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Ecosystem-based management for kelp forest ecosystems

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ABSTRACT

Kelp forests line a quarter of the world's coastlines and provide diverse ecosystem services. While kelps are a harvested resource themselves, they are also foundation species that form the basis of productive ecosystems. Globally, kelps are threatened by a variety of anthropogenic impacts, including overharvesting, overgrazing, invasive species, poor water quality, and the direct and indirect effects of climate change. To address these threats and preserve the services provided by these foundation species, we show that Ecosystem-Based Management (EBM) approaches are well-suited for kelp forest management. To define and illustrate key EBM-inspired approaches for kelp forest management and conservation, we combined key concepts from the EBM literature, the literature on the biology and ecology of kelp forests, and primary information we gathered on case studies of ongoing kelp forest management at regional levels in British Columbia (Canada), California (United States), and northern Chile. Using these three sources of information, we identify six key principles for kelp forest EBM: 1) monitoring at biologically relevant temporal and spatial scales, 2) assessing and addressing cumulative impacts, 3) managing across spatial and institutional scales, 4) co-management with users, 5) employing rapid adaptive management and/or the precautionary principle, and 6) managing food web connections. We explore and illustrate these principles using examples from multiple regions to provide concrete guidance on EBM-inspired strategies that are likely to improve kelp forest management outcomes.

1. Introduction

Kelp forests are highly productive and biodiverse temperate marine ecosystems found along one quarter of coastlines globally [1–4]. They are comprised of large brown algae of the order Laminariales and the myriad species that associate with these marine foundation species [5]. Like many coastal ecosystems, kelp forests are threatened by a suite of anthropogenic impacts [6,7]. Effectively managing kelp forests, however, poses a number of challenges. For instance, kelp forests are notoriously dynamic systems, can be expensive and time-consuming to monitor, are prone to hysteresis, and provide many poorly understood but vital non-extractive ecosystem services [4,8–11].

Understanding the drivers of kelp forest change, the value kelp forests bring to coastal communities, and how to manage them effectively is therefore challenging. Additionally, guidance on managing kelp forests is limited: a literature search for management-relevant research on widely distributed coastal ecosystems like coral reefs, seagrass meadows, and mangrove forests generally returns 1–2 orders of magnitude more results than equivalent searches for kelp forests (Table S1). As global change pushes an increasing percentage of kelp forests towards decline, communities and managers need resources to effectively manage, conserve, and recover their kelp forests [6,12,13].

Given the role of kelps as foundation species in these important ecosystems, the principles of Ecosystem-Based Management (EBM) should be a key framework for effective kelp forest management. EBM rose to prominence in the early 2000s as a movement to manage socio-ecological systems that maintains a broad array of ecosystem services into the future [14]. EBM has been adopted by organizations including the FAO and the Convention on Biological Diversity as a guiding principle and is applied to contexts as diverse as the management of small-scale fisheries to entire watersheds [14,15]. As EBM encompasses a broad, adaptable collection of frameworks, more specific and targeted EBM frameworks have been developed for particular ecosystems, such as coral reefs [16], seagrass meadows [17], forests [18], and riverine systems [19] based on the features of these systems.

A review of the scientific literature yielded few studies that explicitly focused EBM for kelp forests, yet we posit that EBM principles are well aligned with kelp forest management [20,21]. Kelps are ecosystem

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engineers, and thus, there is no way to separate the management of kelp populations from the management of the entire ecosystem [15,22]. As with many coastal habitats, kelp forests can be impacted by both land-based and sea-based human impacts, and thus managing for the cumulative impacts of indirect effects from various uses and industries upstream points to the need for watershed-level governance [14]. Kelp forests are often strongly influenced by food web interactions, such as the classic otter-urchin-kelp paradigm, and therefore managing kelp forests can be intimately linked to managing multiple species and trophic interactions [22]. Additionally, the precautionary principle, a central tenet of EBM, is crucial when managing systems that, like kelp forests, are highly dynamic and expensive to restore [15,22,23]. Finally, kelp forests provide an array of ecosystems services to diverse groups of people. Kelps provide subsistence to Indigenous and recreational harvesters, income for commercial harvesters, recreation to SCUBA divers, raw materials to the pharmaceutical and biofuel industries, lucrative fisheries for kelp forest dependent species such as abalone, urchins, and many fishes, and may have substantial value as sources of blue carbon storage [4,24,25]. With diverse stakeholders valuing different aspects of kelp forests, some of which may be mutually exclusive, managers must consider and manage for many human uses of kelp as well as the intrinsic value of kelp forests in supporting biodiversity and its benefits [14,15,22].

Here, we develop guiding principles for the EBM of kelp forests by evaluating three sources of information: a) scientific literature on marine EBM, b) scientific literature on the biology and ecology of kelp forests, and c) information we gathered on case studies of regional kelp forest management in northern Chile, California (USA), and British Columbia (Canada). In the following sections we outline our process for identifying key EBM components for kelp forests, introduce these guiding principles, and discuss how these principles play out in *in situ* management in these three regions.

2. Developing key principles for kelp forest EBM

Three sources on marine EBM were particularly important for our review: Arkema et al. [22], Long et al. [15], and McLeod and Leslie [14]. These works present broad overviews of marine EBM and its associated principles, such as considering ecosystem connections, creating distinct management boundaries, and acknowledging uncertainty (Table S2). Review of the literature on the biology and ecology of kelp forests helped to identify important characteristics of kelp forest systems for management. First, kelp forests are dynamic across space and time, and thus 'adequate monitoring' can require both high-frequency and widespread surveys [11,15,22]. Kelp forests also can be subject to phase shifts to alternative stable states that are difficult to reverse [9,20] As the costs of restoration are high [23], management should utilize the 'precautionary principle' [13]. Further, kelp forests sit at the intersection of land and sea [3], and are thus subjected to a wide range of anthropogenic impacts [7]. Planning for and managing across these 'cumulative impacts' will be important for kelp management [14]. Next, kelp forests provide a broad range of ecosystem services, from direct harvest to recreation to coastal protection [10,25]. This requires managers to take into account the needs of a diverse set of 'stakeholders' and balance tradeoffs [15,22]. Finally, kelp forest dynamics can be strongly impacted by top-down forces. In many regions kelp forests are structured by top-down ecosystem processes, although bottom-up forces are often crucial as well [26–30]. Thus, 'managing ecological connections', particularly predator and grazer populations, may be an important kelp forest management tool [15,22].

To assess whether current management practices address these key characteristics, we reviewed how kelp forests are managed in three regions: northern Chile, California (USA), and British Columbia (Canada). We focused primarily on understanding the threats present and specific policies implemented in each region that impacted kelp forests. At the outset we characterized the socioecological system in each region using an abbreviated version of Ostrom's SES framework in order to enrich our understanding of the threats and policies with this important contextual information (Table S3) [31,32]. For each region we then reviewed the academic, government, and gray literature for evidence of threats to kelp (e.g. overharvesting, invasive species) and whether/how those threats were managed (Appendix 2).

We then requested feedback from managers and scientists to verify whether our interpretation of key threats and policies according to the literature appeared accurate based on their institutional knowledge and to identify literature we had missed on first review. We communicated with 22 individuals spread across disciplines and institutions in these three regions. These experts included managers involved with creating kelp-relevant policies, academic scientists studying kelp forest ecology or management, and scientists at environmental non-profits working with kelp forests in the region. Experts contributed two kinds of feedback. The first focused on identifying major threats to kelp forests in the area, important literature and policies on the area's kelp forests, and the *in situ* efficacy of policies. While the authors had originally intended to travel to each region for this ground-truthing with experts, due to the COVID-19 pandemic, conversations were held between the lead author and experts via video call, phone call, or email. After these conversations the authors extended their literature search based on their recommendations. The authors then summarized the key threats and kelp forest policies in each region based on extensive literature searches and these expert's first rounds of feedback and then invited these experts to review and verify the information and to identify if anything was incorrect or missing from our evaluation of key threats and policies in their area. For further details, please see Appendix 1.

Finally, we review the key kelp forest characteristics and assessed how they aligned with ongoing management actions from our case studies. Generally, these biologically-based characteristics did align with *in situ* conditions and management approaches to them. For instance, all regions had overlapping threats to kelp forests resulting in cumulative impacts and making causality of changes in kelp abundances difficult to determine. Furthermore, managing food web connections was a popular management strategy. Overall, we identified six principles for EBM of kelp forests:

1) Monitoring at biologically relevant temporal and spatial scales
2) Assessing and addressing cumulative impacts
3) Managing across spatial and institutional scales
4) Co-management approaches
5) Employing rapidly adaptive management and/or the precautionary principle
6) Managing food web connections

We note that some of these principles are of specific importance to kelp forests while others may apply to many kinds of coastal ecosystems [14,33]. For example, kelp forests in high latitude systems like British Columbia can be uniquely responsive to trophic cascades and thus management may depend more heavily on managing top predators and herbivores than other coastal ecosystems such as seagrasses (Principle 6) [26,34–36]. Additionally, most key canopy-forming species have lifespans on the order of just 1–7 years [37,38]. With such short lifespans, kelp forests have minimal capacity for the 'storage effect' and may respond rapidly to changing conditions, which translates into an increased importance of annual to sub-annual monitoring (Principle 1) and adaptive management/the precautionary principle (Principle 5). Below we briefly orient the reader to kelp forests in each region, and then further explore these principles and their *in situ* use in our regional case studies below.

3. Socioecological context of kelp forests in each region

Our case studies focused on three regions with varying socio-ecological contexts for kelp forest use and management in order to develop broadly applicable guiding principles for kelp forest management. Please see the Supplement for a more extensive assessment of regional socioecological context and management regimes (Table S3, Appendix 2).

3.1. British Columbia

British Columbia's kelp communities are dominated by the canopy forming kelps *Macrocystis pyrifera* and *Nereocystis luetkeana* and subcanopy kelps including *Saccharina spp*., *Laminaria setchellii*, *and Costaria costata* among others [39,40]. The British Columbia coastline has complex topography with distinct kelp assemblages on the outer coast versus the more protected, inner coast waters [40]. Important predators of kelp-grazing sea urchins include Sea Otters (*Enhydra lutris*) and the Sunflower Sea Star *(Pycnopodia helianthoides*) and the region is prone to urchin barrens in the absence of these species [27,35,41]. Commercially and culturally important kelp forest species include salmon and rockfish species and several species of endangered abalone [27,42,43]. Direct harvest of kelp is relatively low, and an Ocean Wise assessment rated the harvest as sustainable although data limited [44]. The spawn-on-kelp herring roe fishery, largely conducted by indigenous First Nations members, is an important driver of kelp harvesting, along with smaller harvesting operations for edible algae and fertilizers [44]. Ocean tourism is important in British Columbia, accounting for about 2–3% of its GDP [45]. Over the past two decades, increasing recognition of the rights of First Nations Indigenous peoples have spurred new efforts to coproduce marine management with the First Nations, such as the Marine Planning Process (MaPP) [46].

3.2. California

California's kelp communities are dominated by many of the same species as British Columbia. Key differences include an increasing dominance of the canopy by *Macrocystis* over *Nereocystis* in the southern part of the region and dominance of subcanopy kelps such as *Laminaria farlowii*, *Pterygophora californica, Desmarestia lingulata,* and *Dictyota spp* [47]. California has a diverse array of kelp forest predators, including Sea Otters, the Sunflower Sea Star, California Sheephead (*Semicossyphus pulcher*), and Spiny Lobsters (*Panulirus interruptus*), although their presence and abundance vary regionally [28,47–49]. Some of these species have benefited from California's extensive network of Marine Protected Areas (MPAs) [48,50,51]. In California, harvesting of giant kelp for alginate was previously a lucrative industry, but for the last two decades harvesting has been mostly limited to harvesting kelps for human consumption and as feed for cultured abalone [52]. While recreational harvesting is not tightly regulated, commercial harvesting is managed by the state via a space-based Administrative Bed leasing approach, allowable harvest methods, and limits for *Nereocystis* take for edible seaweed harvesters [53]. Ocean-related tourism and diving, much of it in kelp forests, are culturally and economically important [25]. Invasive algae species, such as *Sargassum horneri* and *Undaria pinnitifada*, have become established in the southern part of the state and threaten native kelp populations in the Channel Islands [54,55]. Interest in kelp forest management and restoration has spiked since the collapse of northern California's *Nereocystis* forests in 2015 [56,57].

3.3. Northern Chile

Northern Chile (usually defined as the area between 18° and 32°) has kelp communities dominated by *Lessonia berteroana* in the intertidal and *Lessonia trabeculata* in the subtidal along with limited populations of *Macrocystis pyrifera* [24,58]. Important kelp grazers include *Tegula* spp. snails and the urchin *Tetrapygus niger,* which can form grazing fronts to create urchin barrens [59,60]. Economically and ecologically important kelp forest species include rocky reef fishes such as the Chilean Sheephead Wrasse (*Semicossyphus darwini)*, the Chilean abalone known as 'loco' (*Concholepas concholepas)*, and keyhole limpets (*Fissurella* spp.) [24,59]. Northern Chile is the world's largest exporter of wild kelp [61]. This economically important industry focuses primarily on L. *berteroana* as well as L. *trabeculata* and *M. pyrifera* [24,61]. Much of this harvest is small-scale, and an estimated 15,000 people in northern Chile make some part of their livelihood from kelp harvesting [61]. Intense overharvesting threatens northern Chile's kelp forests, particularly illegal and unreported harvest due to the large number of informal landing points and limited monitoring and enforcement capacity by the authorities [62,63]. Harvest management is split into two regimes: 1) an extensive network of small Territorial Use Rights Fisheries (TURFs) co-administered by local fishers and government agencies and 2) open access areas managed by regional harvesting plans [64–67]. Northern Chile has experienced less warming in the last decade than much of the world [68,69], and local experts have not yet identified strong impacts of global climate changes on the region's kelp forests.

4. Principles for kelp forest EBM

Below we outline the six guiding principles for EBM of kelp forests that we identified based on their biological characteristics, the EBM literature, and three regional case studies and show evidence for how each principle is utilized in these regions (Table 1). We do not expect the principles we outlined here to encompass a complete or perfect understanding of kelp forest EBM, but rather to serve as a useful starting place for management.

1) **Monitor key parameters at biologically relevant temporal and spatial scales to meet management objectives**

Kelp species are often relatively short lived; either annuals (e.g. *Nereocystis luetkeana*) or short lived perennials (e.g. *Macrocystis pyrifera* in Chile which lives 1–3 years) [59,123]. Short lifecycles make kelps prone to population booms and busts, and natural disturbances, such as storms and climatic oscillations, can dramatically and quickly alter kelp population size [124–126]. Kelp forests are spatially dynamic as well. For instance, *Macrocystis* forests in southern California are synchronized in their population dynamics only when within a few hundred meters of one another, meaning that population changes can vary strongly even at the scale of a few kilometers [127]. For these reasons, kelp forest monitoring may need to include both frequent and widespread monitoring depending on monitoring objectives.

In our case studies, we found that widespread and/or annual to sub-annual monitoring programs yielded important dividends in informing kelp management. In California long-term annual monitoring of kelp extent through aerial surveys and remote sensing and of key kelp forest organisms through SCUBA surveys have revealed the impacts of various threats to kelp forests, such as degraded water quality, predator loss, and a changing climate [74,128,129]. Additionally, these monitoring data have helped to assess the efficacy of management interventions such as MPAs and wastewater legislation [48,55,74,130]. In northern California, long-term aerial monitoring allowed managers to quickly quantify the percent decline in *Nereocystis* populations in 2015 and communicate the severity of the situation [56,57,131].

In Chile, where kelp is a key fishery resource, long-term monitoring conducted by the government-funded Instituto de Fomento Pesquero has focused on kelp forest processes as well as population sizes. Researchers have characterized recruitment rates, mortality rates, growth rates, and reproductive status of harvested kelp species [63,71,72]. While monitoring is not conducted annually, repeated visits to the same sites have allowed characterization of how intense harvesting impacts demographic processes, such as falling rates of reproductive individuals of L. *berteroana* at harvested sites [63]. Additionally, monitoring biological processes has allowed scientists to identify and communicate sustainable harvest recommendations,

Table 1
Examples from the three case study regions of how each principle is utilized in ongoing management efforts. This list is meant to illustrate lessons learned in each region, and is not exhaustive. Blank squares indicate that we could not identify examples that were directly pertinent to kelp forests. Please refer to Appendix 2 for a more complete discussion of ongoing management efforts in each region.

Principles	Northern Chile	California (USA)	British Columbia (Canada)
Monitoring at biologically relevant temporal and spatial scales	Long-term monitoring conducted by the Instituto de Fomento Pesquero at sub-annual scales, includes focus on measuring demographic variables [63,71,72]; Some use of aerial surveys [73]	Widespread annual surveying using SCUBA and remote sensing data, utilizes community scientists, non-profits, academic researchers and government programs [57,74–78]	In past 5 years MaPP developed a regionally-coordinated Regional Kelp Monitoring Program that utilizes First Nation Guardian Watchmen, universities, non-profit institutions [79,80]
Assessing and addressing cumulative impacts (see Appendix 2 for complete discussion on how these threats are managed)	Key documented threats: overharvesting of kelps [63,81,82] intense overfishing of urchin-eating predators, ongoing coastal development and water quality concerns [83–86]	Key documented threats: increasing water temperatures, invasive macroalgae, predator disease, and the legacy of historic predator overharvest [55,56,87–89]	Key documented/putative threats: likely include land-based water quality degradation, the legacy of otter overharvesting, predator disease, kelp overharvesting, and increasing water temperatures [35,41,80,90,91]
Managing across spatial and institutional scales	Water quality improvement efforts that via locally driven lawsuits and national level via national level legislation [85,92–95];	Water quality improvement efforts that have targeted both local-scale point sources of pollution and regionally distributed sources of pollution [74,101–105];	Grazer control via local-scale urchin removal efforts as well as provincial-scale reintroduction of and protections for otters [27,41,111,112]
	Kelp harvesting regulations include local-level management of TURFs as well as regional management of region-wide harvest levels [64,96–100]	Local amelioration of invasive species as well as regionally coordinated ballast water regulations [55,106–110]	
Develop and implement co-management approaches with users	Management of kelp harvest via a TURF system (known as Áreas de Manejo y Explotación de Recursos Bentónicos) managed by local fishers cooperative [85,97,98,113,114]; increased role of local communities in building regional level plans [99,115]	Opportunities for users to comment on kelp harvest regulations [116]	Co-management between the Provincial government and Indigenous First Nations yielding outcomes for kelp forests including a regionally coordinated monitoring program and a review of harvest regulations [46,79,80,112]
Employ adaptive management and/or the precautionary approach	When kelp is a target species in TURFs, its harvest is subject to annual assessments of population status and consequent adjustments to harvest levels [64,96,117]	MPA network is adaptively managed, currently undergoing review and evaluation [118]	Kelp harvesting regulations have been categorized as 'employing the precautionary approach' [44]
Manage food web connections to promote resilience of kelp forests	Documented increases in urchin-eating fish, decreases in urchins, and increases in kelp cover in TURFs [97,98]	MPA network can provide refuges for predators [28,48,50,119]; MLMA provides justification to consider ecological role of managed species when managing [120,121]; use of strategic urchin reduction in key locations [101,122]	Reintroduced and expanding otter populations precipitated trophic cascades that have lowered urchin abundance, decreased average urchin size, and increased kelp forest cover [27,41]; pilot experiments on targeted urchin removal in Gwaii Haanas [112]

such as harvesting L. *berteroana* with a base of ≥ 20 cm [72,132]. Finally, this kind of repeated monitoring allows the government to identify sites with high levels of illegal harvesting and estimate rates of compliance with harvesting regulations [63].

Despite the dividends, monitoring kelp forests at the needed temporal and spatial scales may appear unobtainable in some regions due to cost and logistic challenges. Ongoing advances in the remote sensing of canopy-forming kelps is making low-cost regional monitoring of canopy extent feasible [57,123]. Additionally, the MaPP Regional Kelp Monitoring Program in British Columbia offers some useful lessons [79,80]. This regionally-coordinated program utilizes existing institutions, such as First Nations Guardian Watchmen programs, to conduct a tiered program of information gathering using different survey types, including drone, kayak, and SCUBA surveys, to collect kelp forest data based on the needs and logistic capacity in each area [79,80]. By working with diverse partners and diverse survey types, this program is greatly increasing the spatial and temporal scale of monitoring in British Columbia. Coordinating across these diverse institutions and survey types is uniquely challenging but has the potential to dramatically increase the data available to managers for decision-making.

2) **Assess and address cumulative impacts to maintain kelp forest resilience**

Kelps live primarily in nearshore environments that are impacted by both land-based and ocean-based human activities and thus often face overlapping anthropogenic impacts. These threats can include water pollution, overharvesting of kelp, overharvesting of key predators, invasive species, and the indirect and the direct effects of climate change [7]. In our case studies, we found that each region had multiple documented and putative threats to their kelp forests. For instance, in southern California, current documented threats to kelp forests include increasing water temperatures, invasive macroalgae, predator disease, and the legacy of historic predator overharvest [55,56,87–89]. In northern Chile, overharvesting of kelps is largely seen as the most pressing threat [63,81,82] but intense overfishing of urchin-eating predators, ongoing coastal development and water quality concerns also present local threats [83–86]. In British Columbia, a lack of historic monitoring prevents reliable identification of threats, but these threats likely include some combination of land-based water quality degradation, the legacy of otter overharvesting, predator disease, kelp overharvesting, and increasing water temperatures [35,41,80,90,91].

The cumulative or synergistic effects of multiple interacting threats are likely to increase the probability of kelp forest decline [14,33,133]. For instance, when kelp forests collapsed suddenly in Northern California in 2015, scientists described the conditions that led to the collapse as a “Perfect Storm” of interacting threats, including disease-driven loss of urchin predators, an explosion in urchin densities, and a historic marine heatwave [56]. Rather than focusing management on a single threat, employing resilience-based ideas of mitigating cumulative impacts on kelp forest ecosystems is likely to yield important benefits [14].

3) **Managing kelp forests across multiple spatial and institutional scales**

For common pool resources like kelp forests, polycentric approaches to management are often useful [134,135]. Just as ecological interactions happening at multiple spatial and temporal scales drive kelp forest state [136], policies and management targeting a single threat at multiple institutional scales appeared across all three regions. In northern Chile improving coastal water quality involved local efforts to address point sources of pollution as well as nation-wide policies. For decades the El Salvador copper mine dumped mining tailings directly onto beaches and had devastating impacts on local intertidal and subtidal kelp forests [137,138]. Addressing this problem began at a local level, when residents of impacted towns sued the government for allowing this ocean dumping [95]. In addition, national level legislation around the closure of mining operations, such as Chilean Law N°20.551, have helped improve water quality as well as prevent the development of specific projects that were likely to impact kelp forests [85,92–94].

In British Columbia, restoring kelp forests via grazer control has occurred at local to national levels. Regional introductions of sea otters on Vancouver Island in combination with the protections afforded by national-level listing of otters as an endangered species have restored this predator in parts of its historic range [139,140]. Regionally, increasing otter populations have been consistently tied to decreased urchin grazing and increases in kelp coverage [27,41]. However, in areas where otter reintroduction is undesirable, local efforts to cull urchins can allow for small-scale restoration of kelp forests. For instance, concerned that otters could negatively impact shellfish fisheries, the Haida Nation instead has implemented a large-scale urchin removal experiments in Gwaii Haanas National Park Reserve and Haida Heritage Site in order to improve kelp habitat for abalone and rockfish [111,112].

Most of the threats that have been described thus far impact kelp forests at multiple scales, and thus governance cannot fully steward kelp forests at a single institutional scale [134,135]. Local point sources of water pollution can be controlled, but region-wide wastewater discharge and agricultural runoff may still create eutrophication. Regional kelp forest harvest policies can be sustainable, yet local stands may be overharvested. Thus outcomes of kelp forest management will likely depend on polycentric approaches to management across spatial and institutional scales in kelp forests, particularly when actors and managers at differing scales are aware of and communicating with one another [141].

4) **Develop and implement co-management approaches with users**

Kelps forests provide an array of ecosystem services that support a wide variety of motivated users [10,24,25]. Developing management goals and implementing solutions in partnership with users and/or Indigenous nations has enabled improved outcomes for kelp forest monitoring and sustainable use in all three regions. In British Columbia, this has taken the form of coproduction of kelp forest management by the Provincial government and Indigenous First Nations via the Marine Planning Partnership process [46]. First Nation concerns surrounding the sustainability of kelp harvesting, lack of long-term monitoring information, and maintaining robust habitat to support abalone and rockfish have helped produce a regionally coordinated monitoring program, a review of harvest regulations, and one of the largest, most rigorous urchin removal experiments attempted in North America [79,80,112].

In Chile, enabling small-scale management of kelp harvest via a TURF system (known as Áreas de Manejo y Explotación de Recursos Bentónicos) has locally mitigated unsustainable harvest of kelps and other relevant species via increased monitoring, enforcement and long-term investment in sustainability [65,98]. In many TURFs where managers focus on harvesting non-algal resources, these TURFs create a network of *de facto* no-take zones for overharvested kelps, although the sustainability of individual TURFs can vary widely [85,113,114]. In both regions, engaging motivated users, in the form of Indigenous nations and small-scale harvesters, in kelp forest policy making and implementation has improved management.

Given the aforementioned challenges of monitoring widespread kelp populations regularly along remote coastlines, engaging local users may also have benefits in increasing the scale of monitoring. In California, for example, managers work with another important stakeholder group, recreational divers, to conduct important monitoring and management efforts [76,142]. For example, the citizen science organization Reef Check has played a pivotal role in responding to the collapse of kelp forests in northern California by organizing monitoring efforts and implementing targeted urchin culling [131,143]. Successfully engaging these users does require investment, however, as the outcomes in all of these cases depend on reliable government funding of such partnerships [46,113,144].

Finally, we note that Indigenous peoples and nations are more than stakeholders. According to the U.N. Declaration of the Rights of Indigenous People, they are right sholders that have rights to the lands they traditionally occupied, including the right ‘to determine and develop priorities and strategies for the development of use of their lands or territories and other resources’ [145]. Additionally, given the evidence that when Indigenous peoples are involved in co-management the conservation outcomes are often better, a crucial step in kelp forest management is co-leadership with Indigenous peoples [146,147].

5) **Employ adaptive management and/or the precautionary approach to manage dynamic kelp forests**

For dynamic systems such as kelp forests, standing stock can change rapidly, and thus kelp harvesting policies are one aspect of management that could benefit from rapid adaptive management. While kelp harvesting in many places is seen as a relatively small, cottage industry, even low levels of harvest can generate concerns about sustainability, particularly when populations are threatened by multiple factors. We do see examples in our case studies of adaptive management of kelp harvesting. For instance, in the TURFs of northern Chile where kelp is harvested, annual assessments of population status and consequent adjustments to harvest levels are required [64,117].

In general, however, kelp harvest regulations in each region were updated on decadal timescales. A major barrier to implementing adaptive management in all three regions is obtaining updated data on standing stock for multiple species of harvested kelps. Difficulty tracking realized harvest levels and impacts also stymies adaptive management efforts. In Chile illegal, unreported, and unregulated (IUU) kelp harvest is one of the most important challenges to kelp forest resilience [63,148]. Furthermore, in California and British Columbia the commercial harvest relies on self-reported take, recreational harvesting is minimally tracked, and the impacts of harvesting on particular populations have received very limited study in the last 25 years (although see [151,152]). Overall, obtaining the regular and accurate information on kelp standing stock, harvest levels, and harvest impact needed to support adaptive management remains a challenge.

Given these difficulties, employing adaptive management on the timescales relevant for kelp may not be realistic in many regions. In the face of high variability and uncertainty, EBM theory notes that the precautionary approach is particularly useful when systems are impacted by multiple stressors, are prone to sudden changes, and when hysteresis tends to stymy recovery, all of which apply to kelp forests [14,33,153]. At least two of our three regions require a 'precautionary approach' to fisheries management, so the legal bases exist [67,154]. How to apply the precautionary principle to kelp harvest on time scales relevant to these extraordinarily dynamic systems is less clear. Overall, managing harvest of kelps is a challenging area ripe for technological, social, and policy innovation, which we explore later in this paper.

6) **Manage food web connections to promote resilience of kelp forests**

Kelp forests have been a model ecosystem in the development of scientific theories about top-down control of ecosystems, such as the trophic cascade [20,26,27]. The strength and reliability of top-down control on kelp forests appear to be widely variable depending on region [41,126]. In general, at higher latitudes with simpler food webs, managing for abundant predator populations though fisheries management, harvest bans, or MPAs can support abundant kelp forests [5,41,155,156]. For instance, in British Columbia reintroduced and expanding otter populations have often precipitated trophic cascades that have lowered urchin abundance, decreased average urchin size, and increased kelp forest cover [27,41].

Conversely, in northern California, there are currently no known major urchin predators. Sea otters were never reintroduced following extirpation and Sea Star Wasting Syndrome caused mass-mortality of the urchin-eating sea star *Pycnopodia* around 2014 [131,157]. This lack of urchin predators likely contributed to the collapse of *Nereocystis* forests across northern California in 2015 along with the effects of a historic marine heatwave [56]. Since the 1970s at least, efforts have been made in California to manage urchin abundances directly via targeted culling and fisheries when top predators are lacking [101,158]. Several urchin removal experiments are ongoing in northern California to increase the odds of *Nereocystis* re-establishment in key coves [143].

Managing food web connections including apex predators, mesopredators, and herbivores can have positive outcomes for kelp forests [28], yet it is not a panacea for kelp forest conservation. The importance of managing food web connections will vary regionally [5,155,159]. For instance, although urchin-eating fishes in northern Chile have been severely overfished [84] we found little evidence that urchins were currently overgrazing kelp forests there. Thus, regional-specific knowledge must be utilized to assess the necessity of food-web based kelp forest management. Another caveat is that although grazer removal efforts can be useful on small scales, they are unlikely to remedy overgrazing at regional scales due to the high effort and cost required for effective implementation [23].

Finally, our techniques for managing food web connections may need to shift as global climate change progresses. Historically, overharvesting was one of the greatest threats to kelp forest predator populations and fishery-based interventions, such as harvest bans or MPAs are a frequent management response, as in the case for sea otters in British Columbia and lobsters and California sheephead in California [48,128,140]. As global climate change progresses, non-fishing related collapses of key food web connections may increase and challenge managers to identify solutions beyond fishery-based regulations [160].

5. Opportunities for innovation: from regions to the globe

Looking across these case studies, we identified cross-regional challenges to implementing EBM-inspired kelp forest management but also opportunities. We highlight a few of these here to draw attention to aspects of kelp forest management that are ripe for study and innovation.

5.1. New technology to support monitoring

Emerging technology, particularly remote sensing, is beginning to make regular, widespread monitoring more realistic. Inexpensive moderate resolution satellite imagery can target broad spatial and temporal scales for canopy forming kelps, whereas higher resolution unmanned aerial vehicles (e.g. drones) can perform more focused assessments of kelp forest extent at high priority sites [123,161]. For assessing sub-surface kelp forest metrics, underwater remotely operated vehicles are being adapted for use in structurally complex nearshore rocky reefs [162]. These developing technologies offer a critical opportunity to address Principle 1, monitoring these widely dispersed and highly dynamic systems.

5.2. Improving understanding of putative threats and their management

In these case studies, we found some threats were well documented while many others were putative with little evidence to identify their realized impacts (Appendix 2). Kelp forests present particular challenges to identifying the impact of various threats since they can be difficult systems to work with experimentally. Key kelp species such as *L. trabeculata* , *Macrocystis*, and *Nereocystis* present substantial difficulties for laboratory experiments due to their large adult forms, and field experiments are challenging due to the difficulties and expense of regularly deploying dive teams in waters that are often some combination of cold, wave-exposed, and remote (although notable exceptions exist in places like southern California). This kind of experimental work, both in the lab and in the field, is critical, particularly for more subtle diffuse threats such as changing water quality. Other areas for innovation in identifying the impacts of threats include utilizing 'natural experiments', such as marine heatwaves or the sudden loss of key species to disease, to test ecological theory in the field, as well big data approaches and emerging non-diver based monitoring technologies [57,163].

5.3. Engaging communities for effective kelp forest management

For marine ecosystems, kelp forests are relatively accessible to the local peoples because they are widely distributed, exist in intertidal and nearshore areas, can be accessed by land or sea, and are fixed in place [164]. These aspects of kelp forests suggest that cultivating local stewardship of kelp resources, rather than relying solely on centralized decision-making and enforcement, is likely to improve management. We have outlined excellent examples of these kinds of policies in this paper, including northern Chile's TURFs and British Columbia's MaPP program, but there are many instances in which kelp management is still solely centralized. We suggest that managers continue to push for and experiment with local leadership and engagement along with governance partnerships in response to kelp management challenges [165]. For example, each region we studied struggled to monitor compliance with kelp harvesting regulations, and thus utilizing strategies that maximize the chance of collective action among local users may be more beneficial than focusing on top-down enforcement [44,80,96,116,149,166,167].

5.4. Building a toolbox of interventions at local to medium scales for climate change related impacts

Beyond global divestment from fossil fuels, how can management at local and regional scales mitigate the impacts of global climate change on kelp forests? Emerging ideas we identified in these case studies included breeding and out-planting heat tolerant strains of kelps [168, 169], diverse techniques for kelp forest restoration [13,170,171], identifying whether MPAs increase kelp forest resilience to climate change [28], creating 'spore banks' of genetic diversity for key species [144], recovering populations of key urchin predators [27,160], and protecting remnant patches of kelp [13,171]. Kelps may have higher potential adaptive capacity to changing climatic conditions than other foundation species due to their relatively short generation times [172]. Thus, for local managers one option for enhancing climate resilience may be to mitigate as many abatable stressors to kelp forests as possible, in order to maintain large, genetically diverse populations with increased chances of adapting to a changing climate.

6. Conclusions

Given the difficulties of monitoring and experimenting with kelp forests, their intensely dynamic nature, and their often limited direct commercial value, historically the science of managing kelp forests has been underdeveloped. However, as regions begin to lose their kelp forests to ever-increasing human impacts on coastal ecosystems, managers, users, and Indigenous peoples are asking what can be done to protect these vital ecosystems and the diverse services they provide. We show here that kelp forests are a good context to put EBM theory to practice. Organizing kelp management efforts around an EBM framework and utilizing specific EBM tenets, such as coproducing management solutions with diverse users and using a cumulative impacts framework, can yield important benefits for kelp forests on the ground. We recognize that this paper drew from only three regional case studies and undoubtedly missed important contributions from other regions. We hope, however, that this paper can act as a springboard to encourage further cross-regional exchange on the best practices in kelp forest management and conservation needed to maintain these treasured ecosystems now and far into the future.

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CRediT authorship contribution statement

Sara L Hamilton: Conceptualization, Data curation, Methodology, Investigation, Writing – original, Writing – review & editing. **Mary G. Gleason:** Conceptualization, Funding acquisition, Investigation, Writing – review & editing. **Norah Eddy:** Conceptualization, Funding acquisition, Writing – review & editing. **Natalio Godoy:** Validation, Investigation, Writing – review & editing. **Kirsten Grorud-Colvert:** Conceptualization, Methodology, Investigation, Writing – review & editing, Supervision.

Conflicting interest

The authors have no competing interests to declare.

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Appendix A. Supporting information

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