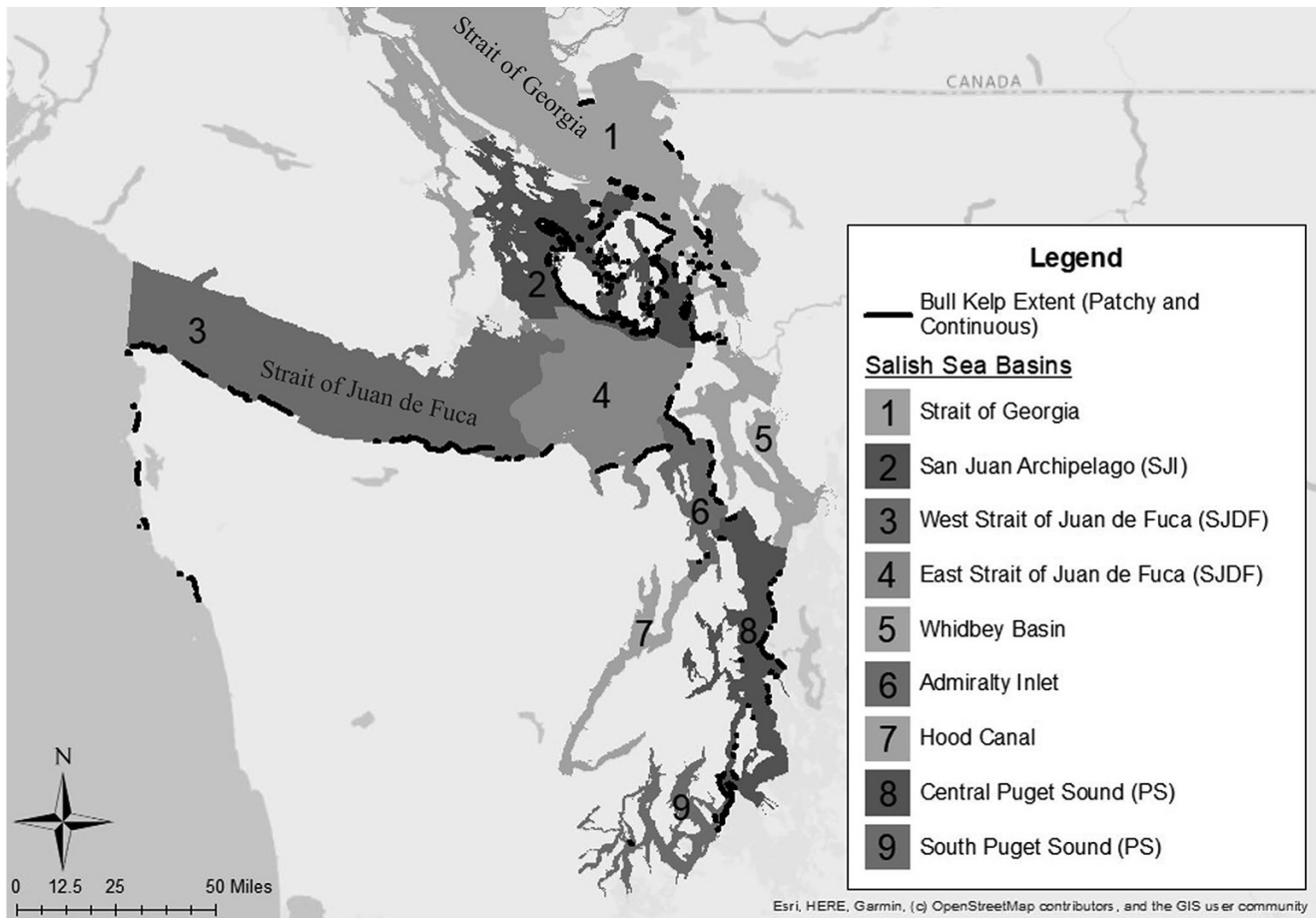


Figure 1.—The U.S. portion of the Salish Sea with the sub-oceanographic basins (ERMA Northwest, 2022) and bull kelp extent (patchy and continuous) (WDNR, 2023).

Eelgrass meadows are generally found in shallower waters, between +1.4 m to -12.0 m relative to mean lower low water (MLLW, Hannam, 2013), then kelp beds. Seventeen species of native kelp reside in Washington waters of the Salish Sea (Calloway et al., 2020), and widespread bull kelp losses, especially in the central and southern basins have been documented (Berry et al., 2019, 2021). A Kelp Conservation and Recovery Plan for Puget Sound was completed in 2020 (Calloway et al., 2020), and bull kelp along the Pacific Coast were petitioned for ESA listing in 2022 (Kelkar and Carden, 2022).

About 40% of Puget Sound’s near-shore area has been altered through dock and pier development, shoreline bulkheading, single family housing,

and industrial port development (Fresh et al., 2011). As such, conservation and restoration of the nearshore environment has been a regional priority for decades (Kelkar and Carden, 2022).

Social and Legal Context

In addition to the complexity and uniqueness of the natural environment, the waters of the Salish Sea are among the commercially, and recreationally, busiest along the west coast. For instance, the Ports of Seattle and Tacoma constitute the fourth largest container gateway in North America (Community Attributes, 2019). In addition, several hundred thousand boat-based recreational fishing trips occur every year, typically in the summer months (WDFW, 2012). Washing-

ton has the largest commercial shellfish industry in the United States, and there are hundreds of thousands of recreational shellfish harvest trips annually (Washington Sea Grant, 2015). Competing uses of the sea surface and water column create potential conflict with other end users, making the emergence of a kelp farming sector potentially problematic.

Importantly, the study area is part of the ancestral territory of 16 western Washington treaty tribes with unique legal rights and political capacities, such as adjudicated Usual and Accustomed (U and A’s)² fishing areas

²Usual and accustomed fishing areas (U and A’s) are spatially delimited areas of marine space fished by tribal community ancestors. U and A’s are tribe-specific and place-based but not exclu-

in marine waters (Singleton, 2009), as well as several other federally-recognized tribes and tribes without federal recognition. Following the “Fish Wars” of the 1960’s and a contentious legal battle, the Boldt Decision (U.S. vs. Washington, 1974) reaffirmed the fishing rights reserved by Western Washington tribes in treaties negotiated with Governor Isaac Stevens in the mid-1850’s on behalf of the U.S. government. The tribes secured recognition as marine resource co-managers and rights to 50% of the harvest from their U and A’s (NWIFC, 2014). Similarly, in 1994 a Federal court ruled that tribes have treaty rights to harvest shellfish in Puget Sound, including on private lands (U.S. vs. Washington, 1994) unless otherwise excluded by legal agreement with the Tribes.

Western Washington treaty tribes are understandably watchful of territorialized activities (e.g., mariculture, marine protected areas, etc.) that could compromise resource access or tenure rights within their U and A’s (Singleton, 2009). They also advocate for habitat protections under treaty rights (ie. the “Culverts Case”, U.S. vs. Washington, 2017), which kelp mariculture may support. The decline of finfish fisheries in the Salish Sea has likely contributed to tribal pursuit of additional income sources. Many tribes currently have shellfish mariculture operations and several are interested in adding kelp farming for commercial and/or subsistence use as well as for potential habitat enhancement benefits (Washington Sea Grant, 2023).

Mariculture in Washington has been increasingly subject to public controversy, including litigation in recent years. The use of pesticides in Willapa Bay and Grays Harbor to control burrowing shrimp, *Neotrypaea californiensis* and *Upogebia pugetensis*, native species that adversely affect oyster production, was subject to public scrutiny and litigation and the pes-

sive. Thus, the same area can include the U and A’s of multiple tribes, and non-treaty resource users are also able to access and harvest from the area (Singleton, 2009).

sicide application permit was ultimately denied by Washington’s Department of Ecology (ECY).³ Similarly, existing net pen operations and shellfish permitting regimes have been litigated. In 2017, the spill from net pens of several hundred thousand farmed Atlantic salmon, *Salmo salar*, in north Puget Sound generated lawsuits and led to Washington’s legislature phasing out the raising of non-native fish in the marine environment (Klein, 2021). In 2020 the U.S. District Court for the Western District of Washington vacated the Army Corps of Engineers’ (ACOE) Nationwide 48 Permit for shellfish activities in the state. The litigation was initiated by several non-profit organizations and the Swinomish Tribe, and it centered around concerns about intertidal and subtidal habitats of fish, eelgrass, *Zostera* sp., and birds, marine substrate, non-native and native species, pollution, and water quality (Klein, 2020). Similarly, in the 1980’s two proposed Washington seaweed farms were stopped by concerns about impacts to shoreline view-scapes and fishing ground accessibility (Egan, 1988).

Although the sociopolitical complexities of marine space use in Puget Sound present a significant challenge to the development of commercial kelp cultivation, the human use of seaweed resources in the Salish Sea is likely as old as the human settlement of the region. Archeological evidence suggests that the Americas may have first been settled by maritime peoples following the rich assemblage of marine resources found in the kelp forests that extend along the Pacific Rim from Japan all the way down to Chile (Erlandson et al., 2007; Erlandson et al., 2015). Based on explorer travelogs, early ethnography, and tribal lore and contemporary practices, kelp has played an important role in traditional technology, subsistence activities, and stories, and continues to be an important part of Pacific Northwest indigenous traditional ecological knowledge (Naar,

³Doenges R. 2018. Letter to Ken Wiegardt, President of Willapa Grays Harbor Oyster Growers Association. 27 Sept. 2018.

2020). Currently, recreational and subsistence harvest of wild seaweeds is allowed in Washington via a Department of Fish and Wildlife (WDFW) seaweed and shellfish license (RCW 79.135.410), and commercial harvest of seaweed that fouls shellfish cultivation gear is allowed via permit by the Department of Natural Resources (DNR) and registration with WDFW through an Aquatic Farm Registration (RCW 15.85.020; WAC 220-370-060).

Potential Ecological Impacts

Our approach to developing farm design guidance for kelp cultivation begins with a consideration of the potential ecological impacts of growing kelp on longlines in open marine waters. The broader Pacific Northwest region, which also includes coasts of Oregon and British Columbia, is considered one of the 25 marine ecoregions worldwide with the greatest potential for restorative kelp farming that could mitigate nutrient pollution, habitat loss, ocean acidification, and trawl fishing pressure, as well as enhance socioeconomic and human health (Theuerkauf et al., 2019). Several recent reviews have discussed the possible ecological impacts associated with kelp farming, many of which emphasize the compelling evidence that kelp cultivation provides significant positive effects for its surrounding environment, including the following ecosystem services: habitat provision, food web support, water quality remediation, carbon sequestration, and shoreline buffering (Campbell et al., 2019; Grebe et al., 2019; Langton et al., 2019; Gentry et al., 2020; Barrett et al., 2022, Forbes et al., 2022). However, these reviews have also stressed the importance of continued monitoring, research, and mitigation measures applied in an adaptive management context to maximize potential benefits while minimizing potential harms.

Building on these broader reviews, we present here a list of possible ecological impacts in the specific context of the southern Salish Sea, flagging issues of particular concern and noting the availability of local data (Ta-

Table 1.—Socio-ecological considerations for kelp species native to the Salish Sea.

	<i>Alaria marginata</i>	<i>Costaria costata</i>	<i>Cymathaere triplicata</i>	<i>Hedophyllum sessile</i>	<i>Laminaria setchellii</i>
Common name	Broad-winged kelp, Ribbon kelp	Five-ribbed kelp, Seersucker kelp	Three-ribbed kelp, Triple rib, Fold-rib kelp	Sea cabbage, Sweet kombu	Southern stiff-stiped kelp, Split blade kelp, Wild N. Pacific kombu
Washington distribution ¹	SJDF, SJI	PS, OC	SJDF, SJI, Whidbey Island (west side)	SJDF, SJI (west side)	Outer SJDF, OC on most exposed areas
Ocean parameters Temperature	Mortality, no recruitment >18 °C (O'Clair and Lindstrom, 2000; Muth et al., 2019) ²	Mortality >20 °C, no recruitment >18°C (O'Clair and Lindstrom, 2000; Muth et al., 2019) ²	Mortality 15-18 °C (O'Clair and Lindstrom, 2000) ²	Mortality >15°C (O'Clair and Lindstrom, 2000) ²	5-15°C optimal; reproduction inhibited >17 °C; no recruitment >18 °C (O'Clair and Lindstrom, 2000; Bartsch et al., 2008; Muth et al., 2019) ²
Nitrate	1-10 µmol/L; optimum 10 µmol/L (Muth et al., 2019) ³	1-10 µmol/L; optimum 5 µmol/L at 12°C (Muth et al., 2019) ³			1-10 µmol/L; optimum 10 µmol/L (Muth et al., 2019) ³
Salinity/turbidity					
Substrate	Rocky (O'Clair and Lindstrom, 2000)	Rocky or woody (O'Clair and Lindstrom, 2000)	Rocky (O'Clair and Lindstrom, 2000)	Rocky (O'Clair and Lindstrom, 2000)	Rocky (O'Clair and Lindstrom, 2000)
Depth	Mid-low intertidal, 3 m (O'Clair and Lindstrom, 2000)	Low intertidal and upper subtidal, >3 m (O'Clair and Lindstrom, 2000)	Low intertidal and upper subtidal, >3 m (O'Clair and Lindstrom, 2000)	Mid to low intertidal, 3 m (O'Clair and Lindstrom, 2000)	Extreme low intertidal and upper subtidal, <10 m (O'Clair and Lindstrom, 2000)
Wave action	Fully sheltered to fully exposed (Mumford, 2007)	Fully sheltered to fully exposed (Mumford, 2007)	Moderately exposed (Mumford, 2007)	Moderate to fully exposed (O'Clair and Lindstrom, 2000)	Moderately sheltered to fully exposed (O'Clair and Lindstrom, 2000)
Life history Canopy form	Prostrate (Gabrielson et al., 2006; Mumford, 2007)	Prostrate (Gabrielson et al., 2006; Mumford, 2007)	Prostrate (Gabrielson et al., 2006; Mumford, 2007)	Prostrate (Gabrielson et al., 2006; Mumford, 2007)	Stipitate (Gabrielson et al., 2006; Mumford, 2007)
Life cycle (sporophyte phenology)	Annual (Luning, 1991)	Annual or perennial (O'Clair and Lindstrom, 2000)	Annual (Mondragon and Mondragon, 2010)	Perennial (2-3 yr) (O'Clair and Lindstrom, 2000)	Perennial (up to 14 yr) (Germann, 1987)
Sporophyte size	<3 m (Luning, 1991)	2 m (O'Clair and Lindstrom, 2000)	4 m (Mondragon and Mondragon, 2010)	150 cm (O'Clair and Lindstrom, 2000)	1.5 m (O'Clair and Lindstrom, 2000)

Macrocystis pyrifera	Nereocystis luetkeana	Pleurophycus gardneri	Postelsia palmaeformis	Pterygophora californica	Saccharina latissima	Lessoniopsis littoralis
Giant kelp	Bull kelp, Bullwhip kelp	Broad-ribbed kelp, Sea spatula	Sea palm	Woody-stemmed kelp, Old growth kelp	Sugar kelp, Sugar wrack	Flat pompom kelp, Strap kelp, Ocean ribbons
SJDF (west of Low Point)	PS, OC	Straits, SJI, Whidbey Is (west side)		SJDF, SJI; rare in central and southern PS	PS, OC	OC, outer SJDF
<16.3 °C optimal; recruitment can occur at 18 °C (O'Clair and Lindstrom, 2000; Schiel and Foster, 2006; Muth et al., 2019) ²	10-15 °C optimal; no recruitment >18 °C (Vadas, 1972; Maxell and Miller, 1996; Muth et al., 2019) ²	14-15 °C triggers senescence; mortality >15 °C (O'Clair and Lindstrom, 2000; Germann, 2011; Pfister and Betcher, 2018) ²	No recruitment >18 °C (Muth et al., 2019) ²	No recruitment >18 °C (Muth et al., 2019) ²	10-15 °C optimal; mortality >19 °C (O'Clair and Lindstrom, 2000; Simonson et al., 2015) ²	No recruitment >18 °C (Muth et al., 2019) ²
1-10 µmol/L; optimum 10 µmol/L at 12°C (Luning, 1991; Muth et al., 2019) ³	1-10 µmol/L; optimum 10 µmol/L (Muth et al., 2019) ³	Low NO ₃ ⁻ leads to blade loss; nitrogen-limited (NO ₃ ⁻ , NH ₄ ⁺) (O'Clair and Lindstrom, 2000; Germann, 2011) ³	1-10 µmol/L; optimum 10 µmol/L (Muth et al., 2019) ³	1-10 µmol/L (Muth et al., 2019) ³	Saturation at 10-20 µmol/L (Simonson et al., 2015) ³	1-10 µmol/L; optimum 5 µmol/L (Muth et al., 2019) ³
Low salinity poorly tolerated at high temperatures (Mumford, 2007) ⁴	Range 26-31 o/00, but 28-29 o/00 ideal; wide salinity tolerance if sedimentation is low (Maxell and Miller, 1996; Mumford, 2007; Lind, 2016) ⁴				26-31 o/00; tolerates low salinity regardless of temperature (Mumford, 2007; Lind, 2016) ⁴	
Rocky (O'Clair and Lindstrom, 2000)	Cobble and rocky (O'Clair and Lindstrom, 2000)	Rocky (O'Clair and Lindstrom, 2000)	Rocky (O'Clair and Lindstrom, 2000)	Cobble and rocky (Druehl and Clarkston, 2016)	Mixed; rock, shell, debris, and even sand in CA (O'Clair and Lindstrom, 2000)	Rocky, very exposed (O'Clair and Lindstrom, 2000)
Lower intertidal to deep subtidal, 5-30+ m (Schiel and Foster, 2006; Druehl and Clarkston, 2016)	Subtidal, 3-17 m (Mumford, 2007)	Extreme low intertidal and upper subtidal, <15 m (O'Clair and Lindstrom, 2000)	High to mid intertidal, <3 m (Luning, 1991)	Low intertidal to subtidal, 2-20 m (typically 10 m) (Dayton, 1985; Mumford, 2007)	Lower intertidal and upper subtidal, <30 m (O'Clair and Lindstrom, 2000)	Low intertidal, 3 m (O'Clair and Lindstrom, 2000)
Fully exposed; wave action with 2-4 cm/s current speed enhances N uptake (Schiel and Foster, 2006; Mumford, 2007)	Fully sheltered to fully exposed; withstands strong currents (O'Clair and Lindstrom, 2000; Mumford, 2007)	Strong currents (O'Clair and Lindstrom, 2000)	Fully exposed; adapted to extreme wave shock (O'Clair and Lindstrom, 2000; Mondragon and Mondragon, 2010)	Fully sheltered to moderately exposed, strong currents (Mumford, 2007)	Fully sheltered to fully exposed (O'Clair and Lindstrom, 2000)	Extremely exposed habitats, heavy surf (O'Clair and Lindstrom, 2000)
Floating (Gabrielson et al., 2006; Mumford, 2007)	Floating (Gabrielson et al., 2006; Mumford, 2007)	Prostrate (Gabrielson et al., 2006; Mumford, 2007)	Stipitate (Gabrielson et al., 2006; Mumford, 2007)	Stipitate (Gabrielson et al., 2006; Mumford, 2007)	Prostrate (Gabrielson et al., 2006; Mumford, 2007)	Stipitate (Gabrielson et al., 2006; Mumford, 2007)
Perennial (O'Clair and Lindstrom, 2000)	Annual (Dayton, 1985; O'Clair and Lindstrom, 2000)	Perennial, deciduous (3-6 yr) (O'Clair and Lindstrom, 2000; Pfister and Betcher, 2018)	Annual (O'Clair and Lindstrom, 2000)	Perennial; (13-25 yr) (Watanabe et al., 1992; Germann, 2011)	Perennial or annual (O'Clair and Lindstrom, 2000)	Perennial (O'Clair and Lindstrom, 2000; Mondragon and Mondragon, 2010)
Up to 30 m (Dayton, 1985)	Up to 36 m (Dayton, 1985; O'Clair and Lindstrom, 2000)	1 m (O'Clair and Lindstrom, 2000)	60 cm (O'Clair and Lindstrom, 2000)	<3 m (Mondragon and Mondragon, 2010)	Up to 3.5 m (O'Clair and Lindstrom, 2000)	1-2 m (O'Clair and Lindstrom, 2000; Mondragon and Mondragon, 2010)

Table continued

Table 1.—Continued.

	<i>Alaria marginata</i>	<i>Costaria costata</i>	<i>Cymathaere triplicata</i>	<i>Hedophyllum sessile</i>	<i>Laminaria setchellii</i>
Ecological adaptations & vulnerabilities	Fast-growing; mid-canopy species; abundant in pools (Luning, 1991; Mumford, 2007)	Opportunistic; disturbed areas; physiology depends on wave action; has potential to tolerate to warming ocean conditions (Dayton, 1985; Muth et al., 2019)	Tattered by July (Mondragon and Mondragon, 2010)	Competes poorly with other kelps; sea urchins avoid but chiton graze heavily; wave action determines growth form (Mondragon and Mondragon, 2010)	Has potential to tolerate to warming ocean conditions (Muth et al., 2019)
Human use ⁵					
Food	Wakame substitute	Palatable, but low caloric value	Generally considered unpalatable (Druehl and Clarkston, 2016)	Palatable, but low caloric value	Kombu substitute (Jungwirth, 2019)
Nutrition	Source of vitamin A, vitamin B6, vitamin K, iodine, calcium, and potassium; contains more than 6% protein (O'Clair and Lindstrom, 2000; Mouritsen, 2013)			Source of trace minerals, complex carbohydrate and saccharides (O'Clair and Lindstrom, 2000)	
Medicine		Anti-inflammatory; thalassotherapy			
Industry		Previous source of potash salts (O'Clair and Lindstrom, 2000; Blasco, 2012; Mouritsen, 2013)			
Art					

¹Abbreviations: SJDF = Strait of Juan de Fuca, SJI = San Juan Islands, PS = Puget Sound, OC = Outer Coast (Gabrielson et al., 2006; Mumford, 2007)

²The same species may have different temperature tolerances between regions. Recruitment refers to sporophyte production.

³Temperature is more limiting than nutrients (Muth et al., 2019). Optimum refers to maximum sporophyte density.

⁴Very little species-specific information is available, but salinity and turbidity are still crucial environmental factors to consider for sporophyte success. With the lack of numerical values, salinity and turbidity could be assessed by observing nearby use (for the possibility of sediment and freshwater influx), local currents/water flow, and the species' canopy form and depth.

⁵With the exception of a few commonly cultivated species, it is difficult to find species-specific human uses. Generally speaking, most kelp species can be put to the following uses: food, nutrition, medicine, art, and industry (food additive, animal feed, fertilizer, biofuel, etc.) (Tiwari and Troy, 2015).

Macrocystis pyrifera	Nereocystis luetkeana	Pleurophycus gardneri	Postelsia palmaeformis	Pterygophora californica	Saccharina latissima	Lessoniopsis littoralis
Adapted for exploitative competition for light/nutrients; susceptible to wave stress and grazing disturbance; has potential to tolerate to warming ocean conditions (Dayton, 1985; Muth et al., 2019)	Opportunistic; frequent disturbed areas; major source of carbon in in-shore intertidal communities; sensitive to grazing; unlikely to tolerate to warming ocean conditions; vulnerable to exposure to petroleum products (Dayton, 1985; O'Clair and Lindstrom, 2000; Muth et al., 2019)	Where amphipod infestation occurs, warmer water temperatures may increase resilience to parasitism (Pfister and Betcher, 2018)	Forms dense stands; competes for space with mussels; unlikely to tolerate to warming ocean conditions (O'Clair and Lindstrom, 2000; Muth et al., 2019)	Long-lived, slow-growing; may form dense stands; adapted to physical stress (wave action, surface exposure) (Dayton, 1985; Mondragon and Mondragon, 2010)	Dusky Tegula snail and sea urchins are common grazers; young sporophytes sensitive to high light levels (O'Clair and Lindstrom, 2000)	Wide holdfast (Mondragon and Mondragon, 2010)
	Consumed pickled, or as a component of salsas, chips, soups, and other foods	Potential kombu substitute; low caloric value (Druehl, 1980; O'Clair and Lindstrom, 2000)	Eaten pickled, steamed or fresh		Commonly used in Asian cuisine; kombu/haidai substitute	
Source of many vitamins and minerals; low in tannins	Source of iodine		Source of fiber (Mondragon and Mondragon, 2010; Mouritsen, 2013)		Source of vitamin C, iodine, potassium, and calcium	Source of trace minerals and complex carbohydrates (Druehl and Clarkston, 2016)
	Mucilage may help treat burns					
Major source of alginate (O'Clair and Lindstrom, 2000; Mondragon and Mondragon, 2010)	Feed for mussels, filter feeders (O'Clair and Lindstrom, 2000; Mondragon and Mondragon, 2010; Mouritsen, 2013)				Potential use for bioremediation (Ahn et al., 1998; O'Clair and Lindstrom, 2000; Bruhn et al., 2016)	
				Stipes used by basket makers (Druehl and Clarkston, 2016)		

ble 3). Unfortunately, given the newness of the kelp mariculture industry in Washington (there are 2 operating open-water sugar kelp farms in Puget Sound and 12 proposed farms undergoing the permitting process as of September 2023⁴), there is very little locally specific research. We addressed some gaps by speaking to researchers and regulators with local mariculture expertise; but, in many

⁴Chadsey, M. Personal commun., 26 Dec. 2023. Washington Sea Grant. 3716 Brooklyn Ave. NE, Seattle, WA 98105.

cases, our judgment about the relative importance of each issue is based on the mix of people and communities, ecological threats, and regulatory concerns unique to the U.S. portion of the Salish Sea. As more data become available, a continuous evaluation of the relative importance and magnitude of each environmental impact—positive or negative—should occur. In the meantime, we have identified the following as high priority potential environmental impacts for the region: marine mammal entanglement, interac-

tions between kelp farm crop and infrastructure with fish communities and forage fish spawning events, benthic shading and disturbance, and genetic effects on wild kelp populations.

Marine Mammal Entanglement

Placing physical structures in the water may disrupt or impede the movement of wildlife, particularly if farms are placed in important feeding, breeding, or migration areas. Though we could find no published reports of marine mammals entangled in sea-

Table 2.—Socio-ecological considerations for kelp species native to the Salish Sea.

	<i>Alaria marginata</i>	<i>Costaria costata</i>	<i>Cymathaere triplicata</i>	<i>Hedophyllum sessile</i>	<i>Laminaria setchellii</i>	<i>Macrocystis pyrifera</i>
Cultivation method ¹						
Source	Wild sorus harvesting, sexual reproduction	Wild sorus harvesting, sexual reproduction				Wild sorus harvesting (parent stock must be adapted to farm site exposure levels), sexual or clonal reproduction
Culture	Culture tubes in nursery aquaria	Culture tubes in nursery aquaria				Inoculation lines in nursery aquaria
Farming	Sporophytes outplanted to floating long-lines (5 m depth) (Blasco, 2012). Blades also have been grown in aerated tanks	Sporophytes outplanted to floating long-lines (5 m depth) or floating raft; co-culture with <i>N. luetkeana</i> (Fu et al., 2010; Blasco, 2012)				Sporophytes outplanted to floating long-line (1.5–5 m depth, depending on season and epiphyte pressure); direct (free floating inoculation line) or indirect (nylon rope seeding); co-culture with <i>P. californica</i> ; avoid siting near high Fe and NH ₄ ⁺ levels (O’Clair and Lindstrom, 2000; Gutierrez et al., 2006; Schiel and Foster, 2006; Westemeier et al., 2006; Macchiavello et al., 2010) Summer (Gutierrez et al., 2006; Macchiavello et al., 2010)
Sorus harvest ²	Fall (Oct.) (Blasco, 2012)	From summer (Jun.) through late fall (Dec.), peak in Sept. (Maxell and Miller, 1996; Blasco, 2012)				
Outplanting ²						Winter outplanting more successful than summer (Gutierrez et al., 2006; Macchiavello et al., 2010)

<i>Nereocystis luetkeana</i>	<i>Pleurophycus gardneri</i>	<i>Postelsia palmaeformis</i>	<i>Pterygophora californica</i>	<i>Saccharina latissima</i>	<i>Lessoniopsis littoralis</i>
Wild sorus harvesting, sexual reproduction	Wild sporophyte harvesting	Wild sorus harvesting		Source: wild sorus harvesting, sexual reproduction	
Culture tubes in nursery aquaria				Culture tubes in nursery aquaria	
Sporophytes directly transplanted to benthic substrate (e.g. rebar stakes); co-culture with <i>C. costata</i> and <i>S. latissima</i> ; siting near eelgrass beds may increase habitat benefits (Merrill and Gillingham, 1991; Maxell and Miller, 1996; O'Clair and Lindstrom, 2000; Carney et al., 2005; Olson et al., 2019; Calloway et al., 2020)	Sporophytes transplanted to floating long-lines (2.5 m depth) (Germann, 2011)	Sori transplanted to cleared rocky substrate bounded by mussels; could be combined with intertidal mussel cultivation (Thompson et al., 2010; Druehl and Clarkston, 2016; Calloway et al., 2020)	Co-culture with <i>M. pyrifera</i> , but may struggle to compete for light (Watanabe et al., 1992)	Sporophytes outplanted to floating long-lines (5 m depth); co-culture with <i>N. luetkeana</i> ; farm in exposed or semi-exposed areas to minimize biofouling (Blasco, 2012; Peteiro and Freire, 2013; Bruhn et al., 2016; PSRF, 2019)	
Late spring (May) through fall (Nov.), with peak production in late summer (Sept.) (Maxell and Miller, 1996)	Spring (Mar.) through fall (Oct./Nov.) (Germann, 2011)	Spores develop in late spring/early summer (O'Clair and Lindstrom, 2000; Thompson et al., 2010)		Fall (Oct.) (Blasco, 2012)	
Winter (Dec.-Feb.) (Calloway et al., 2020)		Spores develop in late spring and summer (O'Clair and Lindstrom, 2000; Thompson et al., 2010)		Winter (Jan.) (PSRF, 2019)	

Table continued

Table 2.—Continued.

	<i>Alaria marginata</i>	<i>Costaria costata</i>	<i>Cymathaere triplicata</i>	<i>Hedophyllum sessile</i>	<i>Laminaria setchellii</i>	<i>Macrocystis pyrifera</i>
Peak growth ²	No discernable peak growth period (Blasco, 2012)	Spring (Mar.-May) (Maxell and Miller, 1996; Blasco, 2012)				Depends on out-planting time (perennial species) (Gutierrez et al., 2006; Macchiavello et al., 2010)
Sporophyte harvest ²	Late spring (Jun), to prevent grazing from snails (Blasco, 2012)	Depending on grazing pressure and tattering, late spring (May) or mid-summer (June/July) (Maxell and Miller, 1996; O'Clair and Lindstrom, 2000; Blasco, 2012)	Late spring, after maximal blade development but before tattering (O'Clair and Lindstrom, 2000)			Late spring, before biofouling becomes a problem (Gutierrez et al., 2006)
(Wild) harvesting recommendations ³	Cut vegetative blades no closer than 4" from the base; leave reproductive sporophylls intact (O'Clair and Lindstrom, 2000; Jungwirth, 2019)			Cut fronds no closer than 6" from holdfast (Jungwirth, 2019)	Cut blades no closer than 2" from the base (Jungwirth, 2019)	

¹ Some species have not yet been commercially cultivated. When available, literature on restoration mariculture and experimental transplants was consulted for species that have commercial potential.

² Limited species-specific information, especially for species that are not commercially cultivated.

³ These are recommendations for wild harvesting that would apply if and only if a self-perpetuating farm is desired and/or permitted (as might be the case with restorative mariculture). Concerns about preserving wild genetic population diversity might, conversely, require complete adult sporophyte removal prior to sorus/spore production.

Nereocystis luetkeana	Pleurophycus gardneri	Postelsia palmaeformis	Pterygophora californica	Saccharina latissima	Lessoniopsis littoralis
Peak density and stipe growth in early summer (June); maximum blade growth in late summer (Aug./Sept.) (Maxell and Miller, 1996)	Rapid growth in winter (Dec.) until peak growth rate is reached in late spring (May) (Germann, 2011)	Late winter/early spring (Thompson et al., 2010)		Winter and spring; highest density reached in late spring (May-June) (Maxell and Miller, 1996; Blasco, 2012)	
Summer, to avoid epiphytes and blade erosion; fall (Oct.) to allow for re-growth (Maxell and Miller, 1996; O'Clair and Lindstrom, 2000; Luning and Mortensen, 2015)	Balding/senescence occurs in summer (June) and fall (Oct.) before regrowth (Germann, 2011)	Spring (Apr.-June) before spore production begins (Thompson et al., 2010)		Spring (Apr.-May), to reduce loss to blade erosion, epiphytes, and grazers; timing affects the proportion of sugars, proteins, minerals (Blasco, 2012; Peterio and Freire, 2013; Luning and Mortensen, 2015; Bruhn et al., 2016; Sharma et al., 2018)	
Only distal ends of blades (>12 m from bulb) should be removed if continued growth is desired (O'Clair and Lindstrom, 2000; Luning and Mortensen, 2015; Jungwirth, 2019)	Breaks at the frond above the abscission zone are non-lethal; individuals live 3-6 years (O'Clair and Lindstrom, 2000; Pfister and Betcher, 2018)	Cut blades at least 2" from base, leaving 1-3" of grooved blade for regrowth (Druehl and Clarkston, 2016; Jungwirth, 2019)		Boiling after harvest can reduce iodine levels, which may be needed for use as food (Luning and Mortensen, 2015)	Harvest no more than 10% of individual plant (Jungwirth, 2019)

weed farms worldwide, the moorings associated with kelp cultivation pose a potential entanglement hazard, particularly for marine mammals (Langton et al., 2019). Gray whales, *Eschrichtius robustus*, seasonally occupy Puget Sound in the spring and summer, and humpback whale sightings in the Salish Sea have increased in recent years (Miller, 2020). Reported whale entanglements in fishing gear have been on the rise on the U.S. west coast in recent years, but are primarily associated with either pot fisheries for crab and fish trapping where a single, relatively slack line may connect traps to individual surface buoys, or to discarded nets from the fishing industry (Assink, 2019). In Puget Sound, whale entanglement in fishing gear is relatively uncommon—five humpback whales were reported entangled in pot fishery gear between 2010 and 2014, and between 2013 and 2017, three gray whales were reported entanglements in pot/trap fisheries (Assink, 2019). Southern resident killer whales have not been observed entangled in fish-

ing gear, though one Bigg's (Transient) killer whale was briefly entangled in pot-fishing gear off the coast of Vancouver Island in 2018 (Haagen, 2018; WWF, 2021).

Additionally, several pinniped species travel to the Salish Sea, including California sea lions, *Zalophus californianus*; harbor seals, *Phoca vitulina*; and the Eastern distinct population of Steller sea lions, *Eumetopias jubatus* (NMFS, 2022a; 2022b; 2022c). Pinniped entanglement and ingestion of marine debris is typically associated with finfish mariculture, wild catch fisheries, and crab pot fisheries, with the primary culprit being discarded or lost rubber bands and plastic packing bands (Kemper et al., 2003; Raum-Suryan and Suryan, 2022). The rate of pinniped entanglement off of Washington's northern coast ranges from 0.41% to 2.13% of the observed population, but entanglement rates within the Salish Sea have not yet been reported (Allyn and Scordino, 2020; Raum-Suryan and Suryan, 2022).

Changes to Fish Communities and Habitat for Forage Fish

Artificial structures in temperate marine waters can change the distribution and habitat use of invertebrates and fish. Artificial reefs and derelict fishing gear are two examples of habitat changes that result in changes to fish use in the Salish Sea (West et al., 1994, Favaro et al., 2010). Kelp farm infrastructure—including anchor systems, ropes, and buoys—introduces substrates for invertebrates and wild seaweed to attach, and also likely attract fish and invertebrate communities that would otherwise not occupy these habitats. In local waters, this type of infrastructure can be used by rockfish; pile perch, *Damalichthys vacca*; striped seaperch, *Embiotoca lateralis*; and shiner perch, *Cymatogaster aggregata*; among other species. Juvenile salmonids, such as coho, *Oncorhynchus kisutch*, and Chinook are similarly attracted to habitat complexity in marine and estuarine waters (Shaffer et al., 2020), and may use

habitat near kelp farm infrastructure for foraging. Larval rockfish are often observed under free-floating algae, seagrass, and detached kelp (Shaffer et al., 1995), and kelp farms may provide similar habitat types, though potentially an ephemeral one given the seasonality of cultivation. A review by Theuerkauf et al. (2022) found that kelp farms had variable effects on marine communities, but generally greater fish abundance, mobile invertebrate abundance, and species richness were observed near kelp farms compared to reference sites.

Buoys and other kelp farm infrastructure on the surface are likely to attract fish-eating birds such as the double-crested cormorant, *Nannopterum auritum*. Similarly, fish predators—such as harbor seals, *P. vitulina*; California sea lions, *Z. californianus*; and river otters, *Lontra canadensis*—could be attracted to kelp farms to feed on fish associated with these habitats. While it is possible that predation on salmonids could increase in waters near kelp farms compared to sites without farming infrastructure, the seasonal growing period for the kelp species most likely to be cultivated, sugar kelp (late fall to early spring), is unlikely to overlap with much of the spring outmigration period for most Pacific salmon populations in the study area. The interaction between juvenile salmon and kelp farms would likely depend on the farm's proximity to areas of outmigration and the timing of farm operations, but this issue warrants additional research.

Additional fish and kelp farm interactions could occur. Pacific herring utilize marine vegetation, such as eelgrass, *Zostera* sp., and macroalgae, as a substrate to deposit their eggs (roe) (Penttila, 2017). Herring spawn-on-kelp fisheries are facilitated by harvesting wild kelp and staging it in known herring spawn locations just prior to or during the anticipated event, or capturing mature herring and holding them in pens until they deposit their eggs on the suspended kelp (Schweigert et al., 2018)

Washington law permits the harvest of Giant kelp, *Macrocystis pyrifera*, used for herring roe on kelp fisheries (RCW 79.135.410). Herring roe-on-kelp fisheries last occurred in the U.S. portion of the Salish Sea in the mid-1990's, but these were closed due to a decline in the Cherry Point population of Pacific herring stock (Sandell et al., 2019). In 2020, cultivated kelp was used by herring during a spawning event at one farm in southeast Alaska, even though the farm was sited in an area without known historic spawning (Milne, 2020). Herring spawning on a cultivated kelp crop in Washington waters would require coordination with WDFW (which has jurisdiction over forage fish), delay crop harvest until the eggs hatch, and/or downgrade product quality due to residual egg material.⁵

Benthic Shading and Disturbance

Benthic vegetation, wildlife, and seafloor structure could be disturbed by anchors or other moorings used in marine mariculture (Grebe et al., 2019). The dense growth of kelp along cultivation lines could prevent photosynthetic radiation (PAR) from reaching the seafloor, thus influencing the amount of light received by natural vegetation or phytoplankton below a farm, if grown in shallow waters (<30 m). Reduced light transmission in the nearshore can impact eelgrass growth and result in plant mortality and fragmentation (WDNR, 2015) depending on the characteristics and percent of shading (Jones and Stokes Associates, 2006; Lambert et al., 2021). However, additions to the seafloor have been found in other types of mariculture to act as artificial reefs and increase habitat for benthic organisms (Tallman and Forrester, 2007; Theuerkauf et al., 2022) and wild kelp habitat in close proximity to seagrass meadows can enhance seagrass ecosystem functionality and landscape connectivity (Olson et al., 2019), though the role of farmed kelp habitat has not yet been

⁵Dionne P. Personal commun., 6 May 2022. Washington Department of Fish and Wildlife, 1111 Washington St. SE, Olympia, WA 98501.

studied in this regard. In contrast, shellfish aquaculture interactions with submerged aquatic vegetation in Washington are an active area of both litigation (Laschever et al., 2020) and scientific research (e.g., Tallis et al., 2009). As our understanding of the effects of on-bottom and off-bottom shellfish culture on native submerged aquatic vegetation evolves, this may involve regulatory changes that are likely to affect seaweed cultivation, especially in the absence of research specific to the impacts of seaweed cultivation. Additional possible impacts to the benthos include the increase of detritus/organic matter, changes in infauna assemblages, and changes in oxygen levels and seawater chemistry (Walls et al., 2017).

Genetic Effects on Wild Kelp

The release of reproductive material from kelp farms into the natural environment is considered by some to be the highest-risk potential environmental impact associated with the expansion of macroalgae mariculture (Campbell et al., 2019). The cultivation of non-native kelp species could lead to the establishment of invasive species that compete with native species for space, light, and nutrients (Campbell et al., 2019) and is not currently permitted in Washington (WAC 220-370-220). Even the cultivation of selectively bred native species could, over time, affect wild populations, leading to greater genetic resemblance between farmed and wild populations and potentially resulting in a loss in genetic diversity, a higher potential for disease transmission, and/or a decline in ecosystem resilience (Buschmann et al., 2017; Grebe et al., 2019). The challenge of maintaining genetic diversity in cultivated marine organisms has been demonstrated in the Salish Sea in pinto abalone (Dimond et al., 2022), and Olympia oysters, (Camara and Vadopalas, 2009), two species which are cultivated in hatcheries for restoration/rewilding purposes, necessitating rigorous hatchery protocols for spawning and production of animals for outplant-

Table 3. – Summary of the potential ecological impacts of cultivating kelp in the Salish Sea, in alphabetical order within each category of Local Relevance. Italics denote issues of particular concern for the region, based on conversations with local researchers, regulators and tribes. Local relevance was determined to be high if a category either had local data to support it and/or was ranked high as a concern in the literature, medium if there was no local data and it had a high or medium ranking in the literature as a concern but had a significant amount of uncertainty, and low if there was no local data and it was ranked medium or low in the literature as a concern and had a significant amount of uncertainty for its impact.

Ecological impact	Potential benefit	Potential concern	Economic considerations	Local relevance	Local data
Benthic/Eelgrass	Farm anchors/moorings create habitat-forming 'reefs.' (Tallman and Forrester, 2007)	Crop blocks PAR-photosynthetic radiation, shading benthic environment below farm. <i>Farm anchors/moorings disturb benthic vegetation, wildlife and seafloor structure.</i> (Grebe et al., 2019)	Additional cost of lower-impact anchor systems.	High	Yes - Concern; Mumford, 2007; Tallis et al., 2009; Thom et al., 2011
Genetics	Assist in selection of high temperature-tolerant strains to withstand ocean warming	<i>Crop populates environment with reproductive material, influencing wild population diversity.</i> (Buschmann et al., 2017; Grebe et al., 2019)	Timing and extent of harvest affects release of reproductive material. ¹	High	N/A
Habitat	Crop provides habitat and refugia for other organisms. (Gentry et al., 2020)	Harvest removes habitat and refugia created by crop. (Wood et al., 2017; Grebe et al., 2019) Predation on fish attracted to farm infrastructure. <i>Forage fish spawn.</i>	Biofouling and epiphytes reduce crop value. (Peteiro and Freire, 2013; Langton et al., 2019) Utilization of crop by protected species delays harvest or reduces crop value.	High	N/A
Water quality	Farm infrastructure provides habitat and refugia for other organisms. (Gentry et al., 2020)	Disruption of wildlife movement and migration. <i>Entanglement hazards for marine mammals.</i> (Langton et al., 2019) Potential source of marine debris. ¹	Utilization of farm infrastructure by protected species delays harvest or reduces crop value. Total or partial loss of farm infrastructure and/or crop.	High	Yes - Benefit; Rensel and Forster, 2007
Disease	Crop extracts nutrients, chemicals and metals from surrounding water column – mitigation of eutrophication, pollution, and HAB. (Imai et al., 2006; Kim et al., 2015; Augyte et al., 2017; Langton et al., 2019; Gentry et al., 2020) Crop absorbs carbon and may stabilize local pH – localized OA mitigation or value in the carbon offset market. (Duarte et al., 2017; Froehlich et al., 2019; Langton et al., 2019; Gentry et al., 2020)	--	Large-scale farms needed to achieve significant water quality benefits. (Gentry et al., 2020) Absorption of some pollutants by crop (i.e. heavy metals) may limit commercial uses.	High	Yes - Benefit; Peabody et al., 2020
Nutrients/Food Web Support	Detritus and particulates and DOM from crop provide food web support for other organisms, affecting the productivity of higher trophic levels. (Miller and Page, 2012) Nitrogen (nutrient) remediation – see Water Quality above	Crop spreads diseases to native kelp population. (Langton et al., 2019) Particulate and dissolved organic carbon overloading. (Grebe et al., 2019) Competition with other organisms in nutrient-poor areas. (Wood et al., 2017; Grebe et al., 2019)	Loss of crop from disease outbreak.	Medium	N/A
Hydrology	Farm infrastructure/crop dampens wave energy, reducing damage to shoreline. (Langton et al., 2019)	Farm infrastructure impacts natural movement of water.	Nutrients increase productivity of co-cultured species, such as shellfish. (Miller and Page, 2012) Timing and extent of harvest affects nutrient supplement. ¹	Medium	N/A
		Farm infrastructure/crop dampens wave energy, reducing damage to shoreline. (Langton et al., 2019)	Larger farms dampen water movement to the detriment of kelp growing in the middle of the farm	Low	N/A

¹Davis J. Personal commun., 1 Jan. 2020. Blue Dot Sea Farms and School of Marine and Environmental Affairs, University of Washington, 3707 Brooklyn Ave. NE, Seattle WA 98105.

ing.⁶ Given the genetic distinctiveness of bull kelp, within the southern Salish Sea, especially within the Puget Sound Main Basin and South Sound (Gierke, 2019), it is possible that other local kelp species have genetic structure that may be spatially and environmentally driven, and that a precautionary approach should be taken initially in managing cultivated stocks.

Farm Design Guidance

With the most locally relevant potential ecological impacts in mind, we now consider the second dimension of our farm design guidance: the kelp cultivation process. This guidance was informed by growers' manuals from seaweed farming in the North Atlantic (Table 4), peer-reviewed articles on experimental mariculture design, and conversations with experts in kelp farming and/or Salish Sea ecology. All information was verified with experts, and local information was prioritized when it was available. The goal of our initial farm design guidance is to maximize potential ecosystem benefits and minimize potential ecological harms without compromising commercial viability. A summary of best practices for kelp cultivation is presented in Table 5.

First, site selection is one of the most important factors for minimizing ecological harm, maximizing ecological benefit, and ensuring a healthy and productive kelp crop. Next, cultivation practices also influence ecosystem service provisioning and crop productivity. Our farm design guidance at the cultivation stage is for in situ cultivation in the marine environment only, and assumes routine monitoring and adequate farm maintenance. For information regarding the hatchery and nursery phases of cultivation, we recommend consulting the various growers' manuals listed in Table 4.

Finally, the harvesting stage can impact the surrounding marine environment, as well as crop health and value. Two additional stages of the

farming cycle—processing and transport to market—are also important, but beyond the scope of this paper. Moving forward, selecting suitable sites, cultivation practices, and harvesting protocols for kelp mariculture would greatly benefit from the development of industry-specific marine spatial planning tools that integrate biophysical, social, economic, and logistical considerations.

Site Selection Considerations

Water Quality

Ensuring cultivated kelp will be grown in cold, nutrient-rich waters with plenty of light will maximize potential yields and lessen the risk of disease. It may also minimize the risk of cultivated kelp diverting nutrients from native vegetation, and could even provide the added benefit of absorbing effluent nutrients in the system. Bacterial contaminants have been detected on kelps (Barberi et al., 2020; Lovdal et al., 2021), so in the absence of understanding how kelp species absorb and retain these pathogens we recommend siting kelp farms in areas that meet current health requirements for shellfish cultivation, as well as avoiding areas with a history of diseased organisms (Bishop et al., 2021).

Additionally, seaweeds absorb heavy metals present in the water (Shams El-Din et al., 2014; Filippini et al., 2021, Hahn et al. 2022). Given the current absence of any federal or state laws or rules to regulate heavy metal content in seaweed products, we recommend following the requirements used at the national level or in the European Union (E.U.) (Barbier et al., 2019). Table 6 provides general suggestions for water quality metrics and human health requirements. As the domestic seaweed industry develops, additional research on bacterial and heavy metal contamination is essential for developing better-informed health standards (though see Hahn et al., 2022, for recent local analysis).

Studies in the E.U. have determined that *E. coli* requirements are unnecessary for the commercial seaweed in-

dustry (Barbier et al., 2019). Prospective farmers should look at current water quality conditions of a potential farm site, as well as seasonal variations and future projections. We also suggest cross-referencing available species-specific information, seen in Table 1, with site conditions for the best outcome. Farmers interested in cultivating kelp for non-consumptive commercial uses, or non-commercial uses (bioremediation, etc.) can consider a wider range of water quality metrics. Though post harvesting processes are beyond the scope of this paper, it should be noted that processing practices may be able to mitigate some of these water quality concerns and should be an area of continued investigation.

Water Flow

A steady current is essential for bringing in the necessary nutrients (e.g., dissolved nitrogen) for kelp to grow while also flushing the area of detritus (Freitag, 2017). Adequate water flow also distributes the dissolved or particulate organic carbon sloughed off the cultivated kelp throughout the system, providing a nutritional supplement to other areas and preventing a nutrient overload on site (Campbell et al., 2019). An ambient current of 10-40 cm/s is optimal, with a maximum of 100 cm/s at peak ebb/flood (~1/2–2 knots) to prevent crop, rope, or mooring damage. Prospective farmers should also consider extreme event (i.e., winter storm) flow rates, not just average flow rates, when designing infrastructure as the strongest storms occur in winter and possibly overlap with peak cultivation periods (see species specific information in Table 1).

Lastly, the selected crop species' current tolerance should correspond to the farm site's level of exposure (Table 1). There is also evidence that water flow tolerance varies by population for some species (i.e., *Macrocystis pyrifera*), so farmers should consider collecting source seed from areas with similar levels of exposure as their farm site (Gutierrez et al., 2006). Whether or not this holds true for oth-

⁶Eardley C. Personal commun., 26 Sept. 2022. Washington Department of Fish and Wildlife, 375 Hudson St, Olympia, WA 98501.

er kelp species is a question for future research.

Water Depth

Appropriate water depth is important from a business perspective to ensure full growth of cultivated kelp species. A sugar kelp farm could be sited in as little as 3.5 m of water,⁷ however, many commercial manuals recommend siting farms in water 5.5 m or deeper (Merrill and Gillingham, 1991; Flavin et al., 2013). In some instances, depth is also a proxy for distance from the shoreline, and excessive distance from the shoreline presents several disadvantages. First, farms located further from shore could increase the likelihood of generating marine space use conflicts. Shoreline protection is also more likely to be provided if farms are located closer to shore, though additional research needs to be conducted on the optimal distance from farm to shore to maximize this potential ecosystem service. Finally, from a business perspective, maintenance, access, and transport costs for farmers increase with distance from the shore. However, would-be farmers must also consider how proximity to shoreline owners and their viewscapes might influence the social acceptance of their operations.

Appropriate water depth is also important from an ecological perspective. Selecting farm sites with moderate water depth helps avoid negative interactions with protected species and habitats within the Salish Sea. Though siting farms in water deeper than the photic zone (about >30 m MLLW) eliminates shading native marine vegetation, farms sited too far from shore in water deeper than 35 m increase the likelihood of humpback whale interactions.⁸

⁷Davis J. Personal commun., 1 Jan. 2020. Blue Dot Sea Farms and School of Marine and Environmental Affairs, University of Washington, 3707 Brooklyn Ave. NE, Seattle, WA 98105.

⁸Lawson, D. Personal commun., 13 Apr. 2020. NMFS, West Coast Regional Office, Long Beach Branch, 501 W Ocean Blvd, Long Beach, CA 90802.

Table 4.—Kelp cultivation resources.

Bergdahl, J. C. 1990. Nori (<i>Porphyra</i> C.Ag.: Rhodophyta) mariculture research and technology transfer along the northeast Pacific coast., in: I. Akatsuka (Editor), <i>Introduction to Applied Phycology</i> , p. 519-551. SPB Acad. Publ., the Hague, Neth.
Canadian Kelp Resources, Ltd. The Canadian Kelp Resources Kelp Seed Production Manual. Rev. May 2015. Bamfield, B.C., V0R 1B0.
Flavin, K., N. Flavin, and B. Flahive. 2013. Kelp Farming Manual: A Guide to the Processes, Techniques, and Equipment for Farming Kelp in New England Waters. Ocean Approved, Biddeford, ME.
Freitag, G. 2017. Seaweed Farming in Alaska. Alaska Sea Grant Marine Advisory Program, Ketchikan, AK. ASG-63, 8 p.
Hurtado, A.Q. 2022. Genetic Resources for Farmed Seaweeds – Thematic Background Study. FAO, Rome. (https://doi.org/10.4060/cb7903en)
Merrill E. and D. M. Gillingham. 1991. Bull Kelp Cultivation Handbook. Applied Algal Research Co. P.O. Box 31104 Seattle, WA 98103.NCRI Publ. NCRI-T-91-011.
Barbier, M., B. Charrier, R. Araujo, S. L. Holdt, B. Jacquemin and C. Rebours. 2019. PEGASUS - PHYCOMORPH European Guidelines for a Sustainable Aquaculture of Seaweeds, COST Action FA1406, Roscoff, France.
Mooney-McAuley, K. M., M. D. Edwards, J. Champenois, and E. Gorman. 2016. Best Practice Guidelines for Seaweed Cultivation and Analysis, Public Output report of the EnAlage project, Swansea, Wales. 36 p.
Redmond, S., L. Green, C. Yarish, J. Kim, and C. Neefus. 2014. New England Seaweed Culture Handbook-Nursery Systems. Conn. Sea Grant, Groton, CT. CTSG-14-01. 92 p.
Rollin, C., R. Inkster, J. Laing, J. Hedges, L. McEvoy. 2016. Seaweed Cultivation Manual. Shetlands Seaweed Growers Project 2014-16. NAFC Marine Centre, Univ Highlands Islands, Gremista, Lerwick, Shetland, ZE1 0PX.
Visch, W. 2019. Sustainable Kelp Aquaculture in Sweden. Ph.D. Thesis, Univ. Gothenburg, Goteborg, Sweden.

Native Aquatic Vegetation

Commercial kelp farms should avoid locations over or near significant stands of native marine vegetation, such as macroalgae or eelgrass beds, and minimize overlap with smaller stands of such vegetation. Current DNR regulations require shellfish farms to provide a 25 ft buffer between native vegetation and the farm perimeter and in the absence of seaweed farm-specific regulations, the same guidance applies (ARD, 2014). However, the interaction between vegetation and shellfish aquaculture, and the impact of overwater structure shading on macroalgae (Lambert et al., 2021), show inconsistent results and is an active area of research, thus future results may justify additional review of this requirement, for both seaweed and shellfish farms.

Observing the location patterns of native vegetation is not only important for regulatory compliance but also may help guide farmers in best mimicking natural conditions for their crop. For example, wild kelp species typically grow on substrates that enable holdfast development such as rocky bottoms and unconsolidated substrates with rock/cobble. Farm

placement above these types of sea-floor substrate, as long as it is bare of native vegetation, may allow the farm to better provide similar habitat and other ecosystem services.

Marine Mammals

To reduce the likelihood of gear interaction, entanglement, and behavioral disruption of large whales, farms should be sited where there is minimal overlap with known large-whale feeding areas and migration corridors (Miller, 2020). For instance, most gray whales within the study area seasonally feed within the North Puget Sound near the Snohomish River delta (Calambokidis et al., 2015). Humpback whales, whose population numbers are increasing, are also known to seasonally feed throughout Puget Sound (Miller, 2020).

Forage Fish Spawning

Prospective kelp farmers should consider avoiding known and consistent herring spawning areas when siting farms. Research is underway in Southeast Alaska regarding best practices to avoid spawning events on cultivated kelp, and findings of this work should be incorporated into Salish Sea

Table 5.—Summary table of kelp farm design guidance.

Farming stage	Key question(s)	Farm design considerations/suggestions	Related potential environmental impact(s)
Site Selection	Where to site? Which species?	Ensure site water quality meets growth requirements for kelp and contaminant requirements for human health.	Water quality, nutrients, disease
		Ensure adequate water flow through the farm.	Nutrients, hydrology
		Site farms in moderate water depth (5.5–35m).	Benthic/eelgrass, habitat
		Minimize or avoid overlap with native aquatic vegetation.	Benthic/eelgrass
		Avoid large whale (i.e., gray whale) feeding areas and migration corridors.	Habitat
		Avoid areas with a prior history of forage fish spawning events	Habitat/species
Cultivation	Which species? How much seed? When to outplant? How much crop? Which materials? Which method(s)?	Cultivate only native species, and multiple species when possible.	Habitat, nutrients, water quality, disease, genetics
		Collect small amounts of seed stock from within the same oceanographic basin.	Genetics
		Use cable anchor lines, taut longlines with a weight of ¾ to 1 ¼ inches.	Habitat/entanglement
		Use embedded anchors for moorings.	Benthic/eelgrass
		Orient longlines parallel to prevailing currents, minimize the use of plastic gear, and ensure proper gear maintenance and disposal.	Habitat
		Place longlines 2–5m deep, 1.8-4.5m apart horizontally and at least 1m apart vertically.	Habitat, nutrients, water quality, hydrology, disease
Harvesting	When to harvest? Which parts? How much crop?	Harvest crop in at peak biomass/ upon maturity of the product.	Genetics, habitat
		Remove the entire crop and all longlines during harvesting.	Genetics, habitat, disease

kelp farms, as appropriate (NMFS, 2021). If herring spawn on farmed kelp occurs, farmers should consult with WDFW and delay harvest until hatching occurs.⁵

Cultivation Considerations

Native Species

Protecting the genetic diversity of wild populations is essential for the conservation and recovery of kelp in Puget Sound (Calloway et al., 2020). To protect the genetic diversity of wild kelp populations and to ensure the crop is relatively adapted to local ecological conditions, we suggest collecting seed stock from wild kelp within the same oceanographic basin as the farm site (Fig. 1) or as close as possible. The sori (reproductive tissue) from the equivalent of 5 to 15 sugar kelp sporophytes (adult “plant” phase) provide enough gametophytes to seed

up to 20 km of line⁹, though in Alaska, another state with a growing kelp mariculture industry, it is currently recommending that sori be collected from at least 50 individual plants to best protect genetic diversity (Gruenthal and Habicht, 2022).

With wild, local broodstock collection as one part of a risk averse pathway, it is important to acknowledge that the development of cultivars (selectively bred varieties), could benefit farmers by allowing them to select for traits that maximize yield, resilience, and profitability (and/or ecosystem services), enable a more efficient use of marine space by allowing greater crop production within a smaller farm footprint, and allow for better adaptation to climate change (Goecke,

⁹Dobbins P. Personal comms., 5 May 2020. World Wildlife Fund, 1250 24th St NW, Washington, DC 20037

2020). Investigations are underway in the United States, Europe, Australia, and South Korea, and under scrutiny of policy makers to selectively breed kelp in an ecosystem-responsible manner (Goecke et al., 2020; Mao et al., 2020; Azra et al., 2022; Huang et al., 2022; Vissers et al., 2023). Genetic risk tools, such as the Offshore Mariculture Escapes Genetics Assessment model, could be adapted to seaweed culture to predict and evaluate the risk of invasions and introgressions from cultured macroalgae on natural algal populations. In the future, farmers or third-party entities might develop cultivars, seed banks, or other seed stock programs derived from native species.⁹ Sterile cultivars for in situ commercial kelp mariculture is already in development elsewhere (Vissers et al., 2023), and would enable more efficient crop production while reducing the risk of

Table 6.—Optimal water quality elements for growing kelp and crop metal/mineral limits for ensuring human health (U.S. requirements unless otherwise noted).

Indicator	Range
Temperature	10-15° C, Max 18° C
Nutrients	1-20 (Optimal >10) $\mu\text{mol/L NO}_3^-$, $>0.3 \mu\text{M PO}_4^{3-}$
Salinity	Minimum 24 ppt
Light Availability at kelp depth	1,000 – 2,000 lumens m^{-2} (20-40 $\mu\text{Em}^{-2}\text{s}^{-1}$)
Fecal coliform	< 30-43 FC/100mL (WA Dept. of Health)
Lead	<10 mg kg^{-1} DM, ppm
Cadmium	<0.5-3 kg^{-1} DM, ppm (from France/EU)
Mercury	<0.1 kg^{-1} DM, ppm (from France/EU)
Inorganic arsenic	<3.0 kg^{-1} DM, ppm
Iodine	<5,000 kg^{-1} DM, ppm

genetically altering wild kelp populations. In addition to the ecological considerations discussed here, the privatization of developed cultivars and related questions of intellectual property rights are likely to be an important economic/social concern similar to seed ownership in terrestrial agriculture. In Table 2 we provide a list of native kelp species with commercial potential.

We also encourage cultivating a diversity of kelp species within farms, as it would likely enhance both ecosystem services and economic returns. In terrestrial settings, crop biodiversity increases the potential number of commercial products and may improve resilience to disease, parasites, predation, or other unexpected natural events (Lin, 2011). Simultaneously growing species with multiple canopy forms (prostrate, stipitate, floating) uses the entire vertical dimensionality of the farm, better mimicking the habitat created by wild kelp beds and maximizing potential growing space, though also adding complexity to farming methods and timeline. A possible combination of species that have complementary canopy forms and have been experimented with include bull kelp, ribbon/winged kelp, *Alaria marginata*, and sugar kelp (Table 2). Farmers could also extend the growing season by sequencing kelp species with different growth and harvesting seasons. This would maintain kelp

biomass and associated ecosystem services in the marine environment for a longer time period.

Importantly, the feasibility of increasing the spatial and temporal biodiversity of kelp farms will depend on the other uses of marine space occurring at or near the farm site. Commercial and subsistence tribal fishing activities, vessel traffic, marine mammal migrations, and/or forage fishing spawning events may preclude having kelp longlines in the water for an extended period of the year. Prospective farmers interested in kelp polyculture should keep these limitations in mind when selecting potential farm sites and communicating with other users of the same marine space.

Anchor Lines and Longlines

Kelp is commonly cultivated on horizontal lines suspended in the water column, either as separated longlines or connected in a grid-like pattern (Hurtado, 2022). These longlines are attached to benthic moorings by anchor lines. A similar setup may use vertical dropper lines instead, one of many potential variations in design.

To minimize the risk of marine mammal entanglement, longlines should be between $\frac{3}{8}$ " and $1\frac{1}{4}$ " diameter and kept as tight as possible for all tidal conditions. Farmers should check the tautness of longlines frequently and do a thorough inspection of moor-

ings every year and after storm events. Other suggestions to minimize risk of entanglement include using cables for the anchor lines and potentially using breakaway toggles or links at multiple points on the cultivation infrastructure. Additional research, however, is needed to test the feasibility (and design) of using breakaway toggles,⁸ to assess the potential for loss of gear.

Embedment Anchors

Although kelp farmers in other regions routinely use concrete moorings¹⁰, DNR currently discourages the use of concrete blocks as moorings to minimize benthic disturbance (WDNR, 2018). Kelp farmers should mostly consider the use of embedded anchors for moorings; however, with additional research, the use of pre-existing concrete moorings could be a viable option given the potential habitat benefit of providing substrate for wild kelp (Tallman and Forrester, 2007). Concrete mooring structures may also be more effective for alternative cultivation techniques, such as those for bull kelp. Concrete moorings located within the photic zone have been effectively used in local bull kelp restoration efforts in Puget Sound (Puget Sound Restoration Fund, 2019).

Longline Orientation

Like many commercial activities occurring on the water, kelp mariculture can be a source of marine debris, which poses a hazard to local marine flora and fauna (Feng et al., 2020). Farmers should minimize the use of plastic materials, including polylines which can erode and shed microplastics into the environment (Napper et al., 2022). They should also ensure the collection and proper disposal of waste materials, excess line, and other debris consistent with applicable local, state, and federal regulations.

To avoid excess wear and tear to equipment in the first place, farms should be oriented so longlines run

¹⁰Piconi, P. Personal comms., 5 Feb. 2020, at Washington Sea Grant Seaweed Farming Workshop. Island Institute, 386 Main St., P.O. Box 648, Rockland, ME 04841.

parallel with the prevailing current. All gear placed in water should be labeled with a unique identifier in the case of loss. Research on the use of recycled carbon fiber cables for grow lines and other gear is underway at one commercial seaweed farm in Washington. Using cables that are stiffer than commercially available lines, have a very long lifespan, and do not shed microplastics through chafe and exposure to UV radiation could contribute to more sustainable farming practices.

Longline Spacing

Determining the appropriate farm scale and density for any particular site requires balancing various tradeoffs. In economic and ecological terms, farm scale and density influence crop productivity, which in turn affects profits, the provisioning of ecosystem services, and the risk of disease, parasites, and predation. In practical terms, longline density will in part depend on vessel size and the ease of movement through the farm. Many of the specifics will depend on site-specific features of farms, including nutrient availability, current strength, tidal regimes, and water depth, as well as adjacent land and water uses.

With these caveats in mind, we suggest spacing longlines 1–4.5 m apart along the horizontal axis (Flavin et al., 2013).^{9,11} If growing multiple species with different canopy forms, a grower may want to use stacked vertical lines to maximize farm space. In this case, farmers should space vertical lines about 1 m apart throughout the depth of the water column, starting 2–5 m below the surface depending on the canopy form of the cultivated species. More locally-based research should be conducted to study the effects of longline density on crop productivity, water quality, habitat provisioning, and other ecosystem services to better inform these preliminary suggestions.

Farm scale in the Salish Sea will likely be more constrained by socio-economic factors than by ecological

factors, with economic viability determining the lower limit and marine space use conflicts setting the upper limit. Few studies have quantified how environmental impacts scale with farm size, but one study on the west coast of Sweden found no ecological costs associated with sugar kelp farms up to 2 hectares (~5 acres) using multiple configurations of longlines (50,200 m longlines vs. 24,400 m longlines) (Visch, 2019). Research on the environmental impact of kelp farms at larger scales should be a high priority.

Harvesting Considerations

Harvest timing

After peak growth (typically in the winter for sugar kelp) kelp will continue to accumulate biomass throughout the next couple of months. Changes in water temperatures and surface nitrogen availability, such as warming during the summer and increased stratification, increase the risk of grazing, epiphytic biofouling, disease, and blade degradation. Additionally, reproduction generally occurs following the peak growth period. To avoid these issues, which could reduce crop value, increase processing time, or spread disease or genetic material to the wild stock, it is best to harvest the crop after the peak growth period. Consult Table 2 for species-specific harvesting seasons.

Crop and Longline Removal

When harvesting an annual species, we suggest removing the entirety of all cultivated plants on the longlines. For perennial species, remove as much reproductive material as possible. These measures minimize the risk of cultivated species spreading reproductive material or diseases into the natural environment and impacting the genetics or health of the wild stock. Where feasible with farm operations and growing methods, we recommend the removal of all longlines after harvest to minimize biofouling, the risk of wildlife entanglements, and to avoid marine space use conflicts—

namely the interference with tribal fisheries.

Future research to inform policy development should investigate the tradeoffs involved in allowing some crop and/or gear to remain in the water for extended time periods. For example, cultivating a diversity of kelp species in rotation throughout the year, or coppicing (partially harvesting and allowing the kelp to regrow for a second harvest) might maximize both ecosystem services and profits. However, these potential benefits would need to be weighed against the risk of wildlife entanglement at the farm site, and farmers would need to consult with tribes and other marine space users in the area. Similarly, in some areas the habitat and nutrient provisioning benefits of leaving non-reproductive crop tissue and farming gear in the water may outweigh the potential risk of gene flow from domestic to wild kelp populations.

Discussion

Key Challenges

While we have outlined practical and precautionary ways prospective kelp farmers could design and operate within the U.S. portion of the Salish Sea, the greatest challenges to developing a new industry may be social acceptance and the ability to co-exist with other pre-existing water and land uses adjacent to the site, including: shipping lanes, fishing and other vessel traffic, viewsheds of private waterfront property owners, tribal U and A's and reservations, marine protected areas and aquatic reserves, proximity to industrial or wastewater treatment facilities, and proximity to processing facilities.

Coordination with tribes is critical to gaining permits to operate a kelp farm. Many tribes take an active role in reviewing local, state, and federal permitting proposals by providing feedback to regulatory entities. Invariably, the infrastructure needed for a kelp farm, such as anchors, lines, and buoys, requires authorization by the Army Corp of En-

¹¹Grebe, G. Personal comms., 5 Nov. 2019. Marine Science Center, Univ. of New England, 11 Hills Beach Road, Biddeford, ME 04005.

gineers (ACOE) under Section 10 of the Federal Rivers and Harbors Act. Tribes may voluntarily review draft permit applications and raise objections directly to the ACOE. With input from the tribe(s), the ACOE must determine whether proposed projects would have more than a de minimis impact to treaty rights, and if they do, the ACOE will not issue permits. The ACOE also consults with the National Marine Fisheries Service and the U.S. Fish and Wildlife Service to assess the actions effects on ESA listed species and designated critical habitat. On a state government level, seaweed farming projects that are proposed in state-owned aquatic lands require authorization from the Washington Department of Natural Resources via a lease agreement. On a local level, the Washington State Shoreline Management Act required jurisdictions to develop Shoreline Master Programs (SMP's). The Act calls for each jurisdiction to develop an SMP that outlines plans to 1) balance and integrate interests of local citizens; 2) address shoreline conditions; 3) consider and influence planning regulations for adjacent lands; and 4) classify shoreline segments into environmental designations (WECY, 2012). SMP's must strive for no net loss of ecological function while still promoting the public use and development of county and city shorelines, using the "best available science" to issue specific guidelines (RCW 90.58). Because seaweed farming is a novel activity in Washington waters, there is virtually no up-front local, state, or Federal guidance to ease permitting for proposed farms.

Depending on their location, kelp farm infrastructure could interfere with pot, dive, gillnet, beach seine, and drift net fisheries targeting Pacific salmon, Dungeness crab, *Metacarcinus magister*, spot and dock shrimp, *Pandalus platyceros* and *Pandalus danae*, and geoduck, *Panopea generosa*, and potentially other fisheries. Early engagement with potentially affected tribes, prior to submitting permits, is critical to developing collab-

orative approaches to locating and operating kelp farms in local waters.

Specifically, we recommend considering locations that avoid or minimize fisheries conflicts. These might include areas with few other targeted resources at the site, or areas that are already "developed" due to the presence of nearshore infrastructure (docks and piers) or activities (shellfish mariculture) that impact fisheries access. Depending on the season, the removal of kelp farm infrastructure following the harvest season, such as lines and buoys, has the potential to partially alleviate conflicts with tribal fisheries (summer), salmon fisheries (late fall), and crab fisheries (winter) but will inevitably still overlap with some fisheries.

Similarly, tribal concerns about environmental degradation from proposed projects are taken under consideration by multiple local and state regulators as well as the ACOE and other federal government agencies with a regulatory role. Legal rulings have also deemed the preservation of fish habitat by state and federal regulators central to upholding treaty rights (NWIFC, 2014). The Western Washington Treaty Tribes have long expressed concern about the loss and degradation of habitats that support treaty fish and shellfish, which they attribute to "a lack of coordinated federal leadership, a failure to exercise authorities, and the disparate application of salmon conservation measures" (Treaty Indian Tribes in Western Washington, 2011). Many tribes have research and conservation programs aimed at restoring habitat functions in the rivers and estuaries that flow into the Salish Sea. They also support marine shoreline and nearshore protection and implement restoration actions such as removal of shoreline armoring and creosote logs, and conducting native oyster restoration projects. For these same reasons, an industry that is potentially ecologically beneficial, such as kelp mariculture, may be of interest to tribal governments.

Developing a Monitoring Framework

Monitoring and evaluating outcomes is a key element of any adaptive management process. The absence of regionally specific data on the ecological impacts or benefits of kelp farming generates uncertainty for resource managers, farmers, and the general public. In light of this uncertainty, further development of the kelp mariculture industry requires the development of a transparent and collaborative monitoring framework based on the best available science. We recognize that monitoring entails a significant burden of both time and resources, but an investment in monitoring can yield valuable information about ecological impacts and economic efficiency that might inform specific regulatory requirements and broader public perceptions related to kelp farming. We also recognize the difference between monitoring that is required by regulators, and monitoring that farmers voluntarily conduct to improve their own farm operations or social license.

Key Process Considerations

Concerns about information-gathering and decision-making processes often underpin social license challenges for marine industries and a lack of trust in regulatory agencies (Uffman-Kirsch et al., 2020). Given the inherent social and political complexity of siting private commercial activities within public waters and the particular challenges of balancing multiple uses of marine space in the Salish Sea (Eichenberg and Vestal, 1992; Marston, 1996), questions about the who, why, and how of monitoring are perhaps even more important than questions about what to monitor. A monitoring framework for kelp mariculture in the region should emerge through a participatory process that engages researchers and regulators, fosters industry accountability, respects tribal sovereignty, and ensures equity and access—particularly for historically excluded groups (LaFrance and Nich-

ols, 2008; Mertens, 2008). The framework should also identify roles and responsibilities for implementing and funding each aspect of monitoring, craft rules about collecting, analyzing, storing, and sharing monitoring data, and consider how monitoring data will be used to inform management recommendations. For example, the framework should distinguish between minimum required monitoring for regulatory and permitting purposes versus voluntary monitoring to assess industry objectives or address community concerns. For guiding principles and key questions to consider when establishing a monitoring framework for kelp mariculture, refer to Table 7. This topic, as well as larger policy recommendations, is addressed in greater detail by The Nature Conservancy's Principles of Restorative Aquaculture (TNC, 2021).

Key Elements to Monitor

Based on the potential environmental impacts we previously identified and the remaining research gaps and uncertainties, we recommend, at a minimum, monitoring the following four elements: 1) water quality, 2) species assemblages, 3) hydrology, and 4) kelp genetics. Within each of these elements, some aspects will be more important from a regulatory perspective (i.e., required), while others will matter more from an industry or community perspective (i.e., voluntary). For required monitoring, farmers should work with regulators in advance to determine the bounds and scope of monitoring activities at their farm and come to a written agreement. As elaborated below, more comprehensive monitoring should be pursued by partnerships among local, state, and federal permitting agencies, NGO's, and academic institutions to develop monitoring regimes appropriately scaled for individual sites and operations.

First, measuring changes from baseline water quality in and around kelp farms will be important for ensuring crop health and product safety, monitoring impacts on ambient nutrient levels, and providing empirical evi-

dence of the water quality improvements expected from kelp mariculture. We suggest required monitoring for water quality parameters related to potential ecological impacts (e.g., dissolved inorganic nitrogen) and public health (e.g., heavy metals, pathogenic bacteria (Lovdal et al., 2021)), and voluntary monitoring for parameters indicating potential benefits of public and/or academic interest (e.g., pH, pCO₂). Potential parameters of water quality to measure are listed in Table 8.

Second, to evaluate the habitat impacts of kelp mariculture, monitoring should include surveys of species assemblages in, around, and below farm sites (reviewed in depth by Corrigan et al., 2022). Species presence and abundance on farm sites could be measured in an absolute sense, or in comparison to baseline conditions or to adjacent areas. Methods might include dive surveys, underwater cameras, eDNA, benthic grabs, or other methods. The most appropriate methods will likely be informed by the intended purpose and audience for monitoring. For example, underwater cameras could yield footage that is valuable for enhancing social license and communicating with the public, while simultaneously providing required and/or useful information to regulators and/or researchers. We also recommend mandatory reporting of any interactions with protected species, such as marine mammal presence or entanglement, forage fish spawning, salmon migration, or changes in submerged aquatic vegetation.

Farm hydrology monitoring should be considered by farmers, including collecting baseline and ongoing data on water depth, wave exposure/velocity, tidal gauge, and substrate to document the potential hydrological impacts of kelp mariculture, as well as better understand and track farm conditions. Regulators and researchers may consider additional data collection, in conjunction with the above, on shoreline slope, exposure, and substrate. These data could clarify the potential for kelp farms to protect the shoreline from storms or vessel traf-

fic. Finally, as a complement to the wild kelp bed monitoring proposed in the Kelp Conservation and Recovery Plan (Calloway et al., 2020), at a minimum kelp farmers should be required to document the location of sori material they use for seed. It might also be helpful for researchers, regulators, and farmers to maintain a seed bank or preserved DNA of harvested sori and kelp crops from different locations to document existing genetic diversity and to track any changes in genotype or phenotype over time (e.g., disease susceptibility, temperature tolerance, etc.). Ideally, this would allow regulators to monitor potential impacts to wild kelp beds as well as facilitate the development of domesticated seed stock by farmers. We recommend seed source documentation as the first priority in developing biosecurity practices for this emerging industry. Biosecurity measures are a critical component of successful mariculture as they aim to prevent, identify, control, and minimize the spread of pathogen and pest infestations among farms, and prevent impacts on surrounding ecosystems. Practices such as farm hygiene, inspection, laboratory testing, quarantine, and rigorous permitting regulations and procedures for import and transplant are common in shellfish and finfish aquaculture and may be similarly developed for seaweed cultivation as a better understanding of pest and pathogen risks for these species emerge.

Other Future Considerations

Co-culture and Polyculture

Interest is increasing in various forms of kelp co-culture and polyculture, which is the cultivation of several commercial marine species within the same structure or farm site. Integrated multi-trophic aquaculture (IMTA) in particular has been proposed as an innovative "ecosystem approach" to maximizing ecological benefits and diversifying commercial opportunities in mariculture (Langton et al., 2019). IMTA systems cultivate primary producers (e.g., seaweeds) to re-

Table 7.—Guiding principles and questions to consider for the development of a kelp mariculture monitoring framework.

Framework component	Guiding principles	Key questions
Participation	Diversity Inclusion Power	Which entities and/or individuals have a stake in industry development? (industry, researchers, tribes, NGOs) Who might be affected by industry development? (residents, workers, recreational users, tribes) Which groups have traditionally been excluded? (groups historically excluded based on race, ethnicity, language, class, education, etc.) Which individuals/organizations have decision-making power in the regulatory and proprietary process? (federal and state regulators, local regulators, tribes)
Roles	Cost/benefits Conflicts of interest Equity	Who is responsible for collecting the data? Who is responsible for analyzing the data? Who is responsible for storing the data? How will these different monitoring activities be funded, and by whom?
Protocols	Access Information Resources	How should monitoring data be collected and analyzed? Knowledge systems (e.g. Western science, Indigenous science, citizen science) Methods (e.g. quantitative tools, indicators and metrics; qualitative tools, indicators and metrics) Frequency (e.g. continuously, monthly, seasonally, annually) Spatial scale (e.g. acre, farm, basin, etc.) How will the results of monitoring be shared, and with whom (e.g. industry, regulators, tribes, researchers, the public)? Who should have direct access to monitoring data (e.g. farmers, regulators, tribes, researchers)? What are the allowable changes from background or control sites that are allowed? What accuracy and precision is required and the required sampling design? Are these changes attributable to the farm or other causes? How will this fit into a “no net loss” requirement?
Recommendations	Adaptive management	How will monitoring data be used to inform management decisions?

cycle the nitrogenous wastes of consumer species (e.g., finfish and shellfish) while also providing particulate organic matter (POM) to filter feeders (e.g., shellfish) (Miller and Page, 2012; Langton et al., 2019). By utilizing the nutrients contained in the waste products of one species as a feed input for another, IMTA systems mitigate some of the environmental impacts of finfish mariculture and could boost farm profitability by reducing inputs and increasing crop biomass. Co-culture has previously been particularly successful with abalone and non-kelp macroalgae species such as dulse and sometimes *Ulva lactuca* (Evans and Langdon, 2000; Demetropoulos and Langdon, 2004; Langdon et al., 2004; Hamilton et al., 2022), in this case co-culturing the seaweed as direct feed for the invertebrate species as well as nitrogenous waste recycling.

Within temperate regions, such as the Salish Sea, the co-culture of kelp and bivalves may be a good entry point into kelp farming, particularly for already established shellfish farmers (Granada et al., 2018; Langton et al., 2019). Although bivalves are typically grown in shallower water than

is recommended for most kelp species, sugar kelp can be cultivated in as little as 1.5 ft of water (Greenwave, 2021; Jiang et al., 2022), making this species a possible candidate for co-culture with bivalves like oysters. Co-culturing is often done on the same line, or on separate lines in close proximity to each other, thus most of our farm design guidance could also apply to co-culture systems. With the inclusion of kelp/seaweed IMTA systems in the new nationwide permit for seaweed mariculture (ACOE, 2021), co-culture systems are a worthwhile area of experimentation and further research in the Salish Sea.

Hybrid Models of Mariculture

Though we have focused on commercial kelp mariculture in this paper, hybrid industry models that combine commercial mariculture with restoration, bioremediation, or mitigation warrant further consideration (see Mizuta et al., 2022 for definitions of aquaculture for environmental purposes). For example, as part of a commercial/restoration hybrid approach, kelp farms could be established in areas where kelp loss has occurred and

Table 8.—Potential water quality indicators to include in a kelp farming monitoring framework.

Purpose	Parameter
Crop health	Temperature Salinity DIN (nitrate, nitrite, ammonia) Phosphorus Turbidity
Human health	Fecal coliform Lead Cadmium Mercury Inorganic arsenic Iodine <i>Vibrio</i> spp. <i>Bacillus</i> spp. <i>Aeromonas</i> spp.
Ecological health	Dissolved inorganic nutrients Dissolved oxygen Chlorophyll-a pH pCO ₂

farmers could leave some kelp crop with reproductive material on the lines to help repopulate kelp beds. Balancing commercial and restoration goals in this manner, however, would require careful research on the population genetics of this region’s native kelp, the establishment of a seed stock distribution program, and thoughtful partnership between farmers and

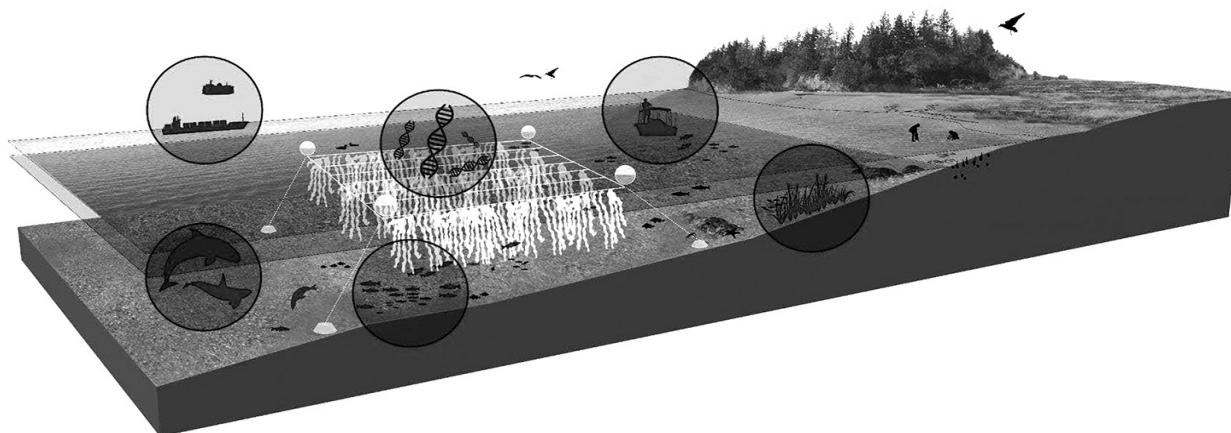


Figure 2.—Schematic of aquatic phase for floating long-line kelp mariculture with the marine interactions of most significance for the Salish Sea indicated: tribal subsistence and commercial fishing, shipping, benthic vegetation (such as eelgrass), forage fish habitat and spawning events, marine mammal entanglement risk, and wild stock genetic diversity.

conservation agencies (Mizuta et al., 2022).

Similarly, kelp mariculture could be sited in areas with excessive nutrients or other water quality issues to aid in bioremediation while simultaneously boosting crop production. The nature of water quality issues at specific sites could limit use of the kelp crop if the targets for bioremediation are harmful to human or animal health. Thus, both careful coordination between farmers and regulators working in environmental and public health and more diverse markets for local kelp products would be necessary (The Nature Conservancy, 2021).

Payment for Ecological Services

Previous studies have modeled the potential effects of seaweed mariculture on hypoxic conditions, ocean acidification, carbon sequestration (Froehlich et al., 2019), and nutrient pollution (Racine et al., 2021) under different scenarios. However, there is significant criticism of the idea that kelp farms could serve as a climate “fix,” particularly due to the lack of evidence that seaweed could be used as a true carbon “sink” or method for sequestration (Troell et al., 2022), challenging hopes for carbon offsets funds as a potential economic framework for the industry. It is likely more beneficial

to utilize a local monitoring framework (such as outlined above) for the industry to build stronger empirical evidence for ecological services (listed in the Potential Ecological Impacts section) provided by kelp farming, and explore the value of those services for potential future payment or subsidies. Understanding how these services may extend beyond the local marine environment, such as offsetting carbon through product replacements for animal feed, fertilizers, bioenergy, etc. (Troell et al., 2022) would be an additional important consideration.

Land-based Culture Operations

Although this paper focuses primarily on open-water culture, land-based culture merits mention, as this approach offers some specific advantages, and avoids a few important potential challenges with kelp farming in open water, namely cetacean entanglement and concerns for genetic effects on local populations. Land-based systems, lacking ropes and other submerged gear in the marine environment, do not pose the same hazards to marine mammals of open-water culture, and allow for sterile, filtered effluent, minimizing genetic contamination and other risks. Including land-based culture among the potential continuum of intensive and extensive kelp

farming and harvest methods could also reduce pressure on wild kelp beds and their associated ecosystems.

Among some of the direct advantages, land-based operations allow for more controlled growing conditions; they may in some cases enable year-round production, high control over quality and product value, enable alteration to morphology and size, can limit or eliminate biofouling, and could avoid introduction of chemical contaminants through influent water treatment (Hafting et al., 2012; Mata et al., 2016; Pereira et al., 2024). Entirely land-based growout operations can also use a variety of culture techniques through harvest, focus on rapid growth, often emphasizing asexual, vegetative reproduction. Land-based operations include hatcheries, which could potentially be used to produce sterile cultivars for later grow-out in more traditional open water farms (Goecke et al., 2020; Vissers et al., 2023). A land-based operation can treat effluent to prevent release of products that could lead to wild reproduction and genetic contamination, decreasing the risk of overwhelming wild stock compositions and diversity reduction or hybridization with, and introgression into, local populations.

The inherently more intensive nature of land-based culture is responsi-

ble not only for many of its advantages, but also incurs specific costs and responsibilities. Additional costs of potentially high energy use, facilities and equipment needs, intensive water treatment, together with some species-specific volume and flow requirements reduce land-based systems application to certain species, life stages, and locations. Significant treatment may be necessary to make incoming water suitable as a culture medium, as well as waste-water treatment to prevent chemical (although seaweeds are well-suited at minimizing nutrient load before effluent release) and biological pollution, prevent transmission of diseases, and prevent spread of introduced species from effluent (Matson et al., 2006; Hafting et al., 2012; Pereira et al., 2024). Monitoring may be necessary to ensure and document success of those goals, and regulatory compliance.

Although many species of red, green, and brown macroalgae have successfully been grown in land-based systems (Evans and Langdon, 2000; Demetropoulos and Langdon, 2004; Langdon et al., 2004; Pang et al., 2009; Hamilton et al., 2022; Moreira et al., 2022), both in research and commercial production (given advantages of their particularly plastic morphology), kelp species are comparatively rare in land-based culture and may present specific challenges. However, there are reports of successful tumble culture of cold water kelp species in the United States (Redmond et al., 2014) and potential for tank culture of kelp species (Purcell-Meyerink et al., 2021).

Conclusion

Kelp farming has generated considerable interest in recent years, both locally and nationally, sparking the need for comprehensive evaluations of the industry's impact on local ecosystems. Here, we provide an initial review of potential kelp farming impacts for the Salish Sea, and recommendations for how to begin this commercial practice so as to maximize those benefits and minimize potential harms. Due to a lack of regionally-specific informa-

tion, we looked broadly at kelp farming practices across the world to inform our recommendations, in addition to considering some socio-ecological issues unique to the Salish Sea.

We found that in general, kelp farming poses few risks to the natural environment, and indeed, may provide many benefits to the surrounding system. However, we recommend careful consideration of native eelgrass beds and other marine vegetation, whale migration and feeding areas, forage fish spawning areas, and native stock availability for sourcing seed when developing farming projects. We also note that following outlined recommendations would not necessarily ensure receiving local, state, and federal authorizations for particular farms. To this end, spatial planning tools, and analyzes similar to Aquaculture Opportunity Areas in Southern California and the Gulf of Mexico (NOAA, 2020), are needed to help guide regulators and potential farmers in determining ideal site locations. In addition to ecological considerations, it is critical that potential farmers coordinate or partner with tribes early on to reduce any potential conflict with usual and accustomed area fisheries (key considerations are summarized in Figure 2). We recommend prioritizing siting farms in areas with pre-existing infrastructure or with low fisheries activity to minimize potential conflicts. With these considerations in mind, we believe that kelp farming may have a promising future in the Salish Sea but will require monitoring and an adaptive management approach to foster social acceptance and economic viability.

Acknowledgments

Many people and entities provided valuable contributions to this work, including Jodie Toft, Betsy Peabody, Hilary Hayford, Brian Allen, Paul Dobbins, Tiffany Waters, Molly Bogeborg, Dan Lawson, Jeff Bash, Morgan Arrington, Laura Hoberecht, the Puyallup Tribe, Nisqually Tribe, Squaxin Island Tribe, Samish Tribe, Skokomish Tribe, Swinomish Tribe, Port Gamble

S'klallam, Jamestown S'klallam Tribe, Washington Department of Natural Resources, NMFS West Coast Region, NMFS Northwest Fisheries Science Center, and NMFS Office of Aquaculture. Special gratitude to Hannah Garfield for creating the kelp farm schematic in Figure 2 and Tom Mumford who provided extensive feedback and guidance at numerous points throughout the multi-year process of creating this paper.

Literature Cited

- Ahn, O., R. J. Petrell, and P. J. Harrison. 1998. Ammonium and nitrate uptake by *Laminaria saccharina* and *Nereocystis luetkeana* originating from a salmon sea cage farm. *J. Appl. Phycol.* 10(4):333–340 (doi: <https://doi.org/10.1023/A:1008092521651>).
- Allyn, E. M., and J. J. Scordino. 2020. Entanglement rates and haulout abundance trends of Steller (*Eumetopias jubatus*) and California (*Zalophus californianus*) sea lions on the north coast of Washington state. *Plos One* 15(8):e0237178. (doi: <https://doi.org/10.1371/journal.pone.0237178>).
- Andrews, K. S., K. M. Nichols, A. Elz, N. Tomlimieri, C. J. Harvey, R. Pacunski, D. Lowry, K. L. Yamanaka, and D. M. Tonnes. 2018. Cooperative research sheds light on population structure and listing status of threatened and endangered rockfish species. *Conserv. Gen.* 19(4):865–878 (doi: <https://doi.org/10.1007/s10592-018-1060-0>).
- Aquatic Resources Division (ARD). 2014. Appendix J. Technical memorandum: Operational definition of an eelgrass (*Zostera marina*) bed. Aquatic Lands Habitat Conservation Plan. Wash. Dep. Nat. Resour., Olympia, Wash. J1–J34 (https://file.dnr.wa.gov/publications/aqr_hcp_2014_app_j_defn_eelgrass_beds.pdf).
- Army Corps of Engineers (ACOE). 2021. Nationwide Permit 55 - Seaweed Mariculture Activities: Effective March 15, 2021, Expiring March 15, 2026. NWP Final Notice, 86 FR 2744 (<https://www.swt.usace.army.mil/Portals/41/docs/missions/regulatory/2021%20NWP/2021%20nwp-55.pdf?ver=QHdBSNNveAV9quZKFHcoeQ%3D%3D>).
- Assink, R. 2019. Humpback whale (*Megaptera novaeangliae*) entanglements in commercial fishing gear on the U.S. west coast: Implications for management and stock structure under the Marine Mammal Protection Act. Ph.D. Dissertation. Univ. Wash., Seattle, Wash. (<http://hdl.handle.net/1773/44354>).
- Augyte, S., C. Yarish, S. Redmond, and J. K. Kim. 2017. Cultivation of a morphologically distinct strain of the sugar kelp, *Saccharina latissima* forma *angustissima*, from coastal Maine, USA, with implications for ecosystem services. *J. Appl. Phycol.* 29(4):1967–1976 (<https://doi.org/10.1007/s10811-017-1102-x>).
- Azra, M. N., V. T. Okomoda, and M. Ikhwanuddin. 2022. Breeding technology as a tool for sustainable aquaculture production and ecosystem services. *Front. Mar.*

- Sci. 9:679529 (<https://doi.org/10.3389/fmars.2022.679529>).
- Barbier M., B. Charrier, R. Araujo, S. L. Holdt, B. Jacquemin, and C. Rebours. 2019. Pegasus: Phycormorph European guidelines for a sustainable aquaculture of seaweeds. European Corp. Sci. Tech., Roscoff, France. Phycormorph COST Action FA1406 (<https://doi.org/10.21411/2c3w-yc73>).
- Barberi, O. N., C. J. Byron, K. M. Burkholder, A. T. St. Gelais, and A. K. Williams. 2020. Assessment of bacterial pathogens on edible macroalgae in coastal waters. *J. Appl. Phycol.* 32:683–696 (<https://doi.org/10.1007/s10811-019-01993-5>).
- Bartsch, I., C. Wiencke, K. Bischof, C. M. Buchholz, B. H. Buck, A. Eggert, P. Feuerpfel, D. Hanelt, S. Jacobsen, R. Karez, and U. Karsten. 2008. The genus *Laminaria sensu lato*: recent insights and developments. *European J. Phycol.* 43(1):1–86 (<https://doi.org/10.1080/09670260701711376>).
- Barrett, L. T., S. J. Theuerkauf, J. M. Rose, H. K. Alleway, S. B. Bricker, M. Parker, M., D. R. Petrolia, and R. C. Jones. 2022. Sustainable growth of non-fed aquaculture can generate valuable ecosystem benefits. *Ecosyst. Serv.* 53:101396 (<https://doi.org/10.1016/j.ecoser.2021.101396>).
- Bergdahl, J. C. 1990. Nori (*Porphyra* C. Ag.: Rhodophyta) mariculture research and technology transfer along the northeast Pacific coast. In Akatsuka, I. (Editor), *Introduction to Applied Phycology*, p. 519–551. SPD Acad. Publ., The Hague, Netherlands.
- Berry H., M. Calloway, and J. Ledbetter. 2019. Bull kelp monitoring in South Puget Sound in 2017 and 2018. *Wash. Dep. Nat. Resour., Nearshore Habitat Prog.* Olympia, WA (https://www.dnr.wa.gov/publications/aqr_nrsh_bullkelp_sps_2019.pdf).
- Berry, H. D., T. F. Mumford, B. Christiaen, P. Dowty, M. Calloway, L. Ferrier, E. E. Grossman, and N. R. VanArendonk. 2021. Long-term changes in kelp forests in an inner basin of the Salish Sea. *Plos One* 16(2):e0229703 (<https://doi.org/10.1371/journal.pone.0229703>).
- Bishop A., H. Wilson, M. Morris, G. Pryor, R. Budnik, C. Brady, A. Miller, and B. Smith. 2021. A guide to aquaculture permitting in Alaska. Alaska Sea Grant, Juneau, AK (avail. at <https://media.fisheries.noaa.gov/2021-11/Alaska-Aquaculture-Permitting-Guide.pdf>).
- Blasco N. 2012. Kelp culture in integrated multi-trophic aquaculture: expanding the temporal limitations. Ph. D. Dissert., Univ. Victoria, Victoria, B.C., Canada (avail. at <http://hdl.handle.net/1828/3996>).
- Bruhn, A., D. B. Tørring, M. Thomsen, P. Canal-Vergés, M. M. Nielsen, M. B. Rasmussen, K. L. Eybye, M. M. Larsen, T. J. S. Balsby, and J. K. Petersen. 2016. Impact of environmental conditions on biomass yield, quality, and bio-mitigation capacity of *Saccharina latissima*. *Aquacult. Environ. Inter.* 8:619–636 (avail. at <https://doi.org/10.3354/aei00200>).
- Buonaccorsi, V. P., C. A. Kimbrell, E. A. Lynn, and R. D. Vetter. 2002. Population structure of copper rockfish (*Sebastes caurinus*) reflects postglacial colonization and contemporary patterns of larval dispersal. *Can. J. Fish. Aquat. Sci.* 59(8):1,374–1,384 (<https://doi.org/10.1139/f02-101>).
- _____, _____, _____, and _____. 2005. Limited realized dispersal and introgressive hybridization influence genetic structure and conservation strategies for brown rockfish, *Sebastes auriculatus*. *Conserv. Genetics* 6(5):697–713 (<https://doi.org/10.1007/s10592-005-9029-1>).
- Burns, R. E. 1985. The shape and form of Puget Sound. Univ. Wash. Press, Seattle, Wash. (avail. at <https://repository.library.noaa.gov/view/noaa/39773>).
- Buschmann, A. H., C. Camus, J. Infante, A. Neri, Á. Israel, M. C. Hernández-González, S. V. Pereda, J. L. Gomez-Pinchetti, A. Golberg, N. Tadmor-Shalev, and A. T. Critchley. 2017. Seaweed production: overview of the global state of exploitation, farming and emerging research activity. *European J. Phycol.* 52(4):391–406 (<https://doi.org/10.1080/09670262.2017.1365175>).
- Calambokidis, J., G. H. Steiger, C. Curtice, J. Harrison, M. C. Ferguson, E. Becker, M. DeAngelis, and S. M. Van Parijs. 2015. 4. Biologically important areas for selected cetaceans within U.S. waters-west coast region. *Aquat. Mamm.* 41(1):39 (<https://doi.org/10.1578/AM.41.1.2015.39>).
- Calloway M., D. Oster, T. Mumford, H. Berry, D. Tonnes, N. Naar, S. Copps, J. Selleck, B. Peabody, J. Toft, B. Allen, and L. Hart. 2020. Puget Sound kelp conservation and recovery plan. Prepared for NOAA-NMFS. Seattle, WA (avail. at https://www.nwstraits.org/media/2880/pugetsoundkelpconservationandrecoveryplan_public_review_draft_1219.pdf).
- Camara, M. D., and B. Vadopalas. 2009. Genetic aspects of restoring Olympia oysters and other native bivalves: balancing the need for action, good intentions, and the risks of making things worse. *J. Shellfish. Res.* 28(1):121–145 (<https://doi.org/10.2983/035.028.0104>).
- Campbell, I., A. Macleod, C. Sahlmann, L. Neves, J. Funderud, M. Øverland, A. D. Hughes, and M. Stanley. 2019. The environmental risks associated with the development of seaweed farming in Europe-prioritizing key knowledge gaps. *Front. Mar. Sci.* 6:107 (<https://doi.org/10.3389/fmars.2019.00107>).
- Carney, L. T., J. R. Waaland, T. Klinger, and K. Ewing. 2005. Restoration of the bull kelp *Nereocystis luetkeana* in nearshore rocky habitats. *Mar. Ecol. Prog. Ser.* 302:49–61 (<https://doi.org/10.3354/meps302049>).
- Carson, H. S., and M. Ulrich. 2019. Status report for the pinto abalone in Washington. *Wash. Dep. Fish Wildl., Olympia, WA* (avail. at <https://wdfw.wa.gov/publications/02031#:~:text=Due%20to%20the%20windling%20numbers,in%20the%20state%20of%20Washington>).
- Christie, H., K. M. Norderhaug, and S. Fredriksen. 2009. Macrophytes as habitat for fauna. *Mar. Ecol. Prog. Ser.* 396:221–233 (<https://doi.org/10.3354/meps08351>).
- Community Attributes, Inc. 2019. The Northwest Seaport Alliance: Marine Cargo Economic Impact Analysis. Community Attributes, Inc. Seattle, WA (avail. at https://www.portseattle.org/sites/default/files/2019-01/CAI_NWSA_Marine_Cargo_Economic_Impacts_190122.pdf).
- Conroy, K., D. Tonnes, N. Naar, K. Page, and B. Peabody. 2023. Shoreline Master Programs: A hindrance or help to kelp conservation in Puget Sound? *Mar. Policy* 155:105771 (<https://doi.org/10.1016/j.marpol.2023.105771>).
- Corrigan, S., A. R. Brown, I. G. Ashton, D. A. Smale, and C. R. Tyler. 2022. Quantifying habitat provisioning at macroalgal cultivation sites. *Reviews in Aquaculture*. (<https://doi.org/10.1111/raq.12669>).
- Dayton, P. K. 1985. Ecology of kelp communities. *Annual review of ecology and systematics*, p. 215–245 (avail. at <https://www.jstor.org/stable/2097048>).
- Demetropoulos, C. L., and C. J. Langdon. 2004. Enhanced production of Pacific dulse (*Palmaria mollis*) for co-culture with abalone in a land-based system: nitrogen, phosphorus, and trace metal nutrition. *Aquaculture*, 235(1–4):433–455. (<https://doi.org/10.1016/j.aquaculture.2003.09.010>).
- Dimond, J. L., J. V. Bouma, H. S. Carson, M. R. Gavry, C. O'Brien, C. Simchick, and K. Sowul. 2022. Efficacy of endangered pinto abalone (*Haliotis kamtschatkana*) stock restoration in the southern Salish Sea from a genomic perspective. *Frontiers in Conservation Science*, p. 52 (<https://doi.org/10.3389/fcsc.2022.911218>).
- _____, R. N. Crim, E. Unsell, V. Barry, and J. E. Toft. 2022. Population genomics of the basket cockle *Clinocardium nuttallii* in the southern Salish Sea: Assessing genetic risks of stock enhancement for a culturally important marine bivalve. *Evol. Appl.* 15(3):459–470.
- Downing, J. 1983. The coast of Puget Sound and its processes and development. Univ. Wash. Press, Seattle, WA.
- Druehl, L. D. 1980. The development of an edible kelp culture technology for British Columbia: I, preliminary studies. *Mar. Resour. Branch, Province of British Columbia, Victoria, British Columbia, Canada*.
- _____, and B. E. Clarkston. 2016. Pacific seaweeds: A guide to common seaweeds of the West Coast. 2nd ed. Harbour Publ., Madeira Park, B.C., Canada.
- Duarte, C. M., J. Wu, X. Xiao, A. Bruhn, and D. Krause-Jensen. 2017. Can seaweed farming play a role in climate change mitigation and adaptation? *Frontiers Mar. Sci.* 4:100 (<https://doi.org/10.3389/fmars.2017.00100>).
- Egan, T. 1988. Guemes Island journal; Will seaweed farming mean paradise lost or kept? *The New York Times*, National ed., Sect. A:14. New York City, NY. (avail. at <https://www.nytimes.com/1988/03/09/us/guemes-island-journal-will-seaweed-farming-mean-paradise-lost-or-kept.html?smid=url-share>).
- Eichenberg, T., and B. Vestal. 1992. Improving the legal framework for marine aquaculture: the role of water quality laws and the public trust doctrine. *Terr. Sea. J.* 2:339 (<https://heinonline.org/HOL/LandingPage?handle=hein.journals/ttsea2&div=17&id=&page=>).
- Elliott Smith, E. A., and M. D. Fox. 2022. Characterizing energy flow in kelp forest food webs: a geochemical review and call for additional research. *Ecography* 2022(6):e05566 (<https://doi.org/10.1111/ecog.05566>).
- Environmental Response Management Application (ERMA) Northwest. Puget Sound Basins. NOAA's Ocean Service [accessed 2022 October 5]. Seattle, WA (avail. at <https://erma.noaa.gov/northwest#x=->

- 123.24443&y=48.21955&z=8.7&layers=1+7531&panel=legend).
- Erlandson, J. M., M. H. Graham, B. J. Bourque, D. Corbett, J. A. Estes, and R. S. Steeneck. 2007. The kelp highway hypothesis: marine ecology, the coastal migration theory, and the peopling of the Americas. *The Journal of Island and Coastal Archaeology*, 2(2):161–174 (doi: <https://doi.org/10.1080/15564890701628612>).
- _____, T. J. Braje, K. M. Gill, and M. H. Graham. 2015. Ecology of the kelp highway: did marine resources facilitate human dispersal from Northeast Asia to the Americas?. *The Journal of Island and Coastal Archaeology*, 10(3):392–411 (doi: <https://doi.org/10.1080/15564894.2014.1001923>).
- Evans, F., and C. J. Langdon. 2000. Co-culture of dulse *Palmaria mollis* and red abalone *Haliotis rufescens* under limited flow conditions. *Aquaculture*, 185(1–2):137–158 (doi: [https://doi.org/10.1016/S0044-8486\(99\)00342-7](https://doi.org/10.1016/S0044-8486(99)00342-7)).
- Favaro, B., D. T. Rutherford, S. D. Duff, and I. M. Côté. 2010. Bycatch of rockfish and other species in British Columbia spot prawn traps: Preliminary assessment using research traps. *Fisheries Research*, 102(1–2):199–206 (doi: <https://doi.org/10.1016/j.fishres.2009.11.013>).
- Feng, Z., T. Zhang, H. Shi, K. Gao, W. Huang, J. Xu, J. Wang, R. Wang, J. Li, and G. Gao. 2020. Microplastics in bloom-forming macroalgae: Distribution, characteristics and impacts. *J. Hazardous Materials* 397:122752 (doi: <https://doi.org/10.1016/j.jhazmat.2020.122752>).
- Filippini, M., A. Baldisserotto, S. Menotta, G. Fedrizzi, S. Rubini, D. Gigliotti, G. Valpiani, R. Buzzi, S. Manfredini, and S. Vertuani. 2021. Heavy metals and potential risks in edible seaweed on the market in Italy. *Chemosphere* 263:127983 (doi: <https://doi.org/10.1016/j.chemosphere.2020.127983>).
- Flavin, K., N. Flavin, and B. Flahive. 2013. Kelp farming manual: A guide to the processes, techniques, and equipment for farming kelp in New England waters. Ocean Approved, Biddeford, ME. (avail. at https://www.researchgate.net/publication/311946411_Kelp_Farming_Manual_a_Guide_to_the_Processes_Techniques_and_Equipment_for_Farming_Kelp_in_New_England_Waters).
- Forbes, H., V. Shelamoff, W. Visch, and C. Layton. 2022. Farms and forests: evaluating the biodiversity benefits of kelp aquaculture. *J. Appl. Phycology*, p. 1–9 (doi: <https://doi.org/10.1007/s10811-022-02822-y>).
- Freitag, G. 2017. Seaweed Farming in Alaska. Alaska Sea Grant Marine Advisory Program, Ketchikan, AK. Report No: ASG-63 (avail. at <https://doi.org/10.4027/sfa.2017>).
- Fresh K., M. Dethier, C. Simenstad, M. Logsdon, H. Shipman, C. Tanner, T. Leschine, T. Mumford, G. Gelfenbaum, R. Shuman, and J. Newton. 2011. Implications of observed anthropogenic changes to the nearshore ecosystems in Puget Sound. Washington Department of Fish and Wildlife, Puget Sound Nearshore Ecosystem Restoration Project, Olympia, WA. Tech. Rep. 2011-03.
- Froehlich, H. E., J. C. Afflerbach, M. Frazier, and B. S. Halpern. 2019. Blue growth potential to mitigate climate change through seaweed offsetting. *Current Biol.* 29(18):3,087–3,093. (doi: <https://doi.org/10.1016/j.cub.2019.07.041>).
- Fu, G., J. Liu, G. Wang, J. Yao, X. Wang, and D. Duan. 2010. Early development of *Costaria costata* (*C. Agardh*) Saunders and cultivation trials. *Chinese Journal of Oceanology and Limnology* 28(4):731–737 (doi: <https://doi.org/10.1007/s00343-010-9051-0>).
- Gabrielson, P. W., T. B. Widdowson, and S. C. Lindstrom. 2006. Keys to the seaweeds and seagrasses of Southeast Alaska, British Columbia, Washington, and Oregon (No. 7). Phycological Contribution, University of British Columbia, Vancouver, British Columbia, Canada.
- Gentry, R. R., H. K. Alleway, M. J. Bishop, C. L. Gillies, T. Waters, and R. Jones. 2020. Exploring the potential for marine aquaculture to contribute to ecosystem services. *Reviews in Aquaculture* 12(2):499–512 (doi: <https://doi.org/10.1111/raq.12328>).
- Germann, I. 2011. Growth phenology of *Pleurophyucus Gardneri* (Phaeophyceae, Laminariales), a deciduous kelp of the northeast Pacific. *Canadian Journal of Botany* 64(11):2538–47 (doi: <https://doi.org/10.1139/b86-336>).
- Germann, I., L. D. Druehl, and H. Hoeger. 1987. Seasonal variation in total and soluble tissue nitrogen of *Pleurophyucus gardneri* (Phaeophyceae: Laminariales) in relation to environmental nitrate. *Mar. Bio.* 96, 413–423 (doi: <https://doi.org/10.1007/BF00412526>).
- Gierke, L. G. 2019. A seascape genetics approach to studying genetic differentiation in the bull kelp *Nereocystis luetkeana*. Ph. D. Dissertation. The University of Wisconsin-Milwaukee, Milwaukee, WI (avail. at <https://www.proquest.com/docview/2345864351?pq-origsite=gscholar&fromopenview=true>).
- Goecke, F., G. Klemetsdal, and Å. Ergon. 2020. Cultivar development of kelps for commercial cultivation—past lessons and future prospects. *Frontiers in Marine Science* 8:110 (doi: <https://doi.org/10.3389/fmars.2020.00110>).
- Granada, L., S. Lopes, S. C. Novais, and M. F. Lemos. 2018. Modeling integrated multi-trophic aquaculture: Optimizing a three trophic level system. *Aquaculture*, 495, 90–97 (doi: <https://doi.org/10.1016/j.aquaculture.2018.05.029>).
- Grebe, G. S., C. J. Byron, A. S. Gelais, D. M. Kotowicz, and T. K. Olson. 2019. An ecosystem approach to kelp aquaculture in the Americas and Europe. *Aquacult. Rep.* 15: 100215 (doi: <https://doi.org/10.1016/j.aqrep.2019.100215>).
- Greenwave. 2021. Oyster farmers in New York grow sugar kelp in just a few feet of water. Holdfast Blog, Greenwave, New York City, NY (avail. at <https://www.greenwave.org/holdfast-blog/shallow-water-kelp-farming-ny>).
- Gruenthal, K. M., and C. Habicht. 2022. Literature review for implementation of the 50-50 rule for cultivation of seaweeds and other aquatic plants in Alaska. Alaska Department of Fish and Game, Division of Commercial Fisheries. Anchorage, AK. Regional Information Report No. 2A22-01.
- Gutierrez, A., T. Correa, V. Munoz, A. Santibanez, R. Marcos, C. Cáceres, and A. H. Buschmann. 2006. Farming of the giant kelp *Macrocystis pyrifera* in southern Chile for development of novel food products. *In* Eighteenth International Seaweed Symposium (p. 33–41). Springer, Dordrecht (doi: https://doi.org/10.1007/978-1-4020-5670-3_5).
- Haagen, R. 2018 June 1. Entangled killer whale saved off B.C. coast. Abbotsford News, Abbotsford, British Columbia, Canada (<https://www.abbynews.com/news/entangled-killer-whale-saved-off-b-c-coast/>).
- Hafting, J. T., A. T. Critchley, M. L. Cornish, S. A. Hubley, and A. F. Archibald. 2012. On-land cultivation of functional seaweed products for human usage. *Journal of Applied Phycology* 24:385–392.
- Hahn, J. L., K. L. Van Alstyne, J. K. Gaidos, L. K. Wallis, J. E. West, S. J. Hollenhorst, G. M. Ylitalo, R. H. Poppenga, J. L. Bolton, D. E. McBride, and R. M. Sofield. 2022. Chemical contaminant levels in edible seaweeds of the Salish Sea and implications for their consumption. *PLoS One*, 17(9):e0269269 (<https://doi.org/10.1371/journal.pone.0269269>).
- Hamilton, S. L., M. S. Elliott, M. S. deVries, J. Adelaars, M. D. Rintoul, and M. H. Graham. 2022. Integrated multi-trophic aquaculture mitigates the effects of ocean acidification: Seaweeds raise system pH and improve growth of juvenile abalone. *Aquaculture* 560:738571 (doi: <https://doi.org/10.1016/j.aquaculture.2022.738571>).
- Hannam, M. P. 2013. The influence of multiple scales of environmental context on the distribution and interaction of an invasive seagrass and its native congener. Ph.D. Dissertation. University of Washington, Seattle, WA (avail. at <https://digital.lib.washington.edu/researchworks/handle/1773/23711>).
- Heare, J. E., B. Blake, J. P. Davis, B. Vadopalas, and S. B. Roberts. 2017. Evidence of *Ostrea lurida* Carpenter, 1864, population structure in Puget Sound, WA, USA. *Mar. Ecol.* 38(5):e12458.
- Hollarsmith, J. A., K. Andrews, N. Naar, S. Staroko, M. Calloway, A. Obaza, E. Buckner, D. Tonnes, J. Selleck, and T. W. Theriault. 2022. Toward a conceptual framework for managing and conserving marine habitats: A case study of kelp forests in the Salish Sea. *Ecol. Evol.* 12(1):e8510 (doi: <https://doi.org/10.1002/ece3.8510>).
- Huang, M., K. R. Robbins, Y. Li, S. Umanzor, M. Marty-Rivera, D. Bailey, C. Yarish, S. Lindell, and J. L. Jannink. 2022. Simulation of sugar kelp (*Saccharina latissima*) breeding guided by practices to accelerate genetic gains. *G3*, 12(3) (avail. at <https://academic.oup.com/g3journal/article/12/3/jkac003/6511442>).
- Hurtado, A. Q. 2022. Genetic resources for farmed seaweeds—thematic background study. FAO, Rome (doi: <https://doi.org/10.4060/cb7903en>).
- Imai, I., M. Yamaguchi, and Y. Hori. 2006. Eutrophication and occurrences of harmful algal blooms in the Seto Inland Sea, Japan. *Plankton and Benthos Research*, 1(2):71–84 (doi: <https://doi.org/10.3800/pbr.1.71>).
- Iwamoto, E. M., A. E. Elz, F. J. García-De León, C. A. Silva-Segundo, M. J. Ford, W. A. Pals-son, and R. G. Gustafson. 2015. Microsatellite DNA analysis of Pacific hake *Merluccius productus* population structure in the Salish Sea. *ICES J. Mar. Sci.* 72(9):2,720–2,731 (<https://doi.org/10.1093/icesjms/fsv146>).
- Jiang, L., H. M. Jansen, O. J. Broch, K. R. Tim-

- mermans, and K. Soetaert. 2022. Modelling spatial variability of cultivated *Saccharina latissima* in a Dutch coastal bay shows benefits of co-cultivation with shellfish. *ICES J. Mar. Sci.* 79:2,324–2,335 (doi: <https://doi.org/10.1093/icesjms/fsac176>).
- Jones and Stokes Associates. 2006 December. Overwater structures and non-structural piling white paper. Jones and Stokes Associates, Bellevue, WA. Prepared for Washington Department of Fish & Wildlife (avail. at <https://wdfw.wa.gov/sites/default/files/publications/00995/wdfw00995.pdf>).
- Jungwirth, J. 2019. Sustainable seaweed harvest methods. Naturespirit Herbs LLC, Williams, OR (avail. at <https://naturespiritherbs.com/sustainable-seaweed-harvest-methods/>).
- Kelkar, M., and K. Carden. 2022. Petition to list bull kelp under the U.S. Endangered Species Act. Center Biol. Diversity, Tucson, AZ, 27 p. (avail. at https://www.biologicaldiversity.org/species/plants/pdfs/Sept1_2022--Bull-Kelp-ESA-Listing.pdf).
- Kemper, C. M., D. Pemberton, M. Cawthorn, S. Heinrich, and J. Mann. 2003. Aquaculture and marine mammals: Co-existence or conflict? *In* N. Gales, M. Hindell, and R. Kirkwood (Editors), *Marine mammals: fisheries, tourism and management issues*, p. 208–228. CSIRO, Collingwood VIC, Australia (avail. at <http://www.monkeymiadolphins.org/wp-content/uploads/2019/10/Kemperetal2003.pdf>).
- Kim, J. K., G. P. Kraemer, and C. Yarish. 2015. Use of sugar kelp aquaculture in Long Island Sound and the Bronx River Estuary for nutrient extraction. *Marine Ecology progress series*, 531, p.155–166 (avail. at <https://doi.org/10.3354/meps11331>).
- Klein, Z. 2020 July 6. Vacatur of NWP 48 in Washington: Insights and implications. University (MS):Sea Grant Law Center (avail. at <https://seagrant.noaa.gov/Portals/0/Documents/SG%20Analysis%20of%20Order%20Vacating%20NWP%2048%20in%20WA.pdf>).
- _____. 2021. Exploring options for granting property rights to offshore aquaculture operations in the exclusive economic zone. *Sea Grant Law and Policy Journal* 11-1:15–69 (avail. at <https://nsglc.olemiss.edu/sglpj/vol11no1/sglpj11.1.pdf>).
- Klinger, T. 2015. The role of seaweeds in the modern ocean. *Perspect. Phycol.* 2:31–39 (doi: <https://doi.org/10.1127/pip/2015/0024>).
- Kumar, P. 2010. Valuation and of ecosystem services: An assessment of conceptual underpinnings. *In* T. Koizumi, K. Okabe, I. Thompson, K. Sugimura, T. Toma, and K. Fujita (Editors), *The role of forest biodiversity in the sustainable use of ecosystem goods and services in agro-forestry, fisheries, and forestry*, p. 29–35. (avail. at <https://hal.inrae.fr/hal-02752463/document#page=31>).
- LaFrance, J., and R. Nichols. 2008. Reframing evaluation: Defining an Indigenous evaluation framework. *Can. J. Prog. Eval.* 23(2):13–31 (doi: <https://doi.org/10.3138/cjpe.23.003>).
- Lambert, M. R., R. Ojala-Barbour, R. Vadas Jr., A. P. McIntyre, and T. Quinn. 2021. Small overwater structures: A review of effects on Puget Sound habitat and salmon. *Wash. Dep. Fish. Wildl.*, 31 p. (avail. at <https://wdfw.wa.gov/sites/default/files/publications/02289/wdfw02289.pdf>).
- Langdon, C., F. Evans, and C. Demetropoulos. 2004. An environmentally-sustainable, integrated, co-culture system for dulse and abalone production. *Aquacult. Eng.* 32(1):43–56 (doi: <https://doi.org/10.1016/j.aquaeng.2004.08.002>).
- Langton, R., S. Augyte, N. Price, J. Forster, T. Noji, G. Grebe, A. St. Gelais, and C. J. Byron. 2019. An ecosystem approach to the culture of seaweed. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-F/SPO-195, 24 p. (avail. at https://repository.library.noaa.gov/view/noaa/35734/noaa_35734_DS1.pdf).
- Laschever, E., K. Byrnes, C. Noufi, and K. Page. 2020. U.S. aquaculture's promise: policy pronouncements and litigation problems. *Environ. Law Rep.* 50(10):10,826–10,839 (avail. at <https://heinonline.org/HOL/Page?handle=hein.journals/elrn50&id=756&collection=journals&index=>).
- Lin, B. B. 2011. Resilience in agriculture through crop diversification: adaptive management for environmental change. *BioScience*, 61(3):183–193 (doi: <https://doi.org/10.1525/bio.2011.61.3.4>).
- Lind, A. 2016. Effects of rising sea surface temperature and decreasing salinity on kelps and associated macroalgal communities Thesis (M.S.) Univ. Alaska Fairbanks, 30 p. (avail. at <https://scholarworks.alaska.edu/handle/11122/6627>).
- Løvdal, B., T. Lunestad, M. Myrmed, J. T. Rosnes, and D. Skipnes. 2021. Microbiological food safety of seaweeds. *Foods* 10(11):2719 (doi: <https://doi.org/10.3390/foods10112719>).
- Lüning, K. 1991. *Seaweeds: their environment, biogeography, and ecophysiology*. Singapore: John Wiley and Sons, 527 p.
- _____. and L. Mortensen. 2015. European aquaculture of sugar kelp (*Saccharina latissima*) for food industries: iodine content and epiphytic animals as major problems. *Botanica Marina* 58(6):449–455 (doi: <https://doi.org/10.1515/bot-2015-0036>).
- Macchiavello, J., E. Araya, and C. Bulboa. 2010. Production of *Macrocystis pyrifera* (Laminariales; Phaeophyceae) in northern Chile on spore-based culture. *J. Appl. Phycol.* 22(6):691–697 (doi: <https://doi.org/10.1007/s10811-010-9508-8>).
- Marston, A. 1996. Aquaculture and the Public Trust Doctrine: Accommodating competing uses of coastal waters in New England. *Vt. Law Rev.* 21(1):335–374 (avail. at <https://heinonline.org/HOL/LandingPage?handle=hein.journals/vlr21&div=17&id=&page=>).
- Mata, L., M. Magnusson, N. A. Paul, and R. de Nys. 2016. The intensive land-based production of the green seaweeds *Derbesia tenuissima* and *Ulva ohnoi*: biomass and bio-products. *J. Appl. Phycol.* 28:365–375 (doi: <https://doi.org/10.1007/s10811-015-0561-1>).
- Matson, S. E., C. J. Langdon, and S. Evans. 2006. Specific pathogen free culture of the Pacific oyster (*Crassostrea gigas*) in a breeding research program: Effect of water treatment on growth and survival. *Aquaculture* 253(1–4):475–484 (doi: <https://doi.org/10.1016/j.aquaculture.2005.09.020>).
- Mao, X., S. Augyte, M. Huang, M. P. Hare, D. Bailey, S. Umanzor, M. Marty-Rivera, K. R. Robbins, C. Yarish, S. Lindell, and J. L. Jannink. 2020. Population genetics of sugar kelp throughout the Northeastern United States using genome-wide markers. *Front. Mar. Sci.* 7:694 (doi: <https://doi.org/10.3389/fmars.2020.00694>).
- Maxell, B. A., and K. A. Miller. 1996. Demographic studies of the annual kelps *Nereocystis luetkeana* and *Costaria costata* (Laminariales, Phaeophyta) in Puget Sound, Washington. *Botanica Marina* 39:479–489 (doi: <https://doi.org/10.1515/botm.1996.39.1-6.479>).
- Merrill, J. E., and D. M. Gillingham. 1991. Bull kelp cultivation handbook. U.S. Dep. Commer., NOAA, Natl. Coastal Resour. Res. Inst. Publ. NCRI-T-91-011, 70 p.
- Mertens, D. M. 2008. Transformative research and evaluation. Guilford Press, NY, 402 p.
- Miller H. 2020. Relating the distribution of humpback whales to environmental variables and risk exposure [thesis]. School of Mar. Environ. Affairs, Univ. Wash., Seattle, Wash. (avail. at <https://digital.lib.washington.edu/researchworks/handle/1773/46497>).
- Miller, R., and H. M. Page. 2012. Kelp as a trophic resource for marine suspension feeders: a review of isotope-based evidence. *Mar. Biol.* 159(7):1,391–1,402 (doi: <https://doi.org/10.1007/s00227-012-1929-2>).
- Milne, S. 2020. Will Northwest seaweed farming finally take off? Seattle Met, Nov. 16. (Digital) (avail. at <https://www.seattlemet.com/eat-and-drink/2020/11/will-northwest-seaweed-farming-finally-take-off-washington-seagrove-kelp/>).
- Mizuta, D. D., H. E. Froehlich, and J. R. Wilson. 2022. Perspectives: The changing role and definitions of aquaculture for environmental purposes. *The Nature Conservancy* (avail. at <https://www.nature.org/en-us/what-we-do/our-insights/perspectives/restorative-aquaculture-for-nature-and-communities/>).
- Mondragon, J., and J. Mondragon. 2010. Seaweeds of the Pacific Coast: common marine algae from Alaska to Baja California. *Sea Challengers Inc.*, Monterey, Calif., 97 p.
- Moreira, A., S. Cruz, R. Marques, and P. Cartaxana. 2022. The underexplored potential of green macroalgae in aquaculture. *Rev. Aquacult.* 14(1):5–26 (doi: <https://doi.org/10.1111/raq.12580>).
- Mouritsen, O. G. 2013. The science of seaweeds: marine macroalgae benefit people culturally, industrially, nutritionally, and ecologically. *Am. Sci.* 101(6):458–466 (avail. at <https://www.americanscientist.org/article/the-science-of-seaweeds>).
- Mumford, T. F. 2007. Kelp and eelgrass in Puget Sound. Seattle District, U.S. Army Corps Eng., Puget Sound Nearshore Partnership Rep. No. 2007-05, 27 p. (avail. at <https://wdfw.wa.gov/sites/default/files/publications/02195/wdfw02195.pdf>).
- Muth, A. F., M. H. Graham, C. E. Lane, and C. D. Harley. 2019. Recruitment tolerance to increased temperature present across multiple kelp clades. *Ecol. Soc. Am.* 100(3), 7 p. (doi: <https://doi.org/10.1002/ecy.2594>).
- Naar, N. 2020. Gaming anthropology: The problem of external validity and the challenge of interpreting experimental games. *Am. Anthropol.* 122(4):784–798 (doi: <https://doi.org/10.1111/aman.13483>).
- Napper, I. E., L. S. Wright, A. C. Barrett, F. N. Parker-Jurd, and R. C. Thompson. 2022. Potential microplastic release from the maritime industry: Abrasion of rope. *Sci. Tot-*

- tal Environ. 804:150155 (doi: <https://doi.org/10.1016/j.scitotenv.2021.150155>).
- NOAA. 2020. Aquaculture Opportunity Areas. 85 Fed. Regist. 67519 (23 Oct. 2020), p. 67,519–67,522 (avail. at <https://www.govinfo.gov/content/pkg/FR-2020-10-23/pdf/2020-23487.pdf>).
- NMFS. 2021. NOAA Fisheries Alaska fiscal year 2021 aquaculture accomplishments. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., 9 p. (avail. at <https://media.fisheries.noaa.gov/2021-09/2021-Alaska-Aquaculture-Accomplishments-Report.pdf>).
- _____. 2022a. Species Directory: California Sea Lion. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv. (avail. at <https://www.fisheries.noaa.gov/species/california-sea-lion>); last updated 21 April 2022, accessed 3 October 2022).
- _____. 2022b. Species Directory: Harbor Seal. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv. (avail. at <https://www.fisheries.noaa.gov/species/harbor-seal>); last updated 19 April 2022, accessed 3 October 2022).
- _____. 2022c. Species Directory: Steller Sea Lion. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv. (avail. at <https://www.fisheries.noaa.gov/species/steller-sea-lion>); last updated 19 September 2022, accessed 3 October 2022).
- Northwest Indian Fisheries Commission (NWIFC). 2014. Understanding tribal treaty rights in western Washington. NW Indian Fish. Commission, Olympia, Wash., 4 p. (avail. at <https://nwifc.org/wp-content/uploads/downloads/2014/10/understanding-treaty-rights-final.pdf>).
- O'Clair, R. M., and S. C. Lindstrom. 2000. North Pacific seaweeds. Plant Press, Auke Bay, AK, 162 p.
- Olson, A. M., M. Hessing Lewis, D. Haggarty, and F. Juanes. 2019. Nearshore seascape connectivity enhances seagrass meadow nursery function. *Ecol. Appl.* 29(5):e01897 (doi: <https://doi.org/10.1002/eap.1897>).
- Pang, S. J., F. Liu, T. F. Shan, S. Q. Gao, and Z. H. Zhang. 2009. Cultivation of the brown alga *Sargassum horneri*: sexual reproduction and seedling production in tank culture under reduced solar irradiance in ambient temperature. *J. Appl. Phycol.* 21(4):413–422 (doi: <https://doi.org/10.1007/s10811-008-9386-5>).
- Peabody B., J. Davis, S. Alin, N. Bednarek, M. Chadsey, R. Feely, M. Horwith, D. Keifer J. Mickett, J. Newton, Z. Siegrist, and J. Toft. 2020. Summary of findings: Investigating seaweed cultivation as a strategy for mitigating ocean acidification in Hood Canal, WA for activities performed May 2015–December 2019. Paul G. Allen Family Foundation and U.S. Navy, 12 p. (avail. at <https://restorationfund.org/wp-content/uploads/2021/01/PAFF-Summary-of-Findings.pdf>).
- Penttila, D. 2017. Marine forage fishes in Puget Sound. Dep. Fish. Wildl., Nearshore Habitat Prog., Tech. Rep. 2007-03, 23 p. (avail. at <https://wdfw.wa.gov/sites/default/files/publications/02193/wdfw02193.pdf>).
- Pereira, R., C. Yarish, and A. T. Critchley. 2024. Seaweed aquaculture for human foods in land based and IMTA systems. In D. I. Hefft and C. O. Adetunji (Editors), Applications of seaweeds in food and nutrition, p. 77–99. Elsevier (doi: <https://doi.org/10.1016/B978-0-323-91803-9.00016-0>).
- Peteiro, C., and O. Freire. 2013. Epiphytism on blades of the edible kelps *Undaria pinnatifida* and *Saccharina latissima* farmed under different abiotic conditions. *J. World Aquacult. Soc.* 44(5):706–715 (doi: <https://doi.org/10.1111/jwas.12065>).
- Pfister, C. A., and S. P. Betcher. 2018. Climate drivers and animal host use determine kelp performance over decadal scales in the kelp *Pleurophyucus gardneri* (Laminariales, Phaeophyceae). *J. Phycol.* 54(1):1–11 (doi: <https://doi.org/10.1111/jpy.12601>).
- _____, M. A. Altabet, and B. L. Weigel. 2019. Kelp beds and their local effects on seawater chemistry, productivity, and microbial communities. *Ecology* 100(10):e02798 (doi: <https://doi.org/10.1002/ecy.2798>).
- Plummer, M. L., C. J. Harvey, L. E. Anderson, A. D. Guerry, and M. H. Ruckelshaus. 2013. The role of eelgrass in marine community interactions and ecosystem services: results from ecosystem-scale food web models. *Ecosystems* 16(2):237–251 (doi: <https://doi.org/10.1007/s10021-012-9609-0>).
- Puget Sound Restoration Fund. 2019. 2018–2022 Canopy Kelp Restoration Program Activity report: April 2019. Grant no. NA18NMF4630180. 8001 Day Road West, Ste. B, Bainbridge Island, WA 98110.
- Purcell-Meyerink, D., M. A. Packer, T. T. Wheeler, and M. Hayes. 2021. Aquaculture production of the brown seaweeds *Laminaria digitata* and *Macrocystis pyrifera*: applications in food and pharmaceuticals. *Molecules* 26(5):1,306 (doi: <https://doi.org/10.3390/molecules26051306>).
- Racine, P., A. Marley, H. E. Froehlich, S. D. Gaines, I. Ladner, I. MacAdam-Somer, and D. Bradley. 2021. A case for seaweed aquaculture inclusion in U.S. nutrient pollution management. *Mar. Policy* 129:104506 (doi: <https://doi.org/10.1016/j.marpol.2021.104506>).
- Raum-Suryan, K. L., and R. M. Suryan. 2022. Entanglement of steller sea lions in marine debris and fishing gear on the central Oregon coast from 2005–2009. *Oceans* 3(3):319–330 (doi: <https://doi.org/10.3390/oceans3030022>).
- Redmond, S., L. Green, C. Yarish, J. Kim, and C. Neefus. 2014. New England seaweed culture handbook—nursery systems. Connecticut Sea Grant CTSG 14 01, 92 p. (avail. at https://digitalcommons.lib.uconn.edu/seagrant_weedcult/1/).
- Reed, D. C., B. P. Kinlan, P. T. Raimondi, L. Washburn, B. Gaylord, and P. T. Drake. 2006. A metapopulation perspective on the patch dynamics of giant kelp in Southern California. In J. P. Kritzer and P. J. Sale (Editors), Marine metapopulations, p. 353–38. Acad. Press (doi: <https://doi.org/10.1016/B978-012088781-1/50013-3>).
- Revised Code of Washington (RCW) 15.85.020. [Aquaculture] Definitions (avail. at <https://ap.leg.wa.gov/RCW/default.aspx?cite=15.85.020>).
- _____. RCW 79.135.410. Seaweed - Personal use limit - Commercial harvesting prohibited - Exception - Import Restriction. <https://ap.leg.wa.gov/rcw/default.aspx?cite=79.135.410>
- _____. RCW 90.58. Shoreline management act of 1971. <https://apps.leg.wa.gov/rcw/default.aspx?cite=90.58>
- Rensel, J. E., and J. R. M. Forster. 2007. Beneficial environmental effects of marine finfish aquaculture. Washington D.C.: National Marine Fisheries Service National Sea Grant College Program, Office of Oceanic and Atmospheric Research. Report No. NA04OAR4170130. <https://corpora.tika.apache.org/base/docs/govdocs1/695/695729.pdf>
- Sandell, T., A. Lindquist, P. Dionne, and D. Lowry. 2019. 2016 Washington State herring stock status report. Olympia (WA): Washington Department of Fish and Wildlife, Fish Program, Fish Management Division. Report No. FPT 19-07. <https://wdfw.wa.gov/sites/default/files/publications/02105/wdfw02105.pdf>
- Schiel, D. R., and M. S. Foster. 2006. The population biology of large brown seaweeds: ecological consequences of multiphase life histories in dynamic coastal environments. Annual review of ecology, evolution, and systematics, p. 343–372. <http://www.jstor.org/stable/30033836>
- Schweigert, J. F., J. S. Cleary, and P. Midgley. 2018. Synopsis of the Pacific herring spawn-on-kelp fishery in British Columbia. Fisheries and Oceans Canada, Science Branch, Pacific Region, Pacific Biological Station. <https://waves-vagues.dfo-mpo.gc.ca/Library/4068121x.pdf>
- Seeb, L. W. 1998. Gene flow and introgression within and among three species of rockfishes, *Sebastes auriculatus*, *S. caurinus*, and *S. maliger*. *J. Heredity* 89(5):393–403 (doi: <https://doi.org/10.1093/jhered/89.5.393>).
- Shaffer, J. A., D. C. Doty, R. M. Buckley, and J. E. West. 1995. Crustacean community composition and trophic use of the drift vegetation habitat by juvenile splitnose rockfish *Sebastes diploproa*. *Mar. Ecol. Prog. Ser.* 123:13–21 (doi: <https://doi.org/10.3354/meps123013>).
- _____, S. H. Munsch, and J. R. Cordell. 2020. Kelp forest zooplankton, forage fishes, and juvenile salmonids of the northeast Pacific nearshore. *Mar. Coastal Fish.* 12(1):4–20 (doi: <https://doi.org/10.1002/mcf2.10103>).
- Shams El-Din, N.G., L. I. Mohamedein, and K. M. El-Moselhy. 2014. Seaweeds as bioindicators of heavy metals off a hot spot area on the Egyptian Mediterranean Coast during 2008–2010. *Environmental Monitoring and Assessment* 186(9):5,865–5,881 (doi: <https://doi.org/10.1007/s10661-014-3825-3>).
- Sharma, S., L. Neves, J. Funderud, L. T. Myrland, M. Øverland, and S. J. Horn. 2018. Seasonal and depth variations in the chemical composition of cultivated *Saccharina latissima*. *Algal Res.* 32:107–112 (doi: <https://doi.org/10.1016/j.algal.2018.03.012>).
- Silliman, K. 2019. Population structure, genetic connectivity, and adaptation in the Olympia oyster (*Ostrea lurida*) along the West Coast of North America. *Evol. Appl.* 12(5):923–939.
- Simonson, E. J., R. F. Scheibling, and A. Metaxas. 2015. Kelp in hot water: I. Warming seawater temperature induces weakening and loss of kelp tissue. *Mar. Ecol. Prog. Ser.* 537:89–104 (doi: <https://doi.org/10.3354/meps11438>).
- Singleton, S. 2009. Native people and planning for marine protected areas: how “stakeholder” processes fail to address conflicts in complex, real-world environments. *Coastal Management*, 37(5):421–440. <https://doi.org/10.1016/j.coastman.2009.08.001>

- org/10.1080/08920750902954072
- Springer, Y. P., C. G. Hays, H. M. Carr, and M. R. Mackey. 2010. Toward ecosystem-based management of marine macroalgae—The bull kelp, *Nereocystis luetkeana*. *Oceanogr. Mar. Biol.*, 48, p. 1.
- Steneck, R. S., M. H. Graham, B. J. Bourque, D. Corbett, J. M. Erlandson, J. A. Estes, and M. J. Tegner. 2002. Kelp forest ecosystems: biodiversity, stability, resilience and future. *Environ. Conserv.* 29(4):436–459 (doi: <https://doi.org/10.1017/S0376892902000322>).
- Tallis, H. M., J. L. Ruesink, B. Dumbauld, S. Hacker, and L. M. Wischert. 2009. Oysters and aquaculture practices affect eelgrass density and productivity in a Pacific Northwest estuary. *J. Shellfish Res.* 28(2):251–261 (doi: <https://doi.org/10.2983/035.028.0207>).
- Tallman, J. C., and G. E. Forrester. 2007. Oyster grow-out cages function as artificial reefs for temperate fishes. *Trans. Amer. Fish. Soc.* 136(3):790–799 (doi: <https://doi.org/10.1577/T06-119.1>).
- Theuerkauf, S. J., J. A. Morris, Jr., T. J. Waters, L. C. Wickliffe, H. K. Alleyway, and R. C. Jones. 2019. A global spatial analysis reveals where marine aquaculture can benefit nature and people. *PLoS One* 14(10):e0222282 (doi: <https://doi.org/10.1371/journal.pone.0222282>).
- _____, L. T. Barrett, H. K. Alleyway, B. A. Costa Pierce, A. St. Gelaais, and R. C. Jones. 2022. Habitat value of bivalve shellfish and seaweed aquaculture for fish and invertebrates: Pathways, synthesis and next steps. *Rev. Aquacult.* 14(1):54–72 (doi: <https://doi.org/10.1111/raq.12584>).
- Thom, R. M., K. E. Buenau, C. Judd, and V. I. Cullinan. 2011. Eelgrass (*Zostera marina* L.) stressors in Puget Sound. Washington D.C.: U.S. Dep. Energy (avail. at https://file.dnr.wa.gov/publications/aqr_eelgrass_stressors2011.pdf).
- Thompson, S. A., H. Knoll, C. A. Blanchette, and K. J. Nielsen. 2010. Population consequences of biomass loss due to commercial collection of the wild seaweed *Postelsia palmaeformis*. *Mar. Ecol. Prog. Ser.* 413:17–31 (doi: <https://doi.org/10.3354/meps08705>).
- Tiwari, B. K., and D. J. Troy. 2015. Seaweed sustainability—food and nonfood applications. *In* Seaweed sustainability (p. 1–6). Academic Press (doi: <https://doi.org/10.1016/B978-0-12-418697-2.00001-5>).
- Treaty Indian Tribes in Western Washington. 2011 July 14. Treaty rights at risk: Ongoing habitat loss, the decline of the salmon resource, and recommendations for change. (avail. at <https://nwifc.org/publications/tribal-technical-reports/>).
- Troell, M., P. J. Henriksson, A. H. Buschmann, T. Chopin, and S. Quahe. 2022. Farming the Ocean—Seaweeds as a quick fix for the climate? *Rev. Fish. Sci. Aquacult.* 31(3):285–295 (doi: <https://doi.org/10.1080/23308249.2022.2048792>).
- The Nature Conservancy. 2021. Global Principles of Restorative Aquaculture. Arlington (VA):The Nature Conservancy. https://www.nature.org/content/dam/tnc/nature/en/documents/TNC_PrinciplesofRestorativeAquaculture.pdf
- Uffman-Kirsch, L. B., B. J. Richardson, and E. I. Van Putten. 2020. A new paradigm for social license as a path to marine sustainability. *Frontiers Mar. Sci.* 7:571373 (doi: <https://doi.org/10.3389/fmars.2020.571373>).
- U.S. v. Washington. 1974. 520 F.2d 676. _____ . 1994. 873 F. Sup. 1422 _____ . 2017. No. 13-35474
- Vadas, R. L. 1972. Ecological implications of culture studies on *Nereocystis luetkeana*. *J. Phycology* 8(2):196–203 (doi: <https://doi.org/10.1111/j.1529-8817.1972.tb04025.x>).
- Vadopalas, B., L. L. Leclair, and P. Bentzen. 2004. Microsatellite and allozyme analyses reveal few genetic differences among spatially distinct aggregations of geoduck clams (*Panopea abrupta*, Conrad 1849). *J. Shellfish Res.* 23(3):693–706. _____, _____, and _____ . 2012. Temporal genetic similarity among year-classes of the Pacific geoduck clam (*Panopea generosa* Gould 1850): a species exhibiting spatial genetic patchiness. *J. Shellfish Res.* 31(3):697–709.
- Visch, W. 2019. Sustainable kelp aquaculture in Sweden [Doctoral thesis]. Gothenburg (Sweden): University of Gothenburg (avail. at <https://gupea.ub.gu.se/handle/2077/62099>).
- Vissers, C., S. R. Lindell, S. V. Nuzhdin, A. A. Almada, and K. Timmermans. 2023. Using sporeless sporophytes as a next step towards upscaling offshore kelp cultivation. *J. Appl. Phycology*, p. 1–8 (avail. at <https://link.springer.com/article/10.1007/s10811-023-03123-8>).
- von Biela, V. R., S. D. Newsome, J. L. Bodkin, G. H. Kruse, and C. E. Zimmerman. 2016. Widespread kelp-derived carbon in pelagic and benthic nearshore fishes suggested by stable isotope analysis. *Estuarine, Coastal and Shelf Science* 181:364–374 (doi: <https://doi.org/10.1016/j.ecss.2016.08.039>).
- Walls, A. M., R. Kennedy, M. D. Edwards, and M. P. Johnson. 2017. Impact of kelp cultivation on the ecological status of benthic habitats and *Zostera marina* seagrass biomass. *Mar. Pollution Bull.* 123(1–2):19–27.
- Washington Administrative Code (WAC) 220-370-060. Aquatic farm registration required. (avail. at <https://ap.leg.wa.gov/WAC/default.aspx?cite=220-370-060>).
- Washington Administrative Code (WAC) 220-370-220. Marine plant aquaculture disease control. (avail. at <https://ap.leg.wa.gov/WAC/default.aspx?cite=220-370-220>).
- Washington Sea Grant. 2015. Shellfish aquaculture in Washington State. Final report to the Washington State Legislature. Seattle: Washington Sea Grant (avail. at https://ap.leg.wa.gov/ReportsToTheLegislature/Home/GetPDF?fileName=WSGShellfishResearchFinalReportRevised_f6498d40-24b7-491e-8e1f-297faee6a53.pdf).
- Washington Sea Grant. 5 Dec. 2023. The first Seaweed Knowledge Symposium covered the challenges and opportunities of a burgeoning field. Seattle: Washington Sea Grant. (avail. at <https://wsg.washington.edu/the-first-seaweed-knowledge-symposium-covered-the-challenges-and-opportunities-of-a-burgeoning-field/>).
- Washington State Department of Ecology. 2012, May. Washington Shoreline Master Program, Chapter 2 Shoreline Mater Program Overview (avail. at <https://apps.ecology.wa.gov/publications/parts/1106010part2.pdf>).
- Washington State Department of Fish and Wildlife (WDFW). 2012. Conservation Plan for ESA Listed Species of Rockfish in Puget Sound. (avail. at <https://www.fisheries.noaa.gov/s3/dam-migration/wdfw-plan.pdf>).
- Washington State Department of Natural Resources (WDNR). ShoreZone Inventory - Kelp. Washington State Department of Natural Resources GIS Open Data [accessed 2023 December 18]. (avail. at <https://data-wadnr.opendata.arcgis.com/datasets/wadnr::shorezone-inventory-kelp/explore>).
- Washington State Department of Natural Resources (WDNR). 2018 March 1. Guidelines for licensing mooring buoys and boatlifts. Olympia (WA):Washington State Department of Natural Resources. (avail. at https://www.dnr.wa.gov/publications/aqr_mb_jarpa_guidelines.pdf).
- Washington State Department of Natural Resources (WDNR), Aquatic Resources Division. 2015 February. Puget Sound Eelgrass (*Zostera marina*) Recovery Strategy. Olympia (WA):Washington State Department of Natural Resources. https://www.dnr.wa.gov/publications/aqr_nrsh_eelgrass_strategy_final.pdf
- Watanabe, J. M., R. E. Phillips, N. H. Allen, and W. A. Anderson. 1992. Physiological response of the stipitate understorey kelp, *Pterygophora californica* Ruprecht, to shading by the giant kelp, *Macrocystis pyrifera* C. Agardh. *J. Exp. Mar. Biol. Ecol.* 159(2):237–252 (avail. at [https://doi.org/10.1016/0022-0981\(92\)90039-D](https://doi.org/10.1016/0022-0981(92)90039-D)).
- WDFW. 2012. Application for an Individual Incidental Take Permit under the Endangered Species Act of 1973, March 2012. Prep. for the National Marine Fisheries Service by the Washington Department of Fish and Wildlife (avail. at <https://media.fisheries.noaa.gov/dam-migration/wdfw-appl.pdf>).
- Wernberg, T., and K. Filbee-Dexter. 2019. Missing the marine forest for the trees. *Mar. Ecol. Prog. Ser.* 612:209–215 (doi: <https://doi.org/10.3354/meps12867>).
- West, J. E., R. M. Buckley, and D. C. Doty. 1994. Ecology and habitat use of juvenile rockfishes (*Sebastes* spp.) associated with artificial reefs in Puget Sound, Washington. *Bull. Mar. Sci.* 55(2–3):344–350 (avail. at <https://www.ingentaconnect.com/content/umrsmas/bullmar/1994/00000055/f0020002/art00008#expand/collapse>).
- Westermeier, R., D. Patiño, M. I. Piel, I. Mairer, and D. G. Mueller. 2006. A new approach to kelp mariculture in Chile: production of free floating sporophyte seedlings from gametophyte cultures of *Lessonia trabeculata* and *Macrocystis pyrifera*. *Aquacult. Res.* v37(2):164–171 (doi: <https://doi.org/10.1111/j.1365-2109.2005.01414.x>).
- Wood, D., E. Capuzzo, D. Kirby, K. Mooney-McAuley, and P. Kerrison. 2017. UK macroalgae aquaculture: What are the key environmental and licensing considerations?. *Mar. Policy* 83:29–39 (doi: <https://doi.org/10.1016/j.marpol.2017.05.021>).
- World Wildlife Fund (WWF). 2021. Farmed seaweed - Impacts. Wash., D.C., World Wildlife Fund (accessed 4 September 2021, avail. at <https://www.worldwildlife.org/industries/farmed-seaweed>).