Seaweed and food security

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1 INTRODUCTION

Should farmed seaweeds become a more important part of our diets and thereby contribute to global food supplies more than they do now? There are reasons to think that the answer to this question is yes, and this chapter explains why. However, first there is a need for perspective on the nature and scale of the challenge involved.

In 2009, the FAO convened a high-level forum on "Feeding the World in 2050" (FAO, 2009). It concluded that by mid-century the world's human population would increase to 9.1 billion, 34% higher than it was in 2009. Also, continued urbanization would mean that in 2050, 6.4 billion of these people (70%) would live in cities. They would be richer on average than current city dwellers and this would most likely mean that their diets would also be richer. The FAO predicted that the consequence of these changes would be that global demand for food by 2050 will increase by 70% or about 5.4 thousand million tons (Gt; FAO, 2009), since annual world food production at that time was about 7.7 Gt. To appreciate what a huge amount that is, consider the production levels today for capture fisheries and aquaculture in Table 11.1. They represent only 1.0% and 0.8%, respectively, of total food production or 1.7% and 1.2% of the needed increase. Or consider that world production of farmed seaweed in 2012 was only 23.8 million tons (Mt), 0.3% of total food production. How is it possible to contemplate an increase in production of farmed seaweed such as to make a significant contribution to 5.4 Gt?

1.1 ASKING MORE OF THE OCEANS

The answer follows from an appreciation of the constraints that now face agriculture, which are detailed in the next section, and from the idea that as we reach limits on what we can ask from our lands, we have barely begun to ask how we might produce more from the sea. The oceans cover over 70% of Earth yet, when freshwater fisheries and freshwater aquaculture production (11.6 Mt and 41.7 Mt, respectively) are deducted from the totals given in Table 11.1, the figures show that they yield only

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Table 11.1 World Food Production in 2012

Food Commodity	Million Tons/Year	Total (%)
Cereals and pulses	2858	32.3
Sugar crops	2103	23.8
Vegetables and fruits (includes tree nuts)	1757	19.9
Roots and tubers	809	9.2
Dairy and eggs	824	9.3
Meat	302	3.4
Fisheries (marine, 79.7 Mt; freshwater, 11.6 Mt)	91	1.0
Aquaculture (marine, 24.7 Mt; freshwater, 41.7 Mt)	67	0.8
Seaweed (farmed, 95.6%; capture, 4.4%)	25	0.3
TOTAL	8836	100

Sources: Data from FAOStat (2014) and FAO (2014).

1.2% of our food. In a world needing to produce 70% more food by 2050, does that make sense and can we do anything about it?

The reason we produce so little food from the oceans is that, until recently, our harvests have been almost entirely extractive, or capture-based, which is a hunting-like activity equivalent to hunter-gathering before humans learned to farm, thereby greatly increasing the productivity of the land through crop and animal husbandry. Moreover, most of what we take from the oceans presently is animals—mostly finfish captured in commercial fisheries. They occupy trophic levels two, three, or more steps up the marine food chain and the loss between each step is about 90% of the food energy consumed. This means, assuming an average trophic level for the world's commercial marine fisheries of 3.0, which is probably a little low (Duarte and Garcia, 2004; Pauly and Watson, 2005), that the 79.7 Mt of fish that were caught in marine fisheries in 2012 (FAO, 2014) derived originally from 7.97 Gt of marine primary producers, mostly microalgae or phytoplankton. The oceans would yield far more food if we could harvest these tiny primary producers directly. However, it is not practical to harvest oceanic microalgae and if we are going to harvest more primary production from the sea we must turn instead to macroalgae (seaweeds), which we can grow in ocean farms (Chapter 3). Like microalgae and plants on land, they need nothing more than sunlight as a source of energy to convert water, carbon dioxide, and inorganic nutrients, which are naturally available in adequate quantities in most coastal locations, into sugars that then provide the chemical energy and intermediaries to synthesize more complex carbohydrates, proteins, fats, and other organic nutrients that are the basis of life.

The apparent potential is huge. There are no practical limits to the availability of water in the oceans, as there are limits on freshwater in agriculture, and they also offer an abundance of space and sunlight. Carbon dioxide is also readily available, to the extent that its dissolution from our greenhouse gas-enriched atmosphere is now causing "ocean acidification." Extracting some of it by capturing it in seaweed biomass would be an environmental benefit. And, perhaps, after 50 years of the development of what might be called "modern aquaculture," we have learned enough now about farming at sea to be able to contemplate taking marine aquaculture to the next level to produce vegetable matter, such as agriculture, as its primary product, thereby enabling it to become a much more substantial contributor to the global food supply.

If there is a resource limitation to a general expansion of seaweed farming, it is probably the availability of inorganic nutrients, like nitrate, phosphate, and potassium in the open oceans away from the world's continental shelves, where there is often no upwelling. On the other hand, nearshore waters in many parts of the world are often overenriched with nutrients caused by upwelling and terrestrial runoff, the latter being mostly from agriculture and sewage discharges. These cause dead zones and nuisance blooms of both micro- and macroalgae in coastal waters worldwide, and to extract them by farming seaweeds is an environmental service (Kim et al., 2014).

1.2 SEAWEEDS AS FOOD

Though still produced on a very modest scale in terms of global food production, many seaweed species are recognized as wholesome, healthful, and tasty foods (McHugh, 2003; Rajapakse and Kim, 2011; Mouritsen, 2013; Radulovich et al., 2015). Mostly, they are produced and eaten in Asia, where they have been a traditional source of food for centuries, though now, due to the popularity of Asian cuisine, they are becoming more widely known and appreciated in the west. It is not unreasonable to suppose that, if seaweed products that were tasty, easy to prepare, and moderately priced were to become readily available outside Asia, they would quickly assume a much more substantial role in the world's vegetable diet. Therefore, it is plausible to think that the global expansion of a seaweed farming industry could supplement our existing food supply and provide a hedge against the possible failure of agriculture to respond adequately to the food security challenges that now face us (Section 2), with environmental services provided as an added benefit.

Given this potential, it is unclear why most considerations of global food insecurity and what to do about it fail even to mention the possibility of turning to the sea to produce more food. There are notable exceptions, for example, Duarte et al. (2009), Radulovich (2011), and Forster (2013a), but for the most part analysis and proposed solutions are limited to how agricultural production might be increased by technology and how future demand for food might be held in check by changing human behavior. The FAO's "Feeding the World in 2050" does not mention seaweeds or even aquaculture and focuses on increased investment in agriculture as well as poverty alleviation in rural areas. Nor are seaweeds considered in the FAO's most recent analysis of "The role of aquaculture in improving nutrition: opportunities and challenges" (FAO, 2014). In general, when the oceans and their fisheries are considered, it is normally in the context of the damage being done to them through overfishing and ocean acidification, rather than on their vast productive potential (The Royal Society, 2012).

There is no doubt that the continued expansion and increased efficiency of agriculture and how its products are used are vital if the world's people are to be adequately fed in 2050. Therefore, this is where the major effort is rightly directed. But what happens if climate change and lack of freshwater intervene to frustrate efforts to improve agricultural efficiency (Section 2)? Or if growing and increasingly prosperous urban societies are unwilling to eat less meat or be less wasteful, unless they are coerced into it by regulations and/or consumption taxes, which they will resist? Would it not be prudent to have a backup plan? Would it not be worth considering to start work now on the development of a parallel system of food production that would produce food without trespassing on more of Earth's terrestrial resources? Doing so would help to correct damage to our marine environment caused by our terrestrial excesses for which, at present, we have no other plausible solutions. The food security threat and the possibilities and challenges of seaweed farming as a contributor to the solution are discussed in the sections that follow.

2 THE FOOD SECURITY THREAT

2.1 LAND

For any particular agricultural cropping system, total primary production (e.g., tons, t) is determined by land area planted (e.g., hectares, ha) and productivity (e.g., t/ha). Due to shortages of additional adequate land on which to expand agriculture, it is now thought that required new food production must come 90% from increases in productivity and only 10% from the use of additional land (OECD-FAO, 2012). Since agriculture has been operating through millennia, much of all available ice-free land is already used for one or another form of food production, particularly for grazing (Aiking, 2011). For example, the food production system of the United States already uses about 50% of the total land area (Pimentel and Pimentel, 2003). Evidencing this limitation, extensive forest areas continue to be cleared for agriculture, as is currently happening in Asia for rubber plantations (Ziegler et al., 2009). Moreover, due to sea-level rise, many highly productive coastal areas will suffer saline intrusion into aquifers and will eventually be flooded (Ivins, 2009). On the other hand, intensifying existing agriculture to increase output, wherever feasible, leads to an increase in externalities, mainly pollution of waters with chemicals, sediments, and nutrients, which eventually reach the sea (Baveye et al., 2011). Further, several crop production systems worldwide, particularly in developed countries, have already achieved optimized high productivity that can hardly be increased significantly without major changes (e.g., breakthroughs such as developing new cultivars that yield far more per planting, which is a strong and well-funded line of research).

By contrast, transformation of low-input agriculture, particularly in tropical developing countries, may allow for substantial increases in yields even without such breakthroughs. This is the presumption behind a sought-after second green revolution in Africa, whereby yield increases can be obtained from traditional rainfed agriculture when key inputs like improved seed and fertilizers are used instead of poor quality seed and no fertilizer, albeit that recurrent losses to drought are an unavoidable risk (Denning et al., 2009; Sanchez et al., 2009).

2.2 FRESHWATER AND CLIMATE CHANGE

Complicating the above, and adding to a persistent decline in agricultural productivity of over 1% per year (FAO, 2009; Funk and Brown, 2009), climate change, as predicted, is already producing negative effects on agriculture. Increases in air temperature, humidity, and rainfall variability, including drought (Lobell et al., 2011; IPCC, 2014; Lobell and Tebaldi, 2014), affect productivity to the point that projections of food production are becoming unreliable (Milly et al., 2008). In general, climate change threatens all countries, yet estimates are that developing countries are the most vulnerable and will bear between 75% and 80% of the costs of damages (IFPRI, 2009; World Bank, 2010; OECD-FAO, 2011). Desertification processes continue and already 45% of the world's land surface is considered drylands, while 12 million ha of land are degraded yearly through lack of water and related processes (UNCCD, 2011). The recent spurt in "land grabbing" in the humid tropics is really more about "water grabbing" than land (Rulli et al., 2013) since, with sufficient water, crops can be grown almost anywhere. Molden (2007), regarding climate change, noted that "mitigation is about gases, adaptation is about water."

To understand this, the most basic yet commonly ignored fact is that a crop, such as soybean or maize, expends and thus needs to extract from the soil ca. 40,000 L of water per ha per day, or more depending on climate; most of this is for evapotranspiration, since only a small fraction stays in the crop (e.g., FAO, 1998). That is why 1000–2000 L (1–2 t) of water are needed to produce a single kilogram (kg) of grain (Pimentel and Pimentel, 2003; Radulovich, 2011). For beef production, estimates range from 15,000 L to 200,000 L of water to produce one 1 kg, and some consider that producing 1 kg of any grain-fed animal protein requires about 100 times more water than is needed to produce 1 kg of grain protein (Pimentel and Pimentel, 2003; Aiking, 2011). In this same manner, thousands of liters of water are required to produce a liter of biofuel from grain, and a kg of fish meat from freshwater pond aquaculture requires around 5000 L of freshwater to account for direct water losses such as evaporation and seepage (Pillay and Kutty, 2005; Bostock et al., 2010), to which water used to produce any feed on land must be added at a rate of several thousand liters more per kg of edible fish weight. As a rule of thumb, it takes one liter of water per kilocalorie of food produced (UNESCO, 2009), which means that the average human consumption of water through food ingestion is 2000 L per day, based on current food production and consumption patterns (Table 11.1).

Medium- to high-yielding agriculture requires a reliable water supply to realize its potential, since one to a few days without adequate water may wipe out the yield of an entire crop. This is the main reason why the first and so far only successful green revolution of recent times was mainly irrigated (Falkenmark et al., 2009). However, a second green revolution based on irrigation is not possible because, just as most of the best land is now already used for agriculture, more so is usable freshwater all over the world. On average worldwide, agriculture takes 70% of usable freshwater for irrigation, while in the United States it uses 80% and in some countries up to 90% (Pimentel and Pimentel, 2003; Madramootoo and Fyles, 2010). Moreover, water is increasingly being diverted from agriculture to provide for other human demands and, because of this and climate change, there may be an 18% reduction in worldwide water availability for agricultural irrigation by the year 2050 (Strzepek and Boehlert, 2010). For these reasons Falkenmark et al. (2009) concluded that by 2050 "Food security will meet considerable problems… food demand will outpace water availability in many regions of the world, despite an optimistic analysis of access to freshwater and efficient use of this water," while Rockstrom et al. (2007) projected that "with unchanged productivity the water required for food production would have to double… in 2050."

Therefore, most attempts to increase both agricultural cropping area and productivity involve rainfed instead of irrigated agriculture. Other than increasing productivity of already existing irrigated agriculture, a new green revolution in developing countries will have to be mostly rainfed (Rockstrom et al., 2007), with the corresponding variability from rainfall vagaries and climate change described earlier. Thus, the major limitation to obtaining necessary increases in agricultural production, whether by incorporating new areas into agriculture or increasing productivity in existing areas, is the lack of sufficient and reliable freshwater (Molden, 2007).

2.3 FISHERIES

Fisheries have traditionally provided the only other source of food besides agriculture, though they are of an extractive and not of a productive nature. However, the yield from marine fisheries production, which provides most of the world's catch, stopped growing in the late 1980s and has remained steady at about 80 Mt/year since then, with the global total capture in 2012 of 79.7 Mt (Table 11.1). In 2011, the main fishing stocks of the world were 61.3% fully exploited and 28.8% overexploited, with only 9.9% underfished (FAO, 2014). Even if fish populations are recovered or rebuilt (Lorenzen, 2008; World Bank-FAO, 2009; Bostock et al., 2010), reputedly a complex problem (Garcia and Rosenberg, 2010), fishing at sea as a purely extractive activity will not be a global solution to hunger when compared to agriculture's close to 9000 Mt of planned and deliberate annual production, including meat (Table 11.1). Moreover, climate change effects, like increases in acidification and temperature of seawater, may well affect fisheries by affecting fish reproduction, primary productivity, and related processes (Hoegh-Guldberg et al., 2007; Crabbe, 2009), leading to the possible extinction of some species (Cheung et al., 2009) and particularly affecting developing countries that rely considerably on fish protein (Allison et al., 2009; Dulvy and Allison, 2009).

Also and notably, of the 79.7 Mt of marine fish caught in 2012, 21.7 Mt were for "nonfood uses," much of it for aquaculture feed (FAO, 2014). These are called "forage" fish and, together with a sizable share of grain, their use as feed is a major issue in the food debate (Alder et al., 2008; Tacon and Metian, 2009; Turchini et al., 2009; NOAA-USDA, 2010). Animals, as heterotrophs, require feed from one source or another in amounts several times larger than the weight they gain from eating it (the ratio of 10:1 in energy was presented earlier). Therefore, claims of feed conversion ratios between one and two for fish and two and three for chickens and pigs can mislead, since these are based on the ratio of highly dense and dry manufactured feeds versus fresh weights of whole animals, including the inedible parts. Thus, animal production is really a highly reductive "food transformation" activity, not true "food production," which is only obtained from autotrophs through biosynthesis, that is the combination of photosynthesis and the uptake and use of inorganic nutrients from soil or water. In this sense, both agricultural cropping and seaweed farming are analogous food production options, and the proposition that animal production should be moved to sea in order to save water (Duarte et al., 2009) is true only to the degree that the feed is also produced at sea. Otherwise, water used to produce feed or feed components on land must be accounted for. This is important because most water consumed by animal production on land is feed-related (Verdegem et al., 2006). Solutions to growing food shortages can be based on producing meat and other products from animals only to the extent that the primary product to feed them is available.

The scenario just depicted, of current and growing food and water limitations when we need to nearly double food production within a few decades, with no clear alternatives available, has prompted yet another round of Malthusian-like fears of famine (e.g., Pimentel et al., 1999; Schade and Pimentel, 2010; Short, 2009). Traditionally, and according to technological capabilities of the times, analyses of the planet's human carrying capacity have only considered agriculture on land and the need to cap the rate of human population growth (Ehrlich, 1968; Meadows et al., 1972; Cohen, 1995), albeit that we now know that both animal and vegetable farming activities can be conducted in the oceans, by far the largest untapped planetary resource. However, in order to truly contribute to increased food production, sea farming, just like agriculture, must be a net source of food and related products, that is, it must produce mostly vegetable matter, as is the case in global food production now. For example, of the 8653 Mt of food produced on land in 2012 (Table 11.1), 87% was vegetable matter and 13% total animal products, including milk and eggs, a ratio of nearly 7:1 (or 25:1 when considering only meat); this ratio would be substantially bigger if plant biomass from pasture were to be included.

This is especially relevant in the context of understanding Earth's human carrying capacity because producing such vegetable matter at sea takes zero freshwater. Even small rates of success may signify massive freshwater savings on land. For example, based on a rough average between agricultural plant and animal production, about 4,000,000 L (one million gallons) of freshwater can be saved on land per ton of food produced at sea (Radulovich, 2011).

3 SEAWEED AS A FOOD STAPLE

In addition to increasing interest in eating seaweeds as “sea vegetables” in the west, claims for their nutritional and/or medicinal value are many and increasingly prominent in dietary publications (Rajapakse and Kim, 2011; Mouritsen, 2013; Jaspars and Folmer, 2013). Therefore, as discussed in Section 1, it is logical and plausible to link this experience with current concerns about food security and to reason that by turning to the sea we can boost our future food supply by growing more vegetable biomass there. But what are the implications and practicalities of actually doing it? The challenges considered in this section include making seaweed products available, palatable, and affordable to billions of people and establishing beyond any doubt that they are at least nutritionally equivalent to foods they eat now. Section 4 looks at the farming, processing, and cost challenges of producing new mass market seaweed products, while Section 5 describes a novel project to introduce tropical seaweeds as food and farmable species to coastal communities.

For a new food source to contribute significantly to future food security, it would not be unreasonable to suppose that it should comprise at least 5% of the human diet. In 2012, the total world production of food was 8.8 Gt (Table 11.1), so 5% would be 440 Mt. However, because seaweeds contain an average of about 85% water, it is not reasonable to equate them with most staple agricultural crops, which for the most part are dryer and more nutritionally dense. Cereals, for example, contain about 15% moisture. Therefore, it is more reasonable to consider seaweed equivalency in terms of dry product (average 20% moisture), which is how most seaweed is already processed and sold after harvesting. In this form, 440 Mt of seaweed is equivalent to 2.2 Gt wet weight, which is 88 times the weight of seaweed produced worldwide now.

Global production (Table 11.2) and consumption of seaweed is not equally distributed presently and some consumers in countries like Japan may eat many times more than the global average. Asian countries dominate world production with 99%

Table 11.2 World Seaweed Production in 2012

Continent (Countries)	Mt	%
Africa (Zanzibar)	0.16	
America	0.005	
Asia	23.55	99% of cultivated
Temperate (China, Japan, Korea Republic, Korea DPR)	14.73	62% of cultivated
Tropical (Indonesia, Philippines, Malaysia, Vietnam)	8.82	37% of cultivated
Europe	0.007	
Oceania	0.02	
Total world cultivated	23.8	95.6% of total
Total world “capture”	1.1	4.4% of total
Total world (cultivated + capture)	24.9	

Sources: Data from FAOStat (2014) and FAO (2014).

of the total, while most maritime countries produce little or none. Therefore, though the numbers above provide perspective on the scale of the challenge involved and can serve to guide public policy if the idea is embraced by society at large, there is clearly potential for major growth, especially outside Asia, and the 5% goal may not be unrealistic. It may also guide industry development because it suggests that, as in agriculture, a few seaweed species will probably have to become accepted as food staples in the same way as we now accept the major agricultural products. This does not mean that there will not continue to be enormous value in having a wide variety of species for consumers to choose from, but for reasons of cost, palatability, and nutritional value it seems likely that a few species will emerge as core commodities. In this respect, it is important to note that the generic use of the term "seaweeds" in books and articles about sea vegetables may sometimes mislead, giving the impression of conformity in their biology and composition, which is not the case. In fact, as described in Chapter 2, seaweeds are as widely diverse in these respects as terrestrial plants, including substantial differences in species between temperate and tropical waters.

The existing seaweed farming industry has already selected several species that do well in farms, such as *Laminaria japonica*, *Saccharina lattisima*, and various *Porphyra* spp. for temperate waters, and *Kappaphycus alvarezii* and some *Eucheuma* spp. for tropical waters, though these latter species are grown mainly for hydrocolloid production, while some *Gracilaria* spp., *Ulva* spp., *Caulerpa* spp., and *Sargassum* spp. are more commonly grown for food, yet in far smaller amounts. However, it is too early yet to settle on winners. The number of seaweed species has been roughly estimated at 8000–10,000 (Lüning, 1990; Thomas, 2002), with extensive regional species richness and global diversity patterns (Abbott and Norris, 1985; Kerswell, 2006). Of these, the FAO (2013) established 34 as the number of cultured seaweed species, and Zemke-White and Ohno (1999) documented that 145 seaweeds species are known to be used for human consumption and 101 for hydrocolloids. Moreover, these and other species have huge potential for further selection and breeding to improve important traits, such as growth and composition, where improvements will help to bring the costs of producing the raw seaweed down and put its value up. By such improvements, combined with increased farm efficiency, seaweed products will come to offer the combination of affordability and nutritional value that are vital if they are ever to become widely used, and thus farmed, as staple foods.

3.1 MARKET DEVELOPMENT

Assuming these improvements will be realized, there are three ways in which markets for seaweeds are likely to develop. First, demand will increase in industrialized countries where consumers can afford to pay a premium for products whose cost reflects the early stage of development of the seaweed value chain. For them, new, appealing, and relatively affordable seaweed products would offer variety and the promise of nutritional benefits that would encourage them to eat more of them, thereby easing pressure on other food commodities. Second, seaweed farming for food can be encouraged in developing countries where there is limited or no seaweed farming presently, or there is farming only for hydrocolloids, and where some coastal communities could improve both their diet and economic circumstances by learning to make more productive use of their nearshore waters. Third, and eventually, seaweeds will be farmed on a large enough scale and at a low enough cost that they can be processed into affordable food ingredients that complement the agricultural staples on which many of the world's people now rely as practically their only source of food.

Of these possibilities, the first seems most likely to move seaweed production and processing forward fastest, even though it might seem counterintuitive that the effort would focus first on feeding people who are already well fed, with benefits accruing only indirectly to those who are food insecure. However, development is likely to occur quickest in countries that have the technical and financial resources to innovate, consumers who are willing and able to pay a premium for such innovation, and aquaculture companies who have a long experience of developing new markets for their products. The latter is especially true of salmon farming companies who are now producing seaweeds as they experiment with integrated multitrophic aquaculture. Their established market networks and product development experience are likely to lead to new seaweed products that are processed and packed for convenience to be used as ingredients in a range of dishes by western consumers. This will help to increase the number of possible applications, including the use of seaweed in foods that are mass produced and consumed, such as pizza. In fact, as discussed in Chapter 7, polysaccharides (i.e., hydrocolloids) extracted from seaweeds are already used as thickeners and gelling agents in many processed food products and, though their role in these products is functional rather than nutritional, it suggests a starting point.

Seaweed production for food in developing, mostly tropical countries is advancing and the potential is extraordinary, considering that 49 of the 79 countries with moderate to extremely alarming global hunger indices have coasts (Welthungerhilfe, 2012). Therefore, its potential food security contribution for the communities that engage in it is very substantial. However, its potential to contribute beyond this will likely depend more on publicly and internationally aided food and nutrition-related development efforts that promote both farming and marketing innovations to create more demand for seaweed products in urban communities. The same applies to the third possibility, which presumes that economies of scale in farming can be achieved and that affordable, processed seaweed products will be developed that can be used frequently as ingredients in a wide range of food offerings, as well as other products like pharmaceuticals and animal feed, if this can be done profitably. These advances will almost certainly have to be made in countries with the resources to invest in the research and development to bring them about.

3.2 NUTRITIONAL EQUIVALENCE

Development will also require that the nutritional value of seaweeds, as well as the effects of their prolonged consumption, are examined more closely. Their chemical composition is reviewed in Chapter 5, which shows how widely this can vary both between species and seasonally within species (MacArtain et al., 2007; Pereira, 2011). They contain carbohydrates, proteins, minerals, fats, and vitamins (Chapters 6, 7, and 8), just like plants, and these often consist of many or most of the specific nutrients that are considered to be an essential part of the human diet. For example, essential amino acids in the protein of the red seaweed *Palmaria palmata* can constitute almost 46% of the total amino acid fraction, an amount quite similar to that recorded for ovalbumin, though the total protein content varies considerably with season (Fleurence, 2004).

The health benefits of eating seaweeds have also been documented. In a review for the Scottish Food Health and Innovation Service (Jaspars and Folmer, 2013), 21 health benefits are listed, including the following:

1. regulation of blood sugar and cholesterol levels,
2. reduction in lipid absorption in the gastrointestinal tract,
3. weight loss and antiobesity effects,
4. cardiac health improvement, and
5. promotion of intestinal health.

However, the benefits of these obviously favorable attributes may not apply equally to all consumers because some of the health benefits of some species seem to be based on the fact that they are relatively indigestible. For example, Fleurence (2004) reports that seaweed protein digestibility in *P. palmata* appears to be limited by the presence of various antinutritional compounds, such as polysaccharides and trypsin inhibitors, and notes that the protein in powder made from this species was only 56% digestible when compared to casein in in vitro digestibility studies. The seaweed carbohydrates (polysaccharides) that are extracted from certain seaweed species for use as gelling agents and thickeners in processed foods are also often indigestible and function as soluble dietary fibers. They offer a wide range of beneficial physiological functions, including increased satiety, increased gut transit time, and reduced cholesterol absorption, but they offer little or no digestible food energy. Moreover, polyphenols extracted from certain brown seaweed species decrease blood glucose levels after high carbohydrate meals, since they interfere with the enzymes amylase and sucrase involved in the digestion and assimilation of carbohydrates (Jaspars and Folmer, 2013).

Therefore, like terrestrial plants, the nutritional value of seaweeds may vary substantially, depending on the species and the nutritional needs and status of those who eat them. The health benefits listed above are obviously highly beneficial to people who are already well fed or overfed, but this may not be the case for certain individuals or those whose diet is nutrient limited. Also, composition is not the same as bioavailability, and studies that report only on the nutrient composition of seaweeds may mislead. As noted earlier, there are thousands of different seaweed species growing in widely different environments and, despite the long experience of consumption of a few species in Asia, little or nothing is known about others. This is especially true of tropical species that may be farmed in the future, some of which may turn out to have uniquely favorable nutritional characteristics that make them especially valuable for large-scale production. Others may be of less value. So, if seaweeds are to be promoted as alternatives to terrestrial plants eaten now and as a solution to global food insecurity, it is necessary to conduct species-specific research on their nutritional value alongside research on farming and product development.

In this context it is interesting to note that in Japan, where seaweed has been eaten for many years, some people can digest it better than others. This is because the bacteria that live in their guts have acquired the genes that encode for the production of enzymes that break down porphyran, the polysaccharide found in *Porphyra* (nori). It is thought that these genes were acquired originally from marine microbes that were likely eaten with "nori" and it is the first clear-cut example in which a gut microbe has gained a new biological niche by acquiring genes from an ingested bacterium (Ledford, 2010). This and other evidence suggest that there is ample scope in the long term to improve the nutritional value of seaweeds through selection, breeding, and processing, but first, there is a need to understand what the specific challenges and opportunities are.

There is another nutritional question that relates to the high concentration of minerals in seaweeds. It is well known that they are rich in nutritionally important minerals, such as iodine, iron, zinc, potassium, magnesium, calcium, selenium, and phosphorus, and their food value is often advocated for this reason (Burtin, 2003; Jaspars and Folmer, 2013). But is it possible to have too much of a good thing? For example, the iodine in some seaweeds may cause increased levels of serum thyroid-stimulating hormone, and there have been case reports of a condition known as carotenodermia (yellowing of the skin) when large amounts of seaweed are eaten frequently (Nishimura et al., 1998). While at present levels of seaweed consumption such concerns are slight and other nutritional benefits are likely to outweigh them, if seaweeds are to become food staples and substitute for foods that humans have been eating for thousands of years, there is a need to be watchful for circumstances in which there may be unanticipated negative consequences.

There is also a need to be watchful for the possible accumulation of toxins in some seaweeds, especially heavy metals, if they are grown in polluted waters. Some seaweeds are known to accumulate certain toxins (Giusti, 2001; Sudharsan et al., 2012), and a health warning based on research conducted on rats has been issued by the UK Food Standards Agency for one edible species, *Hizikia fusiformis*, which accumulates arsenic present in water (Katsuhiko and Konomi, 2012). All of this information reinforces the idea that in turning to the sea to contribute more to the world's food supply than it does now and to help provide the huge quantities of additional food that will be needed in the future, aquaculture is where agriculture was hundreds of years ago. The opportunity is vast and the technical resources available now to take advantage of it would have been unimaginable to early agronomists, but the challenges are no less and there is a need for care as they are confronted.

4 SEAWEED FARMING OPPORTUNITIES AND CHALLENGES

If seaweed is to reach the status of a food staple there are regulatory, operational, and technical questions to answer in addition to those related to the market and nutritional equivalency. They include the following:

- making space available for seaweed farms in coastal waters;
- developing cost-efficient farming, harvesting, and transportation systems, including farms offshore; and
- processing or biorefining raw seaweed to maximize its value.

4.1 SPACE IN COASTAL WATERS

The apparent need and opportunities notwithstanding, it is clear that, if seaweed farming is to advance as imagined, it will be necessary for maritime nations to allow access to space in their coastal waters for seaweed farmers to establish their farms. In all or most cases, the space within each nation's exclusive economic zone (EEZ) is managed by governments in the public interest. There is no private ownership, or body of established land-use law that governs it, as there is on land, and proposed new uses are often resisted by existing users. Consequently, the process of obtaining permission to use coastal space for something new, such as seaweed farming, is often difficult and inhibits entrepreneurial risk taking, which is at the heart of innovation. This has been the case in the development of much marine aquaculture worldwide in the last 40 years and, although seaweed farming promises benefits to society through both food supply and environmental contributions, the process of granting space in coastal waters for new seaweed farms, whether it be through leases or ownership, is still likely to impede progress.

Of course, it is right that governments should be precautionary in managing public assets, but there must be a balance between caution and risk, and, as explained in Section 2, the risk of a future world food crisis is real and urgent. If the case made here is accepted, namely, that seaweed farming is a way to hedge some of that risk, then a case can also be made that using space in coastal waters for seaweed farms is in the public interest and government action to allocate coastal space should follow as a matter of priority.

This prompts the following question: how much coastal space would be needed? Reported annual yields from seaweed farms vary widely from less than 10 t/ha dry weight to more than 100 t/ha dry weight, depending on the species, location, and farming method. For planning purposes, an average yield of 20 t/ha/year dry weight is probably a reasonable working assumption and is used in the calculations below. It is based on average yields from large-scale *L. japonica* farming in China (Chen, 2006). Therefore, to grow 440 Mt would require 22 million ha, or only 0.06% of the oceans' total surface area (361 million km^2), or 0.16% of the world's coastal nations' EEZs (139 million km^2), or 0.86% of the same countries' continental shelves (25.7 million km^2).

However, while it may be possible eventually to grow seaweed at a commercial scale in open water farms many kilometers offshore, or even in floating farms hundreds of kilometers away in the open ocean (Chynoweth, 2002), in the short term, for reasons of engineering and logistics, farms will almost certainly need to be anchored structures nearer to shore. The early stages of development will therefore be more intrusive than the above figures suggest and, though the early farms will also be relatively few in number and probably quite small, governments, if they believe that this is a wise and prudent use of the resource, will have to be willing to deal with potential conflicts about the use of the coastal space that the farms will need. The most likely outcome is that some governments will understand this and the economic benefits it will bring, while others will hesitate, making the global response to the opportunity less multinational and slower than it might otherwise be or need to be.

4.2 DEVELOPMENT OF COST-EFFICIENT FARM SYSTEMS

Seaweed farming is already quite cost efficient. The average cost of production of *L. japonica* in China, for example, is about USD 650–700/t dry weight (Chen, personal communication), while costs reported by the FAO for carrageenan seaweed farming range from an improbable low of USD 30/t dry weight in the Solomon Islands to USD 689/t dry weight in Mexico (Valderrama et al., 2013). By comparison, an estimated cost for producing corn in Iowa in the United States in 2014 was USD 195/t and for soybeans USD 408/t (Iowa State University, 2014), though costs are likely higher in many other countries. Therefore, by comparison with major agricultural commodities produced in the United States, it is expensive, presently, to grow seaweed but not so expensive as to think that with larger-scale development and mechanization it cannot become competitive, especially since some seaweeds have apparent advantages over terrestrial crops. For example, because some of them are fast-growing, it is often possible to produce multiple crops per year in the same space, while the aquatic environment allows for farming all year round in most latitudes. Also, since coastal waters are often rich or overenriched with nutrients, there is no need for fertilizer, which is a substantial input cost incurred by terrestrial farms. Fast growth and multiple crops per year allow for a comparatively high yield per unit area. For example, the 20 t/ha/year dry weight for *L. japonica* in China contrasts with corn and soybean average yields in the United States of about 10 t/ha/year and 3 t/ha/year, respectively.

However, there are also disadvantages. That the seaweed farming industry is centuries behind agriculture in the scale of its farming operations and level of mechanization makes it much less efficient than it might be, with less infrastructure to support it. Arguably, this means it also has more potential to improve, but the work and the investment to do it is still needed. Also, the high water content of seaweeds demands that most farmed seaweed is dried after harvest, which can be expensive, especially if sun drying is not an option. And, as noted earlier, seaweed farmers have barely begun to develop improved, domesticated strains of seaweed that grow better than wild genotypes and/or yield more nutrients of value. These and other challenges, or opportunities, are all susceptible to research and to collaboration between academia and industry but, for that to happen in countries outside Asia, a clear path must be established for an industry to begin.

4.3 OFFSHORE FARMS

The concept of offshore seaweed farms was mentioned earlier as a means of reducing conflicts about the use of space for seaweed farms in nearshore waters. However, “offshore” is hard to define because there are so many permutations of different coastal conditions to which it could apply. Conceptually, it is about the notion of farming in “bigger” water where there is more space and more water volume and where its use for farming intrudes less on other users. Almost certainly, it means distant from the coast, >2 km being one suggestion (Lovatelli et al., 2013), and it also means greater exposure to waves and most likely greater depth, all of which bring engineering and logistic challenges (Forster, 2013b). But, if these can be resolved, it also offers much bigger potential. Some seaweed species may be especially well suited to farming in such environments because they are naturally adapted to living in waves (surf zones) and have air-bladders that allow them to grow upward from a holdfast below the surface; therefore, structures to which they are attached can be anchored below the surface, avoiding the worst of the waves, while at or near the surface they may benefit from the wave-induced water flow across their blades, which breaks down diffusion barriers that may otherwise restrict their access to CO_2 and nutrients (Roesijadi et al., 2008).

Uncertainties about definition and physical matters notwithstanding, it seems quite certain that, if seaweed farming is to develop on a scale where it could provide 5% of our food, most of it must be done offshore eventually. Though 22 Mha is only a small proportion of the total ocean space available, it would represent a substantial intrusion in nearshore waters, even on a global scale. Therefore, the development of offshore farm structures and mechanized operating systems to support them is a priority if the 5% goal is to be achieved. For this reason, developed, technically advanced countries may be better placed to lead such efforts than less advanced countries, even though the latter may have greater need for the food and, therefore, greater incentive to grant permission to use space in their coastal waters for such development.

4.4 PROCESSING SEAWEED TO MAXIMIZE VALUE

Many, if not most, of our staple foods are sold dry to be used as ingredients in processed foods such as bread or in recipe dishes. Drying confers shelf stability without refrigeration and simplifies packaging and distribution, and for these reasons most of the seaweed sold for food today is also sold dry, a common and familiar form being sheets of dried *Porphyra* sp. (nori), which forms the wrap around sushi. In the kitchen dry seaweed products are often rehydrated and used in dishes such as salads, or they may be rehydrated in soups or included with other ingredients in cooked dishes. They may also simply be used dry as a garnish or seasoning. Therefore, the seaweed industry has already developed a wide range of shelf stable foods and, notwithstanding the cost of drying a wet raw material such as seaweed, already uses well-established food processing methods to make product forms that could allow them to become food staples. The challenge of doing this may not be how the raw material is processed but rather how the dried products are promoted, sold, and used as well as how they are made available more widely than they are now at prices that consumers find affordable.

However, it is legitimate to ask if there are other ways in which value might be derived from the raw material. For example, through more sophisticated bioprocessing, or biorefining, could purified products be made that would add value and widen potential demand? This is relevant and topical on two counts. First, there is already a large and well-established seaweed processing industry (Chapters 6, 7, and 8) that extracts the hydrocolloids agar, alginate, and carrageenan from brown and red seaweeds for use mostly as texturing agents, emulsifiers, and stabilizers in processed food products such as ice cream, yogurt, and sausage (Bixler and Porse, 2011). Global sales of these products totaled 86,100 t in 2009 with a total sales value of USD 1018 million or an average value of USD 11.82/kg. So, there is already an established industry producing high value, processed seaweed products that are used mostly in the food industry, albeit as functional ingredients rather than as a nutrient source. However, the protein, fat, and minerals in the seaweeds from which the hydrocolloids are extracted, which represent 70–92% of the raw dried seaweed used, are mostly wasted (Valderrama et al., 2013). This suggests economic opportunity lost and unnecessary costs for effluent treatment or the imposition of environmental costs on receiving waters if the effluent is not treated. Looked at in terms of global food security concerns, this seems like regrettable waste and research to find ways to recover these nutrients could add substantially to the amount of food produced from seaweed that is already harvested.

Second, as described in Chapter 16, there is interest in seaweed as a sustainable fuel source, which has prompted innovation in how best to extract the energy from raw seaweed material. In essence, this means converting the hydrocolloids and other carbohydrates in seaweeds into biomethane by anaerobic digestion (Chynoweth, 2002) or, through more sophisticated processing, converting them into sugars that can then be fermented into ethanol or other alcohols (Van Hal, 2012; Wargacki et al., 2012). The latter approach has the advantage that the process steps involved are less likely than anaerobic digestion to denature the protein and fats in the raw material, which can then, potentially, be recovered for food or feed. Also, by making sugars available first, it provides a carbohydrate feedstock that can be used to produce biochemicals instead of fuel, and these may have a higher value.

Though commercial viability of these or other biofuel production processes remains to be demonstrated, the concept has attracted considerable funds for research in recent years—more, in many cases, than research into production and processing of seaweed for food. This is helping to advance the field as a whole, especially as it means learning how to farm seaweed on a large scale at a lower cost and how to improve the efficiency of biorefining methods to maximize recovery of all valuable constituents, including proteins and fats. It may also have the added benefit of isolating some of the minerals such as potash and iodine in seaweeds that may be cause for concern if eaten in excess in foods and which have value in their own right.

5 MAKING A START: AN EXPERIENCE IN TROPICAL SEAWEED CULTIVATION AND USE AS FOOD

Tropical seaweed cultivation and productivity have been amply demonstrated during recent decades in several countries, particularly in Asia but also in Zanzibar (Table 11.2), yet by far, and different from temperate Asian production, most of the tropical cultivation experience is for hydrocolloid uses instead of food (Valderrama et al., 2013). Although the nutritional adequacy and edibility of tropical seaweeds as human food have been shown, at least at the laboratory level (e.g., Reed, 1907; Robledo and Freile, 1997; McDermid and Stuercke, 2003; Matanjun et al., 2009), seaweeds are essentially an ignored resource in most tropical countries and scant or no cultivation is reported for any purpose, much less for food, in Africa, the United States, Oceania, the Middle East, and Asian countries such as India and Bangladesh (Table 11.2). Considering the varying degrees of food insecurity, extensive coastlines, and millions of coastal inhabitants in need of income-generating employment in many such countries, we evaluated the cultivability of native seaweed species and their use as food in Costa Rica (Radulovich et al., 2013, 2015), a tropical country with coasts on both the Pacific Ocean and the Caribbean Sea and an abundance of native seaweed species (Fernández-García et al., 2011; Wehrtmann and Cortés, 2009).

A lack of methodology to follow made it necessary to establish and implement an agriculture-like protocol to conduct this work and thus to expand its aims into generating experience that could be used in other coastal, tropical, developing countries seeking solutions at sea to their food security needs. The procedure followed consisted of the following:

1. prospecting for seaweed species on both the Pacific and Caribbean coasts, since it was considered essential to use only native species at this early stage;
2. preselecting species based on literature and perceived characteristics, including eating them *in situ*;
3. evaluating preselected species as food;
4. evaluating floating long-line cultivability of preselected species in waters 1.5 m to ca. 10 m deep, using vegetative propagules; and
5. final selection.

5.1 SPECIES SELECTION, COOKING, AND TASTE TRIALS

In all, 42 species from 21 genera were preselected for food and cultivation (Table 11.3). After further food and cultivation tests, 10 species (seven from the Caribbean, *Anadyomene stellata*, *Caulerpa racemosa*, *Codium taylorii*, *Dictyota ciliolata*, *Sargassum*

Table 11.3 Genera of Seaweeds Considered for Cultivability and as Food (with Some Species in Parentheses as Examples)

Green seaweeds (6 genera)
Anadyomene (*stellata*), *Caulerpa* (*racemosa* and *lentillifera*), *Chaetomorpha* (*intestinalis* and *aerea*), *Cladophora* (*vagabunda* and *prolifera*), *Codium* (*tomentosum* and *taylorii*), and *Ulva* (*lactuca*, *fasciata*, *prolifera*, and *compressa*)
Brown seaweeds (4 genera)
Dictyota (*ciliolata* and *stolonifera*), *Laminaria* (*abyssalis* and *brasiliensis*), *Padina* (*crispata* and *durvillaei*), and *Sargassum* (*fluitans*, *liebmannii*, *natans*, *platycarpum*, and *vulgare*)
Red seaweeds (11 genera)
Acanthophora (*spicifera*), *Eucheuma* (*isiforme*, *denticulatum*, and *spinosum*), *Gelidiella* (*acerosa*), *Gelidium* (*serrulatum* and *robustum*), *Gracilaria* (*cervicornis* and *domingensis*), *Gracilariopsis* (*tenuifrons*), *Hydropuntia* (*cornea* and *crassissima*), *Hypnea* (*musciformis* and *spinella*), *Kappaphycus* (*alvarezii*), *Porphyra* (*columbina* and *thuretti*), and *Solieria* (*filiformis*)

platycarpum, and *Gracilaria cervicornis* and four from the Pacific, *Chaetomorpha* sp., *Codium* sp., *Sargassum liebmannii*, with *Ulva lactuca* present on both coasts) were selected as the most promising at this initial stage, which was part of an ongoing effort.

A variety of cooking methods and recipes were tried and tested through tasting panels, including the following:

1. Fresh (raw): as part of salads; blended with fruit and vegetable juices; whole or chopped and then cooked with a variety of dishes like rice and/or beans; prepared alone such as cooked spinach; or mixed in a beverage. They were also baked to crispy or fried in a variety of manners, including a recipe similar to green beans covered with egg batter.
2. Rehydrated after drying and mixed whole or chopped into a variety of dishes such as rice and/or beans or prepared alone like spaghetti.
3. Dried, ground to different levels of coarseness, and used as a partial substitute for wheat and maize flour in a variety of recipes such as cookies, fried chips, grissinis, and spaghetti. They were also used as a meal or a powder to be sprinkled liberally on or into different recipes, including fruit juices and scrambled eggs, or encapsulated into gel capsules to be consumed as a dietary supplement.

Many of the preparations were liked and easily consumed. The most widely accepted ones were the following:

1. *Caulerpa racemosa* and, to a lesser extent, *Codium* spp., served fresh as part of salads as well as *Codium* spp. fried fresh and covered with egg batter;
2. *Sargassum* spp. dried pieces cooked after rehydration with beans at a 10:90 ratio on a dry weight basis (considered of high palatability among participants in several panels who kept asking for more);
3. *Chaetomorpha* sp. cooked and served in a manner similar to spinach;

4. thin, baked grissinis and fried tortilla chips, substituting wheat and maize flours, respectively, with 15% *Sargassum* spp. flour on a dry weight basis;
5. a coarsely ground mixture of three species (*Sargassum* sp., *Ulva lactuca*, and *Gracilaria* sp.) sprinkled liberally on top of different dishes, including blended into fruit and vegetable juices; and
6. the encapsulated mixture of the same three species.

The two latter modes of use were liked very much, to the point that requests for more were received from over 50% of panel participants, even months after the trials (which for these cases lasted 30 days at an ingestion of 1–4 g/d). An interesting and recurrent comment during tasting panels was "I did not expect seaweeds to taste good," reflecting a preconceived resistance that nonetheless was removed after tasting.

Eight of the seaweed species selected, due to advantages in both use as food and cultivation, were subjected to bromatological analyses to determine their content of fat, crude protein, total dietary fiber, and iron on a dry weight basis. Their pooled nutritional content averaged 1.4% fat, 9.8% crude protein, 29.5% total dietary fiber, and 1519 ppm iron. Although there was considerable variation in values, variability was highest in fat content, with over 20 times more in between the highest yielding species (*Dictyota ciliolata*) and the lowest. Iron content and its variability were also high.

5.2 CULTIVATION TRIALS

After minor adjustments of the long-line technology to better fit local conditions, cultivation proved to be simple and effective for many species that were tried, and the methods were easily transferred to fishers, who were eager to implement them through their own pilot projects. For species that were eventually selected, short-term growth rates were within 2.8–7.2%/d while survival rates averaged 84.3% (52.1–100%, not counting recurrent complete die-off of *U. lactuca,* an as yet unexplained phenomenon that is circumvented by frequent harvests). Yields around or over 100 t/ha/year on a fresh weight basis were obtained for *Codium* and *Sargassum*, while the yield of *Gracilaria* and *Ulva*, though lower—76.0 t/ha/year and 51.7 t/ha/year—were quantifiable in spite of high herbivory and recurrent die-off, respectively. While yields averaged 95.7 t/ha/year on a fresh weight basis, when converted into dry weight through a 9.7% ratio established as a mean for 23 species (60°C for 48 h), an average yield of 9.3 t/ha/year on a dry weight basis was obtained. Using the 9.8% crude protein content, a specific yield of 0.91 t/ha/year of crude protein can be obtained at this stage, using no fertilizer or freshwater. These annual total and specific yields compare very favorably with two sequential crops per year of common agricultural crops in tropical developing countries such as bean and maize.

During these trials an interesting and highly significant difference in animal biodiversity within the water column was observed between cultivated seaweed plots and control plots, particularly over barren sandy bottoms. For example, the number of fish individuals and species identifiable with the naked eye in water (individuals >0.05 m long) were four and two throughout a 12-week period in two control areas, while under a cultivated seaweed plot the numbers grew steadily to 97 and 14 at week 12, respectively. The most far-reaching implication is that thanks to its role in attracting biodiversity (comparable in many ways to fish aggregating devices), seaweed farming can be conceptualized within more encompassing schemes, not only with other aquaculture activities, but also to provide services in relation to fisheries and biodiversity, besides those already established such as bioremediation and carbon sequestration.

6 CONCLUSIONS

While the use of seaweeds for food at this experimental stage can be considered in many ways to be successful and many recipes that use up to 15% of dry seaweed on a weight basis are ready for widespread use, several aspects remain to be addressed. Among these, the long-term effects of consuming tropical seaweeds as a substantial portion of the diet should be assessed. Also, even as a very limited component of existing foods in countries with little or no traditional seaweed consumption, the effort to promote widespread acceptance may prove to be challenging, and promotional strategies must be planned alongside farm trials.

Yet different strategies based on this experience can be implemented as first approaches, like using seaweeds that have less of a "fish" smell and taste like *Sargassum* spp. and *Codium* spp., particularly after cooking into recipes with other ingredients that help "mask" flavors. Other treatments to remove this "fish" smell and taste can also be considered. However, the recurrent comment during food tasting panels that participants did not expect seaweeds to taste good indicates that such perceptions can be easily altered. Therefore, many consumers may respond well to seaweeds as food and/or of food products containing them if the appropriate marketing effort is made, particularly considering that seaweeds are becoming a fashionable food complement in the Western world.

The next step, of course, is to produce the right seaweeds at the right cost and in the amounts necessary for widespread consumption. Harvesting from the natural environment, including learning to use "blooms," though limited, can be a good way to start. However, cultivation is the key for sustainable growth, and the importance of having the preferred species for food being at the same time the preferred species for cultivation cannot be overemphasized. Suitable "cultivability" must be matched with suitable use for food, and momentum must be generated in order to break the cycle of "there is no production because there are no markets and there are no markets because there is no production."

Further work is needed in other conditions and in other countries, so that more opportunities as well as limitations are identified rapidly and applied. A consensus of objectives and coordination among researchers is also essential if results are to be generally applicable, and such an effort will need public funding or international aid.

Even a small fraction of what is now allocated to international agricultural research would be enough to build momentum and to demonstrate the nutritional, environmental, and economic benefits of seaweed farming to the tropical world and the lives of the coastal people who live there.

These initial results gain value when seen together with existing experience in the farming of tropical seaweeds for hydrocolloids (Valderrama et al., 2013) and the vast potential areas for mariculture recently identified by the FAO (Kapetsky et al., 2013). Nearly 40% of the world's population live in coastal areas (UNEP, 2006) and many developing tropical countries have coasts with nutrient-rich waters as well as fishing communities ready to begin farming seaweeds for food and income. This is surely an overlooked social and economic development opportunity. That seaweed farming for food can be done without land or freshwater by coastal communities who now depend for their livelihoods on dwindling wild fish resources has far-reaching consequences and suggests it should be an international development priority.

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