

Seaweed Aquaculture for Food Security, Income Generation and Environmental Health in Tropical Developing Countries

To meet carbon emissions targets, more than 30 countries have committed to boosting production of renewable resources from biological materials and convert them into products such as food, animal feed and bioenergy. In a post-fossil-fuel world, an increasing proportion of chemicals, plastics, textiles, fuels and electricity will have to come from biomass, which takes up land. To maintain current consumption trends the world will also need to produce 50–70% more food by 2050, increasingly under drought conditions and on poor soils. Depending on bioenergy policies, biomass use is expected to continue to rise to 2030 and imports to Europe are expected to triple by 2020. Europe is forecast to import 80 million tons of solid biomass per year by 2020 (Bosch et al. 2015).

Producing large volumes of seaweeds for human food, animal feed and biofuels could represent a transformational change in the global food security equation and in the way we view and use the oceans. In 2012, global production of seaweeds was approximately 3 million tons dry weight, and growing by 9% per annum. Increasing the growth of seaweed farming up to 14% per year would generate 500 million tons dry weight by 2050, adding about 10% to the world's present supply of food, generating revenues and improving environmental quality (Table 1). Assuming a conservative average productivity from the best operating modern farms of about 1,000 dry metric tons per km² (1 kg per m²), this entire harvest could be grown in a sea area of about 500,000 square kilometers, 0.03% of

the oceans' surface area, equivalent to 4.4 percent of the US exclusive economic zone.

BENEFITS OF SEAWEED PRODUCTION

The dry-matter composition of seaweeds ranges from 10–30% protein, with red and green seaweeds typically higher than browns (Kim 2012). Harvest season is an important determinant of composition. The lipid portion is typically 1–5% of dry matter (Kim 2012). Taking an average of 19% protein and 3% lipid (Table 2), 500 million dry tons of seaweed would produce about 150 million tons of algae protein and 15 million tons of algae oil. Based on the amino acid profile and some issues with anti-nutritional factors in both seaweed and soy, algae protein can be thought of as roughly similar in value to soy protein. Algae oils, however, can contain long chain omega-3 fatty acids, which make them more comparable to fish oils in nutritional value. Currently, about 1 million tons of fish oil and 250 million tons of soy meal are produced annually (Pike & Jackson 2010, USDA 2015). Accounting for the different protein levels in soy meal compared to algae protein concentrate, 500 million tons of seaweed would represent about 20% of current soy-protein production. Even more dramatic is the potential for lipid replacement; algae oils could represent a 750% increase over current fish oil production. Given the importance of oils containing long chain omega-3 fatty acids, this could be a significant boost to human health, while eliminating the need for fish oil in aquaculture

TABLE 1. Extrapolated ecosystem services from 500 million tons (dry weight) of seaweeds.

| | | |
|----------------------------------|---------------------------|--|
| Ocean area required | 500,000 km ² | Based on average annual yield of 1,000 dry tons/km ² under current best practice. Equals 0.03% of the ocean surface area. |
| Protein for people and animals | 50,000,000 tons | Assumes average protein content of 10% dry weight. Estimated value \$28 billion. Could completely replace fishmeal in animal feeds. |
| Algal oil for people and animals | 15,000,000 tons | Assumes average lipid content of 3% dry weight. Estimated value \$23 billion. Could completely replace fish oil in animal feeds. |
| Nitrogen removal | 10,000,000 tons | Assumes nitrogen content 2% of dry weight. Equals 18% of the nitrogen added to oceans through fertilizer. |
| Phosphorous removal | 1,000,000 tons | Assumes phosphorous content 0.2% of dry weight. Represents 61% of the phosphorous input as fertilizer. |
| Carbon assimilation | 135,000,000 tons | Assumes carbon content 27% of dry weight. Equals 6% of the carbon added annually to oceans from greenhouse gas emissions. |
| Bioenergy potential | 1,250,000,000 MWH | Assumes 50% carbohydrate content, converted to energy. Equals 1% of annual global energy use. |
| Land sparing | 1,000,000 km ² | Assumes 5 tons/ha average farm yield. Equals 6% of global cropland. |
| Freshwater sparing | 500 km ³ | Assumes agricultural use averages 1 m ³ water/kg biomass. Equals 14% of annual global freshwater withdrawals. |

and animal feeds. Current price per ton for soy meal is about \$550 meaning the protein fraction could be worth about \$28 billion. Current price for fish oil is about \$1500 per ton, making the seaweed oil component worth about \$15 billion. Extrapolating an estimate of one job per 10 dry tons of seaweed results in a potential direct employment of 50 million jobs; a standard seafood industry secondary-employment multiplier of 2:1 suggests 100 million jobs could be created overall, roughly the number currently employed in marine capture fisheries.

Pollution Remediation

In 2014, 124 million tons of nitrogen were used globally as fertilizer, of which about half was not taken up by plants, 15%–30% of which ended up in coastal waters (FAO 2015, Lassaletta et al. 2014, Swaney et al. 2012). This has contributed to 245,000 square kilometers of dead zones globally (Diazi & Rosenberg 2008). Seaweed production could absorb many of these excess nutrients while producing at least 1,000 tons dry weight of marine plants per square kilometer or 245 million tons dry weight if all of the dead zones were farmed at this modest intensity (Zhang et al. 2014, Kim et al. 2014, 2015). Assuming nitrogen content of 3% for dry seaweed (Mišurcová, 2012), it would take up 20 tons of nitrogen per square

kilometer. Reaching a global level of 500 million tons of seaweed production would assimilate 10 million tons of nitrogen from seawater, equaling some 30% of the nitrogen estimated to enter the ocean

Phosphorous is not generally a limiting nutrient in the ocean so it does not cause dead zones or other environmental disruptions. However, it is becoming a more limiting nutrient for use on land over time, due to declines in phosphorous reserves as well as the high energy cost involved in creating phosphate fertilizers. Global production of phosphorous as fertilizer was 48 million tons in 2014 (FAO 2015). At an average of about 0.2% phosphorus in dry seaweed, marine agronomy would sequester 15 million tons of phosphorous or nearly a third of the phosphorous produced in fertilizers. If we could use by-products from seaweed culture for their phosphorous content, it could significantly add to fertilizer output or replace other forms of phosphorous production.

Carbon Sequestration

Increasing atmospheric carbon dioxide is causing ocean acidification with serious consequences for marine life (Ciais et al. 2013). In particular, lower pH alters the availability of shell-forming minerals needed by corals, mollusks and myriad microorganisms

(Gatusso & Hansson 2011). Anthropogenic emissions of carbon in 2010 was about 8182 Tg (Boden et al. 2010). Production of 500 million tons of seaweed would absorb 135 million tons of carbon, about 3.2% of the carbon added annually to seawater from greenhouse gas emissions, offering the potential of using carbon credits to improve the profitability of seaweed businesses.

Biofuel

The carbohydrate content of seaweed, about 50% of dry mass, can be used in biofuel production (Garcia-Casal et al. 2007). Capturing the energy in seaweed can be as simple as microbial anaerobic digestion to produce methane or as complex as microbial breakdown of lignins and other complex carbohydrates into simple sugars for use in ethanol production (Wei et al. 2013). An annual harvest of 500 million dry tons of seaweeds with 50% carbohydrate content could produce about 1.25 billion megawatt-hours' worth of methane or liquid fuel. The world used about 85 billion megawatt-hours of energy from fossil fuels in 2012, so energy production from these seaweed products would equate to roughly 1.5% of current energy use from fossil fuels (IEA 2014). Current biomass prices average about US\$50 per dry ton, for a total value of some US\$12.5 billion.

Since all of this can be done without using any land or freshwater, the potential for large-scale seaweed farming to supplement our future food supplies while easing the burden we now impose on the land seems clear. However, for this to happen, we must develop markets, processing systems, production systems, and businesses that will utilize the products from seaweed culture. While seaweed production technology is reasonably well established and important steps have been taken to expand the range of products that can be derived from seaweeds, research and development remain necessary throughout all steps in the seaweed value chain for the industry's full potential to be realized.

COMPOSITION AND USE OF SEAWEEDS

There are three basic types of seaweed: red, brown and green (Figure 1). Brown and green seaweeds are generally eaten for food, while the browns and reds are used in the production of the hydrocolloids: agar, carrageenan and alginate used as industrial thickeners. In 2012, 40% of global seaweed production was eaten directly by humans, 40% consumed indirectly through processed foods and 20% used in a range of industrial applications (FAO Fishstat 2014, Loureiro et al. 2015).

FIGURE 1. Examples of commonly cultured types of seaweed: red (left), green (center), and brown (right). RE Brummett (L), Alyson Myers (C), Chen Jiaxin (R).



TABLE 2. Dry matter composition (%) of Wakame (*Undaria pinnatifada*), Kombu (*Saccharina japonica*), Nori (*Porphyra yezoensis*), Gracilaria (*Gracilaria verrucosa*), and Solieriaceae (collectively: *Kappaphycus alvarezii* and *Eucheuma denticulatum*). Exact composition varies seasonally and locally. Moisture content is typically 80–90% (Pereira, 2011).

| Composition (dw) | Wakame | Kombu | Nori | Gracilaria | Solieriaceae |
|--------------------|--------|-------|-------|------------|--------------|
| Fat | 1–5 | 1–2 | 2 | 0.3 | 0.2 |
| Total Carbohydrate | 45–51 | 52 | 44 | 74 | 63–67 |
| Protein | 12–23 | 7–8 | 31–44 | 12 | 5–6 |
| Minerals | 26–40 | 27–33 | 8 | 6 | 23–26 |

Nutritionally, seaweeds are generally low in fat and rich in carbohydrates, minerals, vitamins and essential micronutrients, particularly antioxidants (Radulovich et al. 2015). Nori is high in protein (Table 2).

For animals, seaweeds and seaweed extracts have been used to feed poultry, sheep, cattle, pigs, abalone and shrimp, stimulating food intake and growth, while decreasing the amount and cost of protein, especially fishmeal, in diets. In aquaculture, the major constraint to increased expansion and profitability is the high price and variability of fishmeal supply needed for feeds. An algal source of protein for fish and shrimp diets would create enormous opportunities to reduce pressure on both terrestrial and marine ecosystems.

The use of seaweed and their extracts as fertilizers has been tested in a number of species and has seen some significant growth in recent years. They are used as foliar fertilizers for cereals, vegetables and fruits to increase stress resistance to fungi and insects (Kim, 2012). They also serve as soil structural amendments, increasing water and nutrient retention (Chojnacka 2012, Vijayaraghavan & Joshi 2015)

Seaweeds are extensively used in traditional medicine with recognized antihelminth, antibacterial, antifungal and antiviral properties (El Gamal 2010). Fucoidan, anti-inflammatory extracted from brown seaweed, can prevent muscle necrosis caused by snake venom (Azofeifa et al. 2008). Several compounds isolated from seaweed have shown anti-cancer properties, while others possess antidiabetic, antihypertensive and hepatoprotective properties (Fukahori et al. 2008, Kim 2012).

Collectively known as hydrocolloids, agars, carrageenan and alginates are polysaccharide

carbohydrates that act as the skeleton of seaweeds and can be extracted and used as clear, flavorless thickeners. Carrageenan and agar are extracted from red seaweeds and are major industrial ingredients used for gelling, thickening and stabilizing food, pharmaceuticals, cosmetics, hand and body lotions, shampoo, soap, toothpaste, gel fresheners and many other consumer products (Samaraweera et al. 2011). Alginates, extracted from brown seaweeds, are used by the textile industry as thickeners for the paste containing dye (Babel et al. 2015). In the food and beverage industry, alginate is used in ice creams and sauces (Kim, 2012). It is also used as a separating agent in water-oil emulsions and as a softening agent in baking (Samaraweera et al. 2011). The chemical and pharmaceutical industries utilize alginate and carrageenan as immobilizing agents for various biocatalysts in commercial synthesis and conversion reactions (Borglum & Marshall 1984, Tønnesen & Karlsen 2002). In the paper industry, alginate is used for surface sizing applications to give a continuous film surface (Bixler & Porse 2010). It also provides an oil-resistant layer that enhances grease repellency (Jost et al. 2014). Other applications of alginate include welding rod coatings (Yin & Lewis, 1981) and binders for fish feed (Duis et al. 1995).

THE SEAWEED AQUACULTURE INDUSTRY

Although wild seaweed beds are harvested in Northern Europe, Chile and Japan, the majority of seaweeds, 99.4% in 2013, are farmed in Asian coastal waters (Fishstat 2014). Main producing countries in 2011 were China (55%), Indonesia (25%), Philippines (9%), South

FIGURE 2. Seaweed production systems: bottom culture of red seaweed in intertidal zones in the tropics (left) and floating line culture of brown seaweeds in temperate areas (right). Photos: Flower Msuya (L) and Chen Jiaxin (R).



Korea (5%), North Korea (2%) and Japan (2%) (FAO Fishstat 2014).

There are two basic types of seaweed farm (Figure 2). Small-scale farmers, mostly in the tropics, produce crops of (mostly) red algae in small patches of intertidal sand flats. Cuttings are inserted into three-strand twisted rope lines staked to the substrate. Grow-out to a harvestable biomass of 3–5 tons dry matter per ha is 2–3 months. In one of the most labor-intensive production systems, that of Zanzibar Island in Tanzania, 83 person-days are required per ton of dry seaweed, equivalent to 4 tons per full time job (Valderamma 2015).

Larger scale operators, mostly in the temperate zones, more commonly use rope lines seeded with (usually) brown algae spores in a hatchery, which are then suspended from floats in the autumn. After 2–3 months, harvesting begins at 10–15 day intervals through the spring, producing approximately 26 tons of dry matter per ha per year (Pereira & Yarish 2008).

There are >30 seaweed species of commercial interest, but the bulk of production is of 6 species: *Kappaphycus alvarezii* and *Eucheuma denticulatum* (collectively 33%) *Saccharina japonica* (Kombu, 25%), *Gracilaria verrucosa* (11%), *Porphyra* spp. (Nori, 8%) and *Undaria pinnatifida* (Wakame, 8%). Seaweed harvest was 21 million tons wet weight worth \$5.4 billion in 2011 (Table 3). Annual growth rate in seaweed aquaculture has been 9% on volume over 2007–2011.

Markets

Seaweed prices have been more or less steady over the last decade, hovering about \$250 per metric ton (Figure 3), with some downward pressure on prices of temperate species due to increased production in China. *Saccharina*, *Porphyra* and *Undaria* are used mostly for direct human consumption, while *Kappaphycus*, *Eucheuma* and *Gracilaria* are used predominantly in the production of consumer products, the breadth of which has kept prices buoyant as global population and affluence have grown. *Kappaphycus* and *Eucheuma* production is most relevant to tropical developing countries.

World hydrocolloid sales in 2013 were over 100,000 tons worth approximately US\$1.2 billion (Table 4). China is the main exporter of refined hydrocolloids, but competes with refineries in Argentina, Canada, Chile, Denmark, France, Japan, Mexico, Morocco, Portugal, North Korea, South Korea, Spain, Russia and the USA. Over recent decades, hydrocolloid sales have grown by an average of about 2% per year. The 2008 financial crises lowered sales for a time, but prices have since recovered somewhat and have recently been rising by about 4% annually, reflecting both increases in demand and cost of production. Europe and North America accounted for the major share of the global alginate market in 2012, but markets in the Asia-Pacific region are ever more important driven by increasing consumption of processed foods and medicines (Bixler & Porse 2010).

TABLE 3. Global production (wet weight) and value of major seaweeds 2000–2012 (FAO 2014).

| Total Quantity (MT) | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | Family/Common Name/Use |
|-------------------------------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|------------------------|
| <i>Saccharina</i> spp | 4106508 | 4035964 | 4219199 | 4138199 | 4041852 | 4401045 | 4413792 | 4634269 | 4784174 | 4951977 | 5171630 | 5286902 | 5703040 | Brown/Kombu |
| <i>Kappaphycus</i> spp | 644464 | 716812 | 827509 | 933878 | 1149711 | 1276986 | 1446278 | 1479253 | 1668328 | 1762590 | 1874577 | 2100146 | 2131018 | Red, industrial |
| <i>Euclidean</i> spp | 299635 | 364959 | 412552 | 477016 | 665913 | 1161711 | 1332279 | 1770684 | 2234094 | 3096103 | 3748013 | 4889726 | 6153352 | Red, industrial |
| <i>Porphyra</i> spp | 529188 | 541047 | 646050 | 540931 | 587490 | 584190 | 585242 | 606741 | 562783 | 554064 | 564234 | 608791 | 691425 | Red, Nori |
| <i>Undaria pinnatifida</i> | 311125 | 232487 | 295973 | 1769202 | 2245301 | 2439737 | 2115381 | 1765644 | 1756249 | 1694540 | 1537339 | 1754504 | 2139477 | Brown; Wakame |
| <i>Gracilaria</i> spp | 60514 | 95582 | 108379 | 81224 | 63423 | 91042 | 191184 | 305999 | 267787 | 296473 | 565366 | 697240 | 831576 | Red, industrial |
| Total Value (1000 USD) | | | | | | | | | | | | | | |
| <i>Saccharina</i> spp | 388809 | 420967 | 404067 | 440136 | 414460 | 425400 | 441978 | 473717 | 323078 | 292185 | 296676 | 292462 | 332155 | Brown/Kombu |
| <i>Kappaphycus</i> spp | 46983 | 51628 | 57162 | 66302 | 93288 | 106465 | 170436 | 135285 | 292092 | 203036 | 265077 | 352363 | 376536 | Red, industrial |
| <i>Euclidean</i> spp | 25999 | 27466 | 42424 | 47229 | 74524 | 167523 | 236582 | 396231 | 307515 | 828976 | 1143390 | 1072815 | 1279364 | Red, industrial |
| <i>Porphyra</i> spp | 1074657 | 1077623 | 1009131 | 891703 | 1072466 | 1091366 | 956627 | 1016761 | 963601 | 1035404 | 1173484 | 1091867 | 1287446 | Red, Nori |
| <i>Undaria pinnatifida</i> | 124054 | 76678 | 97759 | 707079 | 892203 | 969128 | 804050 | 693967 | 757707 | 758326 | 650949 | 722080 | 969260 | Brown; Wakame |
| <i>Gracilaria</i> spp | 35753 | 35753 | 35753 | 35753 | 35753 | 35753 | 35753 | 35753 | 35753 | 35753 | 35753 | 35753 | 35753 | Red, industrial |
| USD/MT | | | | | | | | | | | | | | |
| <i>Saccharina</i> spp | 95 | 104 | 96 | 106 | 103 | 97 | 100 | 102 | 68 | 59 | 57 | 55 | 58 | Brown/Kombu |
| <i>Kappaphycus</i> spp | 73 | 72 | 69 | 71 | 81 | 83 | 118 | 91 | 175 | 115 | 141 | 168 | 177 | Red, industrial |
| <i>Euclidean</i> spp | 87 | 75 | 103 | 99 | 112 | 144 | 178 | 224 | 138 | 268 | 305 | 219 | 208 | Red, industrial |
| <i>Porphyra</i> spp | 2031 | 1992 | 1562 | 1648 | 1826 | 1868 | 1635 | 1676 | 1712 | 1869 | 2080 | 1794 | 1862 | Red, Nori |
| <i>Undaria pinnatifida</i> | 399 | 330 | 330 | 400 | 397 | 397 | 380 | 393 | 431 | 448 | 423 | 412 | 453 | Brown; Wakame |
| <i>Gracilaria</i> spp | 591 | 374 | 330 | 440 | 564 | 393 | 187 | 117 | 134 | 121 | 63 | 51 | 43 | Red, industrial |

FIGURE 3. Global un-weighted average value (1000 USD/Metric Ton dry weight) of farmed seaweed (data from Table 3).



TABLE 4. The market for seaweed-derived hydrocolloids, agars, alginates, and carrageenan in 2013 (Rhein-Knudsen et al. 2015).

| Product | Global Production (MT/year) | Retail Price (US\$/kg) | Gross Market Value (US\$ million/year) |
|-------------|-----------------------------|------------------------|--|
| Agars | 10,600 | 18 | 191 |
| Alginates | 30,000 | 12 | 339 |
| Carrageenan | 60,000 | 10.4 | 626 |

In addition to the traditional uses as food and industrial thickeners, there are nearly 300 known organic metabolites in seaweed (Hu et al. 2012) from which a wide range of seaweed-derived products could be manufactured. As most of the unusual and potentially valuable compounds in seaweeds are present in only very small quantities, major investment in scalable production systems are needed for the industry to move into these new markets (Hafting et al. In Press).

HIGH LIKELIHOOD AREAS FOR SUCCESSFUL SEAWEED FARMING

Seaweed farming could either occur directly on the high seas or in areas nearer to shore. Either way, some source of nutrients to fuel growth is needed. Inshore, seaweeds can grow on nutrients from agricultural

runoff, reducing the impacts of pollution on aquatic ecosystems, but risking the accumulation of heavy metals in the seaweed, render it unfit for human or animal consumption.

On the high seas, nutrients are generally limited, but accumulate in certain areas driven by currents, tides and upwelling onto continental shelves. These nutrients drive high ecosystem productivity by fueling algae growth, the bottom of the food chain. The major upwelling areas, indicated by chlorophyll a (phytoplankton), are shown in Figure 4.

By overlaying continental shelves, currents and tidal flow areas, high-priority zones for seaweed aquaculture can be identified (Figure 5). In developing countries, the major areas of interest for red seaweeds are SE Africa, Southern India, Central Indonesia, Panama, Northern Brazil and NW Australia. For brown seaweeds, likely areas are Southern South America, the NE and NW coasts of North America, NW Europe, Southern Australia and New Zealand. From an international development and poverty alleviation perspective, Panama, Brazil, India and Indonesia seem most suitable. However, it should be noted that this method of identifying high likelihood areas is not exhaustive. Other areas where successful seaweed farming already exists (e.g., China, southern Chile, the Philippines) experience local effects that make them suitable despite other considerations. Globally, such

FIGURE 4. Chlorophyll-a density in the world's oceans. Highest long-term average nutrient density is shown on the bottom of the figure in red (NOAA).

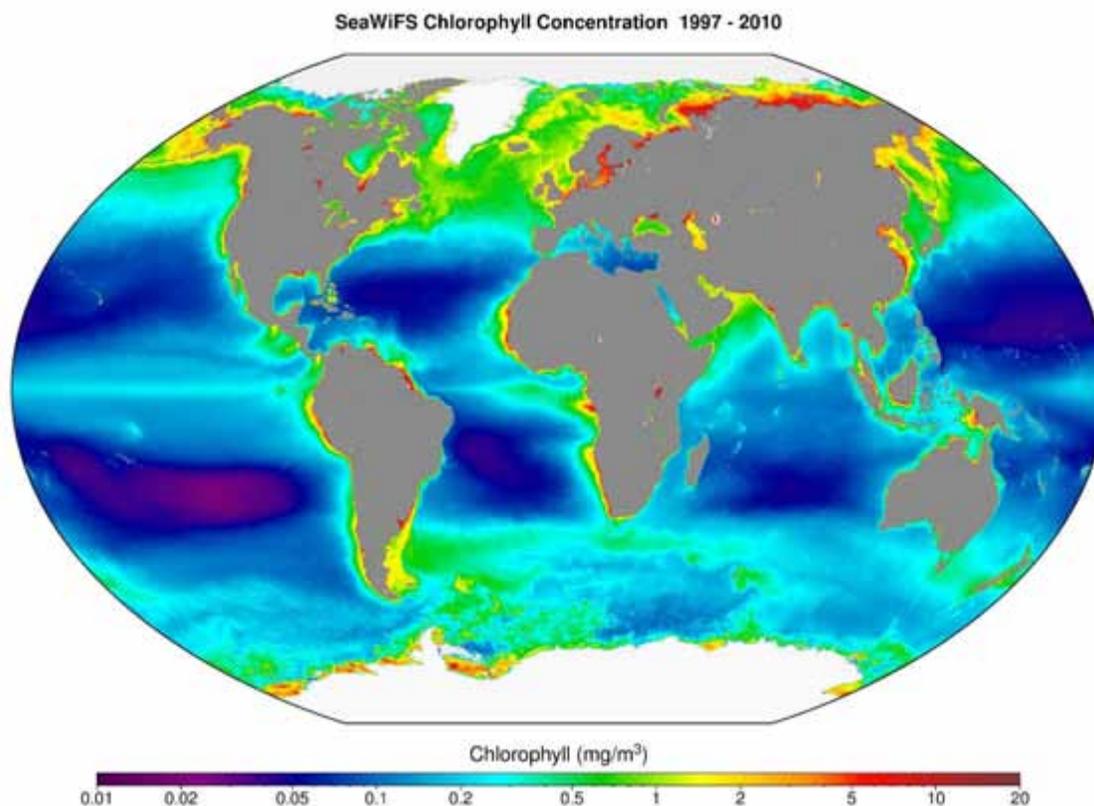


FIGURE 5. High likelihood areas for natural seaweed production, brown for brown seaweeds, red for reds. Greens will generally grow in the same areas as browns. It should be noted that this method of identifying high likelihood areas is not exhaustive. Seaweeds are grown in many areas outside of those indicated and many sites within identified high likelihood areas will not be suitable.



locations should not be ruled out, but verified by more local data collection and analysis.

PRODUCTION ECONOMICS

Relatively little information is available on the economics of seaweed farming as compared to other forms of aquaculture. The few available studies nevertheless provide valuable evidence on the economic benefits of seaweed aquaculture in both temperate and tropical regions. For example, Edwards and Watson (2011) conducted an economic analysis of *Laminaria digitata* farming in Ireland; Philippsen *et al.* (2014) presented a cost analysis for ethanol produced from farmed seaweeds; SINTEF (2014) described a new bioeconomy for Norway based on cultivation and processing of seaweeds while Lenstra *et al.* (2011) and van den Burg *et al.* (2013) examined the economic feasibility of offshore seaweed production in the North Sea.

Valderrama *et al.* (2013, 2015) developed comparative enterprise budgets for eight carrageenan seaweed farming systems (both floating and off-bottom) in Indonesia, the Philippines, Tanzania, India, Solomon Islands and Mexico (Table 5). The systems were selected to illustrate a variety of production and market scenarios currently found in seaweed farms around the world. The study included small-scale, “village-based” operations in Tanzania (270 m of culture lines), large-scale, “industrial” Indonesian farms (30,000 m of culture lines), and intermediate systems in the Philippines, India, Solomon Islands and Mexico.

Productivity ranged from 1.10 kg/m/year in the Indonesian floating farm to 5.43 kg/m/year in the Solomon Islands operation. Farm prices were significantly higher (>US\$0.80/kg of dry seaweed) in Indonesia, the Philippines and Mexico due to their proximity to markets. Tanzania achieved the lowest cost of production (US\$0.06/kg) while the highest costs per kg were computed for the Philippines and Mexico at US\$0.70 and US\$0.65, respectively. Production costs for the other systems were around US\$0.27/kg. Estimated production costs for Indonesia and the Philippines are not necessarily representative of these countries given the large variety of farming systems and local production conditions in these nations.

When net returns from the operations were compared to national and international poverty lines, the superior economic performance of the Indonesian “industrial-scale” farms relative to the family-run operations in Tanzania and India revealed the importance of achieving economies of scale as well as having ready access to markets in order to negotiate better prices. In the case of Tanzania, the small 270 linear m farming units generated a level of income that fell short of the poverty line. However, with production costs of around US\$0.25/kg, the study estimated that Tanzanian farms could generate sufficient revenue to bring a five-family household over the national poverty line if farm price increased to at least US\$0.80/kg and the scale of the operation was expanded to 2,000 m of culture lines. The Valderrama *et al.* (2015) study is noteworthy in that it shows how the economic viability of aquaculture projects may be largely determined by management and market factors rather than biological parameters.

Good business planning is key to successful expansion of the seaweed aquaculture industry if we are to meet growing global demand for biomass, protein, organic chemicals and the many other products derived from seaweeds. With established culture technology and suitable growing conditions in much of the tropics, the principal constraints to growth are appropriate financing mechanisms secured with legal user rights within a secure marine spatial plan.

A SEAWEED FARMING SYSTEM FOR TROPICAL DEVELOPING COUNTRIES

A precise description of a seaweed farming system is not practical in as much as exact parameters and prices will vary according to location, species and market. National investment that aims at realizing the potential of seaweed farming for transformative global scale impacts on ecosystem health will require moving beyond small-scale systems located in intertidal areas to larger-scale systems. Moving onto the high seas has certain attractions in terms of minimizing conflict with other sectors (e.g., tourism, small-scale fishing, local transport), but faces serious constraints in terms of logistics, nutrient density and availability of investment capital. These considerations argue for medium-scale

TABLE 5. Comparative enterprise budgets for *Kappaphycus* seaweed farming systems in 6 developing countries, 2009 (Valderrama et al. 2015).

| Item | Indonesia | | Philippines | | Tanzania | | India | | Solomon Islands | | Mexico | |
|------------------------------------|---------------|--------------|--------------|-------------|-------------|-------------|--------------|--|-----------------|---------------|---------------|---------------|
| | Floating | | Floating | | Off-bottom | Floating | Floating | | Floating | Off-bottom | Floating | |
| Production Parameters | | | | | | | | | | | | |
| Total length of lines (m) | 30,000 | | 2,000 | | 270 | 288 | 2,565 | | 4,000 | | 10,000 | 10,000 |
| Number of cycles per year (cycles) | 8 | 5 | 5 | 63 | 7 | 8 | 6 | | 4,000 | 4 | 4 | 4 |
| Length of a cycle (days) | 45 | 63 | 63 | 45 | 45 | 45 | 45 | | 21,700 | 60 | 60 | 60 |
| Annual yield of dry seaweed (kg) | 33,000 | 2,850 | 2,850 | 806 | 662 | 806 | 5,400 | | 53,778 | 53,778 | 53,778 | 53,778 |
| Annual productivity (kg/m/year) | 1.10 | 1.43 | 1.43 | 2.80 | 2.45 | 2.80 | 2.11 | | 5.43 | 5.38 | 5.38 | 5.38 |
| Cycle productivity (kg/m/cycle) | 0.14 | 0.29 | 0.29 | 0.35 | 0.35 | 0.35 | 0.35 | | 1.34 | 1.34 | 1.34 | 1.34 |
| Farm-gate price (USD/kg) | 0.85 | 1.09 | 1.09 | 0.27 | 0.27 | 0.27 | 0.33 | | 0.38 | 1.00 | 1.00 | 1.00 |
| Gross Receipts | 28,050 | 3,107 | 3,107 | 218 | 179 | 218 | 1,785 | | 8,246 | 53,778 | 53,778 | 53,778 |
| Variable Costs (USD) | | | | | | | | | | | | |
| Propagules | | | | | | | | | | | | |
| Labor | 4,320 | 759 | 759 | 26 | 26 | 28 | 1,041 | | 3,556 | 8,853 | 8,853 | 8,853 |
| Fuel | 29 | 332 | 332 | | | | | | 1,117 | | | |
| Maintenance and repairs | 420 | | | | | | | | | | | |
| Sales and marketing | 600 | | | | | | | | | 7,115 | 7,115 | 7,115 |
| Total Variable Costs | 5,369 | 1,091 | 1,091 | 26 | 26 | 28 | 1,041 | | 4,672 | 29,232 | 29,232 | 29,232 |
| Fixed Costs (USD) | | | | | | | | | | | | |
| Depreciation | 2,501 | 906 | 906 | 24 | 24 | 24 | 432 | | 1,157 | 2,274 | 2,934 | 2,934 |
| Administrative costs | 900 | | | | | | | | | | | |
| Utilities | 120 | | | | | | | | | | | |
| Fees for coastal land usage | | | | | | | | | | 3,109 | 3,109 | 3,109 |
| Total Fixed Costs (USD) | 3,521 | 906 | 906 | 26 | 26 | 24 | 432 | | 1,157 | 5,383 | 6,043 | 6,043 |
| Total Costs (USD) | 8,890 | 1,997 | 1,997 | 52 | 52 | 52 | 1,473 | | 5,829 | 34,615 | 35,275 | 35,275 |
| Net Returns (USD) | 19,160 | 1,109 | 1,109 | 166 | 127 | 166 | 312 | | 2,417 | 19,163 | 18,503 | 18,503 |
| Production Cost (USD/kg) | 0.27 | 0.70 | 0.70 | 0.08 | 0.08 | 0.06 | 0.27 | | 0.27 | 0.64 | 0.66 | 0.66 |

TABLE 6. Capital and operation of a 150 × 150 m *Euchema* spp. seaweed (for carageenan) production module in a generalized tropical developing country. Real Danish prices adjusted for cost of doing business in Indonesia and converted into US\$ @ 1.2 per €.

| | Number | Unit Price | Total per Annum | Notes |
|------------------------|-----------|------------|-----------------|--------------------------------------|
| Seedling Lines | 1874 | 0.83 | \$1555 | |
| Longlines (installed) | 15 | 172 | \$2580 | 1000 m of seedling line per longline |
| Operation | 15 | 170 | \$2550 | |
| | | | \$6685 | |
| Returns | 14.4 tons | \$900 | \$12,960 | 120 tons wet weight |
| Net Profit (per unit) | | | \$6275 | |
| ROI | | | 94% | |
| Production Cost per kg | | | \$0.46 | |

floating rope line investments operating in high potential areas somewhat offshore, but likely still in the EEZ.

Such a system, adaptable to a wide variety of conditions, both temperate and tropical, and species, both red and brown, has been developed by Seaweed Seed Supply A/S in Denmark. The main phases of production are: 1) seaweed spawning, 2) sporophyte attachment and hatchery rearing, 3) grow-out on long lines and, 4) harvest. Table 6 illustrates an indicative production system budget for red seaweeds grown in the nearshore zone (~1 km) in a tropical environment.

Spawning and Hatchery Phases

In the hatchery, seaweeds are induced to release spores through light and temperature manipulation. The spores settle on ropes coiled into baskets suspended in spawning tanks.

The hatchery consists of racks of 120 × 420 × 20cm tanks in four levels. Half of the tanks are made with a double bottom to regulate temperature with recirculating water. Each tanks holds 20 baskets, each with twelve tubes comprised of 5.2 m of 7 mm (20 g per m) Danline® rope wound on a 35 cm tube (Σ 1248 meter seedling line).

Once the mature seaweed has spawned, the sporophytes attach to the seedling ropes. Seedling ropes remain in the hatchery tanks for ~25 days, up

to a sporophyte length of 1 mm. The average time between batches is 30 days.

Light for photosynthesis comes from eight lamps (120 cm, 36 watt, neon) situated on top of each tank. Energy consumption is based on 8 lights/20 baskets; light is on for 17 hours/day.

Tanks with lamps and plumbing are depreciated over 10–15 years. Additional costs include an air blower + plumbing, water supply (pumps, plumbing, fittings, filters, UV Sterilization System), forklift, washing equipment, vehicles, renewal of baskets and tubes, fresh water, salt, misc. hatchery equipment.

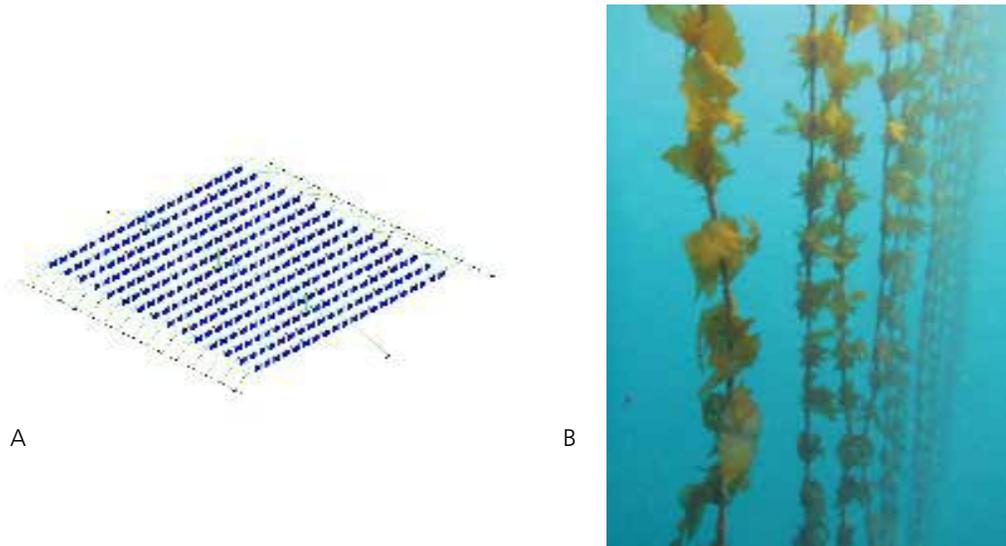
At a production capacity of 1 million meter lines/year (enough for 16 production modules) the hatchery employs 4 full-time workers plus an additional 4 full-time equivalents occasional. A 10 million meter/year hatchery generates 25 full-time jobs, plus an additional 16 full-time equivalent occasional.

Grow-Out and Harvest Phases

Seedling lines are deployed as shown in Figure 6. Screw anchors hold each 150 × 150 m module in place. The longlines are 220 meter (150 m floating + anchorage) and made of 16 mm rope, with 25 buoys (17 liter) along the length and held down with 21 concrete blocks (40 kg).

For deployment, a team (2 men) places 16 baskets (192 tubes; 998 meter seedling lines) on one longline

FIGURE 6. (A) Schematic diagram of a scalable seaweed grow-out module. Each 150 x 150 m module costs approximately \$11,000 and can produce ~120 MT wet weight of seaweed per year. (B) Seaweed sporophytes growing on the seedling lines suspended from the longline. Photo: R. Bjerregaard.



in 2 hours operation from a small boat. Boats for deployment are needed for 2,500 hours/year plus 8 liter/hour diesel fuel.

After 10–12 weeks for *Eucheuma* spp. or 6–7 weeks for *Porphyra* spp., harvesting begins. Some species are harvested in their entirety and new seedling lines installed; others are trimmed every 10–15 days and allowed to regrow throughout the growing season. A team (2 men) harvests one longline with 10 tons (wet weight) in 45 minutes. Harvest boats can offload to a barge in 15 minutes. All together = 60 minutes. On one working day (9 hours) they can harvest 7 longlines. Harvest boats are needed for 3,000 hours/year plus 17 liter/hour diesel fuel. Total production from each 150 x 150 m module is ~120 tons wet material per year.

CONCLUSIONS AND RECOMMENDATIONS

The expansion of seaweed farming in tropical developing countries could have large positive impacts on local poverty, ecosystem management and climate change mitigation. Being able to produce enough biomass and protein for the growing and increasingly wealthy human population with no new land and freshwater

expropriation for agriculture would dramatically reduce humanity's ecological footprint relative to current trends and projections.

The growth of seaweed farming is constrained primarily by lack of proper marine spatial plans and appropriate financing. The current industry in the tropics is based on inshore areas where multiple conflicting users vie for space.

To grow large enough to have a global impact, floating rack systems of the type used in the northern hemisphere should be adapted to tropical conditions so they can be deployed further offshore. Such a system has been field tested under rigorous conditions and has the potential to generate 12 tons of dry seaweed per unit. Although not as productive as the best systems in the north, approximately 42 million of these simpler modular units occupying 950,000 km² could produce 500 million dry tons of seaweed at a total first sale value of \$500 thousand million in current markets.

The need for technological improvements has consequent implications for scale of investment, which could be a hindrance to many potential seaweed growers, creating space for government engagement to support new smaller and medium-scale entrepreneurs.

Other opportunities for engagement by governments and international agencies committed to sustainable development include investments in transport infrastructure, storage facilities, food preparation

and/or hydrocolloid extraction plants, applied research in solar drying and biogas technology *inter alia*, technical training and marine spatial planning.

CONTRIBUTORS

Rasmus Bjerregaard, Seaweed Seed Supply A/S (Denmark)

Diego Valderrama, University of Florida

Neil Sims, Kampachi Farms, Ltd. (USA)

Ricardo Radulovich, University of Costa Rica

James Diana, University of Michigan

Mark Capron, Ocean Forests, Inc. (USA)

John Forster, Forster Consulting, Inc. (USA)

Clifford Goudey, C.A. Goudey & Associates, Inc. (USA)

Charles Yarish, University of Connecticut

Kevin Hopkins, University of Hawaii

Michael Rust, NOAA Fisheries

Cedric McKinnie, World Bank

Thanks to Stefan Kraan, Ocean Harvest Technology; Prof Rene Wijffels, Wageningen University, the Netherlands and Jens Legarth, Fermentation Experts Inc. for valuable technical insights and to Richard P. Stumpf, NOAA National Centers for Coastal Ocean Science and Norman Kuring at NASA for help with chlorophyll *a* mapping.

More information:

Randall Brummett, World Bank,
rbrummett@worldbank.org

Steffen Hansen, Global Environment Facility,
shansen@thegef.org

REFERENCES

- Azofeifa, K., Y. Angulo & B. Lomonte. 2008. Ability of fucoidan to prevent muscle necrosis induced by snake venom myotoxins: comparison of high- and low-molecular weight fractions. *Toxicon* 51(3): 373–380.
- Babel, S., S. Sharma & R. Rajvanshi. 2015. Block printing with reactive dye using sodium alginate. *Man-Made Textiles in India* 43(6): 220–222.
- Bixler, H. J. & H. Porse. 2010. A decade of change in the seaweed hydrocolloids industry. *Journal of Applied Phycology*: DOI 10.1007/s10811-010-9529-3.
- Boden, T. A., G. Marland, and R. J. Andres (2010). Global, Regional, and National Fossil-Fuel CO₂ Emissions. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A. doi 10.3334/CDIAC/00001_V2010.
- Borglum, G. B., & Marshall, J. J. (1984). The potential of immobilized biocatalysts for production of industrial chemicals. *Applied biochemistry and biotechnology*, 9(1), 117–130.
- Bosch, R., M. van d Pol & J. Philp. 2015. Define biomass sustainability. *Nature* 523:526–527.
- Chojnacka, K. (2012). Using the biomass of seaweeds in the Production of Components of Feed and Fertilizers. In S-K Kim (ed) *Handbook of Marine Macroalgae: Biotechnology and Applied Phycology*, pp 478–490.
- Ciais, P., C. Sabine, G. Bala, L. Bopp, V. Brovkin, J. Canadell, A. Chhabra, R. DeFries, J. Galloy, M. Heimann, C. Jones, C. Le Quéré, R.B. Myneni, S. Piao and P. Thornton, 2013: Carbon and Other Biogeochemical Cycles. In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T. F., D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Diaz, R. J. & R. Rosenberg. 2008. Spreading dead zones and consequences for marine ecosystems. *Science* 321: 926–929.
- Duis, K., Inglis, V., Beveridge, M. C. M., & Hammer, C. (1995). Leaching of four different antibacterials from oil- and alginate-coated fish-feed pellets. *Aquaculture Research*, 26(8), 549–556.
- Edwards, M. and Watson, L., 2011. Cultivating *Laminaria digitata*. Irish Sea Fisheries Board, Ireland.
- El Gamal, A. A. (2010). Biological importance of marine algae. *Saudi Pharmaceutical Journal*, 18(1), 1–25.
- FAO (2014). The State of World Fisheries and Aquaculture. *Food and Agriculture Organization of the United Nations*, Rome.
- FAO (2015). World Fertilizer Trends and Outlook to 2018. *Food and Agriculture Organization of the United Nations*, Rome.
- FAO FishStat. (2014). Electronic fisheries database. *Food and Agriculture Organization of the United Nations*, Rome.
- FAOSTAT (2015). *Food and Agriculture Organization of the United Nations Statistics Division*. Rome.
- Fukahori, S., Yano, H., Akiba, J., Ogasawara, S., Momosaki, S., Sanada, S., & Kojiro, M. (2008). Fucoidan, a major component of brown seaweed, prohibits the growth of human cancer cell lines in vitro. *Molecular medicine reports*, 1(4), 537–542.
- García-Casal, M. N., Pereira, A. C., Leets, I., Ramírez, J., & Quiroga, M. F. (2007). High iron content and bioavailability in humans from four species of marine algae. *The Journal of Nutrition*, 137(12), 2691–2695.
- Gattuso, J. P., & Hansson, L. (2011). Ocean acidification: background and history. *Ocean acidification*, 1–20.

- Hu, J., Yang, B., Lin, X., Zhou, X. F., Yang, X. W., & Liu, Y. (2012). Bioactive metabolites from seaweeds. *Handbook of Marine Macroalgae: Biotechnology and Applied Phycology*, 262–284.
- IEA, 2014. Key World Energy Statistics 2014. *International Energy Agency*, Paris.
- Jost, V., Kobsik, K., Schmid, M., & Noller, K. (2014). Influence of plasticiser on the barrier, mechanical and grease resistance properties of alginate cast films. *Carbohydrate polymers*, 110, 309–319.
- Kim, Se-Kwon (Ed). (2012). *Handbook of Marine Macroalgae: Biotechnology and Applied Phycology*. Hoboken, NJ: John Wiley & Sons.
- Kim, J. K., G. P. Kraemer and C. Yarish. 2014. Field scale evaluation of seaweed aquaculture as a nutrient bioextraction strategy in Long Island Sound and the Bronx River Estuary. *Aquaculture* 433:148–156.
- Kim, J. K., S. Kottuparambilm S. H. Moh, T. K. Lee, Y. Kim, J. Rhee, E. Choi, B. H. Kim, Y. J. Yu, C. Yarish and T. Han. 2015. Potential applications of nuisance microalgae blooms. *J. Appl. Phycol.* 27:1223–1234.
- Lassaletta, L., Billen, G., Grizzetti, B., Anglade, J., & Garnier, J. (2014). 50 year trends in nitrogen use efficiency of world cropping systems: the relationship between yield and nitrogen input to cropland. *Environmental Research Letters*, 9(10), 105011.
- Lenstra, J., van Hal, J. and Reith, H., 2011. Economic aspects of open ocean seaweed production. Energy Research Centre of the Netherlands, Petten, the Netherlands.
- Loureiro, R., CMM Gachon & C. Rebours. 2015. Seaweed cultivation: potential and challenges of crop domestication at an unprecedented pace. *New Phytologist*, www.newphytologist.com.
- Mišurcová, L. 2012. Chemical composition of seaweeds, pp. 173–192, in: Se-Kwon Kim. *Handbook of Marine Macroalgae*. Wiley-Blackwell, West Sussex, UK.
- Pereira, L. (2011). A Review of the Nutrient Composition of Selected Edible Seaweeds. In *Seaweed: Ecology, Nutrient Composition and Medicinal Uses*. Pomin, V. H. (Ed.). Nova Science Publishers: Hauppauge, pp. 15–50.
- Pereira, R. & C. Yarish. 2008. Mass production of Marine Macroalgae. In Sven Erik Jørgensen and Brian D. Fath (Editor-in-Chief), *Ecological Engineering*. Vol. [3] of *Encyclopedia of Ecology*, 5 vols. pp. 2236–2247. Oxford: Elsevier.
- Philippesen, A., Wild, P. and Rowe, A., 2014. Energy input, carbon intensity and cost for ethanol produced from farmed seaweed. *Renewable and Sustainable Energy Reviews* 38, 609–623.
- Pike, I. H. & A. Jackson. 2010. Fish oil: production and use now and in the future. *Lipid Technology* 22(3):59–61.
- Radulovich, R., Neori, A., Valderrama, D., Reddy, C. R. K., Cronin, H. & Forster, J. (2015). Farming of Seaweeds. In B. Tiwari and D. Troy (Eds.) *Seaweed Sustainability—Food and Non-Food Applications* (pp. 27–60). Amsterdam: Elsevier.
- Radulovich, R., Umanzor, S., Cabrera, R., & Mata, R. (2015). Tropical seaweeds for human food, their cultivation and its effect on biodiversity enrichment. *Aquaculture*, 436, 40–46.
- Rhein-Knudsen, N., Ale, M. T., & Meyer, A. S. (2015). Seaweed Hydrocolloid Production: An Update on Enzyme Assisted Extraction and Modification Technologies. *Marine Drugs*, 13(6), 3340–3359.
- Samaraweera, A. M., Vidanarachchi, J. K., & Kurukulasuriya, M. S. (2011). Industrial applications of macroalgae. *Handbook of Marine Macroalgae: Biotechnology and Applied Phycology*, 500–521.
- SINTEF, 2014. A New Norwegian Bioeconomy Based on Cultivation and Processing of

- Seaweeds: Opportunities and Research and Development Needs. *SINTEF Fisheries and Aquaculture*, Norway.
- Swaney, D. P., Hong, B., Ti, C., Howarth, R. W., & Humborg, C. (2012). Net anthropogenic nitrogen inputs to watersheds and riverine N export to coastal waters: a brief overview. *Current Opinion in Environmental Sustainability*, 4(2), 203–211.
- Tønnesen, H. H., & Karlsen, J. (2002). Alginate in drug delivery systems. *Drug development and industrial pharmacy*, 28(6), 621–630.
- USDA. 2015. World agricultural supply and demand estimates. WASDE 546. <http://www.usda.gov/oce/commodity/wasde/latest.pdf>.
- Valderrama, D., Cai, J., Hishamunda, N. and Ridler, N., 2013. Social and economic dimensions of carrageenan seaweed farming. Fisheries and Aquaculture Technical Paper 580. FAO, Rome.
- Valderrama, D., Cai, J., Hishamunda, N., Reidler, N., Neish, I. C., Hurtado, A. Q., Msuya, F. E., Krishnan, M., Narayanakumar, R., Kronen, M., Robledo, D., Gasca-Leyva, E. and Fraga, J., 2015. The economics of *Kappaphycus* seaweed cultivation in developing countries: a comparative analysis of farming systems. *Aquaculture Economics and Management* 19, 251–277.
- Van den Burg, S., Bikker, P., van Krimpen M. and van Duijn, A.-P., 2013. Economic feasibility of offshore seaweed production in the North Sea. Presentation at the 2013 Aquaculture Europe Conference. Trondheim, Norway. Available at <http://www.slideshare.net/svdburg/economic-feasibility-of-offshore-seaweed-production-in-the-north-sea>.
- Vijayaraghavan, K., & Joshi, U. M. (2015). Application of seaweed as substrate additive in green roofs: Enhancement of water retention and sorption capacity. *Landscape and Urban Planning*, 143, 25–32.
- Wei, N., Quarterman, J., & Jin, Y. S. (2013). Marine macroalgae: an untapped resource for producing fuels and chemicals. *Trends in biotechnology*, 31(2), 70–77.
- Yin, R. I., & Lewis, J. G. (1981). *U.S. Patent No. 4,257,816*. Washington, DC: U.S. Patent and Trademark Office.
- Zhang, J., Y. Huo, H. Wu, K. Yu, J. K. Kim, C. Yarish, Y. Qin, C. Liu, R. Xu and P. He. 2014. The origin of the *Ulva* macroalgal blooms in the Yellow Sea in 2013. *Marine Pollution Bulletin* 89 (1–2): 276–283.