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Opportunities, challenges and future directions of open-water seaweed aquaculture in the United States

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ABSTRACT
Seaweed aquaculture is a relatively young industry in the United States compared to Asian countries. Early attempts at seaweed aquaculture in California, Washington State, New York and the Gulf of Maine in the 1980s and 1990s did not result in commercial production but provided important lessons. Since 2010, commercial cultivation of kelp (*Saccharina latissima, Laminaria digitata*, and *Alaria esculenta*) and other seaweeds (*Palmaria palmata* and *Porphyra umbilicalis*) began in the Gulf of Maine and Long Island Sound. Seaweed aquaculture is now a fast-growing maritime industry, especially in New England. If seaweed aquaculture is to maintain its momentum, it is important to (1) emphasise the environmental benefits; (2) domesticate a variety of local species; and (3) diversify seaweed products for food, animal feed, phycocolloids, cosmeceuticals, nutraceuticals, and ultimately biofuels if it becomes economically viable due to the cost of production. The exclusive economic zone (EEZ) of the United States offers opportunities for expansion of seaweed aquaculture in an area greater than the entire land mass of the United States and with limited user conflicts. This study reviews the past and current status of seaweed aquaculture in the United States and discusses potential opportunities and challenges of open-water seaweed aquaculture.

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INTRODUCTION

Seaweeds have been consumed by humans around the world for centuries, possibly millennia. A recent study suggested that consuming seaweeds might have been important for human brain growth of early *Homo* ancestors who lived along coasts (Cornish *et al.* 2017). Various seaweeds have also been an important part of Asian cuisine. However, in Western countries, direct consumption of seaweeds is restricted to a few scattered coastal areas (Hunter 1975; Mouritsen *et al.* 2013). In the United States, harvest and consumption of *Palmaria* (dulse) have a long tradition in the state of Maine, USA and in the Canadian Maritime Provinces, probably for more than a century (Mouritsen *et al.* 2013). Ancient Hawaiians also ate seaweeds (called *limu*) as a regular part of their daily diet. Reed (1907) reported that over 70 seaweed species were consumed by Hawaiians. Hawaiians 'cultivated' natural populations of seaweeds growing in their coastal ponds in order to increase their harvest and the quality of *limu* by weeding out undesirable seaweeds. Certain favourite *limu* varieties were transplanted from one island to another in Hawaii (Reed 1907). Hawaiians still consume *limu* (principally *Gracilaria* spp.), although most seaweeds are wild harvested. Beginning in the 1970s, overharvesting severely depleted natural stocks, resulting in a conservation law which limited the harvest of wild seaweeds in Hawaii (Glenn *et al.* 1998; Nagler *et al.* 2003). Alaskan natives also wild harvest and use selected seaweeds on a subsistence basis (Dombrowski 2007). For example, the subsistence harvest of 'black seaweed', a species of *Pyropia*, was estimated to be more than 150 metric tons (fresh weight, FW) in Sitka in 2013 (ADFG 2013). Other wild-harvested seaweeds in Alaska include the bull kelp (*Nereocystis*), giant kelp (*Macrocystis*), and red ribbon seaweed (*Palmaria*).

Global seaweed aquaculture production is over 30 million metric tons (FW) and, in 2016, had an annual value of $11.7 billion (Food and Agriculture Organization [FAO] 2018). Over 99% of the production (i.e. over 29.9 million metric tons) is grown by various methods in Asia. Typically, only five major countries (China, Indonesia, the Philippines, Korea and Japan) produce over 97% of seaweed globally (FAO 2018). Seaweed aquaculture is a relatively new industry in the United States, where commercial cultivation of the brown seaweed *Saccharina latissima* (Linnaeus) C.E.Lane, C.Mayes, Druehl & G.W.Saunders was initiated during the last decade (Flavin *et al.* 2013; Kim *et al.* 2015; Kraemer *et al.* 2014; Redmond *et al.* 2014a; Rose *et al.* 2015). Currently, seaweed aquaculture is one of the fastest growing maritime industries in the coastal waters of New England, USA. Demand by American markets is rapidly increasing due to (1) consumer desire for new protein sources and healthy food supplements; (2) the food industry's interest in sustainable textural additives including phycocolloids; and (3) the need for enhanced food security. Domestic production is well over 1000 metric tons (FW), but

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this is below the threshold to be included in FAO statistics (FAO 2016). US Department of Agriculture's National Agricultural Statistics Service does not include seaweed aquaculture production in its statistical data, although the wild harvest of seaweeds was recorded at about 6500 metric tons with a commercial value of more than US$1 million in 2015. At the same time, the import of seaweed raw materials was more than 10,000 metric tons (over US$73 million; National Marine Fisheries Service Office of Science and Technology 2016), which was used mostly for food and colloids. The present study reviews the past and current status of open-water seaweed aquaculture in the United States and discusses potential opportunities and challenges.

PAST: 1970s–1990s

Marine Biomass Program in California and New York

The US Marine Biomass Program was a research and development programme to develop integrated processes for producing and harvesting seaweeds of interest in the ocean and converting their biomass to methane. The programme began in the early 1970s in California (Flowers & Bird 1984; Neushul 1980, 1986; North *et al.* 1982; Tompkins 1982) as a reaction to the energy crisis caused by an oil embargo imposed by members of the Organization of Arab Petroleum Exporting Countries. The programme in California was initiated by H. Wilcox of the US Naval Undersea Warfare Center. It was supported by the US National Science Foundation and the US Navy from 1972 to 1973. Wilcox continued his work on the Marine Biomass Program with the support of the US Energy Research and Development Agency and American Gas Association from 1974 to 1975 (Neushul 1981, 1986). From 1976, General Electric led this programme with support from the American Gas Association and US Department of Energy's Solar Energy Research Institute. Support for the programme was then transferred to the Gas Research Institute (GRI; Chicago, Illinois USA). General Electric directed the programme until 1984. GRI discontinued the programme in December 1986 (Neushul 1986).

Wheeler J. North and Michael Neushul were involved in the GRI programme in California. North (California Institute of Technology) conducted the development of an offshore kelp farm, using *Macrocystis pyrifera* (Linnaeus) C.Agardh as the key crop, near San Clemente Island, California, in 1972 and 1973. *Macrocystis* was transplanted onto a 150 m × 180 m grid made of ropes, placed 20 m under the surface. However, this initial attempt at seaweed farming failed because the plants and the ropes became tangled, resulting in the complete loss of the kelp and farming structure. North made another attempt with some modifications of the grid using a nearshore site off Corona del Mar, California. Deep water was brought up to nourish the kelp, using airlift bubbling, and the *Macrocystis* grew well (North 1976, 1987; North *et al.* 1982; Wheeler *et al.* 1981). After these attempts, North conducted offshore cultivation of *Macrocystis* again with A. N. Tompkins (General Electric) 6 miles offshore from Laguna Beach. To counter nutrient depletion in this offshore environment, they also brought deep-sea water to the surface and hung a curtain around the farm to retain the nutrients long enough for uptake by the kelps. They transplanted 103 giant kelp plants on a modified module, but a storm event tore off the curtain and damaged the cultivation structure (North 1987; North *et al.* 1982). The final attempt by North, with support from General Electric, was in 1982 at Catalina Island, California. For this, General Electric constructed and installed a large ring structure, which looked like a floating doughnut, 15 m in diameter, supporting a plastic bag. This system was a half sphere in appearance, so it was called a hemi-dome. *Macrocystis* grew well in this system, showing potential for offshore kelp farming. However, in June 1982, the biggest El Niño of the century hit the area, dramatically reducing kelp growth (Neushul 1986; North 1994).

Neushul (University of California at Santa Barbara) also received programme support from 1980 to 1986. In 1981, Neushul cultivated *Macrocystis* near Goleta, California, and provided biomass yield information for *Macrocystis* (Neushul 1986; Neushul & Harger 1985) that North had failed to produce in his offshore work. Whereas North created a completely novel cultivation system, without much consideration of the natural habitats of the kelp, Neushul tried to model his farm system on a natural *Macrocystis* bed. Seven hundred twenty-two individuals were transplanted from nearby kelp beds using a gravel-filled bag planting method. He obtained an average annual highest growth rate of 7 g m^{-2} d^{-1} (Harger & Neushul 1983; Neushul & Harger 1985). The kelp was continuously cultured through the following year at the nearshore farm site, and 11 metric tons (FW) of standing crop was harvested in 12 months (Neushul 1986; Neushul & Harger 1985). A novel planting technology using fertiliser was applied to the nutrient-limited waters of Santa Barbara. Genetic studies of *Macrocystis* were conducted. Neushul developed about 800 strains of *M. pyrifera*. Clones were crossed and morphologically distinctive sporophytes were produced (Harger & Neushul 1983; Lewis *et al.* 1986; Neushul 1986).

The Marine Biomass Program in New York, USA, was initiated in 1980 with support from the GRI, New York State Energy Research and Development Authority, New York Gas Group and the New York Sea Grant Institute (Brinkhuis & Hanisak 1981; Brinkhuis *et al.* 1983, 1984a, 1984b, 1987; Squires & McKay 1983). After a thorough initial screening process to select seaweed species suitable for methane production, '*Laminaria saccharina*' [now *Saccharina latissima* (Linnaeus) C.E.Lane, C.Mayes, Druehl & G.W.Saunders] was selected as the prime candidate for the Marine Biomass Program in New York (Brinkhuis *et al.* 1987). After numerous laboratory and tank experiments were conducted to determine optimal growth conditions for this alga (Brinkhuis *et al.* 1984a), *S. latissima* seed-string was outplanted in an open-water farm using two different cultivation technologies: (1) the Chinese style of attaching individual plants by entwining stipes/holdfast with the line and (2) the Japanese method of inserting segments of seed-string into the culture rope. The kelps were cultivated at different depths at Crane Neck, Long Island, New York (Brinkhuis *et al.* 1983, 1984a, 1987). In 1983, Brinkhuis and associates also developed a new seaweed farm design, the Biological Engineering

Experimental Farm, and crossed gametophytes of *Saccharina* from different populations. Brinkhuis and associates outplanted these crosses at their open-water farm site (Brinkhuis *et al.* 1984b). In late 1980, additional inter- and intraspecific crosses of North Atlantic kelp species were made by another research group led by Yarish and colleagues, with support from the Connecticut Sea Grant College Program to develop suitable strains for kelp aquaculture in Long Island Sound (Egan *et al.* 1989, 1990; Egan & Yarish 1990; Yarish & Egan 1987, 1989; Yarish *et al.* 1990a, 1990b).

Although these early attempts at kelp aquaculture in California, Connecticut and New York showed that nearshore farming of *Macrocystis* and *Saccharina* was viable, the Marine Biomass Program was discontinued in 1986. However, the Connecticut Sea Grant Program continued to support kelp research until 1991 (Egan *et al.* 1990). One of the main reasons for ending the New York research programme was that geologists and oil and gas specialists estimated that there would be no shortage of oil and natural gas for decades to come. In addition, in 1986, the US Department of Energy switched their research focus to microalgal energy production (Neushul 1986).

There were important findings from these earlier studies which were pertinent for subsequent kelp aquaculture attempts in the 2010s (see below). The reproductive peaks of *Saccharina* in Long Island Sound (i.e. late spring and fall/early winter) and the optimal conditions for gametophyte culture for maturation and reproduction were determined through these studies (Brinkhuis *et al.* 1987; Egan *et al.* 1989; Yarish *et al.* 1990a). This information was critical for nursery cultivation technology which was developed later in the 2010s by the Yarish–UConn Labs (Kim *et al.* 2015; Redmond *et al.* 2014a). Understanding the seasonal variation of kelp sporophytes in Long Island Sound (Egan *et al.* 1989; Egan & Yarish 1990; Yarish *et al.* 1990b) would become important information for the advance of open-water cultivation technologies not only in Long Island Sound but throughout New England, Alaska, Washington, and California.

CHALLENGES AND LESSONS LEARNED: The Marine Biomass Program provided some US$20 million over a 12-year period (Neushul 1986) before the programme was discontinued. The biggest drawback of the programme was that kelp farming could not compete on an economic basis with fossil fuel production. In addition to the lack of economic viability, there was criticism from the public and the media. Communications with, and support from, the public are key to receiving a social licence for the success of seaweed aquaculture in the United States. The results of these earlier attempts also underlined the importance of cultivation technologies for both nearshore and offshore waters (e.g. development of new cultivars, improvement of nursery and seeding technology, development of farm gear for offshore environments). Finally, diversification of commercial products derived from cultivated biomass of various seaweeds is critical because the price for one product (e.g. bioenergy) must be low enough to compete with fossil fuel production. The work of North, Neushul, Brinkhuis and others was foundational because they documented their attempts at seaweed aquaculture for the future success of applied seaweed aquaculture research (Brinkhuis *et al.* 1987).

Pyropia (*Porphyra*) farming in Washington state

Another attempt at open-water seaweed aquaculture in the United States occurred in Puget Sound, Washington state in the 1980s. The initiation of cultivating *Pyropia yezoensis* (Ueda) M.S. Hwang & H.G. Choi (formerly '*Porphyra yezoensis*') was led by the Washington State Department of Natural Resources (T.F. Mumford) and the University of Washington (R. Waaland and J.E. Merrill). These scientists worked with Japanese experts (A. Miura and the Zen-nori Cooperative) to obtain technologies from Japan, who provided seed nets of *Pyropia* to growers in Puget Sound. Two reasons were identified for the selection of *Pyropia* for aquaculture (Mumford 1990). First, surface seawater temperature along Washington coasts was found to be ideal for year-round cultivation of *Pyropia*; whereas, the major Asian countries for *Pyropia* production (e.g. China, Korea and Japan) could cultivate only during winter. In addition, in the United States in the 1980s there was a boom of sushi restaurants and a high demand for nori sheets which are manufactured from *Pyropia*. The strains of *Pyropia* used were imported from Japan [six strains of *Pyropia yezoensis* and one strain of *Py. tenera* (Kjellman) N.Kikuchi, M.Miyata, M.S.Hwang & H.G.Choi]. Additionally, local strains of *Pyropia* were developed and cultivated [*Pyropia abbottiae* (V.Krishnamurthy) S.C. Lindstrom, *Py. torta* (V.Krishnamurthy) S.C.Lindstrom, *Py. nereocystis* (C.L.Anderson) S.C.Lindstrom and *Py. pseudolanceolata* (V.Krishnamurthy) S.C.Lindstrom]. The decision to import Japanese strains of *Pyropia* was based upon literature which indicated that the conchocelis of Japanese strains would not reproduce in the cold water and short daylengths prevalent in Washington state (Mumford & Hansen 1987). In addition, the aquaculture trade of spat-bearing shells from Japan to the United States for oyster farms might have already relocated the Japanese conchocelis to Washington state. However, no Japanese *Pyropia* species used in aquaculture have been recorded in either Washington or any neighbouring US states or Canada (Guiry & Guiry 2012). However, they have appeared on the east coast of the United States (Neefus *et al.* 2008; details below).

Pyropia was cultivated in pilot-scale seaweed farms during the 1982 to 1983 winter growing season using modifications of Japanese technologies for nursery and open-water farming – that is, raft-oriented style – utilising floating seeding rafts, nursery sets and production frames (Merrill 1981; Mumford 1987). Only three of seven Japanese strains grew successfully; whereas, all four Washington strains were successful (Mumford 1990). Subsequently, a number of private-sector companies obtained permits for seaweed farming and collaborated in *Pyropia* aquaculture. Based on trials at locations in Washington state, the San Juan Islands appeared to be best suited for *Pyropia* farming due to a favourable mixture of oceanic waters and freshwater run-off, as well as high ambient nutrient levels. However, *Pyropia* did not grow well in lower or central Puget Sound (Mumford 1990). During this period, an organisation for *Pyropia* farming, the Pacific Northwest Nori Growers Association, was formed. Other new businesses such as American Sea Vegetable, New Channel

Nori and Pacific Link were founded in the state (Mumford 1990). However, *Pyropia* farming in Washington was discontinued due to the issues listed below, and none of those businesses associated with *Pyropia* currently exist.

CHALLENGES AND LESSONS LEARNED: Although aquaculture of *Pyropia* in Washington state had many advantages, including technological support from a Washington state agency and the University of Washington (a public university) and demand for production and interest by the industry, prevailing political and social resistance resulted in a negative outcome. In Washington state, at least three permits were needed for seaweed aquaculture, requiring time, money and effort from growers (Mumford 1987). Washington was not the only state with this permitting issue. The legal regime governing coastal waters in the United States gives jurisdiction to individual states. Aquaculture regulations vary from state to state and sometimes even from coastal town to town within a single state, which can complicate the application process (Duff *et al.* 2003; Getchis & Rose 2011; National Research Council 2010). At least 120 federal laws were identified which affected aquaculture, either directly (50 laws) or indirectly (70 laws), and more than 1200 state statutes regulated aquaculture in 32 states (Aspen Research and Information Center 1981). Regulatory complexity was further increased when towns or counties had jurisdiction over local waters. To site and operate, aquaculture enterprises might require more than 30 permits under the purview of local, state and federal agencies, and, permitting could take years to process (Duff *et al.* 2003; Getchis & Rose 2011; Langan *et al.* 2006). In addition, open-water aquaculture activities elicited considerable opposition from shoreline property owners due to the phenomenon known as NIMBY (Not In My Back Yard). NIMBY increases the complexity of permitting processes even more by introducing politics into the process (Hansen 1989). Opposition by stakeholder groups eventually terminated *Pyropia* aquaculture in coastal waters of Washington state (Hansen 1989). In the1980s, the US economy was booming and per capita gross domestic product increased by nearly 23% (Schaller 1992). During this economic boom, there was little urgency to develop coastal environments for seaweed aquaculture.

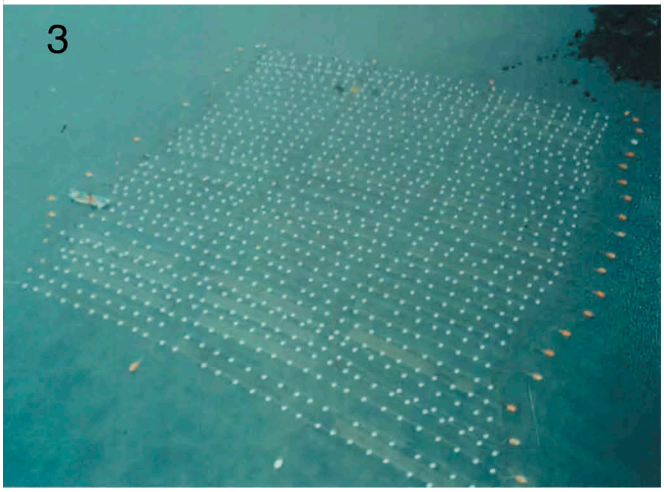
In 1994, Washington state announced a moratorium on all commercial seaweed harvesting from natural populations (Waaland 2004). Seaweed aquaculture was considered to be a viable strategy to support the industry but had been limited to land-based systems (Hall 2011; Waaland 2004). Open-water seaweed aquaculture using *Saccharina latissima* has recently resumed in Puget Sound. However, the main purpose of this project has been to use the nutrient extractive properties of kelp cultivation to mitigate environmental issues of eutrophication and ocean acidification (Puget Sound Restoration Fund 2019).

Pyropia farming in Maine

When attempts to farm *Pyropia* failed in Washington state, the cultivars (i.e. two Japanese strains of *Py. yezoensis*, U51 and H25) and locally developed cultivation technologies were transferred to Coastal Plantations International of Maine (later incorporated into PhycoGen, Inc., Portland, Maine, USA). Unlike Washington state, seaweed farming in Maine was welcomed by both regulators and the public. There was an expectation that seaweed aquaculture could be an additional source of income for impoverished coastal communities in Maine. Additionally, Mainers had eaten seaweeds for more than a century. Harvest of wild seaweed there was already an important industry (Chopin *et al.* 1998; Levine 1997; Levin & Cheney 1998; Yarish *et al.* 1998).

During the 1994–1995 growing season, Coastal Plantations International farmed *Pyropia yezoensis* in Cobscook Bay, Eastport, Maine, using Japanese cultivation technologies. They used both pole and floating culture systems in order to determine the most appropriate farming technique for the Gulf of Maine region (Figs 1–3). The first attempt was unsuccessful because Cobscook Bay was oligotrophic, and insufficient nutrients were available for growth of *Pyropia*. In 1996, this company, in collaboration with the University of Connecticut (C. Yarish) and University of New Brunswick (T. Chopin), moved their 'seeded' nori nets to an area adjacent to an Atlantic salmon (*Salmo salar* Linnaeus) farm at Deep Cove, Eastport, Maine (Connors Aquaculture Inc.; McVey *et al.* 2002; Yarish *et al.* 1997, 1998). This was the first open-water, integrated multitrophic aquaculture practise in the United States. *Pyropia* received a high concentration of nutrients from the farmed fish effluents and grew better than clonal strains of *Pyropia* at the oligotrophic site in Cobscook Bay (Chopin & Yarish 1998; Chopin *et al.* 1998, 1999). However, PhycoGen went bankrupt due to a downturn in the investment environment. No further integrated seaweed aquaculture was attempted until recently in Maine (Levine 2006).

Following this attempt in Maine, cultivar development and strain selection were conducted using native *Pyropia linearis* (Ueda) N.Kikuchi, M.Miyata, M.S.Hwang & H.G.Choi, *Py. yezoensis*, *Py. leucosticta* (Thuret) Neefus & J.Brodie, *Porphyra purpurea* (Roth) C.Agardh, and *Wildemania amplissima* (Kjellman) Foslie. Optimal environmental conditions for ecophysiological activities, including growth, nutrient uptake, pigment content, and photosynthesis, were determined for these target species (Carmona *et al.* 2006; Day 2003; Kim *et al.* 2007, 2008; Kraemer & Yarish 1999; Kraemer *et al.* 2004; Yarish *et al.* 1998, 1999). Critical controlling factors for the life cycles of the putative crop species were studied. For example, He & Yarish (2006) cultured the conchocelis of *Py. yezoensis* (misidentified as *Py. leucosticta* in their paper at the time) not only by using shells (as per the traditional cultivation technology in Asia) but also in a novel, 'free-living' suspension in 13-litre Pyrex jar culture vessels. They determined the conditions for vegetative propagation of 'free-living' conchocelis filaments, which led to the continuous maintenance of stock cultures (i.e. conditions of 15 °C, 40 μmol m^{-2} s^{-1} and 16:8 light:dark). To induce conchosporangia, temperature was increased to 20 °C, photoperiod decreased to 8:16 light:dark, and photon fluence rate was maintained as low as 40 μmol m^{-2} s^{-1}. Conchosporangial filaments were vegetatively propagated and maintained under these conditions for up to 24 weeks. Conchospores were released after 10 days by decreasing the temperature to 15 °C, increasing the photon fluence rate to 60–100 μmol m^{-2} s^{-1}, and increasing the photoperiod to 12:12 light:dark. He & Yarish (2006) estimated that, at their peak release, 1 g (DW) of free conchosporangia could release about 20 million conchospores. These



Figs 1–3. *Pyropia yezoensis* farm at Eastport, Maine. Photos by I. Levine.
Fig. 1. Ikada nursery system.
Fig. 2. Production farm.
Fig. 3. Aerial view of the *Pyropia* farm.

conchospores were seeded onto 16 standard *Pyropia* nets (1.5 × 18 m) and eight small nets (2.0 × 2.5 m). Four seeded standard *Pyropia* nets were then transferred to a site in western Long Island Sound (Bridgeport, Connecticut) for nursery culture. After 43 days, blades grew up to 1.5 cm in length, thereby establishing the effectiveness of 'free-living' conchocelis suspension cultures as an alternative technology for *Pyropia* aquaculture. However, for reasons unknown, the *Pyropia* did not grow after the nets were moved to a nearshore seaweed farm, which was also in close proximity to a wastewater treatment plant outfall in western Long Island Sound (Fairfield, Connecticut; He & Yarish 2006).

CHALLENGES AND LESSONS LEARNED: Obtaining permits for seaweed aquaculture in Maine was, and continues to be, not as difficult as in other states. Maine had a programme that granted limited production aquaculture licence permits to enable prospective aquaculturists to develop their skill set for aquaculture of a particular species (see Maine Department of Marine Resources 2019). Therefore, permits might not be the biggest hurdle for the development of seaweed aquaculture in Maine. A major problem with farming *Pyropia* in Maine was the lack of knowledge related to the ecophysiology of the nonnative Japanese strain and lack of understanding of the oceanography of the Gulf of Maine itself. The Japanese strain of *Py. yezoensis* is a warm–temperate species. This strain had difficulty adapting to prevailing low temperatures, the relatively short growing season and the nutrient-replete waters of the Gulf of Maine (Cheney *et al.* 1998; Levine 1998, 2006; Watson *et al.* 1999).

One must use extra caution before a nonindigenous species is imported for aquaculture (Minchin 2007). Aquaculture permits for cultivating Japanese strains of nori were issued based on evidence that endemic environmental conditions (i.e. sea surface temperature and photoperiod) in the Gulf of Maine were not favourable for the sexual reproduction of these strains (Levine *et al.* 2001; Neefus *et al.* 2008; Watson *et al.* 1999; West *et al.* 2005). In fact, the Japanese commercial cultivar of *Py. yezoensis* was not found in the Gulf of Maine. However, interestingly, this strain was found in Long Island Sound, over 400 km south of the Gulf of Maine, where, as far as can be determined, Japanese cultivars had never been cultivated (Neefus *et al.* 2008; Niwa *et al.* 2005; West *et al.* 2005). Neefus *et al.* (2008) suggested that there had been a single introduction of this strain of *Pyropia* to Long Island Sound, but the vector for this introduction remains unknown. These results suggested that investment in cultivar development is critical for local, native *Pyropia, Porphyra* and *Wildemania* species, which are better adapted to the prevailing conditions of the Gulf of Maine (Blouin *et al.* 2007, 2011).

Pyropia farming in Alaska

The University of Alaska engaged in a 3-year programme funded by the Saltonstall-Kennedy Grant Program in the late 1990s. Research focussed on controlling the life cycles of several different species of *Pyropia*, including *Py. abbottiae, Py. torta, Py. pseudolinearis* (Ueda) N.Kikuchi, M.Miyata, M.S.Hwang & H. G.Choi, *Py. fallax* (S.C.Lindstrom & K.M.Cole) S.C.Lindstrom, *Py. cuneiformis* (= *Wildemania amplissima*), and *Py. pseudolanceolata* Ueda complex (Stekoll *et al.* 1999). Results of studies that were conducted on the response of conchocelis cultures to applied phytohormones found that higher concentrations of plant hormones increased the growth of *Pyropia* conchocelis but did not directly induce conchosporangial formation (Lin &

Stekoll 2007). Juvenile blades of *Py. torta* showed differential growth depending on seeding density and substratum composition (Conitz *et al.* 2013). Photosynthesis of the small blades of *Py. torta* was maximal at 30 psu salinity, 12 °C and over 160 µmol m^{-2} s^{-1} photon fluence rate (Conitz *et al.* 2001). Photosynthesis and respiration rates were investigated for free-living conchocelis cultures (Lin *et al.* 2008). A multifactored experiment showed the importance of nitrogen in the growth of juvenile blades (Conitz *et al.* 2001). Several *Pyropia* species were exposed to various combinations of irradiance, photoperiod and temperature in an effort to define conditions that would reliably induce conchospore maturation and release (Lindstrom *et al.* 2008). Although some success was achieved, only *Py. torta* could be consistently induced to release spores. Preliminary experiments with shell cultures of the conchocelis phase led to the development of techniques for maintaining seeded shells over extended periods. Nets seeded with *Py. torta* from free-living conchocelis were placed in both the greenhouse and in the field for grow-out. Success in outplanting depended on the time of year, method of outplanting and genetic isolate (Stekoll *et al.* 1999). Seawater quality was monitored periodically to correlate with outplantings. Surface water temperatures were low, and salinity and nutrients were high in winter. In late summer, water temperatures were high and nutrients and salinity were very low. Currently, no species of *Pyropia* has been developed to the point where commercial production is feasible in Alaska.

CHALLENGES AND LESSONS LEARNED: Alaska has set up a process for the permitting of aquatic farms jointly administrated by the Alaska Department of Fish and Game (ADFG) and the Alaska Department of Natural Resources (ADFG 2019). In 2015, there were 54 permitted aquatic farms, only a few of which were permitted for seaweed (Pring-Ham & Politano 2016).

The state of Alaska bans the import of nonindigenous species. Therefore, for now, only two species of *Pyropia* would appear to be candidates for further development. These are *Py. abbottiae* and *Py. torta*, or the 'black seaweeds'. The conditions required for *Py. abbottiae* to reliably produce conchospores are still unknown in Alaska. Initial work indicated that conditions are not the same as those found for this species in Washington state (Lindstrom *et al.* 2008). The main obstacle with *Py. torta* is finding environmental conditions and/or a strain that will produce conchospores en masse in order to seed the cultivation nets. To date, release of conchospores takes too long, several days, to seed a net. Other obstacles are the timing and location of outplanting. Late fall may be the optimal time for outplanting because this may minimise fouling of the nets by drifting filamentous algae. Similarly, ideal locations have not been determined. It also needs to be determined whether commercial production would work better using free-living conchocelis cultures or using shell cultures (He & Yarish 2006; Pereira & Yarish 2008). Permitting is not a great hurdle because the ADFG and Alaska Department of Natural Resources have recently been processing several aquatic farm permits for kelp, and presently the NIMBY response is relatively rare. Finally, not enough is known about the population genetics of these nori species for the ADFG to create workable regulations which would govern the collection of parent plants (seed stock) and locations for seaweed farms.

Kelp farming in Alaska

Alaska has a viable fishery of herring spawn on kelp (SOK), also called 'roe on kelp' (Stekoll 2006). Each spring and into early summer, schools of herring spawn on nearshore vegetation such as eelgrass (*Zostera*), *Fucus, Saccharina, Alaria* and *Macrocystis*. An impoundment fishery using *Macrocystis* as the vegetative substratum has proved to be the most valuable. One issue for the SOK fishery is close proximity of *Macrocystis* beds to spawning herring. This has not been the case, and in the 1980s seaweed had to be transported nearly 1000 km from southeast Alaska to spawning grounds in Prince William Sound. A study funded by the Japan Overseas Fishery Cooperation Foundation and the National Coastal Resources Research and Development Institute was initiated in 1988 in Sitka to develop the mariculture of *Macrocystis* for use in the SOK fishery. The study followed the Japanese model for 'kombu' production (Stekoll & Else 1992). It was found that the plants would have to be in culture for at least 2 years because they were not sufficiently large after only a few months of growth. In addition, seeded lines put out later than January showed declining growth in summer (Stekoll 1989; Stekoll & Else 1990). High water temperatures and salinities and low nutrients in August and September weakened the plants to the extent that they were unable to survive winter. However, adding fertiliser to the outplanted lines in August enabled survival and growth throughout the winter and into spring (Stekoll 1999). For this trial, a slow-release solid fertiliser (Osmocote®; The Scott's Company 2019) was placed in nylon sacks tied to the longline and placed between plant sections.

CHALLENGES AND LESSONS LEARNED: It was found that starting outplanting in late fall enabled fronds to reach a size and vitality that enabled them to survive the following fall/winter, without the necessity of adding fertiliser in late summer. Outplanting sites should be located in areas of moderate swell. Grazing by sea urchins was not an issue for outplants on longlines situated above the bottom. However, there was no further need to refine the mariculture of *Macrocystis* after the main SOK fisheries relocated to southeast Alaska at sites much closer to natural beds.

CURRENT: SEAWEED FARMING BOOM IN THE 2010s

Seaweed farming in the Northeast

A dramatic advance in seaweed aquaculture occurred in the United States in 2010. The first commercial kelp farmer in the United States, Ocean Approved, cultivated the native kelp species *Saccharina latissima, Laminaria digitata* (Hudson) J. V.Lamouroux and *Alaria esculenta* (Linnaeus) Greville in the Gulf of Maine. This was enabled by technology transfer from the University of Connecticut, through grants from the National Oceanic and Atmospheric (NOAA) Small Business Innovation Research Program (ADFG 2019; SBIR 2010). Ocean Approved has successfully marketed its products since 2010. Before farming kelps, Ocean Approved wild harvested their kelp but could not meet the demand for volume of their customers. Ocean Approved was concerned with long-term dependence on wild-harvested kelp and related environmental impacts. The company has since developed novel kelp products; for example, freshly frozen kelp noodles, salads, slaws (Atlantic Sea Farms 2019). Ocean Approved has created a strong domestic kelp market because consumers appreciate fresh and fresh-frozen, locally grown kelp products.

Concurrently, seaweed farming was also being developed in southern New England for the purposes of environmental improvement, science education and the culinary market. This work was initiated by the University of Connecticut with the support of the Connecticut Sea Grant Program, the US Environmental Protection Agency's (EPA) Long Island Sound Study and the National Fish and Wildlife Foundation. With nursery technology developed at the University of Connecticut, the cold-water brown seaweed *S. latissima* and the warm-temperate red seaweed *Gracilaria tikvahiae* McLachlan were successfully cultivated in open-water farms in Long Island Sound and New York coastal waters. After the outplanting of juveniles (under 1 mm), the kelp grew as much as 7.0 m in length and had yields of up to 24 kg FW m^{-1} after 6 months (from December to May) in Long Island Sound and New York estuaries (Figs 4, 5; Kim *et al.* 2015; Kraemer *et al.* 2014). *Gracilaria* also grew rapidly with growth rates of up to 16.5% d^{-1} in the New York estuary even during summer (Kim *et al.* 2014). Seaweed aquaculture provided ecosystem services by removing excess nutrients (carbon and nitrogen) from their varied habitats, potentially reducing ocean acidification (US EPA 2013).

In 2011, the first commercial seaweed farm in southern New England, Thimble Island Oyster Co., started cultivation of *S. latissima* with the assistance of the University of Connecticut (Yarish *et al.* 2014, 2015). Bren Smith (owner of Thimble Island Oyster Co., New Haven, Connecticut, USA) co-founded a not-for-profit organisation called GreenWave (www.GreenWave.org) which was dedicated to outreach and extension in order to expand kelp farms regionally and nationally in the United States. Eventually, GreenWave developed a for-profit company, Sea Green Farms, LLC, which provided produce to specialty food markets and restaurants throughout the United States, with offerings of fresh and freshly frozen seaweed products. There are now more than 27 commercially operated open-water seaweed farms throughout the New England states and New York (Peconic Bays, New York), all cultivating *S. latissima*. Open-water *Gracilaria* still faces several regulatory and food safety issues. *Gracilaria* grows during summer when farmers are occupied with their principal business; that is, shellfish culture. Hence, farmers have limited time to devote to the cultivation of *Gracilaria* and its husbandry. Summer cultivation also conflicts with recreational boating and fishing. Finally, heavy fouling by other seaweeds and associated fauna on *Gracilaria* makes it a less desirable product for market (Concepcion *et al.* 2018; Lindell *et al.* 2015).

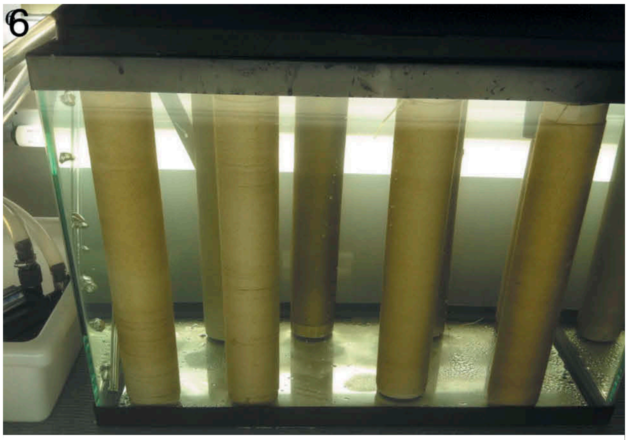
Kelp aquaculture is one of the fastest growing industries in the northeastern United States. Success of the industry in the Northeast is attributed to (1) the development of suitable aquaculture technologies specifically for operating in US waters, (2) strong domestic markets, and (3) strong support from coastal managers, stakeholders and the public due to the demonstrable environmental benefits provided by seaweed aquaculture. A critical approach to seaweed aquaculture in the Northeast, especially in southern New England and the New York estuary, was the overt emphasis placed on environmental benefits (ecosystem services). Long Island Sound and New York coastal waters suffer from high levels of anthropogenic eutrophication,

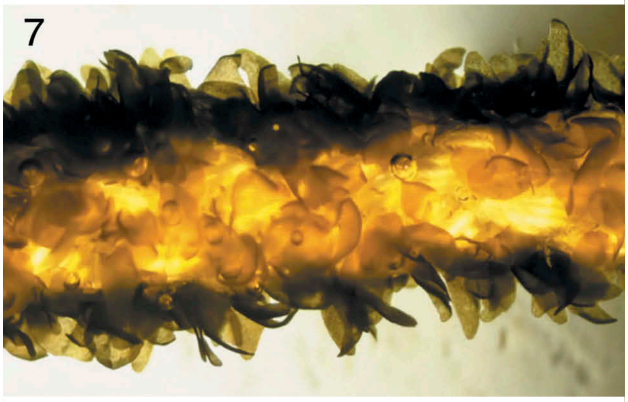
Figs 4, 5 *Saccharina latissima* farms in Long Island Sound.
Fig. 4. Kelp outplanting using seed spool on longlines.
Fig. 5. *Saccharina latissima* grown at Long Island Sound, Connecticut.

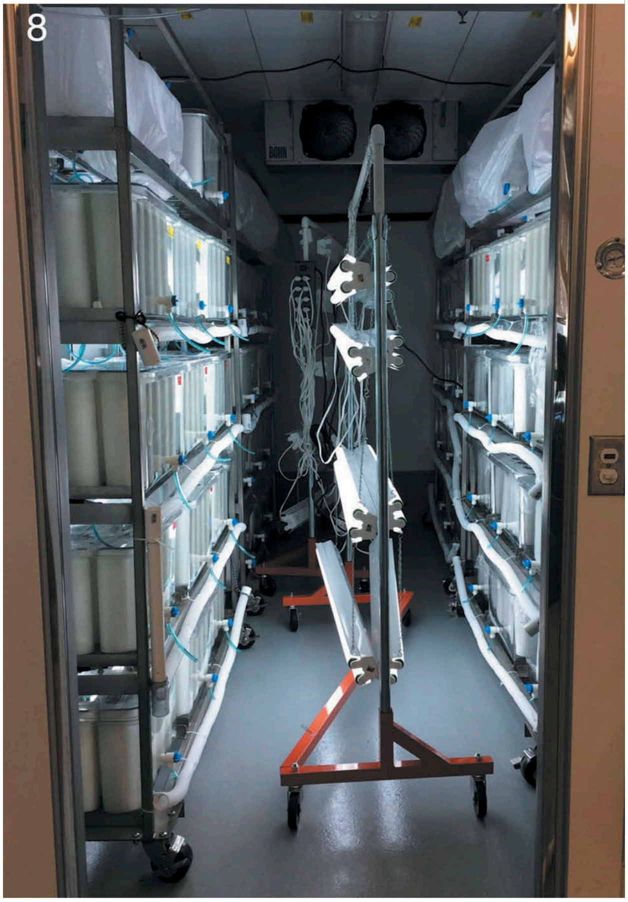
resulting in harmful algal blooms and even hypoxia (Capriulo *et al.* 2002; Kim *et al.* 2015; Lopez *et al.* 2014; Varekamp *et al.* 2014). Seaweed aquaculture was developed in these areas to determine whether year-round seaweed aquaculture could improve water quality by removing excess nutrients. Recent studies showed that seaweed aquaculture can be an efficient way to manage nutrient issues in urbanised estuaries (Kim *et al.* 2014, 2015; Kraemer *et al.* 2014; Rose *et al.* 2015; Tedesco *et al.* 2014). This technology is referred to as 'nutrient bio-extraction' (Kim *et al.* 2017; Rose *et al.* 2015). The US EPA has acknowledged that nutrient bio-extraction is a best management practise (US EPA 2013). With this environmental benefit, along with the economic benefits in the Northeast, seaweed aquaculture received a lot of attention and a strong level of support from coastal managers, stakeholders and the public alike. Efforts to streamline and simplify the permitting process in Connecticut coastal waters are an ongoing process being led by the Connecticut Sea Grant, the Bureau of Aquaculture (Connecticut Department of Agriculture) and the Milford Laboratory, US National Marine Fisheries Service (DeRosia-Banick *et al.* 2015; Getchis & Rose 2011; Getchis *et al.* 2012; Getchis *et al.* 2017; Atlantic Sea Farms 2019). In addition, seaweed aquaculture was recently added to the Noninsured Crop Disaster Assistance Program in the United States, thereby enabling seaweed aquaculturists to apply for federal crop insurance (Department of Agriculture, Farm Service Agency 7 CFR Part 718, Commodity Credit Corporation 7 CFR Parts 1412, 1416, and 1437, Noninsured Crop Disaster Assistance Program; USDA 2014; Hurlburt 2016). Positive support via print, online media and social media has also enhanced the public's perception of seaweed aquaculture in coastal waters of the United States (Aljazeera 2018; Mustain 2014; Goodyear 2015; Smith &; Romanoff 2012; Stahl 2018).

Nursery cultivation technologies developed for seaweeds of commercial interest at the University of Connecticut were transferred to private and public sectors throughout New England, New York and, more recently, Alaska (Figs 6–8; Walker 2018). For example, currently, several commercial-scale kelp nurseries are in operation which provide sufficient kelp seed-string for growers in the Northeast and Northwest regions of the United States (GreenWave for southern New England and New York; Maine Fresh Sea Farms, Bristol, Maine; University of New England, Biddeford, Maine; Springtide Seaweed and Ocean Approved for Gulf of Maine; and Blue Evolution, Kodiak, Alaska). The University of Connecticut and University of Alaska Southeast maintain kelp research hatcheries. Other public institutions, such as the Milford Laboratory, National Marine Fisheries Service, NOAA and Bridgeport Regional Aquaculture Science and Technology Education Center, also maintain kelp nursery systems for production, research and educational purposes.

Processing technologies have been developed in Northeastern United States for the domestic market. Ocean Approved has its own kelp processing facility in Portland, Maine, but their processing technology is proprietary. The University of Connecticut also independently developed a mobile processing facility producing fresh frozen products and transferred this novel technology to the private sector, including Maine Fresh Sea Farms and Sea Green Farms (Yarish *et al.* 2017). With these processing







Figs 6–8. Kelp nursery systems in the United States.
Fig. 6. Standard unit of kelp nursery system using seed spools developed at the University of Connecticut.
Fig. 7. Juvenile sporophytes growing on seed-string.
Fig. 8. Commercial kelp nursery at Kodiak, Alaska.

technologies, kelp shelf life increased significantly, from days to months or even years. Kelp products are provided sustainably to consumers year-round, helping to expand seaweed markets; however, much work remains to advance drying technology for kelp faming in the United States.

Seaweed farming in Alaska

Although for several years there has been interest in seaweed farming, as indicated by aquatic farm applications to ADFG (Pring-Ham & Politano 2016), commercial-scale farming of seaweeds has occurred only relatively recently. In 2015, applied research on seaweed mariculture by the University of Alaska (M. Stekoll) was funded by the private company Premium Oceanic (Blue Evolution of San Francisco, California, USA). Their initial emphasis was on the aquaculture of several seaweed species, including *Saccharina latissima, S. groenlandica, Nereocystis luetkeana* (K.Mertens) Postels & Ruprecht, *Alaria marginata* Postels & Ruprecht, *Ulva* sp. and *Palmaria mollis* (Setchell & N.L. Gardner) van der Meer & C.J.Bird. Subsequently, focus was on kelp species, using seeded strings for outplanting on longlines. Most success was achieved with *S. latissima* and *Alaria*. Follow-up funding from Sea Grant refined the methods for kelp mariculture in Alaska. Generally, the Japanese and University of Connecticut models have been followed. In brief, parent plants are collected in late summer and spore release induced onto seed-string-wrapped PVC pipes. These are incubated under specific conditions of temperature, photoperiod, light and nutrients until sporophyte blades are ready for outplanting. Optimal time for outplanting was determined to be late fall, after upwelling, which increases ambient seawater nutrient concentration. Outplants on longlines were found to grow best at 2–3 m below the surface, reaching a maximum size and quality in April–May. Quality criteria included healthy fronds without fouling. Blue Evolution, in collaboration with the University of Alaska, obtained a commercial 'hatchery' permit for producing seed-string of *S. latissima, Alaria* and other kelp species for sale to farmers. In 2016, three seaweed farms were permitted by the state: two in Kodiak and one in Ketchikan. Outplants of both *Saccharina* and *Alaria* were successful, with over 5000 kg wet weight harvested and sold to Blue Evolution (Fig. 9). There are now three permitted seaweed hatcheries in the state. However, only the Blue Evolution hatchery in Kodiak produced commercial seeded string in the fall of 2017 (Fig. 8).

Applications for aquatic farm permits in Alaska are submitted only during the first quarter of each year. In 2017, there was a large increase in aquatic farm applications for seaweeds (C. Pring-Ham, personal communication). The state was unprepared for so many applications, and with budget cuts, only a few permits were processed in time for outplanting in the fall of 2017. Nevertheless, about 20 km of seeded strings of *Saccharina, Alaria, Nereocystis* and *Eualaria fistulosa* (Postels & Ruprecht) M.J.Wynne were produced in Blue Evolution's Kodiak hatchery and shipped to four commercial kelp farms. Blue Evolution processed about 18,000 kg (FW) of seaweed in 2018 (Blue Evolution, personal communication).

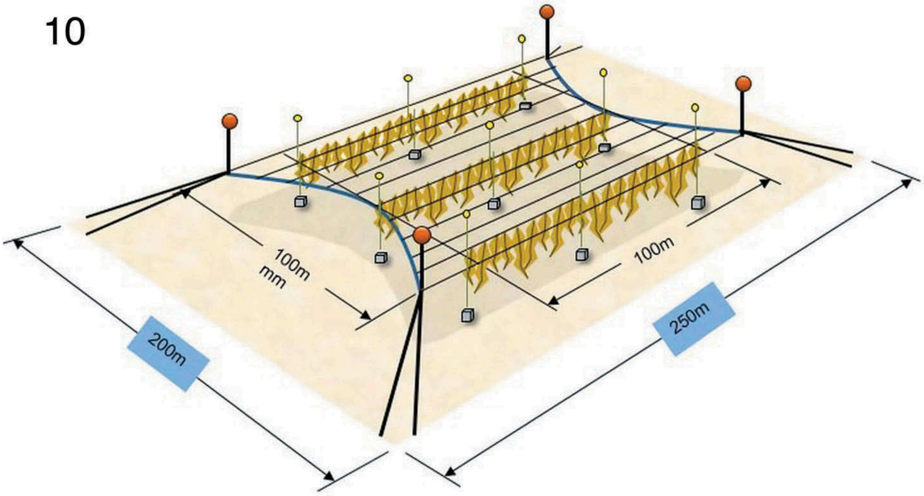
Blue Evolution has been the main driver for seaweed aquaculture in Alaska. Its activities, along with the increasing popularity of seaweeds in the United States, created a great deal of interest in seaweed aquaculture in the state. However, there are still challenges. ADFG is concerned about the effect of farms on natural seaweed populations. The State of Alaska constitution mandates that all natural resources be managed on a sustained yield principle. ADFG has interpreted this to mean that the natural populations must be protected as much as possible. Consequently, ADFG is conservative about the effects of aquatic farms on local population genetics of natural seaweed systems. This led to regulations for seaweed farming that have been difficult to adhere to. For example, for each separate farm, 50 'unrelated' fertile parent plants must be collected from different sites within 50 km of the outplanting site, and all plants need to be harvested from longlines before they become fertile. In addition, it is illegal to select for specific traits. The logic to this regulation is that genetic diversity on the longlines would be essentially clones, and if they were released into the environment, they could upset the natural genetic diversity of these seaweeds. Other issues to be addressed are (1) the delays inherent in the current permitting process, (2) cost of labour in the state, (3) costs of transportation of raw materials and products to markets, (4) the large capital expense required to start an aquatic farm (e.g. multiple permit fees, leases, insurance, equipment, uplands support for hatchery and processing), and (5) the need to develop profitable products.

In 2016, the governor of Alaska, in order to help aquatic farming become a success, created a Mariculture Task Force (ADFG, 2018) to make recommendations for aquaculture support in the state. This task force addressed a number of issues seen as bottlenecks for Alaskan mariculture development, and their final report (ADFG 2018) was officially approved by the governor in the spring of 2018.

Seaweed farming in other states

In 2015, seaweed farming in Washington state resumed in Puget Sound. The Puget Sound Restoration Fund, in collaboration with the University of Washington, Washington Sea Grant, and NOAA Pacific Marine Environmental Laboratory, received a $1.5 million grant from the Paul G. Allen Family Foundation to grow sugar and bull kelp in Puget Sound (Paul G. Allen Family Foundation 2015; Stahl 2018). The purpose of this project was to develop a local strategy to ameliorate the effects of ocean acidification. A pilot-scale co-cultivation of *Gracilaria* and oysters was also conducted in the Chesapeake Bay to evaluate the combined ecosystem service (i.e. nutrient bio-extraction potential) role of seaweed aquaculture, with additional support from the Maryland Sea Grant. However, these practices are still in an early stage of development or too small-scale to evaluate at this time (Li *et al.* 2012).

CHALLENGES AND LESSONS LEARNED FROM CURRENT PRACTICES: Although seaweed aquaculture has been a considerable success economically and ecologically, especially in the Northeast during the past 8 years, challenges still exist. The permit process continues to be a major hurdle for prospective growers. Many variables must be considered in the nearshore environment when growers apply for a seaweed aquaculture permit, including



Figs 9-10. *Saccharina latissima* harvest at Kodiak, Alaska. Photo by Tamsen Peeples, Blue Evolution, LLC.
Fig.10. Kelp farm design for the New England waters designed by C. Goudey (Goudey and Associates; Yarish *et al.* 2014).

recreational boat and fishing activities, marine mammal populations, and water quality (Buck 2007; Duff *et al.* 2003; Hopkins *et al.* 1997; Würsig & Gailey 2002), resulting in limited areas available for seaweed farming in nearshore environments. Offshore waters do not have as many user conflicts. Therefore, offshore areas should be considered for sustainable seaweed farming (Buck *et al.* 2004; Cicin-Sain *et al.* 2001; Tiller *et al.* 2013). To this end, the MARINER (Macro Algae Research Inspiring Novel Energy Resources) programme (ARPAe-DOE 2017), Advanced Research Projects Agency–Energy (ARPA-E), US Department of Energy, contracted with the NOAA in the development and deployment of information tools for mariculture (MARINER AquaMapper). Specifically, in the near term, NOAA is working to provide geospatial data to help participating MARINER-supported teams determine the scalability of their respective mariculture production and harvesting in the US exclusive economic zone (EEZ). Scalability is important because only very large farms will be economically viable for energy production. In order to better support this effort, NOAA developed biogeophysical data layers and metrics that will be used for scalability analysis in an atlas that is to be publicly released by the end of December 2018 (NCCOS 2019).

Global climate change has pushed some kelp populations northwards along the northeast coast of the United States. For example, some kelp species, including *A. esculenta* and *L. digitata*, have become rarer in their southern New England distribution. Populations of sugar kelp (*S. latissima*) also declined over recent decades (Augyte *et al.* 2017; Egan & Yarish 1988, 1990; Gerard 1997; Redmond 2013; Witman & Lamb 2018; Yarish *et al.* 2017). Developments of gametophyte-based seed banks and new strains of kelp produced via hybridisation may be critical to help resolve such issues. With these technologies, temperature-tolerant kelp germplasm could be provided to growers in southern New England, similar to what has been done traditionally in Asia (Hwang *et al.* 2017, 2018, 2019; Zhang *et al.* 2016, 2018).

Kelps have been the major seaweed aquaculture species in the United States for several reasons; for example, publicly funded cultivation technologies for nursery and open-water farming have been made available through open-source portals (Connecticut Sea Grant 2014; Flavin *et al.* 2013; Redmond *et al.* 2014a). Kelps are relatively easy to grow, even for novices. However, there has been demand for other seaweed species, including *Palmaria, Porphyra*/*Pyropia, Chondrus, Gracilaria*, and *Sargassum*. Although cultivation technologies for these species are more complex than those for kelp (Redmond *et al.* 2014a, 2014b), domesticating a diversified range of seaweed species will be critical for the aquaculture industry to grow sustainably in the United States. Several research projects in academia are underway to develop the required species-specific, open-water cultivation technologies (Blouin *et al.* 2007, 2011; Kim *et al.* 2014; Stekoll *et al.* 1999). However, to date, none of these species has been commercialised.

OFFSHORE AQUACULTURE: THE FUTURE OF SEAWEED AQUACULTURE IN THE UNITED STATES?

The year 2018 may be important in the history of seaweed aquaculture in not only the United States but possibly the world. ARPA-E of the US Department of Energy supported 18 innovative projects with a total of US$22 million to develop offshore seaweed aquaculture technologies. This programme, called MARINER, is the largest funding opportunity for seaweed aquaculture in the United States and probably one of the largest investments for offshore seaweed aquaculture in the world. The length of the US shoreline is over 20,000 km, with the longest shoreline in Alaska (over 10,000 km), followed by Florida (more than 2000 km) and Louisiana (1350 km). A number of nearshore areas are potentially available for seaweed farming. However, suitable areas for seaweed aquaculture and permits may be very limited because nearshore areas in the United States are intensively utilised for recreation, with the exception of Alaska where the major competing issues are fishing and the limited number of roads along the coast. The United States has the largest EEZ in the world at over 11,350,000 km^2 (NOAA 2018). The EEZ may provide the best opportunities for seaweed aquaculture to expand in the United States because (1) sufficient areas to produce large amount seaweeds are available without conflict with recreational and/or fishing activities, and (2) permits for seaweed aquaculture can be more easily obtained than for nearshore waters.

The purpose of the MARINER programme is to develop critical tools that will allow the nascent macroalgal industry in the United States to leverage this tremendous resource and become a world leader in the production of marine biomass and, therefore, to improve energy security and economic competitiveness of the United States. Seaweed biomass can potentially be used for biofuels; other applications include biorefinery (Zollmann *et al.* 2019), human food and animal feeds. The challenge of this programme is to dramatically reduce capital and operating costs of seaweed cultivation, while significantly increasing the range of its deployment by expansion into the offshore environment (ARPAe-DOE 2017; ADFG n.d.). Giant kelp (*M. pyrifera*), sugar kelp (*S. latissima*), *Sargassum* spp., *Eucheuma isiforme* (C.Agardh) J.Agardh and other seaweed species are planned for cultivation in the EEZ offshore environments in many biogeographic regions of the United States, including the Gulf of Mexico, Hawaii, Washington, Alaska, New England, California, and the Caribbean Sea. These projects include many different aspects of seaweed aquaculture, from breeding and seeding technologies to farm system design and management technologies (e.g. Fernández *et al.* 2019) to novel harvest technologies required for offshore environments (Fig. 10). It is expected that a selective breeding programme will improve both productivity and composition of the kelps *S. latissima* and *M. pyrifera*, which could serve as feedstock for biofuels. ARPA-E's goal is to develop tools and a pathway towards low-cost (under US$100/dry weight [DWT]) seaweed feedstock that could supply 10% of transportation fuel in the United States (Lindell *et al.* 2018). Innovative cultivation and harvest systems also need to be developed. These include free-floating farm systems, pumping deep seawater to fuel seaweed growth; self-diving buoy systems to protect farms from wave motion; automated monitoring systems; drone technology to move farm systems to safe locations during storm events; and for harvest (ARPAe 2015).

CONCLUSIONS

Seaweed aquaculture history in the United States is relatively recent compared to Asian countries such as China, Korea and Japan (see Hwang *et al.* 2019). However, seaweed aquaculture globally is a fast-growing industry. Efforts at seaweed aquaculture in Washington state and the Gulf of Maine during the 1980s and 1990s provided important practical lessons and foundational science, and the success of kelp aquaculture since 2010 was built on knowledge obtained from earlier attempts. For seaweed aquaculture to further succeed and gain public acceptance in the United States, it is important to emphasise the associated environmental benefits. The EEZ of the United States, the blue ocean, offers opportunities for expansion of seaweed aquaculture into an environment greater than the entire land mass of the United States, in an area where there has been limited human activity. Domestication of various indigenous species is critical. Product diversification is also needed to further develop products ranging from food and phycocolloids to animal feeds and biofuels. Seaweeds for energy will be economically viable not only if oil prices increase but also if seaweed production costs can be significantly decreased, which is one goal of the MARINER programme. Therefore, continuous efforts must be made not only to increase productivity by developing cultivation technologies (nursery and open water, including offshore) and new cultivars but also to enhance biomass-to-biofuel conversion efficiency.

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