https://doi.org/10.25923/gehf-0855

Untangling how kelp contributes to coastal resilience in Alaska: literature review and community discussions

Authors

Paxton, Avery B.
Freedman, Ryan M.

May 2024

NOAA TECHNICAL MEMORANDUM NOS NCCOS 335

NOAA NOS National Centers for Coastal Ocean Science

Suggested Citation

Paxton, A.B. and R.M. Freedman. 2024. Untangling how kelp contributes to coastal resilience in Alaska: literature review and community discussions. National Oceanic and Atmospheric Administration, National Ocean Service, National Centers for Coastal Ocean Science. NOAA Technical Memorandum 335. 30 pg. https://doi.org/10.25923/gehf-0855

Photography Credits

All images used in this report were taken by NOAA NCCOS unless otherwise indicated. Cover image was provided by First Name Last Name (Affiliation).

Disclaimer

If any commercial product/company is mentioned, add this disclaimer: Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Untangling how kelp contributes to coastal resilience in Alaska: literature review and community discussions

Prepared by

NOAA National Ocean Service
National Centers for Coastal Ocean Science
Silver Spring, MD

Authors

Paxton, Avery B.[1]
Freedman, Ryan M.[2]

1. National Centers for Coastal Ocean Science, National Ocean Service, National Oceanic and Atmospheric Administration, Beaufort, NC, USA.

2. Channel Islands National Marine Sanctuary, National Ocean Service, National Oceanic and Atmospheric Administration, Santa Barbara, CA, 93106, USA.

May 2024

NOAA NOS NCCOS TECHNICAL MEMORANDUM 335

United States Department of Commerce

Gina M. Raimondo
Secretary

National Oceanic and Atmospheric Administration

Richard W. Spinrad, Ph.D.
Under Secretary of Commerce for Oceans and Atmosphere and NOAA Administrator

National Ocean Service

Nicole LeBoeuf
Assistant Administrator

Table of Contents

Abstract

Kelp forests provide multiple ecosystem services but face global declines. Losses have been triggered by a combination of threats, including habitat degradation, pollution, marine heatwaves, climate change induced temperature stress, and altered trophic dynamics. The extent to which kelp contributes to coastal resilience remains poorly understood, which represents an important information gap for coastal managers trying to safeguard ecosystem services in the face of kelp decline. This study aimed to determine the role of kelp in coastal resilience in Alaska through a literature review and community discussions. The literature review demonstrated that while some evidence exists on how kelp relates to coastal resilience, especially related to ecological functions and services, there are substantial knowledge gaps surrounding coastal protection, socioeconomic and cultural values, and food production. Discussions with community members to further elucidate perspectives on kelp's contribution to coastal resilience helped contextualize the breadth of knowledge gaps, especially those related to coastal protection and habitat mapping. For example, it remains largely unknown whether kelp provides coastal protection benefits in Alaska, and in most of the state's waters, information on the spatiotemporal distribution of kelp is lacking. Based on the literature review and community discussions, we identified pressing research questions that can help fill these knowledge gaps and guide future research inquiries regarding the role of kelp in conferring coastal resilience benefits in Alaska.

1. Background

When coastal resource managers and scientists consider ecosystems that provide coastal resilience benefits, salt marshes, oyster reefs, and coral reefs typically come to mind. This is because it has been well-documented that these ecosystems can protect coastal communities and associated infrastructure by attenuating wave energy and reducing coastal flooding (Bridges et al. 2015, Narayan et al. 2016, Chausson et al. 2020, Temmerman et al. 2022). Kelp forests can likewise attenuate wave energy (Rosman et al. 2007, Rosman et al. 2013) and – albeit to a lesser extent – reduce coastal erosion. Yet, these submerged vegetative systems are not widely regarded as providing notable coastal resilience benefits (Morris et al. 2020). Given that kelp forests face global declines from compounding threats like marine heatwaves, increased storm strength and frequency, pollution, and habitat degradation (Krumhansl et al. 2016), synthesizing primary literature and meeting with community members to understand the extent to which kelp forests can potentially contribute to and can be used to bolster coastal resilience (e.g., provide nature-based solutions) is warranted.

The goal of this report is to determine how kelp in Alaska, United States (US) contributes to coastal resilience. To meet this goal, we first reviewed primary literature on how kelp, in particular canopy kelps, in Alaska relates to coastal resilience. Second, we met with Alaska-based community members to understand perspectives on the role of kelp in coastal resilience. Third, we synthesized findings from the literature review and community discussions to outline future research directions that will help enhance our collective understanding of how kelp contributes to and can be strategically used to improve coastal resilience. We use a broad definition of coastal resilience that includes not only coastal protection but also ecological functions and services, food production through primary and secondary pathways, and socioeconomic and cultural values.

2. Literature review

2.1. Methods

2.1.1. Search for articles

The search for articles was conducted using the Web of Science Core Collection. The search was scoped during summer 2023, and the final search was executed on 3 January 2024. The search string was created using Web of Science syntax. The final search string focused on canopy kelps:

Population terms: kelp* OR nereocystis* OR macrocystis* OR “submerged aquatic vegetation*”
AND
Coastal protection terms: wave* OR break* OR current* OR wind* OR flood* OR inundat* OR “storm surge*” OR erod* OR erosion* OR “coastal hazard*” OR storm* OR attenuat* OR mitigat* OR protect* OR dissipat* OR dampen* OR stabili$* OR trap* OR buffer* OR armour* OR armor* OR barrier* OR accret* OR adapt* OR breakwater* OR mediat* OR reduc* OR flow* OR hydrodynamic*
OR
Food production terms: aquacultur* OR maricultur* OR silvicultur* OR harvest* OR wrack* OR “food product*” OR cultivat* OR planted OR planting* OR farm*
OR
Cultural and socioeconomic terms: aesthetic* OR touris* OR recreat* OR econom* OR social* OR capital* OR livelihood* OR employment* OR job* OR income* OR security* OR credit* OR savings* OR debt* OR poverty* OR expenditure* OR inflation* OR cost* OR housing* OR safety* OR health* OR education* OR skills* OR rights OR empower* OR governance* OR “traditional knowledge*” OR “traditional

value*" OR "traditional ecological knowledge*" OR subsistence* OR "spiritual belief*" OR "religious belief*" OR "generational connection*" OR heritage* OR "cultural heritage*" OR "cultural practice*" OR festival* OR "sacred site*" OR "cultural identit*" OR viewshed* OR "view shed*" OR "good* and service*"]
AND
Alaska terms: alaska*

Search results were downloaded as a .RIS reference file. All articles were screened first by title and abstract for relevance and second by full text screening. We used the software Swift-Active Screener (Howard et al. 2020) for title and abstract screening. Each article was screened manually by one screener, and articles were prioritized according to the Swift active-learning algorithm. Articles that passed title and abstract screening were then screened at the level of full text.

To be eligible to pass screening and thus be included in the literature review, an article was required to report on kelp in Alaska and either ecological functions, food production, socioeconomic and cultural values, or coastal protection.

Using custom R code, we summarized the number of articles that were included versus excluded. For excluded articles, we also summarized the exclusion rationale (e.g., not in Alaska, no kelp, no resilience outcome). For included articles, we summarized the category or categories of coastal resilience that they provided information about. We then synthesized findings across the selected articles into four categories: ecological functions, food production, socioeconomic and cultural values, and coastal protection.

2.2. Results

The search for peer-reviewed literature in Web of Science returned 80 potentially relevant articles. Of the 80 articles, 59 were included (Appendix 1) during title and abstract screening, whereas 21 were excluded (Figure 1; Appendix 2). Of the articles that were excluded, most were excluded because they did not relate to coastal resilience (n=9) or did not report on kelp (n=9). Several studies (n=6) were excluded because they did not take place in Alaska.

The included studies reported on a variety of coastal resilience topics ranging from ecological functions and food production to cultural values and socioeconomic factors (Figure 3). The highest number of articles focused on ecological functions associated with Alaskan kelp forests (n=38), followed by studies that reported on more general ecosystem services (n=9) and secondary food production (n=6). Several studies focused on socioeconomic aspects of resilience (n=4), primary food production from wild sources (n=4), and coastal protection (n=4). A few studies reported on primary food production from mariculture (n=3) or cultural values (n=2). Brief summaries of key articles on the role of kelp in coastal resilience in Alaska follow.

2.2.1. Ecological functions

Kelp plays a key role in ecological functions, largely by providing habitat for a diversity of marine life in Alaska. The literature base detailed how kelp can provide habitat for species ranging from spider crabs (Daly and Konar 2010) and Pacific sand lance (Johnson et al. 2008) and Pacific octopus (Scheel 2002, Scheel and Bisson 2012) to sea otters (Wolt et al. 2014). Kelp can be co-located near juvenile marbled murrelet nurser-

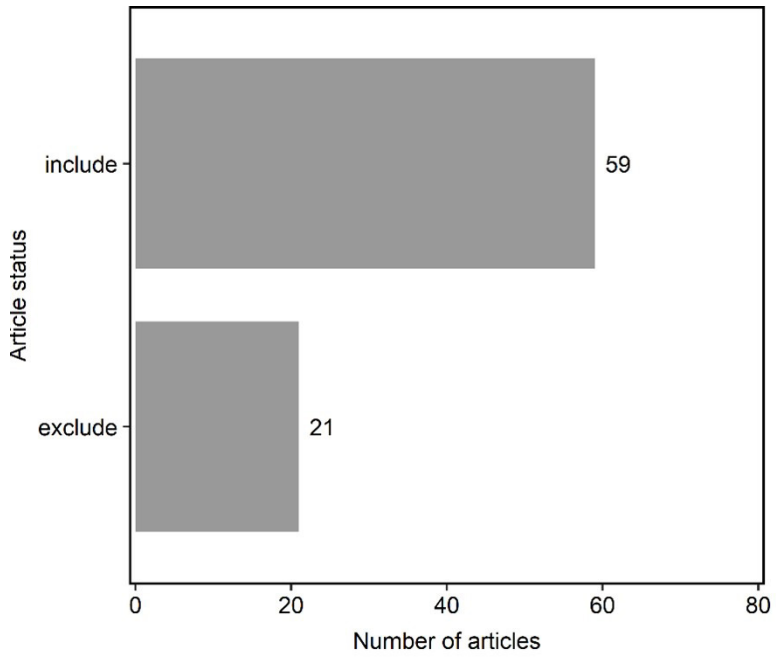

Figure 1. Number of articles that were excluded and included during title and abstract screening.

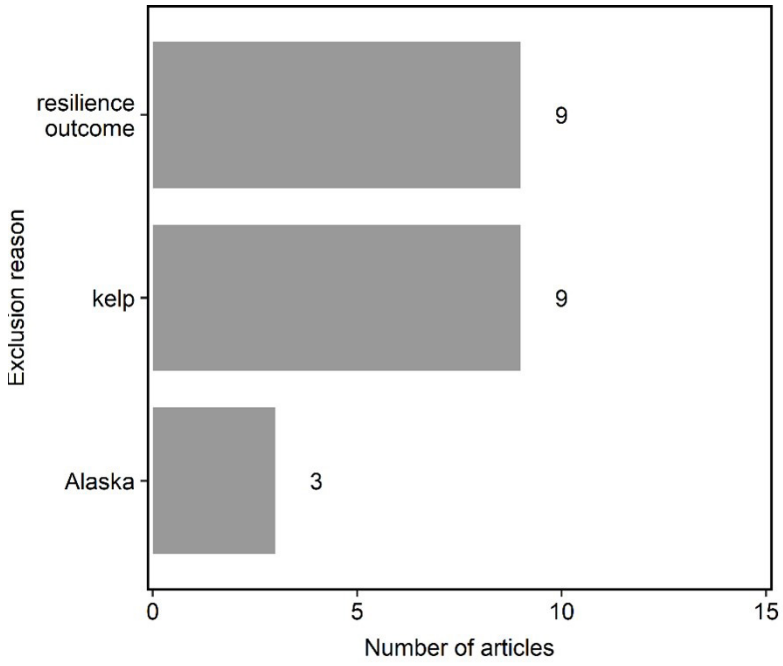

Figure 2. Number of articles excluded during title and abstract screening and their exclusion rationale. Articles were excluded because they did not have resilience outcomes, did not relate to kelp, and did not take place in Alaska.

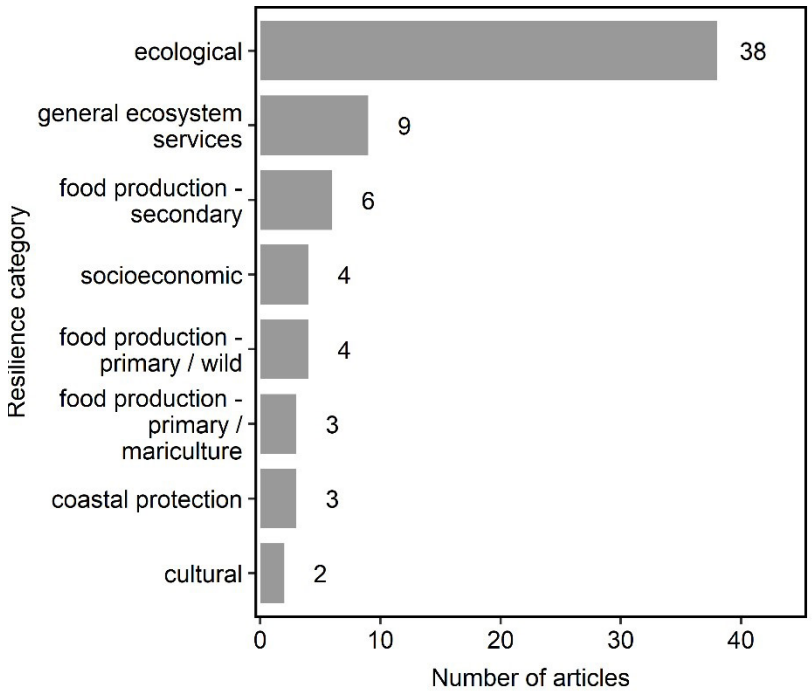

Figure 3. Number of articles by kelp resilience category. Some articles contained more than one resilience category (e.g., multi-category), so articles can appear in more than one bar.

ies (Kuletz and Piatt 1999), and kelp wrack provides habitat for terrestrial arthropods (Sikes and Slowik 2010, Ulaski et al. 2023). Kelp can act as a bioindicator for contaminants (Burger et al. 2007) and can help uptake nitrogen from seabird guano (Wainright et al. 1998).

2.2.2. Food production

Kelp in Alaska contributes to food production through primary and secondary pathways. Primary pathways include direct harvest of wild kelp (Johnson et al. 2019, Ulaski et al. 2020) and harvesting kelp as part of mariculture (Stekoll and Else 1990, Stekoll et al. 2021). Secondary pathways include the presence of carbon derived from kelp in benthic nearshore fishes that can be harvested (von Biela et al. 2016), and more broadly through the food web subsidies provided by kelp, such as those that support trophic cascades (Estes et al. 2004). Some pathways are more blended. For example, when herring deposit their eggs on kelp blades, the herring roe can be directly harvested but can also support larger predators within the food web (Surma et al. 2018).

2.2.3. Socioeconomic and cultural values

Several studies described the socioeconomic and cultural importance of kelp in Alaska. For example, the humans that colonized the Aleutian Islands harvested kelp and depended on kelp because it provided habitat for a variety of marine life (West et al. 2007). Present day Alaska Natives also conduct traditional and cultural harvest of kelp resources (Johnson et al. 2019). Recent research suggests economic value and viability associated with the sugar kelp industry (Heidkamp et al. 2022), hydrothermal liquefaction technology using kelp (Rosales-Asensio et al. 2023), and in supporting herring egg production (Deriso et al. 2008).

2.2.4. Coastal protection

Few articles discussed the role of kelp in coastal protection in Alaska. One article found that canopy-forming bull kelp, Nereocystis luetkeana, can reduce current velocity (Hondolero and Edwards 2017). Hondolero and Edwards (2017) conducted an in situ study in Kachemak Bay, showing that two different types of kelp forests, those dominated by Nereocystis leutkeana and those with Eularia fisulosa, both reduced current velocity, but the reductions in current velocity were minor compared to prevailing currents in the geographic area.

3. Community discussions

In addition to the literature review, we convened a series of discussions with community members, rights holders, and subject matter experts to gather information on knowledge gaps related to kelp and coastal resilience in Alaska. These informal discussions were intended to provide an additional source of information to complement the literature review. Discussions were held both virtually and in person. We developed discussion questions in advance to cover a breadth of topics. In some discussions, questions were skipped because of time constraints or because the discussions moved in another direction. Below, we provide the a priori questions, notes from community discussions, and synthesized discussion findings.

3.1. Questions for community discussions

We prepared multiple questions on the role of kelp and coastal resilience to discuss with community members. These questions were developed by the project investigators. The questions were:

1. How do you rely/depend on/interact with kelp resources?
2. What are the core benefits you/Alaskan Communities gain from a healthy kelp forest?
3. What would be the community response if kelp was lost?
4. For each of the following, what would you say kelp's role is in:
   a. Coastal protection/infrastructure.
   b. Food production
   c. Socio-economic outcomes
   d. Cultural heritage
5. How would you rank the importance of kelp to your local community on a scale of 1-10?
6. How worried are you about the impacts of climate change on your community, especially regarding impacts to coastlines?
   a. Have you considered what role kelp could play in these potential impacts?
   b. If so, please explain more about what you see as kelp's role. (might be redundant but good to reinforce)
   c. What aspects of your community do you see most at risk and which aspects of your community do you expect to be able to adapt?
7. What are the critical knowledge gaps you see in understanding kelp's role in a sustainable or resilient future over the next 50 years?
8. What are the biggest obstacles towards using kelp to address coastal resilience challenges? (Coastal resilience challenges were left open for interviewees.)
9. For restoration practitioners / resource managers:
   a. What are the biggest obstacles for successful kelp restoration?
   b. What factors do you consider when siting or planning kelp restoration?

c. How do you consider coastal resilience and coastal protection when planning or siting restoration?

10. For aquaculture practitioners / resource managers:
    a. Describe the process that your organization uses to plan for aquaculture.
    b. Do you consider multiple uses / multiple benefits when planning for aquaculture? For example, do you plan for aquaculture in areas that require coastal protection (which kelp could potentially provide)?
11. What are the biggest gaps in our understanding of kelp spatial distribution (e.g., mapping)?
12. What products or services would be most helpful for your organization to help guide decisions / inform practices?
13. Do you have any ongoing projects to research kelp?
14. Is there anything around this topic that you would like to share with us that we may be missing?

3.2. Summarized community discussions

We asked the prepared questions (section 3.1) to community members from a variety of sectors, including academia, non-profits, industry, and government from 11 July 2023 to 18 August 2023. Some questions were tailored to specific types of community members, such as those in industry or those in management roles, and so were posed to select community members. Summaries of the notes from community discussions follow.

3.2.1. Sitka Sound Science Center (Lauren Bell, Research Director)

Note: This discussion occurred virtually on 11 July 2023.

Question: How do you rely/depend on/interact with kelp resources?
- Alaskan communities directly depend upon kelp as a food source, and kelp is traditionally harvested.
- Kelp is harvested for herring roe but also for personal consumption of kelp material.
- Kelp is important for traditional communities because herring spawn on kelp.
- A variety of subsistence fishery species, such as abalone, shellfish, and crab, rely on kelp throughout their life histories.
- There are rich oral histories related to how communities interact with kelp forests, including the “kelp highway hypothesis.” The hypothesis states that communities would kayak and harvest in the gap between kelp and land because this area was calm due to the wave attenuation service provided by the kelp.

Question: What are the core benefits you/Alaskan Communities gain from a healthy kelp forest?
- Biodiversity is the key value that Alaskan Communities derive from kelp.
- Kelp also forms coastal nursery habitats and builds robust and complex food webs.
- Kelp is a valuable ecosystem that also supports resources that people use.

Question: What would be the community response if kelp was lost?
-If kelp is lost, a center point of biodiversity and the food web would be lost.

Question: What is kelp’s role in coastal protection / infrastructure?
-Kelp attenuates waves, which allows people to access coastal areas for subsistence and recreational activities, especially in the lee of the kelp.

- Kelp likely plays a bigger role in southeast Alaska in providing coastal protection needed for water transit rather than for coastal protection of infrastructure.

Question: What is kelp's role in food production?
- Kelp mariculture is up-and-coming in Alaska.
- Kelp is a fairly minor subsistence harvest product for people internal to Alaska and the US, but there is a potential for a kelp harvesting industry for export elsewhere.
- Several organizations harvest kelp for food, including Barnacle Foods.
- Kelp facilitates secondary production. For example, bull kelp is a key driver of bottom-up factors and a base carbon source for primary and secondary consumers.

Question: What is kelp's role in socio-economic outcomes?
- There is a massive tourism industry for kelp and the surrounding marine environment that includes kayaking, wildlife viewing, and more.
- Kelp is used for herring spawn, and the associated socio-economic outcomes of selling that herring spawn are not insignificant to coastal communities.
- Mariculture has growing socio-economic outcomes.

Question: What is kelp's role in cultural heritage?
- Kelp is integral to the environment, which Tribal and Indigenous People feel strongly tied to. For example, the Tlingit and specifically women of the Kiks.ádi Clan are known as herring protectors. There is a saying that "when the tide is out, the table is set" that shows the close connection between Alaskan Communities and marine resources, including kelp, as food items.

Question: How would you rank the importance of kelp to your local community on a scale of 1-10 (10 most important)?
- 7

Question: How worried are you about the impacts of climate change on your community, especially regarding impacts to coastlines?
- Lauren's dissertation showed that giant kelp will do well in southeast Alaska under expected warming and acidification compared to subarctic kelps.
- There are many unknowns regarding future interactions between giant kelp and bull kelp.
- Lauren is concerned about impacts to the diversity of food sources available for consumers, as well as the impacts to energy flow within coastal food webs.

Question: What aspects of your community do you see most at risk and which aspects of your community do you expect to be able to adapt?
- There are serious concerns given that communities are so closely tied to marine resources.
- For example, commercial fishing plays a key role in livelihoods and will be negatively impacted unless the fishing community adapts. The fishing fleet knows that they must adapt to ecological changes already occurring but that process can be slow.
- Traditional practices and historical use of kelp ecosystems will change; with these changes, we would expect lost cultural practices, although communities may adapt.
- Individuals with fewer socio-economic resources will be most impacted, and this can particularly impact subsistence practices.

Question: What are the critical knowledge gaps you see in understanding kelp's role in a sustainable or resilient future over the next 50 years?
- It is not well understood how kelp fuels coastal food webs. While it is easy to see that kelp forests are biodiversity engines because of the habitat that they create, the food subsidy component is harder to see and requires additional research.
- There is a lot of discussion right now about the role of kelp in carbon sequestration. This could be an area of future research.
- Mapping the diversity of kelp forest ecosystems and how kelp helps facilitate biodiversity is a key to understanding the role of kelp in coastal resilience.

Question: What are the biggest obstacles towards using kelp to address coastal resilience challenges?
- A big challenge in southeast Alaska is access because giant kelp in southeast Alaska is in remote areas that are understudied.
- Generally, the kelp forests that are accessible to research often have more pronounced human impacts because they are accessible to all. For example, Lauren's dissertation suggested that sea otter hunting resulted in changes to kelp forests.

Question: What are the biggest gaps in our understanding of kelp spatial distribution (e.g., mapping)?
- Mapping kelp distributions is challenging because satellite imagery isn't optimal and because there are frequently overcast conditions. There are no on-the-ground mapping efforts that Lauren is aware of.
- There are several long-term surveys, such as Jim Estes' surveys from the Aleutian Islands to southeast Alaska, that include spatial data

Question: What products or services would be most helpful for your organization to help guide decisions / inform practices?
- Mapping kelp spatial distributions is important for user groups thinking about coastal access and harvesting locations. Maps would be most valuable with a high temporal frequency of data collection to maximize utility to user groups.
- There may be coastal protection and multi-functional restoration avenues and areas of exploration that could be valuable for sandy beaches and back bays that are sheltered and do not currently have kelp.

3.2.2. NOAA Alaska Fisheries Science Center (Jordan Hollarsmith, Mariculture and Macroalage Lead Research Biologist)

Note: This discussion occurred virtually on 13 July 2023.

Question: How do you rely/depend on/interact with kelp resources?
- There is a growing industry of mariculture and harvest of kelp on an industrial scale.
- People also collect herring eggs from kelp on a commercial scale, but there are also recreational and subsistence components.
- Red algae is collected for subsistence and recreational harvest currently and since time immemorial.
- Many species, such as rockfish, abalone, and crabs, coexist with kelp, and so their secondary production is important.

Question: What are the core benefits you/Alaskan Communities gain from a healthy kelp forest?
- There is an aesthetic value associated with kelp given its beauty and scenic aspects.
- Kelp is part of oral histories. Kelp has been used as a navigational tool for First Nations.
- Overall, there are strong connections between people and kelp.

Question: What would be the community response if kelp was lost?
- Loss of kelp would be spiritually devastating.
- Data on kelp abundance are rare; anecdotal evidence is the main source of information. Data on kelp loss are also limited. There has been giant kelp expansion in south-central Alaska.
- Historical ecology suggests that there have been shifts in kelp species abundance, but there are associated caveats.

Question: What are the biggest gaps in our understanding of kelp spatial distribution (e.g., mapping)?
- Mapping kelp spatial distributions is very difficult. Spatial extent is a critical indicator of the ecosystem health. Mapping is an important need.

Question: What is kelp's role in coastal protection?
- There is a need to determine whether kelp, especially kelp farms, can reduce erosion or not. There is some evidence for wave and current dampening in California, but there are questions about how this relates to kelp beds in Alaska.
- There is erosion around muddy banks where a kelp farm that reduces erosion could theoretically help. Inside waters have erosion mainly from tidal flow and mass wasting events. Most of the natural kelp is in rocky areas that are not prone to erosion.
- South Central and South East Alaska have glacial inputs so are very silty, and this impacts kelp growth. Growth of kelp to provide wave damping would require a different situation and directed effort. Green infrastructure would require a directed effort.

Question: What is kelp's role in food production?
- Families and individuals harvest kelp and red algae to eat. Direct take is common; kelp can be turned into Nori, dried, and used as a topping. Kelp can be chopped and added to burgers.
- Mariculture is rapidly growing. A major issue will be scaling up the industry to be profitable. Barnacle Foods is the best example to date.
- Kelp is harvested for herring roe, and most of the roe goes to Japanese markets.

Question: What is kelp's role in socio-economic outcomes?
- Juneau has a lot of tourism but none of it has to do with kelp. Other areas, though, are likely different.
- There are aesthetic values associated with kelp.
- Juvenile salmonids also use kelp as important habitat, including as predation refuge, so there is a secondary production value.

Question: What is kelp's role in cultural heritage?
- Historically, kelp was used as a navigation aid to indicate where food could be found. There are creation myths that also reflect this.
- Kelp is an important part of stories, the feeling of belonging, and the feeling of home.

Question: What are the biggest obstacles for successful kelp restoration?
- There isn't really an effort in Alaska to restore kelp, whereas there is in other areas like California and Salish Sea.

Question: How would you rank the importance of kelp to your local community on a scale of 1-10?
- Juneau: 4 or 5
- Alaska overall: 6, given the role of kelp in supporting fisheries.

Question: How worried are you about the impacts of climate change on your community, especially regarding impacts to coastlines?
- There is extreme concern given that high latitude waters are rapidly warming, acidification is happening rapidly, and there are additional stressors. From a kelp perspective, there are many unknowns about the effects of climate change.

Question: Have you considered what role kelp could play in these potential impacts?
- There is a lot of enthusiasm about kelp's potential to sequester carbon.
- Kelp could provide structured habitat to help ease climate change impacts.

Question: What are the critical knowledge gaps you see in understanding kelp's role in a sustainable or resilient future over the next 50 years?
- There are too many knowledge gaps. There are questions such as: what species use kelp (and during which life phases), what is the current level of kelp biomass, how does kelp biomass enter the food web, what is the role of kelp is in coastal protection, how does species composition changes over time, how does carbon and nutrient cycling occur in kelp, and what are the interactions between kelp and harmful algal blooms?

Question: Is there anything around this topic that you would like to share with us that we may be missing?
- Re: kelp and coastal protection - There is a need to document whether kelp has a coastal protection role in Alaska, even if the hypothesis is that kelp doesn't provide coastal protection benefits. If, however, kelp is found to have a small role in coastal protection, that could potentially provide a big ecosystem service because of the amount of kelp and the length of the coastline in Alaska.

3.2.3. Barnacle Foods (Lia Heifetz, Co-founder)

Note: This discussion occurred virtually on 25 July 2023.

Question: How do you rely/depend on/interact with kelp resources?
- Barnacle Foods' business is built around sharing kelp and using foods accessible to people. They harvest wild kelp but also work with kelp farmers to harvest farmed kelp.
- The business focuses on both wild and farmed kelp to make sure that their harvesting practice is sustainable.
- They also collect kelp data to inform ocean health and aquaculture. For example, they have conducted aerial kelp mapping using drones for the past three years to map and quantify the abundance and distribution of wild kelp.

Question: What are the biggest gaps in our understanding of kelp spatial distribution (e.g., mapping)?
- There is a big need for kelp mapping. Barnacle Foods has been conducting mapping in Alaska using drone imagery.
- Mapping could help inform kelp farm siting and harvesting limits.

Question: What would be the community response if kelp was lost?
- Many communities native, rural, and indigenous communities depend on kelp for their livelihoods, families, and foods.

Question: What are the core benefits you/Alaskan Communities gain from a healthy kelp forest?
- Kelp forests are vital parts of healthy ecosystems.

Question: What is kelp's role in socio-economic outcomes?
- Kelp provides important habitat for juvenile fish.
- Some individuals use kelp in their gardens as fertilizer.

Question: How would you rank the importance of kelp to your local community on a scale of 1-10?
- For Barnacle Foods - 10
- For local community - 6 or 7

Question: Have you considered what role kelp could play in potential impacts of climate change on your community, especially regarding impacts to coastlines?
- Kelp may be a potential tool for climate mitigation.

Question: What aspects of your community do you see most at risk and which aspects of your community do you expect to be able to adapt?
- Alaskan Communities interact closely with the natural environment through food and recreation, so changing climate could impact the way of life.

Question: What are the critical knowledge gaps you see in understanding kelp's role in a sustainable or resilient future over the next 50 years?
- Baseline data (e.g., maps) are missing. Maps are needed to help understand impacts that inform decision making. Mapping would be most valuable if done before installation of kelp farms.

3.2.4. Sitka Tribe of Alaska (Chuck Miller, Culture and Community Liaison)

Note: This discussion occurred virtually on 9 August 2023.

Question: How do you rely/depend on/interact with kelp resources?
- Kelp has many different uses.
- The community harvests herring roe that spawn on kelp.
- Oftentimes, they roll up the kelp and eat it and the herring roe like a big sandwich.
- Elders have said that during the spring, they would bake king salmon in a beach oven lined with kelp. Bull kelp bulbs were used to make hooks.
- Hair kelp can be used like a grappling hook.
- Black seaweed is harvested, dried, ground, and then eaten; it is a staple of the Tribal Peoples.

Question: What are the core benefits you/Alaskan Communities gain from a healthy kelp forest?
- Kelp helps everything from underneath to on top of the water. It creates an environment for other fishes and animals that Tribal Peoples harvest. For example, kelp forests create habitat for sea urchins that they eat.
- A healthy kelp bed creates areas where trollers can maneuver right next to the kelp bed to catch king salmon. According to one elder, bigger or heftier king salmon tend to hang out by kelp beds, but not the younger or smaller king salmon.
- In southeast Alaska, there is an issue with sea otter overpopulation. The sea otters eat so many abalone and urchins that kelp forests thrive and often prevent Tribal Peoples from accessing normal harvest areas around rocks and islands. For example, if a kelp bed is overgrown, then you have to go out and around the kelp bed or else the boat prop will become stuck. If you're in an outboard, you can raise the motor up a bit, but the prop will likely still get stuck. Sometimes there are spots where you can cut through nooks and crannies to avoid going outside of the kelp; this is important because you don't want to go

outside of the kelp in a small boat because of weather and seas in the Gulf of Alaska.
- In ancient days, people would paddle with canoes. There was a story about a man who got lost at sea with two brothers in-law 300 years ago. They were taken out to the open ocean while hunting and a storm came up. The storm was so intense that the men couldn't make it back to shore safely. They ended up on a Polynesian Island and had to learn how to navigate back. There is a part of the story where when the men came back and were close to home, there was a place near town where they pulled bull kelp over the thwarts of the boat to rejuvenate themselves because they were so tired. The kelp helped keep their canoe in place and keep them warm.

Question: What would be the community response if kelp was lost?
- If kelp is lost, it would affect everything around it. In ancient days, they used everything around them. Modern technologies have changed culture, and a lot of knowledge has been lost from one generation to the next. Failure of knowledge transfer has impacted native people, along with trauma and white-washing. Alcoholism and disease wiped out knowledge bearers.

Question: How would you rank the importance of kelp to your local community on a scale of 1-10?
- 9 because a healthy kelp bed indicates a healthy sea with plentiful fish and abundance. If something happens to kelp and they start to disappear, it would indicate that there is something wrong with the sea.

Question: How worried are you about the impacts of climate change on your community, especially regarding impacts to coastlines?
- Animals in the water, such as sea otters and harbor seals, require food sources in kelp beds. Sea birds target kelp beds, too, as do needlefish and other fish that king salmon and other large fish target.
- His mom and elders notice cycles. They have been experiencing huge landslides with loss of life over the past multiple years. The landslides occur right up against the water. Sometimes they happen above kelp forests.
- Black tailed deer rely on kelp because they eat kelp that washes up on beaches.

Question: What are the critical knowledge gaps you see in understanding kelp's role in a sustainable or resilient future over the next 50 years?
- There is a traditional story about Raven, who is the creator of everything in their culture. There was a time when the tides were not allowed to go out. Raven and people were getting hungry. Raven needed his favorite food (sea urchins), and to get the urchins would climb down bull kelp in the water. Raven got tired of doing this. There was a woman of the tides (similar to a witch), who Raven got mad at and grabbed broken sea urchin shells and spanked her butt with it. He wouldn't stop until she released the tides on a regular basis twice a day since people were hungry. There is a regalia that depicts the Raven going down into the sea with two bull kelps; the regalia have been passed down from relatives and are beautiful and beaded.
- People need more education on kelp and why it is important. There could be a collaboration with the tribe to help share this information and find oral histories and personal stories. There are a lot of Tribal Peoples in southeast Alaska that would like to make their own kelp products like Barnacle Seafood.

Question: What are the biggest gaps in our understanding of kelp spatial distribution (e.g., mapping)?
- People should be educated about kelp. In science class growing up, they learned about how bull kelp can make agar that can be used in makeup, ice cream, etc.
- It would be helpful to have knowledge of where kelp beds are located and whether they are expanding or shrinking. He has noticed that there seems to be more kelp in some places and in others that there is

no longer kelp but it was there before. It is important to understand kelp spatial distributions for people who harvest kelp, as well as for people who boat around kelp (e.g., prop tangling - see above).

3.2.5. Alaska Ocean Observing System (Thomas Farrugia, Alaska Harmful Algal Bloom Coordinator)

Note: This discussion occurred in person on 14 August 2023 and did not follow all questions.

Question: What are the biggest gaps in our understanding of kelp spatial distribution (e.g., mapping)?
- AOOS has an ocean data explorer (data portal) that contains a variety of products. One of the tools that they are working on would help with spatial planning and permitting for mariculture. They are actively working on trying to make predictive layers that identify suitable areas for kelp mariculture.
- Data on kelp spatial distribution would be helpful for mariculture siting. A habitat suitability map would be key to constituents AOOS serves. Any spatial data that would help know where to site farms would be valuable.

General: climate and shifts in kelp resources
- Kelp is not seen as a limited resource, but there are conversations about how fish, invasive species, and harmful algal blooms may shift with climate change.
- Change detection is important but also challenging since the coastline in Alaska is so extensive.
- There is increasing interest in understanding where kelp could be seeded in the future.
- Macrocystis has been appearing but not in enough quantities that people are thinking about using it for commercial and recreational purposes yet.

3.2.6. Alaska Pacific University (Brad Harris, Professor)

Note: This discussion occurred in person on 14 August 2023 and did not follow all questions.

Question: What is kelp's role in coastal protection / infrastructure?
- The Alaska notion of coastal protection is different than in many other places in the US because there is comparatively little coastal development and it is such a high energy environment.
- There are concerns about coastal protection in some locations in Alaska, and there are opportunities to understand how frequency and intensity of disturbances relate to kelp and whether kelp could help mitigate these potential impacts.

Question: What are the biggest gaps in our understanding of kelp spatial distribution (e.g., mapping)?
- Few locations have been monitored over time. Those that have had some monitoring are in proximity to Kachemak Bay or are in southeast Alaska. Most kelp forests are completely unmapped, and this remains a key information gap.
- Species distribution model (or similar) approaches could be considered to help understand kelp distribution, especially with covariates like red cucumbers.
- Understanding mechanisms associated with kelp forests is the biggest need. This could include natural disturbance and energy in the coastal areas and how that relates to kelp presence and other metrics, such as rearing grounds for juvenile commercial species.
- There are key linkages between kelp forests and rockfish. Rockfish are poorly assessed in kelp forests, so this could be an avenue of future inquiry.

3.2.7. Alaska Sea Grant (Davin Holen, Coastal Community Resilience Specialist)

Note: This discussion occurred in person on 14 August 2023 and did not follow all questions.

Question: What is kelp's role in coastal protection / infrastructure?
- Most of the areas in Alaska that require coastal protection (e.g., western Alaska) may not be suitable for kelp. This is because most of the kelp production is in the Gulf of Alaska where there is not as much coastal loss.
-Although, in Kodiak there are some areas that are experiencing land loss, and kelp could potentially reduce erosion.
- Southeast Alaska communities aren't experiencing much erosion, but they do experience landslides.

Question: What is kelp's role in food production?
- There is a big potential for kelp to produce food and provide jobs. Barnacle Seafood is demonstrating this. Other areas like Cordova and Valdez might be suitable, as well as Port Graham and Kachemak Bay
- Communities in southeast Alaska, such as Sitka, harvest kelp with herring roe. This also occurs in Prince William Sound. This provides ecosystem services and economic value for communities; for example, in Sitka communities can harvest and sell herring roe.
- There may be synergies between kelp and shellfish that can be leveraged in mariculture operations.
- Kelp provides habitat for rockfish. There have been observations that juvenile rockfish are rearing inside kelp mariculture farms.

Question: What is kelp's role in socio-economic outcomes?
- Kelp is often used for fertilizer. This has been done by the Yakutat Tribe.

Question: What is kelp's role in cultural heritage?
- Tribal Communities fish for rockfish, and rockfish use kelp as habitat.
- Kelp mariculture could provide income for subsistence economies, especially when there is a transition away from a source like Caribou that are moving north.
- Commercial fishing income has declined, and in Kodiak commercial fishers supplement income with secondary sources like kelp mariculture. This works because the sectors operate during different seasons.
- Key research needs for kelp mariculture include where kelp mariculture can be sited, and where / how to get the products to market.
- There could be values in siting kelp and shellfish farming side-by-side.

Question: What are the biggest gaps in our understanding of kelp spatial distribution (e.g., mapping)?
- Mapping kelp distribution is a definite need that would be very welcome. There is a lack of data, and kelp maps would be a great benefit.
- Kelp maps would benefit the mariculture industry for siting farms in low conflict areas.
- Kelp maps would also benefit Tribal Communities looking to develop workforce capacity or business development related to kelp.

Question: How worried are you about the impacts of climate change on your community, especially regarding impacts to coastlines?
- Lack of employment is a driving issue, and climate change is impacting local communities, especially in the aftermath of extreme events like typhoons.
- Green infrastructure is being tried and considered; however, challenges exist. For example, concrete modules and rip-rap breakwaters are too expensive. Communities have tried planting grasses, but in some

places, there is 75-100 ft of land loss per storm. Kelp could potentially help mitigate these effects. In Anchorage, nature-based solutions have been used along the Tony Knowles Coastal Trail; these include seagrass planting and rock installations, both of which have been relatively effective.

3.2.8. National Park Service (Heather Coletti, Marine Ecologist)

Note: This discussion occurred in person on 14 August 2023 and did not follow all questions.

- Kelp is important for a variety of coastal species.
- There are indirect benefits of kelp production for a variety of reasons such as the creation of nursey habitat for nearshore fishes, habitat for invertebrates that are a food source for shorebirds, sea otters and even terrestrial species like bears, and an additional source of carbon for animals that thrive within coastal regions.
- Monitoring and restoration, supported by the Exxon Valdez Oil Spill Trustee Council, in southcentral Alaska is active and includes intertidal and nearshore sites, which may provide insight as to the role of kelps in nearshore food webs.

Question: What are the biggest gaps in our understanding of kelp spatial distribution (e.g., mapping)?
- Mapping and inventorying resources, including kelp, is important, but change detection is even more critical. This is because change is happening rapidly in Alaskan waters, and there are limited baseline data to detect or monitor changes.
- Offshore and subtidal kelps are a big knowledge gap. For example, sea otters are recolonizing, and there are likely cascading effects in the subtidal ecosystem, but there are many unknowns such as what does the coastal ecosystem look like when a keystone species has recovered? What does this indicate in terms of coastal resilience?
- Fundamental mechanistic ecosystem research is still needed in Alaska.

Question: What products or services would be most helpful for your organization to help guide decisions / inform practices?
- There are knowledge gaps related to kelp wrack subsidies and how wrack may boost invertebrate biodiversity and biomass on beaches and shorelines.
- Inventorying and mapping the distribution of resources is key. NPS would use kelp spatial mapping products for multiple purposes, including change detection.
- Current intertidal monitoring efforts in some regions of Alaska could be expanded offshore to encompass subtidal kelps and examine the relationship between intertidal and subtidal environments.

3.2.9. Kachemak Bay National Estuarine Research Reserve (Katherine Schake, Manager; Syverine Bentz, Coastal Training Program Coordinator; Lauren Sutton, Research Coordinator; Jasmine Mauerer, Harmful Species Lead)

Question: What are the biggest gaps in our understanding of kelp spatial distribution (e.g., mapping)?
- Understanding how to map kelp appropriately is a key knowledge gap, especially because of mariculture interest. Potential methods include drone and ROV surveys.
- Determining ecosystem services associated with kelp is key and currently missing; this might be a more critical need than mapping. There is an emphasis in Alaska on preservation and conservation rather than mitigation and restoration.

- There are potentially seed beds nearby that could be used to mapped over time and used to detect changes.
- An umbrella approach could include mapping, change detection, and vulnerability assessments.

Question: What is kelp's role in coastal protection / infrastructure?
- Kelp helps buffer coastal communities and could be used as baffling in harbors.

3.3. Synthesized community discussions

We synthesized community discussions broadly to highlight the state of the science related to kelp and coastal protection, food production, socioeconomic and cultural values, and habitat mapping.

3.3.1 Coastal protection

It is largely unknown whether kelp provides coastal protection benefits in Alaska. Based on research in other regions, it is possible that kelp does help mitigate coastal erosion and attenuate wave energy, but this remains unexplored in Alaska. Understanding the role of kelp in coastal protection in Alaska is challenging because of the expansive rocky and high-energy shoreline, which might also suggest that kelp plays a minimal role in erosion mitigation in most of Alaska. There is anecdotal evidence that by attenuating wave energy, kelp creates a "lee" between the open water and shore that is used by coastal communities to harvest fish and other species. There are areas in Alaska that experience land loss, and kelp could be explored as a potential solution to help mitigate these losses, but this must be coupled with rigorous scientific evaluations. There are multiple caveats, however. First, along some shorelines, kelp does not persist, so using kelp for coastal protection would require significant changes to local ecosystems, which could have unintended consequences and adverse ecological effects. Although, there may also be options to bolster kelp in locations where it has persisted along particular shorelines, such as Jakolof Bay. Second, much of the land loss stems from acute storm events; such storms might overwhelm the coastal protection benefits of kelp. Despite the caveats, community members agree that key gaps remain in collective understanding of ecosystem services provided by kelp, and the potential to provide coastal protection services is one potential service that could be investigated. Even if kelp does not provide substantial coastal protection benefits in Alaska, community members would like to know more about where and how kelp does or does not provide such benefits.

3.3.2. Food production

Kelp is harvested by Alaskan communities as a nutritious food source for individuals and communities. For example, kelp is harvested, dried, and used as a food topping. Kelp can also be pickled, harvested with herring roe, and used to make agar used in foods like ice cream. Additionally, the kelp mariculture industry is rapidly developing in Alaska with bull kelp, sugar kelp, and ribbon kelp as the primary species being investigated for farming (NOAA 2024). While there has been success in farming kelp, it has been challenging to develop economically viable products. Beyond primary production, kelp supports secondary production. For example, kelp is key habitat for commercially and recreationally harvested species, such as salmon, rockfish, and invertebrates. Kelp can also be used as fertilizer to support soil health and terrestrial food production.

3.3.3. Socioeconomic and cultural values

In some parts of Alaska, kelp plays a key role in tourism, as it supports recreational and subsistence access to calm waters in the lee of kelp, supports charismatic megafauna like otters, and supports target fishery

species like rockfish. Kelp has an aesthetic value and also a significant cultural value. Kelp has been used by Alaska Native Tribal Communities since time immemorial and is intricately woven into oral histories and Tribal stories. By playing a key role in ecosystems, kelp supports livelihoods and job opportunities. These job opportunities may be expected to grow with the potential development of a broader mariculture industry.

3.3.4. Kelp habitat mapping

Understanding of kelp spatial distribution is lacking in the state of Alaska and was identified by community members as a key need. Community members pointed to the lack of spatial information as a key information gap but also wanted to set baselines to track interannual changes in kelp spatial distribution. Mapping products are required for mariculture siting, resource assessments (e.g., rockfish, salmon), and to quantify ecosystem services, for example. Multiple mapping techniques should be explored so that mapping can be conducted in remote locations, as well as those that are more easily accessible. Mapping efforts could dovetail with additional in situ, long-term ecological monitoring surveys.

4. Future research directions

Based on the literature synthesis and community discussions, we have identified pressing knowledge gaps and accompanying research questions worthy of future inquiry in Alaska. A number of key information gaps were highlighted; most critically there was a general lack of spatial and temporal data on where beds exist. The ephemeral nature of kelp beds means that mapping data would need to be periodically collected to allow for change detection and to best inform management decisions. Additionally, many regions also have areas of persistent kelp beds, and it would be useful to identify those locations and document changes in species over time, such as the potential spread of Macrocystis pyrifera in Alaska. Beyond this critical baseline data gap, there were many outstanding questions about the ecosystem services kelp provides. Discussions highlighted how Alaskan communities are intrinsically linked to their local natural resources and how the limited scientific information available is concentrated on how kelp supports the ecosystems, food production, and cultural services. Lastly, there are a number of questions related to kelp mariculture and the socio-economic viability of that market. Future research questions that were illuminated by the literature review and community discussions are highlighted below.

4.1. Research questions related to kelp ecosystem services

- What ecosystem services are provided by canopy and subcanopy kelp in Alaska?
- How do kelp ecosystem services compare in different geographic areas of Alaska?
- Which ecosystem services are most valuable to local communities?

4.2. Research questions related to kelp habitat mapping

- What is the most effective approach to map canopy-forming kelp?
- What is the most effective approach to map subcanopy kelp?
- What is the spatial distribution of canopy-forming and subcanopy kelp?
- Can habitat mapping approaches accurately detect change in kelp extent over time?
- How can advanced technologies and artificial intelligence be used to improve kelp mapping techniques?
- What are the priorities for kelp mapping (species-specific, location-specific, etc.)?

4.3. Research questions related to kelp and coastal protection

- Does wave energy differ in coastal areas with and without kelp?
- Do areas with kelp experience less erosion than areas without kelp?
- What physical processes do canopy and subcanopy kelp alter and to what extent?
- What is the role of canopy and subcanopy kelp in coastal protection?
- Is there improved access for fisheries and other community uses in areas with kelp compared to those without (e.g., calmer waters in lee of kelp)?
- Are there particular areas devoid of kelp that experience coastal land loss or erosion that could benefit from kelp introduction?

4.4. Research questions related to kelp and food production

- To what extent do kelp mariculture and shellfish aquaculture facilitate one another, and what is the underlying mechanism?
- How should kelp mariculture be sited with regard to ecosystem function and seascape ecology?
- To what extent (abundance, biomass, temporal scale, spatial scale) do rockfish rely on kelp during ontogeny?
- How do fish, invertebrates, and other species of interest use subcanopy and canopy-forming kelp during their life history?
- What is the socio-economic viability of kelp mariculture?

4.5. Research questions related to kelp and culture

- How has kelp been used since time immemorial by Alaska Native Tribal Communities?
- What are the oral histories associated with kelp in Alaska?
- What is the cultural value of kelp to Alaska Native Tribal Communities?

5. Acknowledgements

We thank the NOAA National Centers for Coastal Ocean Science for supporting this study. We thank K. Holderied, D. Hondolero, R. Whippo, and the staff of the NCCOS Kasitsna Bay Lab for hosting us during this study. We thank all community members for their time, expertise, and valuable insights. We thank B. Puckett and C. Steenrod for their support throughout the project. We thank R. Whippo and K. Holderied for thoughtful reviews of this report. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of the U.S. Government, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

6. References

Bridges, T. S., P. W. Wagner, K. A. Burks-Copes, M. E. Bates, Z. A. Collier, C. J. Fischenich, J. Z. Gailani, L. D. Leuck, C. D. Piercy, J. D. Rosati, E. J. Russo, D. J. Shafer, B. C. Suedel, E. A. Vuxton, and W. T. V. 2015. Use of natural and nature-based features (NNBF) for coastal resilience. US Army Engineer Research and Development Center, ERDC SR-15-1, Vicksburg, MS.

Burger, J., M. Gochfeld, C. Jeitner, M. Gray, T. Shukla, S. Shukla, and S. Burke. 2007. Kelp as a bioindicator: Does it matter which part of 5 m long plant is used for metal analysis? Environmental Monitoring and Assessment 128:311-321.

Chausson, A., B. Turner, D. Seddon, N. Chabaneix, C. A. J. Girardin, V. Kapos, I. Key, D. Roe, A. Smith, S. Woroniecki, and N. Seddon. 2020. Mapping the effectiveness of nature-based solutions for climate change adaptation. Glob Chang Biol 26:6134-6155.

Daly, B., and B. Konar. 2010. Temporal trends of two spider crabs (Brachyura majoidea) in Alaska, USA. CRUSTACEANA 83:659-669.

Deriso, R. B., M. N. Maunder, and W. H. Pearson. 2008. Incorporating covariates into fisheries stock assessment models with application to Pacific herring. Ecological Applications 18:1270-1286.

Estes, J. A., E. M. Danner, D. F. Doak, B. Konar, A. M. Springer, P. D. Steinberg, M. T. Tinker, and T. M. Williams. 2004. Complex trophic interactions in kelp forest ecosystems. Bulletin of Marine Science 74:621-638.

Heidkamp, C. P., L. V. Krak, M. M. R. Kelly, and C. Yarish. 2022. Geographical considerations for capturing value in the US sugar kelp (Saccharina latissima) industry. Marine Policy 144.

Hondolero, D., and M. S. Edwards. 2017. Changes in ecosystem engineers: the effects of kelp forest type on currents and benthic assemblages in Kachemak Bay, Alaska. Marine Biology 164.

Howard, B. E., J. Phillips, A. Tandon, A. Maharana, R. Elmore, D. Mav, A. Sedykh, K. Thayer, B. A. Merrick, V. Walker, A. Rooney, and R. R. Shah. 2020. SWIFT-Active Screener: Accelerated document screening through active learning and integrated recall estimation. Environment international 138:105623.

Johnson, A. C., J. Noel, D. P. Gregovich, L. E. Kruger, and B. Buma. 2019. Impacts of submerging and emerging shorelines on various biota and Indigenous Alaskan harvesting patterns. Journal of Coastal Research 35:765-775.

Johnson, S. W., J. F. Thedinga, and K. M. Munk. 2008. Distribution and use of shallow-water habitats by Pacific sand lances in Southeastern Alaska. Transactions of the American Fisheries Society 137:1455-1463.

Krumhansl, K. A., D. K. Okamoto, A. Rassweiler, M. Novak, J. J. Bolton, K. C. Cavanaugh, S. D. Connell, C. R. Johnson, B. Konar, S. D. Ling, F. Micheli, K. M. Norderhaug, A. Perez-Matus, I. Sousa-Pinto, D. C. Reed, A. K. Salomon, N. T. Shears, T. Wernberg, R. J. Anderson, N. S. Barrett, A. H. Buschmann, M. H. Carr, J. E. Caselle, S. Derrien-Courtel, G. J. Edgar, M. Edwards, J. A. Estes, C. Goodwin, M. C. Kenner, D. J. Kushner, F. E. Moy, J. Nunn, R. S. Steneck, J. Vasquez, J. Watson, J. D. Witman, and J. E. Byrnes. 2016. Global patterns of kelp forest change over the past half-century. Proceedings of the National Academy of Sciences 113:13785-13790.

Kuletz, K. J., and J. F. Piatt. 1999. Juvenile Marbled Murrelet nurseries and the productivity index. Wilson Bulletin 111:257-261.

Morris, R. L., T. D. J. Graham, J. Kelvin, M. Ghisalberti, and S. E. Swearer. 2020. Kelp beds as coastal protection: wave attenuation of Ecklonia radiata in a shallow coastal bay. Ann Bot 125:235-246.

Narayan, S., M. W. Beck, B. G. Reguero, I. J. Losada, B. van Wesenbeeck, N. Pontee, J. N. Sanchirico, J. C. Ingram, G. M. Lange, and K. A. Burks-Copes. 2016. The effectiveness, costs and coastal protection benefits of natural and nature-based defences. PLoS One 11:e0154735.

NOAA. 2024. State of Alaska Aquaculture Report. National Oceanic and Atmospheric Administration. Rosales-Asensio, E., E. Segredo-Morales, N. Gómez-Marín, A. Pulido-Alonso, and C. Sierra. 2023. A techno-economic appraisal of green desel generation through hydrothermal liquefaction, leveraging residual resources from seaweed and fishing sectors. Water 15.

Rosman, J. H., M. W. Denny, R. B. Zeller, S. G. Monismith, and J. R. Koseff. 2013. Interaction of waves and currents with kelp forests (Macrocystis pyrifera): Insights from a dynamically scaled laboratory model. Limnology and Oceanography 58:790-802.

Rosman, J. H., J. R. Koseff, S. G. Monismith, and J. Grover. 2007. A field investigation into the effects of a kelp forest (Macrocystis pyrifera) on coastal hydrodynamics and transport. Journal of Geophysical Research 112.

Scheel, D. 2002. Characteristics of habitats used by Enteroctopus dofleini in Prince William Sound and Cook Inlet, Alaska. Marine Ecology - Pubblicazioni Della Stazione Zoologica Di Napoli I 23:185-206.

Scheel, D., and L. Bisson. 2012. Movement patterns of giant Pacific octopuses, Enteroctopus dofleini (Wülker,1910). Journal of Experimental Marine Biology and Ecology 416:21-31.

Sikes, D. S., and J. Slowik. 2010. Terrestrial arthropods of pre- and post-eruption Kasatochi Island, Alaska, 2008-2009: a shift from a plant-based to a necromass-based food web. ARCTIC ANTARCTIC AND ALPINE RESEARCH 42:297-305.

Stekoll, M. S., and P. V. Else. 1990. Cultivation of Macrocystis integrifolia (Laminariales, Phaeophyta) in southeastern Alaskan waters. Hydrobiologia 204:445-451.

Stekoll, M. S., T. N. Peeples, and A. E. T. Raymond. 2021. Mariculture research of Macrocystis pyrifera and Saccharina latissima in Southeast Alaska. Journal of the World Aquaculture Society 52:1031-1046.

Surma, S., T. J. Pitcher, R. Kumar, D. Varkey, E. A. Pakhomov, and M. E. Lam. 2018. Herring supports Northeast Pacific predators and fisheries: Insights from ecosystem modelling and management strategy evaluation. PLoS One 13:e0196307.

Temmerman, S., E. M. Horstman, K. W. Krauss, J. C. Mullarney, I. Pelckmans, and K. Schoutens. 2022. Marshes and mangroves as nature-based coastal storm buffers. Annual Review of Marine Science 13.

Ulaski, B. P., B. Konar, and E. O. Otis. 2020. Seaweed reproduction and harvest rebound in Southcentral Alaska: Implications for wild stock management. Estuaries and Coasts 43:2046-2062.

Ulaski, B. P., E. O. Otis, and B. Konar. 2023. How landscape variables influence the relative abundance, composition, and reproductive viability of macroalgal wrack in a high latitude glacial estuary. Estuarine Coastal and Shelf Science 280.

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.

Wainright, S. C., J. C. Haney, C. Kerr, A. N. Golovkin, and M. V. Flint. 1998. Utilization of nitrogen derived from seabird guano by terrestrial and marine plants at St. Paul, Pribilof islands, Bering sea, Alaska. Marine Biology 131:63-71.

West, D., M. Crawford, and A. B. Savinetsky. 2007. Genetics, prehistory and the colonisation of the Aleutian Islands. EARTH AND ENVIRONMENTAL SCIENCE TRANSACTIONS OF THE ROYAL SOCIETY OF EDINBURGH 98:47-57.

Wolt, R. C., S. E. Finerty, and R. W. Davis. 2014. Time and energy allocation of female sea otters (Enhydra lutris) with pups in Alaska. Journal of Experimental Marine Biology and Ecology 461:93-101.

7. Appendix 1: List of included articles

Antrim, L. D., R. M. Thom, W. W. Gardiner, V. I. Cullinan, D. K. Shreffler, and R. W. Bienert. 1995. Effects of petroleum-products on bull kelp (Nereocystis luetkeana). Marine Biology 122:23-31.

Aumack, C. F., K. H. Dunton, A. B. Burd, D. W. Funk, and R. A. Maffione. 2007. Linking light attenuation and suspended sediment loading to benthic productivity within an Arctic kelp-bed community. JOURNAL OF PHYCOLOGY 43:853-863.

Beas-Luna, R., F. Micheli, C. B. Woodson, M. Carr, D. Malone, J. Torre, C. Boch, J. E. Caselle, M. Edwards, J. Freiwald, S. L. Hamilton, A. Hernandez, B. Konar, K. J. Kroeker, J. Lorda, G. Montaño-Moctezuma, and G. Torres-Moye. 2020. Geographic variation in responses of kelp forest communities of the California Current to recent climatic changes. Global Change Biology 26:6457-6473.

Bonsell, C., and K. H. Dunton. 2021. Slow community development enhances abiotic limitation of benthic community structure in a High Arctic kelp bed. Frontiers in Marine Science 8.

Burger, J., M. Gochfeld, C. Jeitner, M. Gray, T. Shukla, S. Shukla, and S. Burke. 2007. Kelp as a bioindicator: Does it matter which part of 5 m long plant is used for metal analysis? Environmental Monitoring and Assessment 128:311-321.

Carney, B., D. Tessler, H. Coletti, J. M. Welker, and D. Causey. 2023. Stable isotope-determined diets of Black Oystercatchers Haematopus bachmani in the northern Gulf of Alaska. MARINE ORNITHOLOGY 51:125-135.

Daly, B., and B. Konar. 2008. Effects of macroalgal structural complexity on nearshore larval and post-larval crab composition. Marine Biology 153:1055-1064.

Daly, B., and B. Konar. 2010. Temporal trends of two spider crabs (Brachyura majoidea) in Alaska, USA. CRUSTACEANA 83:659-669.

Dean, T. A., J. L. Bodkin, S. C. Jewett, D. H. Monson, and D. Jung. 2000. Changes in sea urchins and kelp following a reduction in sea otter density as a result of the Exxon Valdez oil spill. Marine Ecology Progress Series 199:281-291.

Deriso, R. B., M. N. Maunder, and W. H. Pearson. 2008. Incorporating covariates into fisheries stock assessment models with application to Pacific herring. Ecological Applications 18:1270-1286.

Dunton, K. H., S. V. Schonberg, and D. W. Funk. 2009. Interannual and spatial variability in light attenuation: Evidence from three decades of growth in the arctic kelp, Laminaria solidungula. Page 271 Smithsonian at the Poles: Contributions to International Polar Year Science: A Smithsonian Contribution to Knowledge.

Ebert, T. A., L. M. Barr, J. L. Bodkin, D. Burcham, D. Bureau, H. S. Carson, N. L. Caruso, J. E. Caselle, J. T. Claisse, S. Clemente, K. Davis, P. M. Detwiler, J. D. Dixon, D. O. Duggins, J. M. Engle, J. A. Estes, S. D. Groth, B. M. Grupe, P. Halmay, K. P. Hebert, J. C. Hernández, L. J. Jurgens, P. E. Kalvass, M. C. Kenner, B. Konar, D. J. Kushner, L. C. Lee, D. L. Leighton, G. Montaño-Moctezuma, J. E. Munk, I. Olguin, J. S. Palleiro, D. O. Parker, J. S. Pearse, D. J. Pondella, L. Rogers-Bennett, S. C. Schroeter, A. O. Shelton, J. Sonnenholzner, I. K. Taniguchi, G. R. VanBlaricom, J. C. Watson, B. P. Weitzman, J. P. Williams, J. Yakimishyn, and Z. N. Zhang. 2018. Size, growth, and density data for shallow-water sea urchins from Mexico to the Aleutian Islands, Alaska, 1956-2016. Ecology 99:761-761.

Estes, J. A., E. M. Danner, D. F. Doak, B. Konar, A. M. Springer, P. D. Steinberg, M. T. Tinker, and T. M. Williams. 2004. Complex trophic interactions in kelp forest ecosystems. Bulletin of Marine Science 74:621-638.

Estes, J. A., D. F. Doak, A. M. Springer, and T. M. Williams. 2009. Causes and consequences of marine mammal population declines in southwest Alaska: a food-web perspective. Philosophical Transactions of the Royal Society of Biological Sciences 364:1647-1658.

Estes, J. A., and D. O. Duggins. 1995. Sea otters and kelp forests in Alaska - generality and variation in a community ecological paradigm. Ecological Monographs 65:75-100.

Estes, J. A., M. T. Tinker, T. M. Williams, and D. F. Doak. 1998. Killer whale predation on sea otters linking oceanic and nearshore ecosystems. Science 282:473-476.

Gierke, L., N. C. Coelho, T. Khangaonkar, T. Mumford, and F. Alberto. 2023. Range wide genetic differentiation in the bull kelp Nereocystis luetkeana with a seascape genetic focus on the Salish Sea. Frontiers in Marine Science 10.

Gorra, T. R., S. C. R. Garcia, M. R. Langhans, U. Hoshijima, J. A. Estes, P. T. Raimondi, M. T. Tinker, M. C. Kenner, and K. J. Kroeker. 2022. Southeast Alaskan kelp forests: inferences of process from large-scale patterns of variation in space and time. Proceedings of the Royal Society of Biological Sciences 289:20211697.

Hamilton, J., and B. Konar. 2007. Implications of substrate complexity and kelp variability for south-central Alaskan nearshore fish communities. Fishery Bulletin 105:189-196.

Heidkamp, C. P., L. V. Krak, M. M. R. Kelly, and C. Yarish. 2022. Geographical considerations for capturing value in the US sugar kelp (Saccharina latissima) industry. Marine Policy 144.

Hollarsmith, J. A., J. C. Cornett, E. Evenson, and A. Tugaw. 2023. A century of canopy kelp persistence and recovery in the Gulf of Alaska. Annals of botany.

Hondolero, D., and M. S. Edwards. 2017. Changes in ecosystem engineers: the effects of kelp forest type on currents and benthic assemblages in Kachemak Bay, Alaska Marine Biology 164.

Hondolero, D., and M. S. Edwards. 2017. Changes in ecosystem engineers: the effects of kelp forest type on currents and benthic assemblages in Kachemak Bay, Alaska. Marine Biology 164.

Johansson, M. L., F. Alberto, D. C. Reed, P. T. Raimondi, N. C. Coelho, M. A. Young, P. T. Drake, C. A. Edwards, K. Cavanaugh, J. Assis, L. B. Ladah, T. W. Bell, J. A. Coyer, D. A. Siegel, and E. A. Serrao. 2015. Seascape drivers of Macrocystis pyrifera population genetic structure in the northeast Pacific. Molecular Ecology 24:4866-4885.

Johnson, A. C., J. Noel, D. P. Gregovich, L. E. Kruger, and B. Buma. 2019. Impacts of submerging and emerging shorelines on various biota and Indigenous Alaskan harvesting patterns. Journal of Coastal Research 35:765-775.

Johnson, S. W., J. F. Thedinga, and K. M. Munk. 2008. Distribution and use of shallow-water habitats by Pacific sand lances in Southeastern Alaska. Transactions of the American Fisheries Society 137:1455-1463.

Kennish, M. J. 2004. NERRS research and monitoring initiatives. Journal of Coastal Research:1-8.

Konar, B. 2000. Limited effects of a keystone species: trends of sea otters and kelp forests at the Semichi Islands, Alaska. Marine Ecology Progress Series 199:271-280.

Kuletz, K. J., and J. F. Piatt. 1999. Juvenile Marbled Murrelet nurseries and the productivity index. WILSON BULLETIN 111:257-261.

Kuo, E. S. L., and E. Sanford. 2013. Northern distribution of the seaweed limpet Lottia insessa (Mollusca: Gastropoda) along the Pacific coast. Pacific Science 67:303-313.

Naidu, A. S., L. W. Cooper, B. P. Finney, R. W. Macdonald, C. Alexander, and I. P. Semiletov. 2000. Organic carbon isotope ratios (δ ¹³C) of Arctic Amerasian Continental shelf sediments. International Journal of Earth Sciences 89:522-532.

Okamoto, D. K., M. S. Stekoll, and G. L. Eckert. 2013. Coexistence despite recruitment inhibition of kelps by subtidal algal crusts. Marine Ecology Progress Series 493:103.

Powell, G. C., D. Pengilly, and S. F. Blau. 2002. Mating pairs of red king crabs (Paralithodes camtschaticus) in the Kodiak Archipelago, Alaska, 1960-1984. Pages 225-245 Crabs in Cold Water Regions: Biology, Management, and Economics.

Raymond, W. W., J. B. Schram, G. L. Eckert, and A. W. E. Galloway. 2021. Sea otter effects on trophic structure of seagrass communities in southeast Alaska. Marine Ecology Progress Series 674:37-58.

Rosales-Asensio, E., E. Segredo-Morales, N. Gómez-Marín, A. Pulido-Alonso, and C. Sierra. 2023. A techno-economic appraisal of green desel generation through hydrothermal liquefaction, leveraging residual resources from seaweed and fishing sectors. Water 15.

Scheel, D. 2002. Characteristics of habitats used by Enteroctopus dofleini in Prince William Sound and Cook Inlet, Alaska. Marine Ecology - Pubblicazioni Della Stazione Zoologica Di Napoli I 23:185-206.

Scheel, D., and L. Bisson. 2012. Movement patterns of giant Pacific octopuses, Enteroctopus dofleini (Wülker,1910). Journal of Experimental Marine Biology and Ecology 416:21-31.

Schoch, G. C., and H. Chenelot. 2004. The role of estuarine hydrodynamics in the distribution of kelp forests in Kachemak Bay, Alaska. Journal of Coastal Research:179-194.

Siddon, E. C., C. E. Siddon, and M. S. Stekoll. 2008. Community level effects of Nereocystis luetkeana in southeastern Alaska. Journal of Experimental Marine Biology and Ecology 361:8-15.

Sikes, D. S., and J. Slowik. 2010. Terrestrial arthropods of pre- and post-eruption Kasatochi Island, Alaska, 2008-2009: a shift from a plant-based to a necromass-based food web. Arctic, Antarctic and Alpine Research 42:297-305.

Smith, E. A. E., M. D. Fox, M. L. Fogel, and S. D. Newsome. 2022. Amino acid delta C-13 fingerprints of nearshore marine autotrophs are consistent across broad spatiotemporal scales: An intercontinental isotopic dataset and likely biochemical drivers. Functional Ecology 36:1191-1203.

Smith, E. A. E., C. Harrod, and S. D. Newsome. 2018. The importance of kelp to an intertidal ecosystem varies by trophic level: insights from amino acid δ ¹³C analysis. Ecosphere 9.

Spurkland, T., and K. Iken. 2011. Kelp bed dynamics in estuarine environments in subarctic alaska. Journal of Coastal Research 27:133-143.

Stekoll, M. S. 2019. The seaweed resources of Alaska. Botanica marina 62:227-235.

Stekoll, M. S., L. E. Deysher, and M. Hess. 2006. A remote sensing approach to estimating harvestable kelp biomass. Journal of Applied Phycology 18:323-334.

Stekoll, M. S., and P. V. Else. 1990. Cultivation of Macrocystis integrifolia (Laminariales, Phaeophyta) in southeastern Alaskan waters. Hydrobiologia 204:445-451.

Stekoll, M. S., T. N. Peeples, and A. E. T. Raymond. 2021. Mariculture research of Macrocystis pyrifera and Saccharina latissima in Southeast Alaska. Journal of the World Aquaculture Society 52:1031-1046.

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. Environmental Conservation 29:436-459.

Stoner, A. W., B. J. Laurel, and T. P. Hurst. 2008. Using a baited camera to assess relative abundance of juvenile Pacific cod: Field and laboratory trials. Journal of Experimental Marine Biology and Ecology 354:202-211.

Surma, S., T. J. Pitcher, R. Kumar, D. Varkey, E. A. Pakhomov, and M. E. Lam. 2018. Herring supports North-east Pacific predators and fisheries: Insights from ecosystem modelling and management strategy evaluation. PLoS One 13:e0196307.

Ulaski, B. P., B. Konar, and E. O. Otis. 2020. Seaweed reproduction and harvest rebound in Southcentral Alaska: Implications for wild stock management. Estuaries and Coasts 43:2046-2062.

Ulaski, B. P., E. O. Otis, and B. Konar. 2023. How landscape variables influence the relative abundance, composition, and reproductive viability of macroalgal wrack in a high latitude glacial estuary. Estuarine Coastal and Shelf Science 280.

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.

Wainright, S. C., J. C. Haney, C. Kerr, A. N. Golovkin, and M. V. Flint. 1998. Utilization of nitrogen derived from seabird guano by terrestrial and marine plants at St. Paul, Pribilof islands, Bering sea, Alaska. Marine Biology 131:63-71.

Walker, L. R., D. S. Sikes, A. R. Degange, S. C. Jewett, G. Michaelson, S. L. Talbot, S. S. Talbot, B. Wang, and J. C. Williams. 2013. Biological legacies: Direct early ecosystem recovery and food web reorganization after a volcanic eruption in Alaska. ECOSCIENCE 20:240-251.

Watson, J. C., M. W. Hawkes, L. C. Lee, and A. Lamb. 2021. The dynamics and geographic disjunction of the kelp Eisenia arborea along the west coast of Canada. Botanica marina 64:395-406.

Watt, J., D. B. Siniff, and J. A. Estes. 2000. Inter-decadal patterns of population and dietary change in sea otters at Amchitka Island, Alaska. Oecologia 124:289-298.

West, D., M. Crawford, and A. B. Savinetsky. 2007. Genetics, prehistory and the colonisation of the Aleutian Islands. Earth and Environmental Science Transactions of the Royal Society of Edinburgh 98:47-57.

Wolt, R. C., S. E. Finerty, and R. W. Davis. 2014. Time and energy allocation of female sea otters (Enhydra lutris) with pups in Alaska. Journal of Experimental Marine Biology and Ecology 461:93-101.

8. Appendix 2: Data on included and excluded articles.

Dataset that includes the screening decision (include vs. exclude) for each article. If an article was excluded, the exclusion reason is provided. If an article was included, the resilience category or categories that it related to are provided. The data set can be accessed here:
https://coastalscience.noaa.gov/project/untangling-how-canopy-kelp-contributes-to-coastal-resilience-in-the-u-s-pacific/

U.S. Department of Commerce

Gina M. Raimondo, *Secretary*

National Oceanic and Atmospheric Administration

Richard Spinrad, Ph.D, *Under Secretary for Oceans and Atmosphere*

National Ocean Service

Nicole LeBoeuf, *Assistant Administrator for National Ocean Service*

The mission of the National Centers for Coastal Ocean Science is to provide managers with scientific information and tools needed to balance society's environmental, social and economic goals. For more information, visit: http://www.coastalscience.noaa.gov/.