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An ecosystem approach to kelp aquaculture in the Americas and Europe

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ABSTRACT

Kelp farming is increasing along the temperate coastlines of the Americas and Europe. The economic, ecological, and social frameworks surrounding kelp farming in these new areas are in contrast with the conditions of progenitor kelp farming regions in China, Japan, and Korea.

Thus, identifying and addressing the environmental and social impacts of kelp farming in these regions is vital to ensuring the industry's long-term sustainability. Here, a conceptual model of the human and natural systems supporting this nascent kelp aquaculture sector was developed using Maine, USA as a focal region. Potential negative impacts of kelp aquaculture were identified to be habitat degradation, overfishing of wild seeds, predation and competition with wild fish and genes, and transmission of diseases. Increased food security, improved restoration efforts, greater fisheries productivity, and alternative livelihoods development were determined to be potential positive impacts of kelp aquaculture. Changes in biodiversity and productivity resulting from either negative or positive impacts of kelp aquaculture were confirmed to have downstream effects on local fisheries and coastal communities. Recommendations to improve or protect the ecosystem services tangential to kelp farming include: define ecosystem and management boundaries, assess ecosystem services and environmental carrying capacity, pursue ecologically and socially considerate engineering, and protect the health and genetic diversity of wild kelp beds. Recommendations to ensure that kelp farming improves the well-being of all stakeholders include: increase horizontal expansion, expand and teach Best Management Practices, and develop climate change resiliency. Additionally, an integrated management strategy should be developed for wild and farmed kelp to ensure that kelp aquaculture is developed in the context of other sectors and goals.

1. Introduction

Marine seaweed farming is a rapidly expanding practice. In 2016, the global production of farmed seaweed reached an estimated 30 million tonnes (Food and Agriculture Organization (FAO), 2018). Approximately 27% of this production was kelp; a group of ca. 30 genera of large brown seaweeds belonging to the order Laminariales. The temperate coastlines of China, Japan, and Korea have historically been the epicenters of kelp farming (Food and Agriculture Organization (FAO), 2016). Recently, the practice has expanded to regions in Europe (Sweden, Norway, Iceland, Ireland, and the Faroe Islands), North America (Canada and USA), and South America (Chile). In the USA, kelp have been farmed in Maine, New Hampshire, Massachusetts, Connecticut, Rhode Island, Washington, and Alaska. Total production in the Americas and Europe in 2014 was approximately 54,000 tonnes valued at US $51 million (Food and Agriculture Organization (FAO), 2016).

American and European production of cultivated kelp was equivalent to 1.5% of global gross production in 2014. However, it accounted for 4% of the value because European and American economic, ecological, and social frameworks surrounding kelp farming are in contrast with the conditions of progenitor kelp farming regions in Asia. Kelp from Asia is grown and traded at commodity scales (Food and Agriculture Organization (FAO), 2017). Furthermore, kelp consumption

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in Asia has been mostly contingent on price and taste (Chapman et al., 2015). In contrast, kelp of European and American origin is considered a specialty product. It is typically selected for its nutritional value and ecological and ethical farming practices (Chapman et al., 2015). Consequently, kelp produced in the Americas and Europe sells for an average of US$ 944 t^{-1} wet weight (Food and Agriculture Organization (FAO), 2016), whereas in Korea it sells for ca. US$ 177 t^{-1} (Food and Agriculture Organization (FAO), 2017). As such, the sustainability of American and European kelp farming is crucial to its viability. Established aquaculture industries (e.g., tilapia, carp, and shrimp) have undergone similar evaluations which resulted in Best Management Practices (BMPs) and guidelines to increase the industry sustainability (Azad et al., 2009; Fletcher, 2012; Lebel et al., 2002; Mungkung et al., 2013).

The Ecosystem Approach to Aquaculture (EAA) is a widely-adopted framework for evaluating aquaculture practices. It was developed by aquaculture experts at the FAO using observations of well-established industries farming aquatic animals. Three strategic principles define the EAA guidance (Food and Agriculture Organization (FAO), 2010):

1) "Aquaculture development and management should take account of the full range of ecosystem functions and services, and should not threaten the sustained delivery of these to society."
2) "Aquaculture should improve human well-being and equity for all relevant stakeholders."
3) "Aquaculture should be developed in the context of other sectors, policies, and goals."

In addition to functioning as a stand-alone strategy, the EAA principles contributed to many of the Sustainable Development Goals and Targets set by the United Nations in 2015 (Hambrey, 2017) and have helped to steer the aquaculture sector to more sustainable and holistic practices (Brugre et al., 2018). However, the resonance of the approach has not been uniform across all user groups (Brugre et al., 2018). Thus, the present study sought to explore the appropriateness and the value of the EAA for the incipient kelp aquaculture subsector outside Asia. The FAO literature on the EAA was assessed for its relevance to small-scale kelp aquaculture. Then, the EAA strategy and principles were used to recommend practices that can be adopted to promote the long-term sustainability of the kelp industry.

2. Methods

2.1. Site description

Maine, USA, was used as a case study to explore the pertinence of the EAA to the new kelp aquaculture industry. Aquaculture has generally been supported by Maine's economy and culture historically centered around fishing, shipbuilding, forestry, agriculture, extractive industries, manufacturing, and tourism (Maine State Planning Office (MSOP) and Rose, 2003). The region's protected coastline and water temperature ranging from 0.5 to 17.5 °C (NOAA, 2018a, 2018b) are particularly well-suited for kelp aquaculture. In 2010, the first kelp farm in the United States was started in Casco Bay, Maine. The farmers used techniques originating from Asia, which were adapted and further developed in conjunction with Dr. Yarish and Dr. Kim at the University of Connecticut (Flavin et al., 2013). In the decade since many small kelp farms have been established along the Maine's 5500 km of rocky coastline. State-wide harvest data depict a 3-fold increase in the production of farmed marine seaweeds from 2015 to 2018 (Maine Department of Marine Resources (DMR), 2018). In 2018, sixteen entities collectively reported harvest of 24.2 wet tonnes of farmed marine algae from Maine, the majority of which was kelp (Maine Department of Marine Resources (DMR), 2018).

The sugar kelp Saccharina latissima and the winged kelp Alaria esculenta are the most extensively farmed kelp species in Maine and in the United States (Augyte et al., 2017; Kim et al., 2015, 2017; Rose et al., 2015). Both species are members of the Phaeophyceae class, commonly referred to as brown algae. S. latissima and A. esculenta are abundant throughout much of the artic and along temperate coasts between the 16 °C summer isotherm and the 19–20 °C isotherms, respectively (Breeman 1988; Lning, 1990). S. latissima and A. esculenta exhibit rapid growth from early winter to late spring, reaching 2 to 5 m within approximately six months (Azevedo et al., 2016; Handå et al., 2013; Redmond et al., 2014).

Cultivation of S. latissima and A. esculenta is based around the species' lifecycle which includes a heteromorphic alternation of generations between a microscopic gametophyte and a "frond-like" sporophyte (Schreiber, 1930). The latter is targeted for grow-out. There are multiple ways of seeding sporophytes for grow-out, but they all begin at least once by collecting sorus, or reproductive tissue, from mature diploid sporophytes. Spore release from the sorus is achieved using desiccation and warming (Flavin et al., 2013). The released zoospores then mature as microscopic, filamentous gametophytes (Graham et al., 2016). In more advanced nurseries, these gametophytes are sorted by sex, and then either held indefinitely, crossed to produce specific strains, or cloned before being blended to produce juvenile sporophytes (Flavin et al., 2013; Redmond et al., 2014). Otherwise, the gametophytes can be applied to a thin seed line with spray-seeding or settling techniques (Flavin et al., 2013; Redmond et al., 2014). Following application to a substrate, the gametophytes become fertile. Mature eggs release a pheromone that causes the antheridium to break apart and directs sperm to an egg for fertilization (Graham et al., 2016). Then zygotes grow in place of the female gametophyte to form juvenile sporophytes (Flavin et al., 2013; Graham et al., 2016). The young sporophytes are raised on land in aquaria with artificial nutrients and light until the sporophytes are 2 to 10 mm in length (Flavin et al., 2013; Redmond et al., 2014).

In the grow-out phase, the juvenile sporophytes are transferred from the aquaria to longlines in the ocean. There they will continue to grow

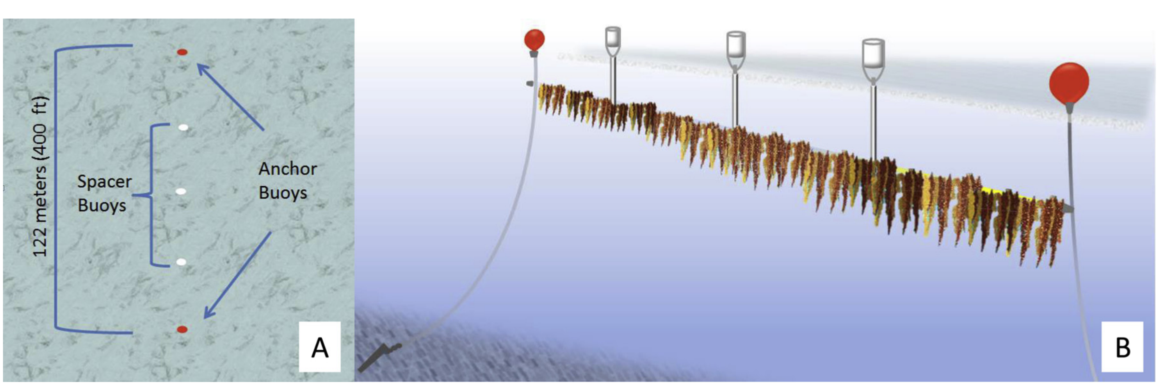

Fig. 1. Longline kelp aquaculture as commonly practiced in Maine: 122 m longline as seen from above (A) and the side (B).

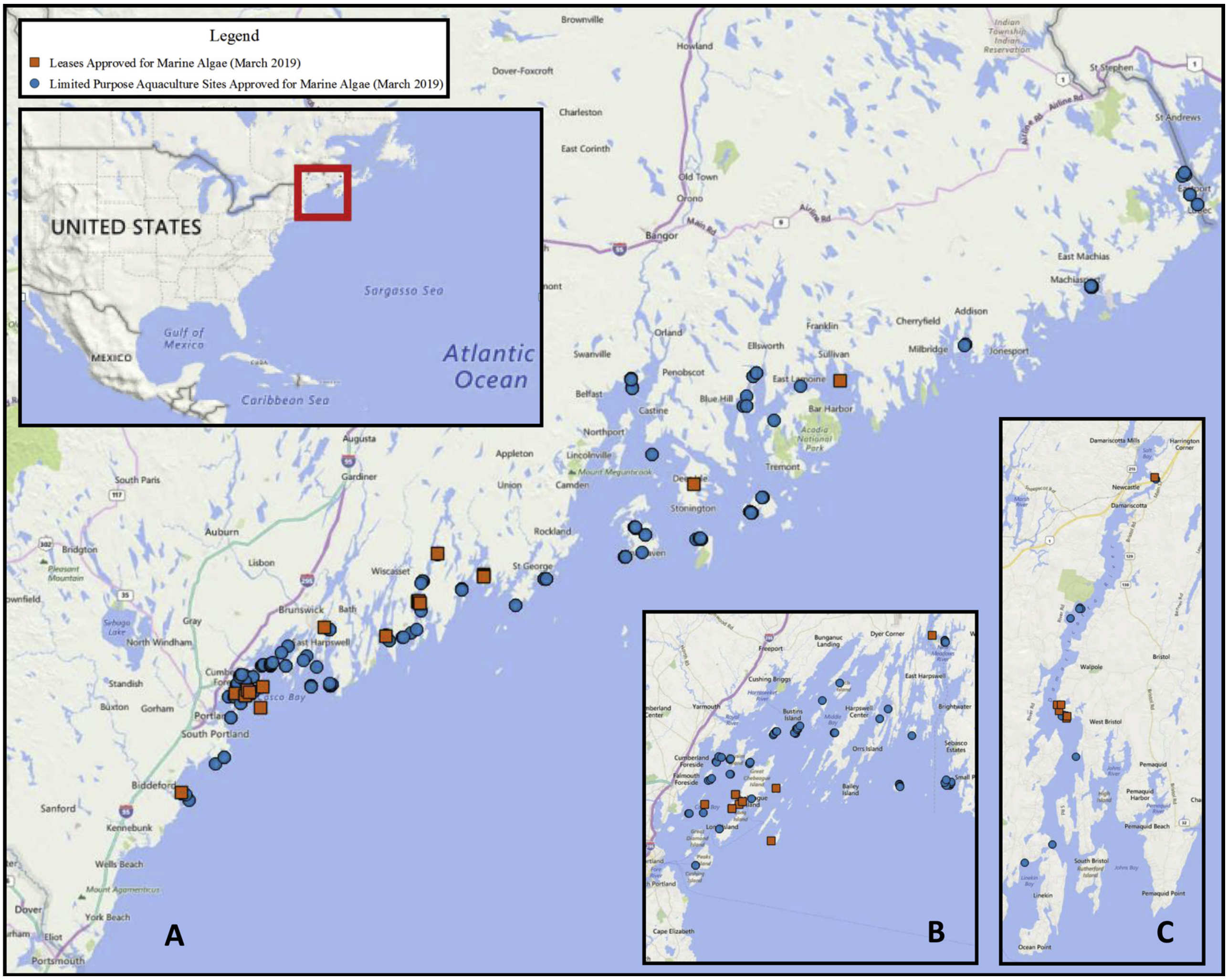

Fig. 2. Aquaculture Lease Sites (orange squares) and Limited Purpose Aquaculture Sites (blue circles) approved to grow marine seaweeds along the coastline of Maine (A), in Casco Bay (B) and on the Damariscotta River (C). Data source: Maine Department of Marine Resources (DMR), 2019b, 2019c). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

using natural light and available nutrients in the water column. The most common deployments in Maine consist of 1 to 1.25 cm sinking rope, called a longline, anchored with moorings and chain (Fig. 1). Longlines are typically 122 m, but some variation occurs. Intermediate floats and spacers with counter-weights are used to maintain the longline 2 to 2.5 m below the water surface. Suspending the longline at this depth ensures that the kelp receives adequate light to grow while also protecting it from wave action and boat travel.

In the Northwest Atlantic, the grow-out cycle for S. latissima and A. esculenta spans roughly September through May. Sometimes, the late availability of reproductive tissue from wild kelp beds has delayed the seeding of individual farms into October or November. Laboratory techniques to induce sorus tissue from vegetative sporophytes could prevent delayed farm deployment, but this is not yet commercial practice in Maine. In this region, most kelp farms are harvested once in late April or May to maximize total farm biomass and minimize fouling (e.g., snails, tunicates, hydroids, bryozoans, and amphipods). Harvesting practices vary according to the end-use of the kelp.

All kelp aquaculture sites in the State must be approved by the Maine Department of Marine Resources (DMR). Under guidelines set by the Maine Legislative Branch, the DMR has the authority to issue three types of aquaculture agreements: Limited Purpose Aquaculture Licenses (LPAs), Experimental Leases, and Standard Leases (Maine Legislature, 2017a, 2017b). The Maine DMR (2019a) provides the following guidance regarding each agreement:

- LPAs are typically 122 square meters. They are the easiest to acquire and can be issued by permit. LPAs are licenses, not leases, which are valid for one year. They can be renewed but are not transferrable. An individual is allowed to apply for a maximum of 4 LPAs per year but can supervise up to 12. As with any license, the State reserves the right to revoke issuance or decline renewal of the license should the holder fail to comply with all requirements.
- Experimental leases can encompass up to 1.6 ha. They are valid for three years and the lease cannot be renewed unless they are used for scientific research. A site visit by the Maine DMR's environmental scientists is necessary to approve the lease. An adjudicated hearing is required if the DMR receives 3 or more letters from interveners.
- Standard leases can be up to 40 ha. The application process is stringent and includes an adjudicated hearing. Standard leases are valid for 20 years, renewable, and transferable as long as they are active and in compliance with all existing regulations. Applicants for standard leases must attend a pre-application meeting and share a draft application with the DMR. A public scoping session must also be held with the host municipality before submitting a final lease application for review. Applicants for a standard lease are required to obtain a permit from the U.S. Army Corps of Engineers (USACE). They must also alert the United States Coast Guard to ensure that the

site is included in the agency's navigational updates.

The DMR review criteria for both aquaculture LPAs and leases include consideration of existing fisheries and licensed sites, navigation, essential wildlife habitat, recreational use, riparian landowners, and ecologically sensitive flora and fauna (Maine Department of Marine Resources (DMR), 2019a). Thus, success in the lease application process requires working knowledge of the social and ecological systems connected to the proposed site. Careful site selection and evaluation are critical to ensuring a smooth application process.

Maine's tiered system for aquaculture agreements has facilitated the expansion of seaweed aquaculture in the region. In the spring of 2019, there were 189 LPAs and 23 standard or experimental leases approved for marine seaweeds within Maine state waters (Maine Department of Marine Resources (DMR), 2019b, 2019c). However, many of the LPAs may be purely speculative at this time. LPAs and leases approved for marine seaweed cultivation are widely distributed along the State's coast and in two areas of higher concentration: Casco Bay and the Damariscotta River (Fig. 2).

2.2. Analytical approach and data survey

Kelp aquaculture is a practice that leverages biology and ecology within a social, economic, and political context. Thus, identifying the human and natural components of the broader kelp aquaculture system is required to properly evaluate its sustainability (Liu et al., 2007a; Whitney et al., 2017). The organizational, temporal, and spatial interactions occurring between the components are equally important (Liu et al., 2007b; Pulver et al., 2018). Industry observation, along with data collected through four focus groups and 24 semi-structured interviews with industry participants, regulators and extension staff, provided the data used to determine the physical and social components of kelp aquaculture.

The scope of this study was limited to activities and relationships directly tied to the farming of raw kelp. Buyers of raw kelp, primary and secondary kelp processing facilities, buyers and retailers of kelp products, consumers of kelp products, and vertically-integrated business models rest outside the scope of this evaluation. We inserted the human and ecological relationships connecting each physical or social component to generate a conceptual model of kelp aquaculture in Maine (Fig. 3). These causal relationships were classified according to the EAA principle that best defines the relationship. The principles have been abbreviated as 1) Ecosystem Services, 2) Social Justice, and 3) Activity Integration.

Then, the conceptual model representing the kelp aquaculture system was used to identify and describe stakeholders in the production of farmed kelp (Fig. 4). Together the list of stakeholders and conceptual model were used to evaluate the relevance of the FAO's identified common issues and impacts of aquaculture for kelp farming (Fig. 5). If an FAO-listed issue or impact was determined applicable to kelp aquaculture in Maine, we used the associated EAA guiding principle in combination with peer-reviewed literature and information from the industry observation, focus groups, and interviews to propose actions addressing the potential concern.

The FAO technical report on the Ecosystem Approach to Aquaculture (2010) lists the most common ecological and social impacts associated with aquaculture systems (Fig. 5). Both positive and negative impacts are considered, and the impacts are sorted according to whether they are inputs or outputs in the aquaculture system. The FAO's list was developed primarily considering fed aquaculture (e.g., fed finfish and shrimp culture) and not seaweed aquaculture. Thus, there is a need for careful assessment of the appropriateness and applicability of these stated impacts for kelp aquaculture. The aforementioned conceptual map and stakeholder list were both used in this evaluation. If an FAO potential impact was identified as not applicable to kelp aquaculture in Maine (white boxes in Fig. 5), then a justification for this decision is provided in thesubsections of this article. Conversely, if an FAO potential impact is relevant to kelp aquaculture in the Americas and Europe (light grey boxes in Fig. 5), the nature of the concern is described in the appropriate subsection. A precautionary approach is especially warranted when evaluating an emerging industry. The EAA guidance also emphasizes precautionary measures (Food and Agriculture Organization (FAO), 2010). As such, each potential impact is considered at a coastline-scale (i.e., multiple kelp farms) and with the expectation that the industry will continue to grow rapidly. The common issues and impacts are presented and discussed in order of appearance (left to right).

3. Results

3.1. Potential input impacts of kelp aquaculture

Possible input impacts are grouped under the categories of water, land and coastal habitats, seeds, and feeds (Fig. 5).

3.1.1. Water

The production of farmed kelp has little consumptive freshwater use. In the nursery phase, minimal freshwater is used to rinse tanks during water changes. Inland nurseries using artificial seawater require additional freshwater as the solvent in the seawater preparation. This water need is equivalent to the size of the aquarium, typically 100–500 L, but it can be sterilized and recirculated. Inland nurseries using pumped and filtered seawater have similar rates of saltwater consumption. During grow-out, all water use is by definition non-consumptive.

3.1.2. Land and coastal habitats

The FAO concerns regarding negative impacts to land and coastal habitats vary in their applicability to kelp aquaculture. Land salinization, the first concern listed, is associated with inland aquaculture of marine and estuarine organisms and does not apply to marine kelp aquaculture. The potential for physical habitat degradation and associated biodiversity losses, productivity declines, and protection services lost are relevant to kelp aquaculture. These potential impacts are associated with the possibility of marine mammal entanglement in the longlines, the mooring system, and seafloor shading at shallow farm sites. The FAO does not list potential positive impacts to habitat resulting from aquaculture. However, preliminary work suggests that some seaweed farms can have higher marine species richness and abundance than wild kelp farms or nearby areas without aquaculture.

The possibility of marine mammal entanglement in kelp longlines is an emerging concern among stakeholders in kelp aquaculture. For instance, habitat for the endangered North Atlantic right whale, Eubalaena glacialis, extends along the Maine coastline (Kraus et al., 2005; NOAA, 2016). Entanglement in non-mobile fishing gear has historically been one of the primary causes of individual mortalities (Kraus et al., 2005; NOAA, 2016). No case of entanglement in kelp longlines has been reported, but the concern for possible marine mammal entanglement will be amplified as a growing number of kelp farms are deployed. Risks of right whale entanglement are also expected to increase as kelp farms expand in size or move further offshore.

Localized impacts to the benthos could potentially result from moorings used to secure the longline or bottom-shading by kelp grown in shallow waters. The permitting process in the State of Maine, by way of USACE, requires eel-grass delineation and also considers the potential loss of any benthic vegetation (Maine Department of Marine Resources (DMR), 2019a, 2019b, 2019c; U.S. Army Corps of Engineers (USACE), 2015). As a result, most farms are sited above sand or mud substrate where marine life is less abundant or diverse. Mooring chain scour can cause a small loss of physical habitat, but the tension through the longline system keeps the mooring chain and line from rotating. The impact on the benthos is less than the disturbance caused by a small

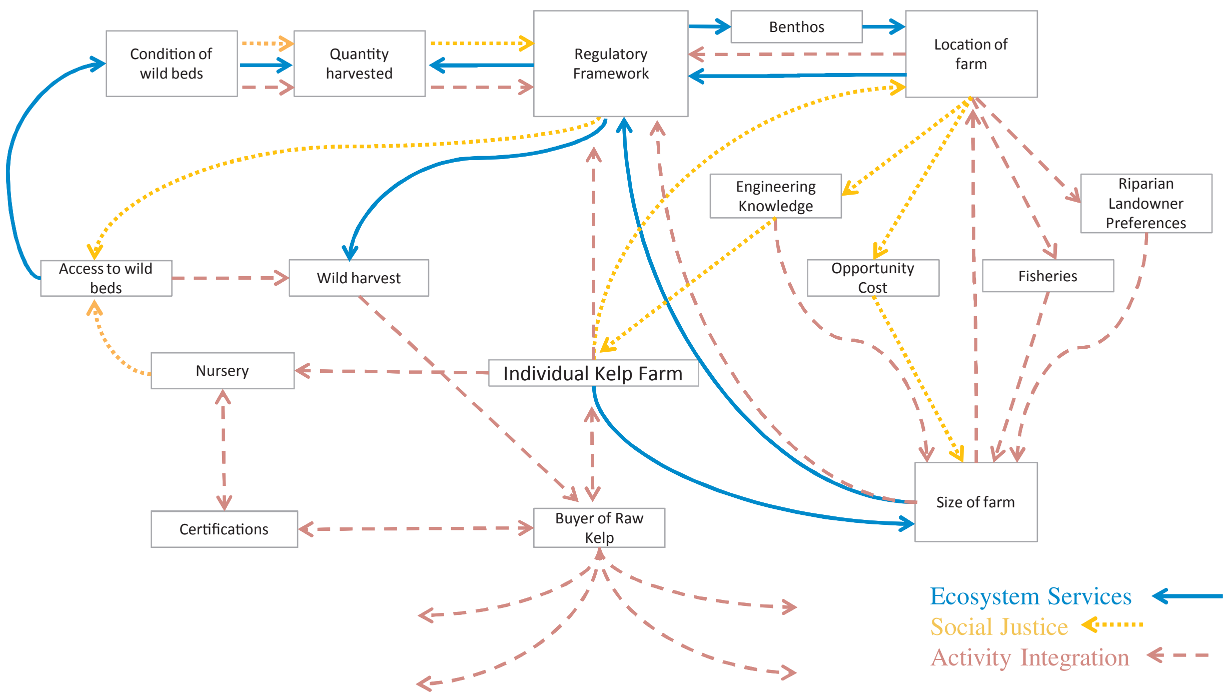

Fig. 3. The human and environmental relationships supporting kelp aquaculture. Relevance to Ecological Approach to Aquaculture guiding principles (FAO 2010) is indicated as 1) Ecosystem Services (solid blue lines), 2) Social Justice (dotted yellow lines), and 3) Activity Integration (dashed red lines). Directional arrows depict a chain of events or decisions associated with each factor. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

boat mooring. Another concern is that shading from large-scale seaweed farms could affect primary production or other ecosystem dynamics (Stvant et al., 2017). Seafloor shading has been associated with decreased heterogeneity in subtidal communities in estuaries and the nearshore environment (Glasby, 1999; Miller and Etter, 2008), where kelp aquaculture is predominately sited. Impacts of shading are likely negligible for kelp farms installed at sites where the seafloor is deeper than the euphotic zone. Similar to concerns with marine mammal entanglement, the potential impacts to the benthic habitat are primarily related to the size of an individual farm and the density of farms along the coast.

A few studies have investigated the positive habitat contributions from seaweed farming. A study on the coast of Ireland found different species assemblages and higher species richness in the holdfasts of suspended kelp farms when compared to wild kelp beds (Walls et al., 2016). On the Pacific and Caribbean coasts of Costa Rica, the waters around cultivated Codium sp, Graciliaria sp, Sargassum sp, and Ulva sp plots had a significantly higher number of fish species and individuals than areas without aquaculture (Radulovich et al., 2015). These initial studies are promising, yet more research is needed to fully understand the extent to which seaweed installations can serve as robust marine habitat. For example, little is known about how harvesting at the end of the season, effectively complete removal of the cultivated kelp canopy, influences the fauna shown to congregate around the farms (Wood et al., 2017). More studies are also needed to understand how much variation occurs between regions and seaweed species.

3.1.3. Seeds

Efforts towards laboratory-based sorus management and induction are underway, but the Maine kelp aquaculture industry is presently reliant on wild kelp beds as the source of reproductive tissue for seed (Kim et al., 2017). Consequently, concerns related to seed production for kelp aquaculture include potential over-harvesting of wild sorus tissue and the spread of parasites or non-indigenous hitchhiker species. These ecological concerns are further accentuated by the lack of studies examining existing or prospective biodiversity losses, productivity declines, and protection services lost or gained as the result of kelp farming.

Wild kelp is a perennial primary producer and foundation species providing habitat and food that structures community composition in the rocky intertidal (Christie et al., 2009; Lüning 1990; Steneck et al., 2002). Epiphytic algae, gastropods, amphipods, sea urchins, sea stars, and fish inhabit kelp beds (Steneck et al., 2002). These, in turn, become food for large crabs, lobsters, carnivorous fish, and other predators (Steneck et al., 2002) which are often consumed by humans. Therefore, seemingly small changes to the structure or genetic makeup of the wild population could cause reverberations throughout the ecosystem. Decreased abundance in another intertidal foundation species has led to community composition shifts in the Gulf of Maine (Sorte et al., 2017). These impacts could ultimately affect the marine food web structure and the coastal ecosystem's ability to provide supporting services for marine organisms and humans. A change in wild kelp populations would also directly affect wild kelp harvesters. Indirect impacts could reach wild coastal fisheries which provide an essential source of protein for human consumption and a source of income for marine fishermen.

Currently, sorus tissue harvesters access and trim reproductive kelp from natural beds at low tide. Bycatch is not a concern because they can selectively trim their target species. Some harvesters remove only half of the blade and leave the rest to grow back. The ecological risk associated with wild sorus harvesting lies in the potential for over-harvesting quantities of sorus tissue that might impact the natural lifecycle of the organism or the longevity of the kelp community. Historically, targeting exclusively reproductive individuals has had drastic consequences for continued success in reproduction and recruitment of the species (Sadovy and Domeier, 2005; Sala et al., 2001). The maximum annual harvest of sorus is not established, and thus, the responsibility for sustainable practices rests with the harvesters. The Maine Seaweed Council (MSC) recommends that no more than 30% of the biomass, based on assessment at the beginning of the harvest, should be removed from a single S. latissima kelp bed each year (Maine Seaweed Council (MSC), 2014). The amount of sorus tissue currently collected for kelp farming is minimal compared to kelp biomass removed by wild

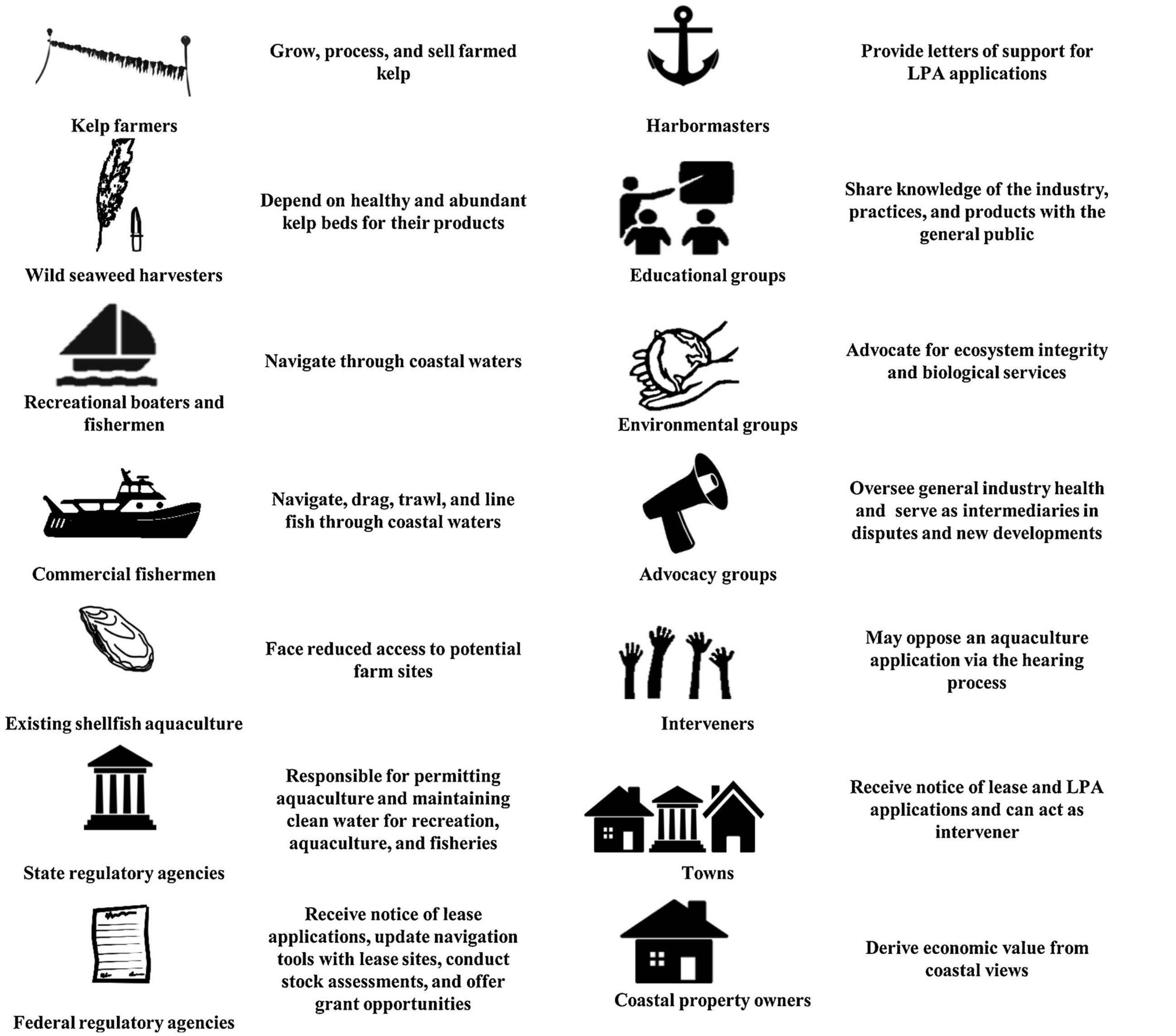

Fig. 4. Stakeholders in the kelp aquaculture industry (all post-harvest activities were excluded).

harvesting and winter storms. Nevertheless, as observed in the Maine urchin fishery, there is a risk of fishery collapse when industry growth outpaces regulations (Johnson et al., 2012).

The EAA recommends applying the precautionary approach when ecosystem resilience or thresholds are unknown (Food and Agriculture Organization (FAO), 2010). Sorus tissue harvesting in Maine falls into this category. As more individuals enter the industry, it is plausible that sorus tissue could be harvested at a rate impacting natural replenishment or juvenile sporophyte recruitment. If replenishment or recruitment is substantially reduced, it will negatively affect the biodiversity and productivity of wild kelp beds. The marine organisms that inhabit the kelp beds and people that rely on them will also be impacted.

Seaweed aquaculture also has the potential to unintentionally spread parasites or introduce non-indigenous species to new regions (Cottier-Cook et al., 2016; Skjermo et al., 2014). The current methodology employed to produce kelp seed in Maine encourages cleaning of sorus tissue with a razor blade, Betadine-R solution at 5 mL/L, and a series of rinses with sterilized seawater (Flavin et al., 2013; Redmond et al., 2014). This methodology is designed to remove epiphytic algae and attached organisms like ciliates and bryozoans (Flavin et al., 2013; Redmond et al., 2014). If some of these species survive the nursery procedures, they could be introduced into a new region when kelp seed is deployed at the start of a growing season. Currently, no sanitary regulations exist for kelp seed production in Maine.

3.1.4. Feeds

No added feeds are used in kelp farming. Kelp is an autotroph able to use energy from the sun, carbon dioxide, oxygen, and nutrients to grow. Most of the FAO concerns with aquaculture feeds are not applicable to kelp farming, with the exception of the potential impact on marine ecosystem productivity. This impact could be either positive or negative.

It has been proposed that kelp farms installed in nutrient-poor areas may have a negative impact on marine ecosystem productivity (Wood et al., 2017). The farmed kelp can compete with other marine algae and plants for dissolved nutrients and minerals (Wood et al., 2017). No detrimental effects on marine water conditions have been reported around small and dispersed farms currently established in Maine. Nevertheless, this potential impact should be considered as kelp farming intensity increases along the coastline. For instance, severe nutrient limitation has been documented in areas with intensive seaweed cultivation, such as Korea and Japan (Park et al., 2018; Shim et al., 2014; Zhang et al., 2004).

Contrariwise, kelp farming activities may positively influence

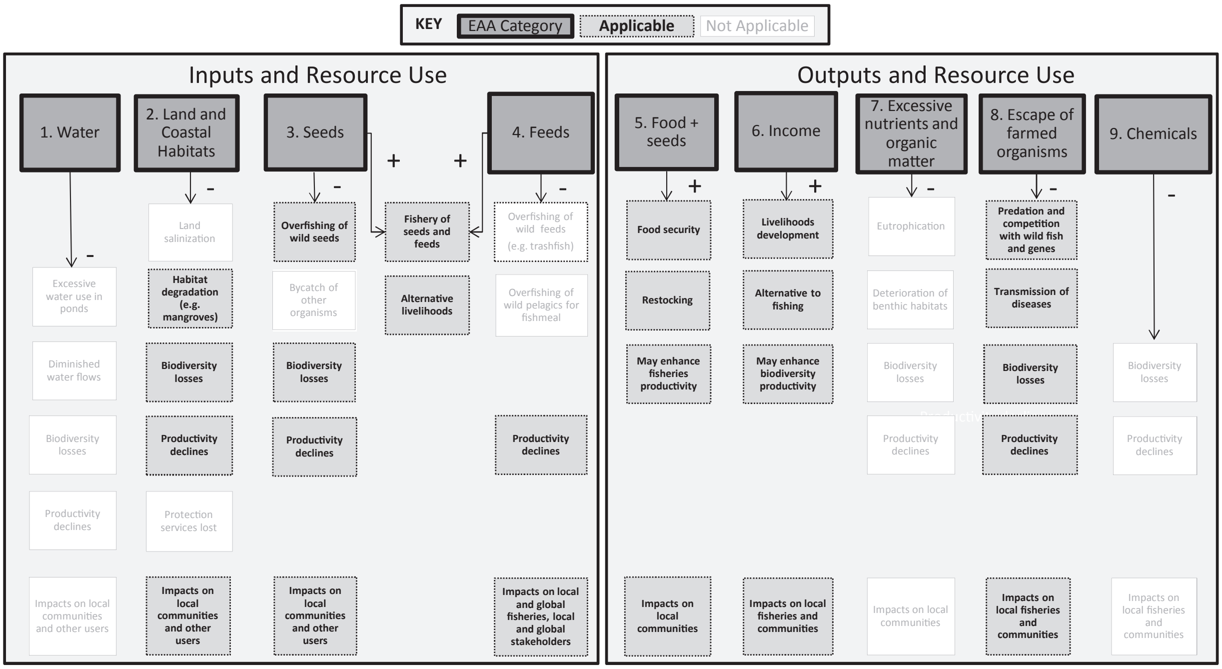

Fig. 5. Potential issues and impacts related to aquaculture inputs (left) and outputs (right) identified by FAO (2010). The potential issues and impacts are organized by category (dark grey boxes). Light grey boxes denote issues and impacts that are applicable to kelp aquaculture. White boxes signify issues and impacts that do not apply to kelp aquaculture. Plus signs indicate positive impacts and minus signs represent negative impacts.

marine ecosystem productivity when used as a bioextraction, or bioremediation strategy. This approach exploits the metabolic needs of kelp to intentionally remove excess nutrients or carbon dioxide in nearshore waters experiencing nutrient pollution, ocean acidification, and carbonate limitation (Chung et al., 2011; Duarte et al., 2017; Krause-Jensen and Duarte, 2016; Rose et al., 2014, 2015). Studies regarding the nitrogen bioremediation potential and the degree of photosynthetically-driven carbon dioxide assimilation of kelp aquaculture in Maine are in progress. Meanwhile, findings from other species and regions help to characterize the potential benefits. Studies from nearby Connecticut, USA, show that S. latissima farms can address eutrophication by removing 38 to 180 kg of nitrogen hectare^{-1} at the time of harvest (Kim et al., 2015). In China, harmful algal blooms (HABs) along the coast have been effectively mitigated by large-scale cultivation of the red algae G. lemaneiformis and P. yezoensis (Wu et al., 2015, 2017; Yang et al., 2015a, 2015b). At a farm-level scale, the localized alkalization offered by seaweed is thought to be beneficial for both corals and shellfish using calcification to make shells (Branch et al., 2013). With regards to carbon sequestration, it has been estimated that the world's seaweeds could potentially sequester a range of 61 to 268 Tg C yr^{-1} through export to the deep sea or burial in coastal sediments (Krause-Jensen and Duarte, 2016). The high end of this range is more carbon burial than salt marshes, mangroves, and seagrasses combined (Duarte et al., 2013).

3.2. Potential output impacts of kelp aquaculture

Output impacts are grouped by the categories of food and seeds, income, excessive nutrients and organic matter, escape of farmed organisms, and chemicals (Fig. 5).

3.2.1. Food and seeds

Kelp aquaculture can have a positive impact on food security. The practice offers direct benefits to food security when kelp is used as food for humans. It indirectly benefits food security when used as a livestock feed, fertilizer, an input in aquaculture systems, or for fisheries enhancement. These contributions, combined with negligible needs for freshwater or arable land, make kelp aquaculture an increasingly attractive method for providing food for a growing global population.

Farmed kelp can contribute to the protein and energy requirements of both humans and livestock (Morrissey et al., 2001; Makkar et al., 2016). Kelps are a source of carbohydrates, fiber, vitamins (A, B, and B-12), minerals (iron, iodine, potassium, calcium), and omega-3 long-chain fatty acids (Food and Agriculture Organization (FAO), 2018; Morrissey et al., 2001). Beyond basic nutritional requirements, there is also evidence that alginates derived from brown seaweeds can have ample benefits for human gut health (Brownlee et al., 2005). Some brown seaweeds have bioactive compounds that could be used in small doses as prebiotics for ruminants and other livestock (Makkar et al., 2016).

Research into appropriate serving sizes and bioavailability of these nutrients for humans and other organisms is imperative. In a similar manner to plants, seaweeds assimilate inorganic elements like arsenic, iodine, and other minerals from their surrounding environment (Graham et al., 2016). Thus, more guidelines for serving size are needed. Biorefinery studies (i.e., application of enzymes) to increase the bioavailability nutrients or remove unwanted minerals from kelps (Schiener et al., 2017) would also be helpful. Advancements in both arenas will further validate the potential for farmed kelp to contribute to food security.

Seaweed installations can make indirect contributions to food security by enhancing fisheries productivity and output efficiencies of other aquaculture operations. The longlines may provide habitat and food for wild organisms (see subsection 3.1.2) or cultured organisms. For example, in Chile and on the West Coast of the United States, wild Macrocystis pyrifera is harvested to feed cultured abalone (Camus et al., 2019; The Cultured Abalone Farm, LLC, 2015). In the future, this biomass could come from aquaculture (Camus et al., 2019). Additionally, kelp farms may offer localized alkalization of coastal water benefitting wild and cultured shellfish growth (subsection 3.1.5). The extractive properties of seaweeds have also been shown to mitigate the potential impacts of animal excrement when used in integrated multi-trophic aquaculture (IMTA) systems (Troell et al., 1999a, 1999b).

3.2.2. Income

Kelp aquaculture is an accessible marine livelihood that can supplement or replace income from existing ocean foods production. Small-scale kelp farming requires little capital investment, which makes it more realizable to newcomers than other forms of aquaculture. In Maine, the equipment cost for a 122-meter longline is less than US $1000 (T. Olson, pers. comm., 2016). Collaborative relationships between industry, researchers, and extension agents have also played an instrumental role in supporting new entrants to the industry. Of particular note are the numerous, free or low-cost, educational resources available to prospective kelp farmers. The Kelp Farming Manual (Flavin et al., 2013) is a digital document providing detailed guidance for site selection, farm equipment, and nursery techniques. The New England Seaweed Culture Handbook, Nursery Systems (Redmond et al., 2014) focuses on the biology, cultivation methods, and cultivation systems for kelp and three other seaweeds. It is also available online. In addition to these print resources, many nonprofit organizations and academic institutions have provided workshops in culturing techniques and business management for prospective kelp farmers. In Maine, Coastal Enterprises Inc. (CEI), Island Institute, Maine Sea Grant, Maine Seaweed Exchange, and University of Maine Cooperative Extension have all offered classes or workshops on topics related to seaweed aquaculture.

Thus, market issues, perhaps more than grow-out technology, most threaten the economic viability of kelp farming. Substantial market development is still necessary for American and European growers (Bjerregaard et al., 2016; Skjermo et al., 2014). On a global scale, seaweeds and their derivatives are used in food products, animal feed, pharmaceuticals, beauty products, biofuels, and agricultural products (Food and Agriculture Organization (FAO), 2018; Graham et al., 2016). However, almost all kelp farmed in Maine is used in food products (i.e., kelp noodles, kelp puree, kelp spice mix) because individual farmers struggle to access larger purchasers or have chosen to integrate vertically (Griffin and Warner, 2017). Better access and competitiveness within existing markets, and the creation of new markets, will help to solidify kelp aquaculture as an alternative or supplemental livelihood.

3.2.3. Excessive nutrients and organic matter

Kelp is a non-fed organism. Thus, kelp farming has no tangential impacts of excess feed or feces on the surrounding water quality. Kelp does produce a small amount of water and oxygen as the byproducts of photosynthesis. However, both water and oxygen are readily incorporated by saltwater, so the direct byproducts of seaweed cultivation are not of ecological concern. On the contrary, the byproduct oxygen from seaweed farms has been understood to provide the ecosystem service of oxygenation (Vásquez et al., 2014).

There is some concern that organic matter sloughed or dislodged from kelp farms could have a negative environmental impact. There can be a loss of organic matter from the farm during winter storms or due to natural blade erosion. Sloughing of material from wild kelp beds is generally understood to be a positive contribution to secondary production (Krumhansl and Scheibling, 2012). Nonetheless, it has been suggested that sloughed cultivated kelp could contribute to nutrient over-enrichment or the de-oxygenation of sediments if a sizeable amount were to settle on the seafloor (Skjermo et al., 2014). This risk applies mostly to areas with low water exchange rates or naturally abundant algae. Ultimately, further investigation into the fate and quantity of biomass leaving kelp farms is needed to fully evaluate the potential impacts of this organic matter (Skjermo et al., 2014).

3.2.4. Escape of farmed organisms

The FAO presents concerns that farm escapees could prey on, or compete with, wild organisms in the farm vicinity. The concern of predation does not apply because kelp is an autotroph, but the threat of competition with wild organisms is still valid. If cultivated kelp enters its reproductive phase, the sorus tissue or released zoospores can be carried by ocean currents to areas where they might compete for habitat or interbreed with wild kelp. Uncontrolled, this potential crop-to-wild gene flow could lead to loss of genetic diversity, the transmission of diseases to wild kelp populations, and an overall decline in ecosystem resilience (Buschmann et al., 2017; Cottier-Cook et al., 2016; Hutchings and Fraser, 2008).

The risk of decreased genetic diversity resulting from crop-to-wild gene flow is highly related to industry seed production strategies. Currently, a small amount of reproductive tissue, generally from 1 to 3 mature individuals, is used to produce billions of spores (Flavin et al., 2013; Redmond et al., 2014). This renders enough seed for multiple small kelp farms. As a result, the organisms on an individual farm have a similar genetic composition. If these individuals reach maturity, they will release gametes into the surrounding ecosystem that could outcompete or replace wild gametes. Then, over time, the local kelp populations could experience genetic erosion trending towards a genetic makeup similar to that of the farmed species.

Genetic diversity in a population is correlated with disease resistance (Gjedrem, 2005). Therefore, the current seed production methods used in Maine may leave kelp more susceptible to disease. Industry-wide disease outbreaks in cultured Pacific white shrimp (Litopenaeus vannamei) and Atlantic salmon (Salmo salar) demonstrate the potential impacts of limited breeders and inbreeding practices (Cottier-Cook et al., 2016; Doyle, 2016; Luvesuto et al., 2007). Intensive culture of the red seaweeds Kappaphycus alvarezii and Eucheuma denticulatum in Asia and Africa have also been significantly affected by ice-ice and other diseases which are presumed to be the result of low genetic variation in cultured stocks (Hafting et al., 2015; Halling et al., 2013). Several diseases have been observed in cultivated Saccharina japonica, a close relative to S. latissima, which is intensively cultivated in Asia. These include rot disease, twisting disease, and blister disease, which are believed to be environmentally induced (Getchis, 2014; Tseng, 1986). Stipe blotch and dark spot disease have also been observed in S. japonica and believed to result from interactions with marine bacteria or fungi (Getchis, 2014; Tseng, 1986).

It remains uncertain whether the aforementioned diseases will appear in Maine or other parts of the Americas and Europe (Getchis, 2014). As with many of the potential output impacts, disease risks will become more relevant as the scale of commercial cultivation increases (Buschmann et al., 2014). In the face of uncertainty, the precautionary principle should be applied. A kelp-disease outbreak could be devastating to the Maine kelp industry and associated human communities. It also poses considerable risk to wild kelp populations.

3.2.5. Chemicals

Current kelp aquaculture practices exclude the application of chemicals to the farmed area or surrounding marine environment. Therefore, additional concerns listed under this category are not applicable.

4. Discussion

Long-term ecological and social sustainability is vital to the continued growth and success of kelp farming. The strategy and principles of the Ecosystem Approach to Aquaculture can be used, in combination with lessons learned from other industries, to proactively address the relevant concerns presented above. Recommendations for practices, research, and resource management to address the potential impacts of kelp aquaculture are presented below. The recommendations are grouped by EAA principle providing the most considerable guidance (Table 1). Stakeholders connected with each recommendation are also listed.

4.1. Recommendations Using EAA Principle of Ecosystem Services

The first principle of the EAA advises that aquaculture planning and development should not threaten ecosystem functions or services (Food

Table 1
Recommendations for new actions, research, and resource management to further ensure the long-term sustainability of kelp aquaculture in the Americas and Europe. Recommendations were developed using the FAO's Ecosystem Approach to Aquaculture strategy and principles (2010).

Ecosystem Services	Social Justice	Activity Integration
• Define Ecosystem and Management Boundaries	• Increase Horizontal Expansion	• Integrate Kelp Aquaculture and Kelp Harvesting into a Seaweed Management Plan
• Assess Ecosystem Services and Environmental Carrying Capacity	• Expand and Teach Best Management Practices (BMPs)	
• Pursue Ecologically and Socially Considerate Engineering	• Develop Climate Change Resiliency	
• Protect Health and Genetic Diversity of Wild Kelp Beds		

and Agriculture Organization (FAO), 2010). This principle rests on the assumptions that ecosystems provide services benefiting living beings and humans are an integrated part of ecosystems. Multiple high-priority actions can be undertaken to bring kelp aquaculture in Maine into greater alignment with the principle of Ecosystem Services. These recommended actions are: 1) define ecosystem and management boundaries, 2) assess ecosystem services and environmental carrying capacity, 3) pursue ecologically and socially considerate engineering and siting, and 4) protect health and genetic diversity of wild kelp beds.

4.1.1. Define ecosystem and management boundaries

Defining the ecosystem and management boundaries for kelp aquaculture will work to prevent habitat degradation and associated biodiversity losses, productivity declines, and impacts on local communities and other users. This effort will facilitate monitoring and more targeted use-designations according to the biophysical conditions of the region. The marine commons frequently experiences mismatches between ecosystem and management scales, but socio-ecological systems that share the same ecosystem and management boundaries have higher chances at sustainability (Berkes, 2006). Defined management boundaries can also help to limit potential competition with wild kelp, crop-to-wild gene flow, and the transmission of diseases. Additionally, this action addresses the risk of overfishing for wild seeds by providing a framework for regional oversight of sorus tissue collection. Stakeholders connected with this recommendation include kelp farmers, wild seaweed harvesters, recreational boaters and fishermen, commercial fishermen, existing shellfish aquaculture, state regulatory agencies, federal regulatory agencies, harbormasters, educational groups, environmental groups, advocacy groups, interveners, towns, and coastal property owners.

Specific zones for sorus tissue harvesting could be defined using a variety of methods ranging from low to high levels of required effort and expense. The presence or absence of S. latissima or A. esculenta could be used to determine the bioregions. Either existing observations, historical records, or some combination of both could be employed. Using existing datasets would produce a relatively inexpensive assessment if done at a bay scale. A more sophisticated approach would be to model and analyze the direction and velocity of currents, which facilitates the movement of spores, using studies of wild kelp spore dispersal as a baseline. At least one spatial predictive probability model of potential spore distribution has been developed by combining field-measured geophysical attributes with modeled variables (Bekkby and Moy, 2011). A study in support of this approach found that the connectivity of kelp beds (Ecklonia radiata) in Australia varies according to the strength of boundary currents (Coleman et al., 2009). The most comprehensive method for defining the bioregions, although quite costly, would be to conduct and use a detailed analysis of the wild kelp population structure. For example, along the relatively linear coast of California, a genetic distance-based model showed that habitat continuity and geographic distance played critical roles in population structure and gene flow (Alberto et al., 2010). This effect may be amplified along Maine's highly rugose coastline.

Urgent explication of management boundaries will also inform seedstock guidelines and localization of strain selection. Genetic and population structure studies on macrophytes in the Northwest Atlantic have been sparse. However, a fine-scale structure assessment of S. latissima in eastern portions of the state was recently completed (Breton et al., 2018). This study found overall low genetic diversity but did note significant fine-scale structuring of populations along portions of Maine's somewhat continuous eastern coastline (Breton et al., 2018). Moreover, the most considerable genetic difference was observed between two populations separated by a small geographic distance. These findings suggest that the driving factors influencing the interconnectivity of Maine's sugar kelp populations are dynamic and not entirely explained by location. As a first step towards bioregional seedstock guidelines, seaweed nurseries could commit to only using genetic strains and reproductive material collected from the same bioregion as the farm site (Yarish et al., 2017).

4.1.2. Assess ecosystem services and environmental carrying capacity

Further quantifying the ecosystem services and environmental carrying capacity associated with kelp aquaculture will lessen the potential for habitat degradation and associated biodiversity losses and productivity declines. It will aid in the establishment of an evidence-based limit for aquaculture expansion. Such efforts will also further understanding of the interactions between kelp farms and productive fisheries. Increased knowledge of the ecosystem services offered by kelp farms will allow for more strategic placement of farms to maintain and enhance biodiversity, ecosystem productivity, and income. Stakeholders connected with this recommendation include kelp farmers, wild seaweed harvesters, recreational boaters and fishermen, commercial fishermen, existing shellfish aquaculture, state regulatory agencies, federal regulatory agencies, harbormasters, educational groups, environmental groups, advocacy groups, interveners, towns, and coastal property owners.

The term environmental carrying capacity refers to the ability of ecosystem services to tolerate a particular activity without unacceptable impact (Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP), 1986). Environmental carrying capacity assessment is a core tenet of the EAA principle of Ecosystem Services. The scale at which environmental carrying capacity evaluation occurs should be a function of the features or resource services targeted for protection (i.e., estuary, bay, or basin-wide). Therefore, careful delineation of ecosystem and management boundaries (subsection 4.1.1) is the first step to assessing environmental carrying capacity. Resource managers and policymakers should use best available science to delineate these ecosystem and management boundaries.

Once the boundaries are established, the ability of each designated region to support kelp farming activities should be assessed. Kelp farming occupies physical space in the ecosystem and also requires dissolved carbon, nitrogen, phosphorus, and trace metals. There is a need for regional studies exploring the origin and availability of these elements and nutrients. A greater understanding of regional water circulation and exchange is also important (Park et al., 2018). More insight into the ecological interactions between the farms and other associated organisms is warranted. For example, little is known about the microbial communities associated with kelp farms, the degree of fish and invertebrate aggregation around these installations (Walls et al., 2017), or the final destination of algal material sloughing from the degrading kelp tips. Information regarding the changes in planktonic ecosystems near kelp farms and the impacts of respiration by kelp farms during the night is also scarce.

An environmental carrying capacity assessment for the Gulf of Maine would include an evidence-based estimate of the maximum hectares of kelp farms that could be supported by each region without affecting any ecosystem services. One such effort concluded that a two-hectare seaweed farm in Sweden had either a positive effect, or no effect, on the supporting (e.g., biogeochemical cycling, habitat), regulating (e.g., mitigating eutrophication), and provisioning ecosystem services (e.g., food) in the region (Hasselstrm et al., 2018). This Swedish study serves as a useful starting point. Similar evaluations should be repeated in each region where kelp is cultivated. Regional repetition of studies will help to ensure that variations in geophysical and ecological processes are adequately captured.

A greater understanding of the ecosystem services provided by kelp aquaculture installations will foster social acceptance of the industry (Alleway et al., 2019; Rose et al., 2014). Wild seaweed communities provide numerous ecosystem services, and many of these functions are also accredited to seaweed aquaculture installations (Chung et al., 2017; Millennium Ecosystem Assessment (MEA), 2005). These include food provision, raw materials, biodiversity enrichment, increased habitat volume, provision of food and shelter, nutrient mitigation, wave attenuation, and carbon-dioxide removal (Chung et al., 2011; Duarte et al., 2013; Food and Agriculture Organization (FAO), 2003; Kim et al., 2015; MacArtain et al., 2007; Mork, 1996; Radulovich et al., 2015; Rose et al., 2010, 2014, 2015; Sondak et al., 2017). New knowledge regarding the magnitude of these ecosystem services will further inform estimates for the equilibrium between increased kelp aquaculture and sustained health of the surrounding marine ecosystem.

4.1.3. Pursue ecologically and socially considerate engineering

The ecologically considerate engineering of aquaculture installations will ensure that kelp farms do not have unacceptable impact on other marine organisms. Avoiding impact on marine fauna will become increasingly important as the kelp industry grows and moves further offshore. Socially considerate engineering will minimize potential impacts to the viewsheds of local communities. Stakeholders connected with this recommendation include kelp farmers, recreational boaters and fishermen, commercial fishermen, existing shellfish aquaculture, state regulatory agencies, federal regulatory agencies, harbormasters, environmental groups, interveners, towns, and coastal property owners.

Minimizing opportunities for marine mammal entanglement is the most pressing issue not currently addressed by the regulatory process or BMPs. Gear modification has been proposed for various fisheries to reduce North Atlantic right whale entanglements in fishing gear. These measures have not been successful (Knowlton et al., 2012), so there are few proven examples of gear modifications for the kelp industry to follow. Until effective modification for non-mobile gear is determined, kelp farmers can demonstrate effort towards preventing entanglement by ensuring that their farms are sited outside of critical habitat for the North Atlantic right whale (NOAA, 2016). Due to the current LPA limits set by the Maine DMR, the most common longline length in Maine is 122 m. Farmers applying for a larger, full lease could maintain short longlines and provide passageways between longlines to facilitate marine mammal movement through the farm. Dispersed longlines may also reduce the possible impacts from seafloor shading at shallow sites and minimize benthic disturbance from the mooring system. Effects of seaweed farms on the benthos should be better researched and systematically documented (Stvant et al., 2017) so that siting criteria can be re-evaluated if substantial changes to farm size or density occur. Each of farm management strategies to reduce marine mammal entanglement, benthic shading, and mooring scour would also likely reduce the density of surface buoys. Consequently, the visual impact of kelp farming would be lessened for coastal landowners and other water users.

4.1.4. Protect health and genetic diversity of wild kelp beds

Best practices and continued scientific efforts to protect the health and genetic diversity of wild kelp beds will lessen the risks associated with the dislodgement of farmed kelp. Genetic impacts and the loss of genetic diversity have been pinpointed as critical challenges for aquaculture (Convention on Biological Diversity (CBD), 2011; Food and Agriculture Organization (FAO), 2010; United Nations, 2015). Specifically, Achi Strategic Goal B, Target 6 challenges that, by 2020, ecosystem-based approaches should be used for sustainable management and harvest of aquatic plants to reduce pressure on biodiversity (Convention on Biological Diversity (CBD), 2011). Defining bioregions for reproductive strain production, developing specific and disease-resistant strains, and building diverse seed banks can reduce the likelihood of disease outbreak and prevent related biodiversity and productivity losses. Modifying harvest of sorus tissue, developing regional sorus harvesting guidelines, and gravitation away from wild seed also preemptively address the threat of overharvesting wild sorus tissue. Stakeholders connected with this recommendation include kelp farmers, wild kelp harvesters, and environmental groups.

Establishing laboratory-based seedbanks will provide a reliable seedstock for the industry and reduce the impact of kelp aquaculture on wild kelp beds (Kim et al., 2017; Redmond et al., 2014). In Japan, reproductive tissue is sourced from farms kept solely for this purpose (Chen, 2006). Direct sourcing of reproductive tissue from kelp farms in Maine is challenging due to the timing of sorus production. Kelp farms are harvested from March through May in Maine to avoid biofouling associated with warmer summer water. Sorus tissue availability is limited and highly variable during these months. A study conducted during these months, focused on wild populations of kelp in Long Island Sound, Connecticut, found that only 3–30% of individuals sampled were reproductive (Yarish and Penniman, 1990). Photoperiod mediates sporangia production (Lning, 1988), so farmed populations are expected to mirror the incidence of sorus production observed in wild populations growing in similar conditions throughout the region.

Many universities and research groups use laboratory-based kelp germplasm for research purposes (S. Lindell, pers. comm., 2019; Martins et al., 2017; Peteiro et al., 2016). These practices have yet to be widely adopted by the kelp industry in Maine mostly due to inexperience, lack of instruments, and limited nursery facilities. In the meantime, a hybrid approach could be utilized. Methods have been developed to induce sorus tissue production in a laboratory setting by manipulating the photoperiod and mechanically preventing the transport of the sporulation inhibitors (Forbord et al., 2012; Pang and Lüning, 2004). This technique can also be used to maintain year-round production of zoospores and sporophytes in nurseries (Forbord et al., 2012). Efforts towards optimized species-specific protocols for cryogenic preservation of spores and gametophytes are also underway in Maine and Sweden (N. Price, pers. comm., 2019; Visch, 2018).

Ultimately, creating an industry independent of wild sorus tissue sources will ensure the scalability and sustainability of kelp aquaculture (Kim et al., 2017). Developing specific kelp strains will allow farmers to have a reliable source of seed throughout the year while targeting specific crop characteristics. It may also provide more reliability regarding the morphometric attributes of the farmed product. Strain development offers the opportunity for novel product and intellectual property development (Loureiro et al., 2015). However, there remains a concern that cultivated strains originating from native genotypes could cross-hybridize with wild individuals. This effect has been studied in S.

japonica by collecting wild kelp from an area with no seaweed cultivation and two cultivars from intensive seaweed culture in China and Japan (Liu et al., 2012). Higher genetic diversity was observed in the wild kelp, and this was interpreted as an indication that domestication might be accompanied by decreased genetic diversity and a narrower germplasm base of cultivars (Liu et al., 2012). In due time, sterile kelp strains could be developed to prevent crop-to-wild gene flow (Loureiro et al., 2015). Techniques for sterile-strain production of S. latissima are of interest to multiple research teams (Sjtun, 2017, S. Lindell, pers. comm., 2019).

Continued prospecting of nursery and grow-out strategies for other disease-resistant strains and previously uncultivated species is also essential. Intensive seaweed monoculture, or the widespread cultivation of a single species or strain, has been linked with disease (Hafting et al., 2015). Just as in agriculture, diversified cultivation and crop rotation can interrupt disease cycles and help producers reduce and manage the risk of disease (Krupinsky et al., 2002). Parallel work on both fronts is needed. Diversified cultivation, supported by the development of cultivation strategies for previously uncultivated species, may be within shorter reach than the establishment of disease-resistant strains. In Chile, for example, seeding and grow-out of two previously uncultivated Laminariales, Lessonia trabeculata and Macrocystis pyrifera, has been successful (Camus et al., 2018, 2019). Voluntary dissemination of these methods, similar to the widespread sharing of seeding and grow-out techniques for S. latissima, will increase the resilience of the budding industry. As seen in other cultivated species, the establishment of disease-resistant strains and disease-free nurseries can also help to prevent crop damage (Hafting et al., 2015). Disease-resistant strains will be vital to restocking efforts if crops are lost to disease (Cottier-Cook et al., 2016).

Small changes to existing sorus tissue harvesting can help to protect the health of wild kelp beds until wild sorus tissue harvesting is no longer needed. For example, harvesters could commit to removing only half the thallus of an individual kelp sporophyte and leaving the rest to regrow. In Maine, a minimum cutting height requirement is already in place for rockweed, or Ascophyllum nodosum (Maine Department of Marine Resources (DMR), 2014). Ascophyllum physiology and harvesting practices are dissimilar from S. latissima and A. esculenta. However, the existing legislation sets a precedent that may result in more readily available social acceptance for a minimum cutting height BMP.

4.2. Recommendations using EAA Principle of Social Justice

The second EAA principle counsels that aquaculture activities should be equitable and improve human well-being (Food and Agriculture Organization (FAO), 2010). This principle assumes that educated stakeholders participating in a transparent process will make decisions that support maximum well-being (Food and Agriculture Organization (FAO), 2010). An additional perspective from a finer-resolution assessment of successful socio-ecological systems identified governance, decision-making, livelihoods, well-being, and adaption to current and future climate change as critical components for successful interactions in a marine-based socio-ecological system (Charles, 2012). Maine's robust state aquaculture legislation means that governance and decision-making in the kelp industry are already highly transparent and aimed at providing maximum well-being. Therefore, the areas of most considerable improvement under the EAA principle of Social Justice include: 1) increase horizontal expansion, 2) share education in Best Management Practices (BMPs), and 3) develop climate change resiliency.

4.2.1. Increase horizontal expansion

Increasing horizontal expansion within the kelp industry will create more jobs and maximize the potential income generated by kelp aquaculture. Diversification of labor across multiple organizations at each step of the supply chain will also result in more stability around kelp production activities and provide opportunities for specialization. Independent kelp seed providers, or nurseries, are an example of a specialization that could occur within the supply chain. Improving the reliability of seed production and access will help to ensure that kelp farming is an accessible alternative to fishing. Stakeholders connected with this recommendation include kelp farmers, commercial fishermen, existing shellfish aquaculture, educational groups, and advocacy groups.

Diffusion and Innovation Theory (Rogers, 1962) explains how new ideas, practices, or products are adopted over time. Innovations are not readily accepted by the entirety of society, but rather, they "diffuse" through it gradually because individuals sit along a spectrum of risk-seeking to risk-adverse (Rogers, 1962). This theory can be used to anticipate new entrants to, and continued development of, the kelp industry. Kelp aquaculture has been promoted as an alternative or supplement to other ocean-based livelihoods (i.e., commercial fishing, shellfish aquaculture, tourism) (Lem, 2016; Redmond et al., 2014). In Maine, kelp farming has already captured the innovators and early adopters. They comprise a small segment of the total population that sees the need for change, is willing to take the risk, and can serve as leaders (Rogers, 1962). The limited, but successful, and vertically-integrated companies in the state are a testament to the work of innovators and early adopters (Engle et al., 2018).

The early and late majorities are the much larger sectors of the population that need evidence of success before adopting an innovation (Rogers, 1962). Adoption of kelp aquaculture by the early and late majorities will require more investment in seaweed production and processing systems (Bjerregaard et al., 2016), post-harvest storage, distribution, and value-added product development. Creation of a robust primary market will also increase the attractiveness and sustainability of kelp farming as an alternative livelihood. Similarly, kelp seed production needs to become more predictable. Nurseries must be able to reliably supply large quantities of high-quality seed (Skjermo et al., 2014). New entrants in the industry may have more specialized, targeted experience in automation and distribution that could be applied to kelp seed production. Alternatively, the formation of a nursery cooperative would help to improve the reliability of kelp seed in the region. Equipment, knowledge, and seeded line could be collectively shared and produced by the cooperative.

4.2.2. Expand and teach Best Management Practices (BMPs)

Industry-wide BMPs for seaweed harvesting, management, cultivation, and processing need to be developed quickly (Rebours et al., 2014) and in parallel with the expansion of American and European kelp aquaculture. The entrepreneurs, foodies, fishermen, and biotech companies entering the industry have varying levels of education in aquaculture, husbandry, crop management, and marine ecosystems. In the absence of unified industry standards, there is a risk that uninformed individuals could act in a manner than subjects an entire region or industry to economic or ecological risk. Dissemination and development of additional BMPs support new entrants to the industry and thereby promotes livelihood development. More specifically, widespread awareness and application of on-farm BMPs will address the potential transmission of diseases from cultivated to wild kelp. Educating growers on these same practices can also reduce potential crop loss from fouling or disease which would otherwise affect local businesses and communities developing around kelp aquaculture. Stakeholders connected with this recommendation include kelp farmers, wild kelp harvesters, educational groups, and state regulatory agencies.

An independent, neutral entity should develop a unifying list of BMPs for the nascent kelp industry. This entity could be a council, a non-profit organization, an industry alliance, or a growers' guild. This group is advised to confer an advisory board comprised of members from each stakeholder group (Fig. 4). It will be beneficial to consult terrestrial farmers and land managers as experts on transferrable crop and ecosystem management strategies. Maine has a history of collaborative decision-making via stakeholder advisory boards regarding the management of marine resources. For example, the salmon farming companies in Maine, recognizing impending threats to the ecological and social sustainability, penned the Finfish Bay Management Agreement through a neutral third party entity, the Maine Aquaculture Association (Maine Aquaculture Association (MAA), 2002). More recently, the Maine Legislature passed legislation requiring the development of a Fishery Management Plan (FMP) for rockweed (Maine Department of Marine Resources (DMR), 2014). A diverse stakeholder group comprised of industry, academic, and environmental organizations was convened by the Maine Department of Marine Resources who oversaw the FMP's development and Maine Sea Grant facilitated the meetings.

The advisory board would document existing BMPs and develop new ones. The board could also establish a centralized repository for this information. The Manual for the Identification and Management of Aquaculture Production Hazards (Getchis, 2014) provides a list of some BMPs that can help to reduce risk in seaweed aquaculture. Examples include selecting sites with sufficient current flow and nutrient levels, only out-planting during optimal growing conditions, and maintaining optimal densities to reduce fouling from epiphytes. Additional BMPs could be developed around this existing guidance.

Farmed seaweeds are at risk for diseases and severe fouling from epiphytes (Food and Agriculture Organization (FAO), 2017). In these two technical problems lie immediate opportunities for the industry to raise awareness and develop BMPs. Study of intensive seaweed cultivation in other parts of the world suggests that Maine will see an increased prevalence of disease and fouling in the future. Adopting BMPs from these established industries could help to prevent future crop loss or, in the case of a very severe outbreak, industry collapse. Some examples of BMPs specifically designed to prevent disease outbreak include preventing culture lines from touching the seafloor at low tide, planting and harvesting around settlement windows of planktonic herbivores, harvesting early, and optimizing culture conditions to prevent physiological stress (Cottier-Cook et al., 2016; Getchis, 2014; Walls et al., 2017). In the event of a specific disease outbreak, necessary quarantine procedures will include keeping a log of environmental parameters, removing all visibly infected or unhealthy kelp, and preventing cross-contamination before sanitation (Cottier-Cook et al., 2016; Getchis, 2014; Walls et al., 2017).

Once they are developed, it is imperative that the BMPs be effectively shared with all relevant stakeholders. Over the last decade in Maine, public-sector entities have provided education for prospective kelp growers through general aquaculture training programs (Island Institute, 2017; Maine Sea Grant, 2018). However, these programs are not seaweed-specific, and the growth of the industry has outpaced them. More recently, a few fee-for-service and contract farmer-training options have been offered (see: Ocean Approved, Sea Greens Farms, and Springtide Seaweed). The benefit of new entrants paying for training is that they can learn about BMPs. However, the second principle of EAA mandates equal access for all stakeholders (Food and Agriculture Organization (FAO), 2010). Paid-training programs may exclude some potential entrants due to cost. Thus, they may not be the optimal pathway for educating stakeholders and industry members when other institutional resources are available. In Maine for example, the Maine Seaweed Council (MSC) is well-poised to draft and provide training on Maine-specific kelp aquaculture BMPs.

4.2.3. Develop climate change resiliency

The FAO does mention climate change as a potential concern for aquaculture in the 2010 technical guidelines. Almost ten years later, the imminent ecological and social impacts of climate change cannot be overlooked. The forecasted shifts in ranges and distributions of algae resulting from rising water temperatures and changes in ice cover, salinity, dissolved oxygen, and circulation are particularly relevant to aquaculture (IPCC, 2007). More broadly, coastal development and pollution, combined with climate change impacts, will also create increased stress on coastal communities and habitats (IPPC 2007). Consideration of climate change impacts in integrated planning and development stages will increase the capacity for stakeholders to adapt to them (IPCC, 2007, 2014; Whitney et al., 2017). Developing climate change resiliency within the budding kelp aquaculture industry will help to ensure that farmed kelp can contribute to food security despite a changing climate. Further efforts towards temperature-tolerant strain development can uphold kelp aquaculture as a marine-based livelihood in warmer water. Stakeholders connected with this recommendation include kelp farmers, wild seaweed harvesters, recreational boaters and fishermen, commercial fishermen, existing shellfish aquaculture, state regulatory agencies, federal regulatory agencies, harbormasters, educational groups, environmental groups, advocacy groups, interveners, towns, and coastal property owners. Each stakeholder in kelp aquaculture is likely to experience impacts of climate change, but the degree and timing of the impact remain unknown.

The forecasted changes in water temperatures pose a threat to the cultivation of S. latissima and A. esculenta that rely on cool water (Park et al., 2017). Ambient water temperature affects recruitment, photosynthesis, growth, and reproduction of seaweeds (Lning, 1988, 1990; Wiencke et al., 1994). Studies of S. latissima and A. esculenta gametophyte survival under high temperatures show a switch from reproduction to vegetative growth with increasing water temperature (Park et al., 2017). These findings suggest that more southern kelp populations may be negatively impacted by the forecasted warming (Park et al., 2017). Increased water temperatures could also affect the beneficial microbiome associated with the organisms. For instance, a study of the red alga Delisea pulchra showed that increased water temperatures could negatively affect the holobiont, or microbes living on the alga, that provide chemical defenses against disease (Harder et al., 2012).

Recent observations show that the Gulf of Maine is warming faster than 99% of the global ocean (Pershing et al., 2015). Research into culture and grow-out techniques for temperature-tolerant strains of kelp has been prompted by the observed and projected warming in the Gulf of Maine. Recently, laboratory protocols for producing temperature tolerant strains of A. esculenta were developed (C. Quigley, pers. comm., 2018). This development is an excellent first step in climate change resiliency for the industry because A. esculenta appears to be more temperature constrained than S. latissima (Park et al., 2017). High-temperature tolerant strains for S. latissima are a high priority for research due to the prolific cultivation of this species (Kim et al., 2017) and they are likely to be available soon. In Korea, they have employed selective breeding technologies to develop two temperature-tolerant strains of Saccharina japonica (Hwang et al., 2018). In addition to tolerating higher seawater temperatures, these strains also performed well in strong wave action and yielded more biomass than the control algae (Hwang et al., 2018).

More basic physiology experiments, culturing-method development, and grow-out assays will also help to improve the industry's climate change resiliency. Insufficient knowledge of seaweed biology, physiology, and reproduction is a significant hurdle for large-scale commercialization of seaweed aquaculture in Chile (Buschmann et al., 2017). This paucity is also highly evident in Maine. Efforts in each of these research tracks will support crop diversification and increase the adaptive capacity of the industry to respond to the potential consequences and opportunities resulting from climate change.

4.3. Recommendations using EAA Principle of Activity Integration

The third principle of the EAA instructs that aquaculture development should be integrated with other sectors and management efforts (Food and Agriculture Organization (FAO), 2010). The FAO further conveys that this can be achieved through multi-sectoral, or integrated planning and management. Indeed, case studies and conceptual modeling from across the world demonstrate that conservation is more successful if the users of shared environmental resources are also linked together socially (Bodin et al., 2014). With the development of kelp aquaculture in Maine, there are now multiple users of wild kelp beds. Therefore, one of the most straightforward actions to reconcile kelp aquaculture within the existing use of the resource is to integrate the management and planning of kelp harvesting.

4.3.1. Integrate kelp aquaculture and kelp harvesting into a seaweed management plan

This recommendation addresses the potential overharvesting of wild sorus tissue by consolidating requests for, and records of, all kelp harvesting. More comprehensive management of wild kelp beds ensures the viability of wild kelp harvesting as an economic livelihood. Harvesting BMPs and zonation of sorus harvesting areas will also protect the seed source for future research and industry development. Stakeholders connected with this recommendation include kelp farmers, wild kelp harvesters, and state regulatory agencies.

With the growth of kelp aquaculture, the need for more comprehensive monitoring and management of natural kelp beds is increasingly important (Buschmann et al., 2013; Frangoudes 2011). Similar to many other kelp farming regions, Maine has an existing fishery in which harvesters collect mature S. latissima, A. esculenta, and L. digitata sporophytes by hand. Harvesters in the wild kelp fishery are required to keep and report detailed effort and landings records, including area harvested, seaweed species, and biomass landed (Maine Department of Marine Resources (DMR), 2015). However, recreational harvest rules in Maine allow harvesting of ≤22.6 kg of seaweed per day without a license. Sorus tissue harvest can go unreported because the amount of tissue required for kelp nursery operations is usually much lower (see subsection 2.1) than the reporting threshold. Under reporting of wild tissue harvest renders effective monitoring and sustainable management of the fishery more challenging.

An integrated kelp management plan can support the development of the cultivated kelp industry while providing more protection for the natural kelp beds. In such a plan, individuals or companies harvesting wild sorus tissue for seed stock production would be held to the broader management regulations for the seaweed fishery. Integrated management for all interactions with wild kelp beds will, at a minimum, allow regulators to track effort, quantity, and spatial distribution of sorus harvest. This data can be integrated into the broader fisheries management plan for seaweeds. Ecological indicators like density, biomass, recruitment, and population structure could be used to link regions with different harvesting regimes under a co-management effort (Vega et al., 2014). Informed and integrated management is needed to ensure the sustainability of wild kelp beds and the livelihood of both kelp farmers and wild kelp harvesters.

5. Conclusion

Approximately 58% (25) of the 43 potential issues and impacts originally described by the FAO working group in the EAA document are relevant to kelp aquaculture. Thus, most of the strategy and principles of the EAA can be used to establish protocols and actions to promote the ecological and social sustainability of the nascent kelp industry. The concerns and recommendations described in the present study address ecological, social, and management aspects of kelp production. The major ecological concerns are the alignment of management and ecosystem boundaries and the potential impact to the wild kelp beds from seed sourcing and transfer of species beyond natural limits. Best Management Practices applied at key leverage points within the system would help the kelp industry to address many of the relevant ecological concerns. Low barriers to entry and rapid growth of the industry are the leading factors accentuating potential social conflicts. Recommendations to address the social sustainability of the industry are focused on the development of BMPs and the education of stakeholders to accept them, increasing horizontal expansion, and the development of climate-change resiliency. It is also recommended that kelp aquaculture and sorus harvesting activities be integrated into a broader fishery management plan for seaweeds.

The assessment and recommendations developed with the focus on the Maine kelp industry are believed to be applicable to other kelp industries in the Americas and Europe. Some adaptations will be necessary to fit the practices, ecosystems, and attitudes of the different kelp-producing countries and latitudes. Further studies in other regions where kelp farming is starting are necessary to establish a general and predictive model for development of this nascent industry.

Declaration of Competing Interest

None.

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References

Alberto, F., Raimondi, P.T., Reed, D.C., Coelho, N.C., Leblois, R., Whitmer, A., et al., 2010. Habitat continuity and geographic distance predict population genetic differentiation in giant kelp. Ecology 91 (1), 49–56.

Alleway, H.K., Gillies, C.L., Bishop, M.J., Gentry, R.R., Theuerkauf, S.J., Jones, R., 2019. The ecosystem services of marine aquaculture: valuing benefits to people and nature. BioScience 69 (1), 59–68.

Augyte, S., Yarish, C., Redmond, S., Kim, J.K., 2017. Cultivation of a morphologically distinct strain of the sugar kelp, Saccharina latissima forma angustissima, from coastal Maine, USA, with implications for ecosystem services. J. Appl. Phycol. 29 (4), 1967–1976. https://doi.org/10.1007/s10811-017-1102-x.

Azad, A.K., Jensen, K.R., Lin, C.K., 2009. Coastal aquaculture development in Bangladesh: unsustainable and sustainable experiences. Environ. Manage. 44 (4), 800–809. https://doi.org/10.1007/s00267-009-9356-y.

Azevedo, I.C., Marinho, G.S., Silva, D.M., Sousa-Pinto, I., 2016. Pilot scale land-based cultivation of Saccharina latissima Linnaeus at southern European climate conditions: growth and nutrient uptake at high temperatures. Aquaculture 459, 166–172. https://doi.org/10.1016/j.aquaculture.2016.03.038.

Bekkby, T., Moy, F.E., 2011. Developing spatial models of sugar kelp (Saccharina latissima) potential distribution under natural conditions and areas of its disappearance in Skagerrak. Estuar. Coast. Shelf Sci. 95 (4), 477–483.

Berkes, F., 2006. From community-based resource management to complex systems. Ecol. Soc. 11 (1), 45. Available from URL: http://www.ecologyandsociety.org/vol11/iss1/art45/.

Bjerregaard, R., Valderrama, D., Sims, N., Radulovich, R., James, D., Carpon, M., et al., 2016. Seaweed Aquaculture for Food Security, Income Generation and Environmental Health in Tropical Developing Countries. World Bank Group, Washington, DC.

Bodin, Ö., Crona, B., Thyresson, M., Golz, A.L., Tengö, M., 2014. Conservation success as a function of good alignment of social and ecological structures and processes. Conserv. Biol. 28 (5), 1371–1379.

Branch, T.A., DeJoseph, B.M., Ray, L.J., Wagner, C.A., 2013. Impacts of ocean acidification on marine seafood. Trends Ecol. Evol. (Amst.) 28, 178–186.

Breton, T.S., Nettleton, J.C., O'Connell, B., Bertocci, M., 2018. Fine-scale population genetic structure of sugar kelp, Saccharina latissima (Laminariales, Phaeophyceae), in eastern Maine, USA. Phycologia 57 (1), 32–40.

Brownlee, I.A., Allen, A., Pearson, J.P., Dettmar, P.W., Havler, M.E., Atherton, M.R., et al., 2005. Alginate as a source of dietary fiber. Crit. Rev. Food Sci. Nutr. 45 (6), 497–510.

Brugère, C., Aguilar-Manjarrez, J., Beveridge, M.C., Soto, D., 2018. The ecosystem approach to aquaculture 10 years on–a critical review and consideration of its future role in blue growth. Rev. Aquac. 11 (3), 493–514. https://doi.org/10.1111/raq.12242.

Buschmann, A.H., Stead, R.A., Hernández-González, M.C., Pereda, S.V., Paredes, J.E., Maldonado, M.A., 2013. Un análisis crítico sobre el uso de macroalgas como base para una acuicultura sustentable. Rev. Chil. Hist. Nat. 86 (3), 251–264.

Buschmann, A., Prescott, S., Potin, P., Faugeron, S., Vasquez, J., Camus, C., et al., 2014. The status of kelp exploitation and marine agronomy, with emphasis on Macrocystis pyrifera, in Chile. Adv. Bot. Res. 71, 161–188.

Buschmann, A.H., Camus, C., Infante, J., Neori, A., Álvaro, I., Hernández-González, M.C.,

et al., 2017. Seaweed production: overview of the global state of exploitation, farming, and emerging research activity. Eur. J. Phycol. 52 (4), 391–406. https://10.1080/09670262.2017.1365175.
Camus, C., Infante, J., Buschmann, A.H., 2018. Overview of 3 year precommercial seafarming of Macrocystis pyrifera along the Chilean coast. Rev. Aquac. 10 (3), 543–559.
Camus, C., Infante, J., Buschmann, A.H., 2019. Revisiting the economic profitability of giant kelp Macrocystis pyrifera (Ochrophyta) cultivation in Chile. Aquaculture 502, 80–86.
Chapman, A., Stévant, P., Larssen, W., 2015. Food or fad? Challenges and opportunities for including seaweeds in a Nordic diet. Botanica Marina 58 (6), 423–433. https://10.1515/bot-2015-0044.
Charles, A., 2012. People, oceans, and scale: governance, livelihoods, and climate change adaptation in marine social-ecological systems. Curr. Opin. Environ. Sustain. 4 (3), 351–357.
Chen, J., 2006. Cultured Aquatic Species Information Programme—Laminaria japonica. Cultured Aquatic Species Fact Sheets. FAO Inland Water Resources and Aquaculture Service (FIRI). Available from URL: http://www.fao.org/fishery/culturedspecies/Laminaria_japonica/en (Accessed 8 August 2018). .
Christie, H., Norderhaug, K.M., Fredriksen, S., 2009. Macrophytes as habitat for fauna. Mar. Ecol. Prog. Ser. 396, 221–234.
Chung, I.K., Beardall, J., Mehta, S., Sahoo, D., Stojkovic, S., 2011. Using marine macroalgae for carbon sequestration: a critical appraisal. J. Appl. Phycol. 23 (5), 877–886.
Chung, I.K., Sondak, C., Beardall, J., 2017. The future of seaweed aquaculture in a rapidly changing world. Eur. J. Phycol. 52 (4), 495–505. https://10.1080/09670262.2017.1359678.
Coleman, M.A., Gillanders, B.M., Connell, S.D., 2009. Dispersal and gene flow in the habitat-forming kelp, Ecklonia radiata: relative degrees of isolation across an east–-west coastline. Mar. Freshw. Res. 60 (8), 802–809. https://doi.org/10.1071/MF08268.
Convention on Biological Diversity (CBD), 2011. The Aichi Targets. Available from URL: https://www.cbd.int/sp/targets/ (Accessed 8 August 2018). .
Cottier-Cook, E., Nagabhatla, N., Badis, Y., Campbell, M., Chopin, T., Dai, W., et al., 2016. Safeguarding the Future of the Global Seaweed Aquaculture Industry. United Nations University and Scottish Association for Marine Science Policy Brief 12 pp.
Doyle, R.W., 2016. Inbreeding and disease in tropical shrimp aquaculture: a reappraisal and caution. Aquac. Res. 47 (1), 21–35. https://doi.org/10.1111/are.12472.
Duarte, C.M., Losada, I.J., Hendriks, I.E., Mazarrasa, I., Marbà, N., 2013. The role of coastal plant communities for climate change mitigation and adaptation. Nat. Clim. Chang. 3 (11), 961–968.
Duarte, C.M., Wu, J., Xiao, X., Bruhn, A., Krause-Jensen, D., 2017. Can seaweed farming play a role in climate change mitigation and adaptation? Front. Mar. Sci. 4.
Engle, C., Azure, C., Kotowicz, D., McCann, J., 2018. Potential Supply Chains for Seaweed Produced for Food in the Northeastern United States: Final Report. Available at URL:. . https://www.crc.uri.edu/download/Seaweed-Supply-Chain-Analysis-FINAL.pdf.
Food and Agriculture Organization (FAO), 2003. A Guide to the Seaweed Industry. Fisheries Technical Paper 441, Rome. 118 pp. Available at URL:. http://www.fao.org/3/a-y4765e.pdf.
Food and Agriculture Organization (FAO), 2010. aquaculture development, 4. Ecosystem approach to aquaculture. FAO Technical Guidelines for Responsible Fisheries. No. 5. Suppl. 4, Rome. Available from URL: http://www.fao.org/docrep/013/i1750e/i1750e00.htm.
Food and Agriculture Organization (FAO), 2016. The State of World Fisheries and Aquaculture 2016 - Contributing to Food Security and Nutrition for All, Rome. 200 pp. Available from URL:. http://www.fao.org/fishery/en.
Food and Agriculture Organization (FAO), 2017. Committee on Fisheries: Sub-Committee on Aquaculture. Thematic Background Study No. 4: Genetic Resources for Farmed Seaweeds. Ninth Session, 24–27th October 2017, Rome. Available from URL:. http://www.fao.org/cofi/46056-0e272e19f4b0051d1e1c3b679e5ca8ada.pdf.
Food and Agriculture Organization (FAO), 2018. The State of World Fisheries and Aquaculture 2018 – Meeting the Sustainable Development Goals, Rome. 227 pp. Available from URL:. http://www.fao.org/3/I9540EN/i9540en.pdf.
Flavin, K., Flavin, N., Flahive, B., 2013. Kelp Farming Manual: A Guide to the Processes, Techniques, and Equipment for Farming Kelp in New England Waters. Available from URL:. https://static1.squarespace.com/static/52f23e95e4b0a96c7b53ad7c/t/52f78b0de4b0374e6a0a4da8/1391954701750/OceanApproved_KelpManualLowRez.pdf.
Fletcher, W.J., 2012. National application of sustainability indicators for Australian fisheries - part 2: ecosystem based frameworks for aquaculture, multi-fishery, and international applications. FRDC Report - Project 2000/145, Part 2. Fisheries Research Report No 235. Department of Fisheries, Western Australia.
Forbord, S., Skjermo, J., Arff, J., Handå, A., Reitan, K.I., Bjerregaard, R., 2012. Development of Saccharina latissima (Phaeophyceae) kelp hatcheries with year-round production of zoospores and juvenile sporophytes on culture ropes for kelp aquaculture. J. Appl. Phycol. 24 (3), 393–399. https://doi.org/10.1007/s10811-011-9784-y.
Frangoudes, K., 2011. Seaweeds fisheries management in France, Japan, Chile, and Norway. CBM-Cahiers de Biologie Marine 52 (4), 517.
Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESAMP), 1986. Environmental capacity: an approach to marine pollution prevention. Reports and Studies GESAMP No. 30. 49 pp.
Getchis, T.L., 2014. Northeastern US Aquaculture Management Guide. A Manual for the Identification and Management of Aquaculture Production Hazards. Northeastern Regional Aquaculture Center and USDA. Available from URL: http://agresearch.umd.edu/sites/agresearch.umd.edu/files/_docs/NE_Aquaculture_Management_Guide_2014.pdf (Accessed 1 September 2018).
Gjedrem, T., 2005. Basic genetics. In: Gjedrem, T. (Ed.), Selection and Breeding Programs in Aquaculture. Springer, Dordrecht, pp. 9–21.
Glasby, T.M., 1999. Interactive effects of shading and proximity to the seafloor on the development of subtidal epibiotic assemblages. Mar. Ecol. Prog. Ser. 190, 113–124. https://doi.org/10.3354/meps190113.
Griffin, J., Warner, B., 2017. Pursuit of Sea Vegetable Market Expansion: Consumer Preferences and Product Innovation. Available from URL:. Island Institute. http://www.islandinstitute.org/sites/default/files/Edible%20Seaweed%20Summary%20Report%209-15-17.pdf.
Graham, L., Graham, J., Wilcox, L., Cook, M., 2016. Algae, 3rd edn. LJLM Press, Madison, WY.
Hafting, J.T., Craigie, J.S., Stengel, D.B., Loureiro, R.R., Buschmann, A.H., Yarish, C., et al., 2015. Prospects and challenges for industrial production of seaweed bioactives. J. Phycol. 51 (5), 821–837.
Halling, C., Wikström, S.A., Lilliesköld-Sjöö, G., Mörk, E., Lundsør, E., Zuccarello, G.C., 2013. Introduction of Asian strains and low genetic variation in farmed seaweeds: indications for new management practices. J. Appl. Phycol. 25 (1), 89–95.
Hambrey, 2017. the 2030 agenda and the sustainable development goals: the challenge for aquaculture development and management. Fisheries and Aquaculture Circular No. 1141. Food and Agriculture Organization of the United Nations, Rome.
Handå, A., Forbord, S., Wang, X., Broch, O.J., Dahle, S.W., Størseth, T.R., et al., 2013. Seasonal- and depth-dependent growth of cultivated kelp (Saccharina latissima) in close proximity to salmon (Salmo salar) aquaculture in Norway. Aquaculture 414–415, 191–201. https://doi.org/10.1016/j.aquaculture.2013.08.006.
Harder, T., Campbell, A.H., Egan, S., Steinberg, P.D., 2012. Chemical mediation of ternary interactions between marine holobionts and their environment as exemplified by the red alga Delisea pulchra. J. Chem. Ecol. 38 (5), 442–450.
Hasselström, L., Visch, W., Gröndahl, F., Nylund, G.M., Pavia, H., 2018. The impact of seaweed cultivation on ecosystem services – a case study from the west coast of Sweden. Mar. Pollut. Bull. 133, 53–64. https://doi.org/10.1016/j.marpolbul.2018.05.005.
Hutchings, J.A., Fraser, D.J., 2008. The nature of fisheries- and farming-induced evolution. Mol. Ecol. 17 (1), 294–313.
Hwang, E.K., Liu, F., Lee, K.H., Ha, D.S., Park, C.S., 2018. Comparison of the cultivation performance between Korean (Sugwawon No. 301) and Chinese strains (Huangguan No. 1) of kelp Saccharina japonica in an aquaculture farm in Korea. Algae 33 (1), 101–108.
IPCC, 2007. Summary for policymakers. In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., Miller, H.L. (Eds.), Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA Available from URL: https://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-spm.pdf.
IPCC, 2014. In: Core Writing Team, Pachauri, R.K., Meyer, L.A. (Eds.), Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland Available from URL: http://www.ipcc.ch/pdf/assessment-report/ar5/syr/SYR_AR5_FINAL_full_wcover.pdf.
Island Institute, 2017. Aquaculture. Available from URL: http://www.islandinstitute.org/aquaculture (Accessed 30 July 2018). .
Johnson, T.R., Wilson, J.A., Cleaver, C., Vadas, R.L., 2012. Social-ecological scale mismatches and the collapse of the sea urchin fishery in Maine, USA. Ecol. Soc. 17 (2).
Kim, J.K., Kraemer, G., Yarish, C., 2015. Use of sugar kelp aquaculture in Long Island Sound and the Bronx River Estuary for nutrient extraction. Mar. Ecol. Prog. Ser. 531, 155–166. https://doi.org/10.3354/meps11331.
Kim, J.K., Yarish, C., Hwang, E.K., Park, M., Kim, Y., 2017. Seaweed aquaculture: cultivation technologies, challenges, and its ecosystem services. Algae 32 (1), 1–13. https://doi.org/10.4490/algae.2017.32.3.3.
Knowlton, A.R., Hamilton, P.K., Marx, M.K., Pettis, H.M., Kraus, S.D., 2012. Monitoring North Atlantic right whale Eubalaena glacialis entanglement rates: a 30 yr retrospective. Mar. Ecol. Prog. Ser. 466, 293–302.
Kraus, S.D., Brown, M.W., Caswell, H., Clark, C.W., Fujiwara, M., Hamilton, P.K., et al., 2005. North Atlantic right whales in crisis. Science 309 (5734), 561.
Krause-Jensen, D., Duarte, C.M., 2016. Substantial role of macroalgae in marine carbon sequestration. Nat. Geosci. 9 (10), 737–742.
Krumhansl, K.A., Scheibling, R.E., 2012. Production and fate of kelp detritus. Mar. Ecol. Prog. Ser. 467, 281–302. https://doi.org/10.3354/meps09940.
Krupinsky, J.M., Bailey, K.L., McMullen, M.P., Gossen, B.D., Turkington, T.K., 2002. Managing plant disease risk in diversified cropping systems. Agron. J. 94 (2), 198–209.
Lebel, L., Tri, N.H., Saengnoree, A., Pasong, S., Buatama, U., Thoa, L.K., 2002. Industrial transformation and shrimp aquaculture in Thailand and Vietnam: pathways to ecological, social, and economic sustainability. Ambio 31 (4), 311–323. https://doi.org/10.1579/0044-7447-31.4.311.
Lem, P., 2016. Just 1 Word for Maine's Future: Seaweed. Scientific American. Available from URL: https://www.scientificamerican.com/article/just-1-word-for-maine-s-future-seaweed/ (Accessed 12 November 2019). .
Liu, J., Dietz, T., Carpenter, S.R., Alberti, M., Folke, C., Moran, E., et al., 2007a. Complexity of coupled human and natural systems. Science 317 (5844), 1513–1516. https://doi.org/10.1126/science.1144004.
Liu, J., Dietz, T., Carpenter, S.R., Folke, C., Alberti, M., Redman, C.L., et al., 2007b. Coupled human and natural systems. Ambio 36 (8), 639–649. https://doi.org/10.1579/0044-7447.
Liu, F., Yao, J., Wang, X., Repnikova, A., Galanin, D.A., Duan, D., 2012. Genetic diversity and structure within and between wild and cultivated Saccharina japonica (Laminariales, Phaeophyta) revealed by SSR markers. Aquaculture 358, 139–145.

Loureiro, R., Claire, M., Gachon, M., Rebours, C., 2015. Seaweed cultivation: potential and challenges of crop domestication at an unprecedented pace. New Phytol. 206 (2), 489–492. https://doi.org/10.1111/nph.13278.

Lüning, K., 1988. Photoperiodic control of sorus formation in the brown alga Laminaria saccharina. Mar. Ecol. Prog. Ser. 45, 137–144.

Lüning, K., 1990. Seaweeds: Their Environment, Biogeography, and Ecophysiology. Wiley, New York, NY pg. 55.

Luvesuto, E., Freitas, P.D., Galetti Jr., P.M., 2007. Genetic variation in a closed line of the white shrimp Litopenaeus vannamei (Penaeidae). Genet. Mol. Biol. 30 (4), 1156–1160. https://doi.org/10.1590/S1415-47572007000600021.

MacArtain, P., Gill, C.I., Brooks, M., Campbell, R., Rowland, I.R., 2007. Nutritional value of edible seaweeds. Nutr. Rev. 65 (12), 535–543.

Maine Aquaculture Association (MAA), 2002. Finfish Bay Management Agreement. Available from URL:. https://www.greateratlantic.fisheries.noaa.gov/sed/aquaculture/ne/maine_aquaculture_assoc_finfish_bay_management_plan.pdf.

Maine Department of Marine Resources (DMR), 2014. Fishery Management Plan for Rockweed (Ascophyllum nodosum). Available from URL:. https://www.maine.gov/dmr/science-research/species/rockweed/documents/DMRRockweedFMPJan2014.pdf.

Maine Department of Marine Resources (DMR), 2015. Landings Program. Chapter 8; Section 8.20.C.Landings Program. Chapter 8; Section 8.20.C.

Maine Department of Marine Resources (DMR), 2018. Maine Aquaculture Harvest Data: Marine Algae (2015 – 2018). Available at URL:. https://www.maine.gov/dmr/aquaculture/harvestdata/index.html.

Maine Department of Marine Resources (DMR), 2019a. Procedural Rules. Chapter 2, Aquaculture Lease Regulations. Available from URL: https://www.maine.gov/dmr/laws-regulations/regulations/documents/Chapter2-04012019.pdf (Accessed 21 April 2019). .

Maine Department of Marine Resources (DMR), 2019b. Limited Purpose Aquaculture Sites; Updated 21 March 2019. Maine Department of Marine Resources Open Data. Available from URL:. https://dmr-maine.opendata.arcgis.com/datasets/mainedmr-aquaculture-limited-purpose-aquaculture-sites.

Maine Department of Marine Resources (DMR), 2019c. AQ Leases; Updated 21 March 2019. Maine Department of Marine Resources Open Data. Available from URL:. https://dmr-maine.opendata.arcgis.com/datasets/mainedmr-aquaculture-aq-leases.

Maine Legislature, 2017a. Title 12: Conservation. Part 9: Marine Resources. Subpart 1: Administration. Chapter 605: General Department Activities. Subchapter 2: Leases and Special Licenses.

Maine Legislature, 2017b. Title 12: Conservation. Part 9: Marine Resources. Subpart 2: Licensing. Chapter 623: Shellfish, Scallops, Worms, and Miscellaneous Licenses. Subchapter 4: Miscellaneous Species. Article 1: Licenses. Available from URL: http://www.mainelegislature.org/legis/statutes/12/title12sec6810-B.html (Accessed 21 April 2019). .

Maine Sea Grant, 2018. Aquaculture in Shared Waters. Available at URL: https://www.seagrant.umaine.edu/aquaculture/aquaculture-in-shared-waters (Accessed 30 July 2018). .

Maine Seaweed Council (MSC), 2014. A Field Harvesters Guide to Maine Seaweeds. Available at URL:. http://www.seaweedcouncil.org/wp-content/uploads/MSC-Field-Guide-Aug-2014-FINAL-reformatted-new-url.pdf.

Maine State Planning Office (MSOP), Rose, G., 2003. A Brief History of the Maine Economy. Available at URL:. State Planning Office, pp. 17. https://digitalmaine.com/spo_docs/17.

Makkar, H.P.S., Tran, G., Heuzé, V., Giger-Reverdin, S., Lessire, M., Lebas, F., et al., 2016. Seaweeds for livestock diets: a review. Anim. Feed Sci. Technol. 212, 1–17.

Martins, N., Tanttu, H., Pearson, G.A., Serrão, E.A., Bartsch, I., 2017. Interactions of daylength, temperature, and nutrients affect thresholds for life stage transitions in the kelp Laminaria digitata (Phaeophyceae). Botanica Marina 60 (2), 109–121.

Millennium Ecosystem Assessment (MEA), 2005. Ecosystems and Human Well-Being Vol. 5 Island Press, Washington, DC.

Etter, R.J., Miller, R.J., 2008. Shading facilitates sessile invertebrate dominance in the rocky subtidal Gulf of Maine. Ecology 89 (2), 452–462. https://doi.org/10.1890/06-1099.1.

Mork, M., 1996. The effect of kelp in wave damping. Sarsia 80 (4), 323–327.

Morrissey, J., Kraan, S., Guiry, M.D., 2001. A Guide to Commercially Important Seaweeds on the Irish Coast. Irish Bord Iascaigh Mhara/Irish Sea Fisheries Board.

Mungkung, R., Aubin, J., Prihadi, T.H., Slembrouck, J., van der Werf, H.M., Legendre, M., 2013. Life cycle assessment for environmentally sustainable aquaculture management: a case study of combined aquaculture systems for carp and tilapia. J. Clean. Prod. 57, 249–256. https://doi.org/10.1016/j.jclepro.2013.05.029.

NOAA, 2016. Marine Mammal Stock Assessment Reports by Species/Stock: Right Whale, North Atlantic. National Marine Fisheries Service. Available from URL: https://www.fisheries.noaa.gov/national/marine-mammal-protection/marine-mammal-stock-assessment-reports-species-stock#cetaceans—large-whales(Accessed 9 September 2018).

NOAA, 2018a. Shoreline Mileage Of the United States. NOAA Office for Coastal Management. Available from URL: shoreline.noaa.gov/faqs.html?faq = 2 (Accessed 12 September 2018).

NOAA, 2018b. Water Temperature Table of the Northern Atlantic Coast. Available from URL: https://www.nodc.noaa.gov/dsdt/cwtg/natl.html (Accessed 5 September 2018). .

Pang, S.J., Lüning, K., 2004. Breaking seasonal limitation: year-round sporogenesis in the brown alga Laminaria saccharina by blocking the transport of putative sporulation inhibitors. Aquaculture 240 (1–4), 531–541.

Park, J., Kim, J.K., Kong, J., Depuydt, S., Brown, M.T., Han, T., 2017. Implications of rising temperatures for gametophyte performance of two kelp species from arctic waters. Botanica Marina 60 (1), 39–48. https://doi.org/10.1515/bot-2016-0103.

Park, M., Shin, S.K., Do, Y.H., Yarish, C., Kim, J.K., 2018. Application of open water integrated multi-trophic aquaculture to intensive monoculture: a review of the current status and challenges in Korea. Aquaculture 497, 174–183.

Pershing, A.J., Alexander, M.A., Hernandez, C.M., Kerr, L.A., Le Bris, A., Mills, K.E., et al., 2015. Slow adaptation in the face of rapid warming leads to collapse of the Gulf of Maine cod fishery. Science 350 (6262), 809–812.

Peteiro, C., Sánchez, N., Martínez, B., 2016. Mariculture of the Asian kelp Undaria pinnatifida and the native kelp Saccharina latissima along the Atlantic coast of Southern Europe: an overview. Algal Res. 15, 9–23.

Pulver, S., Ulibarri, N., Sobocinski, K.L., Alexander, S.M., Johnson, M.L., McCord, P.F., et al., 2018. Frontiers in socio-environmental research: components, connections, scale, and context. Ecol. Soc. 23 (3), 23. https://doi.org/10.5751/ES-10280-230323.

Mata, R., Radulovich, R., Umanzor, S., Cabrera, R., 2015. Tropical seaweeds for human food, their cultivation and its effect on biodiversity enrichment. Aquaculture 436, 40–46. https://doi.org/10.1016/j.aquaculture.2014.10.032.

Rebours, C., Marinho-Soriano, E., Zertuche-González, J.A., Hayashi, L., Vásquez, J.A., Kradolfer, P., et al., 2014. Seaweeds: an opportunity for wealth and sustainable livelihood for coastal communities. J. Appl. Phycol. 26 (5), 1939–1951. https://doi.org/10.1007/s10811-014-0304-8.

Redmond, S., Green-Gavrielidis, L., Yarish, C., Kim, J., Neefus, C., 2014. New England Seaweed Culture Handbook: Nursery Systems. Available from URL:. Connecticut Sea Grant CTSG-14-01. http://seagrant.uconn.edu/publications/aquaculture/handbook.pdf.

Rogers, E.M., 1962. Diffusion of Innovations. Free Press of Glencoe, New York, NY.

Rose, J.M., Tedesco, M.A., Wikfors, G.H., Yarish, C., 2010. International Workshop on Bioextractive Technologies for Nutrient Remediation Summary Report. Available from URL:. . https://www.maine.gov/legis/opla/OABioextractiveTechnologiesfo%20NutrientRemediation.pdf.

Rose, J.M., Bricker, S.B., Tedesco, M.A., Wikfors, G.H., 2014. A role for shellfish aquaculture in coastal nitrogen management. Environ. Sci. Technol. 48 (5), 2519–2525. https://doi.org/10.1021/es4041336.

Rose, J.M., Bricker, S.B., Deonarine, S., Ferreira, J.G., Getchis, T., Grant, J., et al., 2015. Nutrient bioextraction. Encyclopedia of Sustainability Science and Technology. pp. 1–33.

Sadovy, Y., Domeier, M., 2005. Are aggregation-fisheries sustainable? Reef fish fisheries as a case study. Coral Reefs 24 (2), 254–262.

Ballesteros, E., Sala, E., Starr, R.M., 2001. Rapid decline of Nassau grouper spawning aggregations in Belize: fishery management and conservation needs. Fisheries 26 (10), 23–30.

Schiener, P., Zhao, S., Theodoridou, K., Carey, M., Mooney-McAuley, K., Greenwell, C., 2017. The nutritional aspects of biorefined Saccharina latissima, Ascophyllum nodosum and Palmaria palmata. Biomass Convers. Biorefinery 7 (2), 221–235.

Schreiber, E., 1930. Untersuchungen über parthenogenesis, geschlechtsbestimmung und bastardierungsvermögen bei laminarien. Planta 12 (3), 331–353.

Arff, J., Skjermo, J., Aasen, I.M., Broch, O.J., Carvajal, A.K., Christie, H.C., et al., 2014. A New Norwegian Bioeconomy Based on Cultivation and Processing of Seaweeds: Opportunities and R&D Needs. SINTEF.

Shim, J., Hwang, J.R., Lee, S.Y., Kwon, J.N., 2014. Variations in nutrients & CO2 uptake rates of Porphyra yezoensis Ueda and a simple evaluation of in situN & C demand rates at aquaculture farms in South Korea. Korean J. Environ. Biol 32, 297–305. https://doi.org/10.11626/KJEB.2014.32.4.297.

Sjøtun, I.K., 2017. Presentation at MACROSEA 2017 Annual Meeting: WP3 Genetics and Disease I. Available at URL:. https://www.sintef.no/globalassets/sintef-ocean/macrosea-prosjektweb/annual-meeting/wp3-genetics-and-disease-i-by-inga-kjersti-sjotun.pdf.

Sondak, C.F.A., Ang Jr, P.O., Beardall, J., Bellgrove, A., Boo, S.M., Gerung, G.S., et al., 2017. Carbon dioxide mitigation potential of seaweed aquaculture beds (SABs). J. Appl. Phycol. 29 (5), 2363–2373. https://doi.org/10.1007/s10811-016-1022-1.

Sorte, C.J.B., Davidson, V.E., Franklin, M.C., Benes, K.M., Doellman, M.M., Etter, R.J., et al., 2017. Long-term declines in an intertidal foundation species parallel shifts in community composition. Glob. Chang. Biol. 23 (1), 341–352. https://doi.org/10.1111/gcb.13425.

Steneck, R.S., Graham, M.H., Bourque, B.J., Corbett, D., Erlandson, J.M., Estes, J.A., et al., 2002. Kelp forest ecosystems: biodiversity, stability, resilience, and future. Environ. Conserv. 29 (4), 436.

Stévant, P., Rebours, C., Chapman, A., 2017. Seaweed aquaculture in Norway: recent industrial developments and future perspectives. Aquac. Int. 25 (4), 1373–1390.

The Cultured Abalone Farm, LLC, 2015. Kelp Harvest Plan. Available from URL: http://www.fgc.ca.gov/meetings/2015/Feb/Exhibits/13_1_Kelp_Harvest_Plan_CulturedAbaloneFarm_011415.pdf (Accessed 21 April 2019). .

Troell, M., Kautsky, N., Folke, C., 1999a. Applicability of integrated coastal aquaculture systems. Ocean Coast. Manag. 42, 63–70.

Troell, M., Rönnbäck, P., Halling, C., Kautsky, N., Buschmann, A., 1999b. Ecological engineering in aquaculture: use of seaweeds for removing nutrients from intensive mariculture. J. Appl. Phycol. 11, 89–97.

Tseng, C.K., 1986. Laminaria mariculture in China. In: Doty, M.S., Caddy, J.F., Santelices, B. (Eds.), Case Studies of Seven Commercial Seaweed Resources. FAO Fisheries Technical Papers (281), 311 pp.

United Nations, 2015. Transforming Our World: The 2030 Agenda for Sustainable Development. Resolution Adopted by the General Assembly. Available from URL:. https://sustainabledevelopment.un.org/content/documents/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf.

U.S. Army Corps of Engineers (USACE), 2015. Department of the Army General Permit for the State of Maine. Available from URL:. http://www.nae.usace.army.mil/Portals/74/docs/regulatory/StateGeneralPermits/ME/Maine_General_Permit_2015.pdf.

Vásquez, J.A., Zuñiga, S., Tala, F., Piaget, N., Rodríguez, D.C., Vega, J.M.A., 2014.

Economic valuation of kelp forests in northern Chile: values of goods and services of the ecosystem. J. Appl. Phycol. 26 (2), 1081–1088. https://doi.org/10.1007/s10811-013-0173-6.

Vega, J.M.A., Broitman, B.R., Vásquez, J.A., 2014. Monitoring the sustainability of Lessonia nigrescens (Laminariales, Phaeophyceae) in northern Chile under strong harvest pressure. J. Appl. Phycol. 26 (2), 791–801. https://doi.org/10.1007/s10811-013-0167-4.

Visch, W., 2018. Underpinning the development of algal biotechnology: cryopreservation of brown algae gametophytes. Presented at the Tjärnö International Seaweed Conference.

Walls, A., Kennedy, R., Fitzgerald, R., Blight, A., Johnson, M., Edwards, M., 2016. Potential novel habitat created by holdfasts from cultivated Laminaria digitata: Assessing the macroinvertebrate assemblages. Aquac. Environ. Interact. 8, 157–169. https://doi.org/10.3354/aei00170.

Walls, A.M., Edwards, M.D., Firth, L.B., Johnson, M.P., 2017. Successional changes of epibiont fouling communities of the cultivated kelp Alaria esculenta: predictability and influences. Aquac. Environ. Interact. 9, 57–71.

Whitney, C.K., Bennett, N.J., Ban, N.C., Allison, E.H., Armitage, D., Blythe, J.L., et al., 2017. Adaptive capacity: from assessment to action in coastal social-ecological systems. Ecol. Soc. 22 (2), 22.

Wiencke, C., Bartsch, I., Bischoff, B., Peters, A.F., Breeman, A.M., 1994. Temperature requirements and biogeography of Antarctic, Arctic, and amphiequatorial seaweeds. Botanica Marina 37 (3), 247–260.

Wood, D., Capuzzo, E., Kirby, D., Mooney-McAuley, K., Kerrison, P., 2017. UK macroalgae aquaculture: what are the key environmental and licensing considerations? Mar. Policy 83, 29–39. https://doi.org/10.1016/j.marpol.2017.05.021.

Wu, H., Huo, Y., Zhang, J., Liu, Y., Zhao, Y., He, P., 2015. Bioremediation efficiency of the largest scale artificial Porphyra yezoensis cultivation in the open sea in China. Mar. Pollut. Bull. 95 (1), 289–296.

Wu, H., Kim, J.K., Huo, Y., Zhang, J., He, P., 2017. Nutrient removal ability of seaweeds on Pyropia yezoensis aquaculture rafts in China's radial sandbanks. Aquat. Bot. 137, 72–79.

Yang, Y., Chai, Z., Wang, Q., Chen, W., He, Z., Jiang, S., 2015a. Cultivation of seaweed Gracilaria in Chinese coastal waters and its contribution to environmental improvements. Algal Res. 9, 236–244.

Yang, Y., Liu, Q., Chai, Z., Tang, Y., 2015b. Inhibition of marine coastal bloom-forming phytoplankton by commercially cultivated Gracilaria lemaneiformis (Rhodophyta). J. Appl. Phycol. 27 (6), 2341–2352.

Yarish, C., Penniman, C.A. (Eds.), 1990. Economically Important Marine Plants of the Atlantic: Their Biology and Cultivation. Connecticut Sea Grant College Program, Marine Sciences Institute, University of Connecticut at Avery Point.

Yarish, C., Kim, J.K., Lindell, S., Kits-Powell, H., 2017. Developing an environmentally and economically sustainable sugar kelp aquaculture industry in southern New England: from seed to market. EEB Articles 38 Available from URL: http://opencommons.uconn.edu/eeb_articles/38.

Zhang, J., Nagahama, T., Ohwaki, H., Ishibashi, Y., Fujita, Y., Yamazaki, S., 2004. Analytical approach to the discoloration of edible laver "Nori" in the Ariake Sea. Analytical sciences 20 (1), 37–43.