Chapter 22
Seaweed and Man

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22.1 Aquacultural Production of Seaweeds and Its Economic Relevance

22.1.1 Introduction

Despite an Asian aquaculture tradition of many centuries, aquatic farming on the global scale is still a young sector of food production that has grown rapidly in the last 50 years. Seaweeds, a colloquial but widely used term for macroalgae, play an important role in this business which remains a growing, vibrant, and important production sector for healthy human food.

As archaeological investigations in Chile testified, seaweeds have been used by humans for about 14,000 years (Dillehay et al. 2008). According to earliest written records, they were consumed in Japan during the Asukaand Nara Era approx. 1,500 years ago. Even food products directly made from seaweeds have a long

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C. Wiencke and K. Bischof (eds.), *Seaweed Biology*, Ecological Studies 219, DOI 10.1007/978-3-642-28451-9_22, © Springer-Verlag Berlin Heidelberg 2012

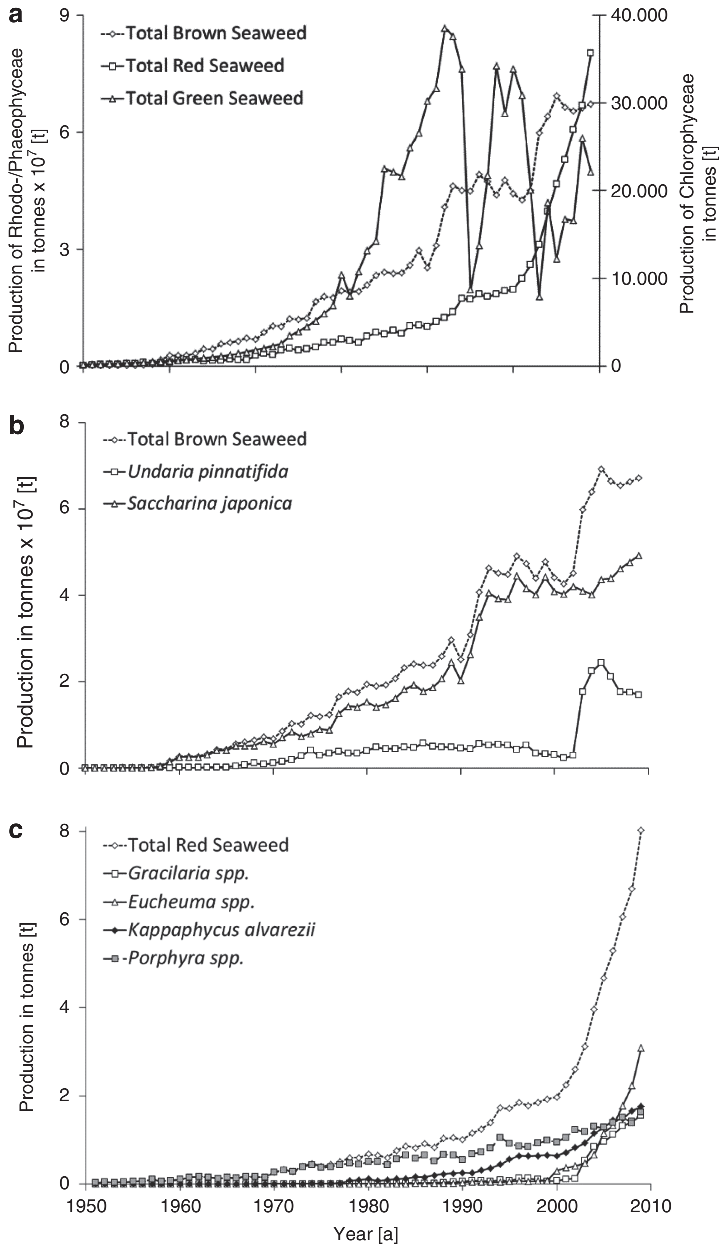
tradition and can be traced back to the fourth century in Japan and the sixth century in China (Tseng 1987; Mc Hugh 2003). Exclusively wild seaweed was used, which limited it as a food source up to the Middle Ages. Later, during the Shogun regime in the Tokugawa Era (1600–1800 AD) fishermen constructed artificial substrates for fish farming which also allowed various seaweed species to grow upon. Ever since, seaweeds have been cultivated in the sea (Tamura 1966). Increasing demand over the last 50 years has outstripped the ability to supply the required biomass from natural (wild) stocks which triggered a dramatic growth of seaweed production from aquaculture sources.

Following Bartsch et al. (2008) farmed seaweeds are used for various applications, as food as well as in the textile, pharmaceutical, cosmetic, and biotechnological industry. As a source of food for human consumption seaweeds can be used in different forms – for instance in salads, sushi recipes, or as various food additives. Other purposes are the use on the health market advertising its minerals and enzymes. Industrial macroalgal use includes the extraction of phycocolloids and biochemicals (Sahoo and Yarish 2005; Pereira and Yarish 2008). A wide range of potential utilizations of seaweeds and/or algal compounds are referred to in Sect. 22.3.

The accessibility and reliability of data on "aquatic plants" (FAO classification) concerning collection from the wild as well as aquaculture production is still not sufficiently consolidated and spread. Acknowledging the shortcomings the Food and Agriculture Organisation of the United Nations (FAO) has continually improved its assessment of the available sources of information, evaluated and updated them, and with addition of some educated estimates published annual statistics that may well serve as a useful guide to world seaweed production and marketing. The latest report by the FAO on "The State of World Fisheries and Aquaculture 2010" contains data up to 2008 (FAO 2010a). Including the latest available data from 2009 (FAO 2011b), we can show the state and development of this industry up to that year and present the new numbers adjusted by the FAO for the period 1997–2005 (Fig. 22.1) after China revised its production statistics based on its Second National Agricultural Census 2007 (FAO 2010–2011). Since China by far runs the most intensive aquaculture business worldwide, numbers on global aquaculture production had to be decreased by about 8% (FAO 2011b).

22.1.2 Aquaculture Production of Seaweeds

Farm production of "aquatic plants" has permanently been expanded since 1970 with an average annual growth rate of 7.7%. It is overwhelmingly dominated by macroalgae (seaweeds) while cultivation of microalgae on a large commercial scale is still in its infancy.



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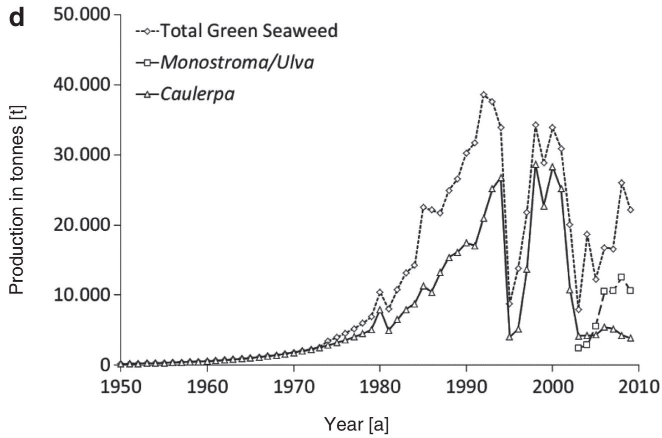

Fig. 22.1 Global production of seaweeds over time according to FAO (2011a). (**a**) Overview of the three groups of seaweeds. (**b**) Global aquaculture production of brown seaweeds with the most important crops used for food and production of alginate. (**c**) Global aquaculture production of red seaweeds comprising the most important agarophyte *Gracilaria*, the carageenophytes *Eucheuma* and *Kappaphycus*, and the high value food algae of the genus *Porphyra*. (**d**) Global aquaculture production of green seaweeds showing "green nori" as a relatively new crop among the most important algae sold for food

22.1.2.1 Species Variety

In 2009, the greatest biomass of cultured species (Fig. 22.2) were the popular food kelps *Saccharina japonica* (formerly *Laminaria japonica*), named "Kombu," with 4.9 million tons annually, and *Undaria pinnatifida,* also known as "Wakame," with 1.7 million annual tons. Among the rhodophytes that are produced the carrageenophytes *Kappaphycus alvarezii* and *Eucheuma* spp., both known as "Cottonii," (4.8 million tons), the red agarophytes of the genus *Gracilaria*, called "Ogonori" in Japan (296,000 tons), and the red *Porphyra* spp. valuable as food alga "Nori" (1.6 million tons) are particularly important. Other species like *Palmaria*, *Chondrus*, or the green *Ulva*, etc. are produced to a minor extent (FAO 2011a).

22.1.2.2 Biomass Yield and Value

To date and worldwide more than 14.7 million tons of seaweeds (miscellaneous vascular flowering plants like Zostera spp. or eel grass etc. not included) are commercially produced, 6% collected from wild stock, 94% farmed. The seven top seaweed farming countries deliver 99.95% of the global farmed volume and are all situated within Asia: Most productive is most productive is China with 54% followed by Indonesia with 20% and the Philippines with 12%. Chile is the most important seaweed farming country outside Asia having produced 88,147 tons in 2009, which is more than 99.9% of America's (north and south) total volume.

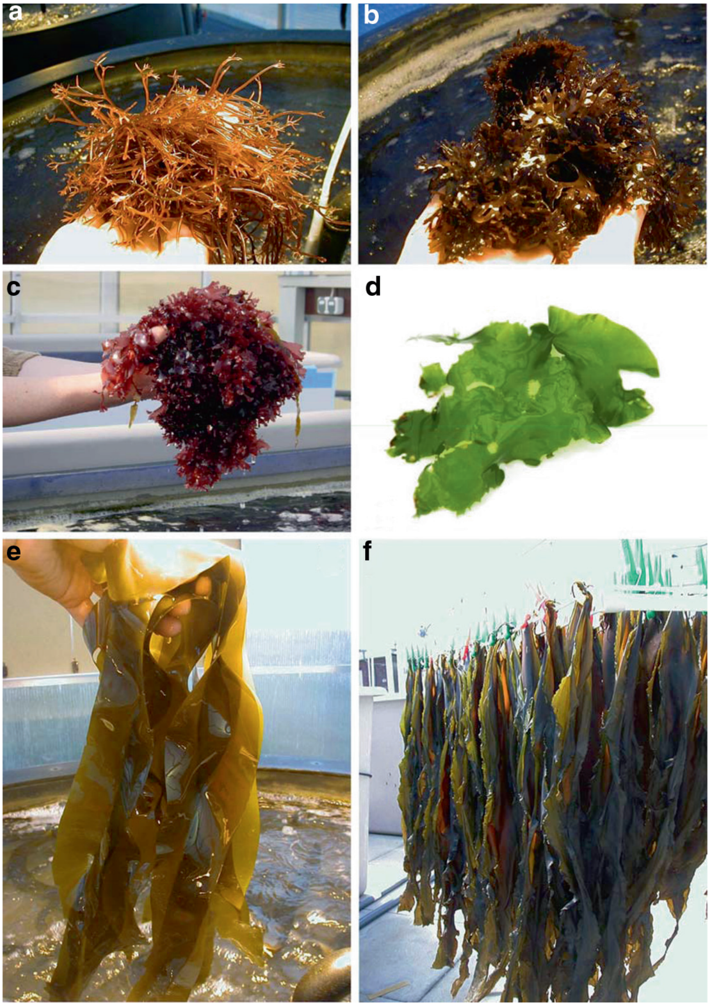

Fig. 22.2 Examples of macroalgae grown in aquaculture. (**a**) *Solieria*, a carrageenophyte; (**b**) *Chondrus crispus* "Irish Moss" carrageenophyte; (**c**) *Palmaria palmata*, used as feed for abalone; (**d**) *Ulva lactuca*, used for bioremediation (uptake of excess nutrients) and feed; (**e**, **f**) *Saccharina latissima*, after 9 months in tank culture and (**f**) phylloids drying for storage demonstrating how evenly they are grown. (Photographs **a**, **b**, **c**, **e**, **f** by K. Lüning with permission)

Next in the ranking according to production volume are countries mostly from Africa (e.g., Tanzania, Madagascar, South Africa, and Namibia) with 108,400 t in 2009 and Western Europe (e.g., Spain, France, Italy, and the Russian Federation), which are responsible for the remaining biomass production volumes. Finally, the Pacific Ocean Islands grow just a small amount of seaweed and produced 2,377 tons in 2009 (Fiji, Kiribati, and Solomon Islands) (FAO 2011a, 2010b).

22.1.3 Methods of Production and Technical Design

Quite a great amount of preliminary observations and experimental setups are necessary for a commercially successful cultivation of seaweeds. To pick the right choice of species thorough knowledge of the alga's often complicated life cycle and a good control of the different life stages are crucial. Likewise local weather conditions, the temperature range, wave action, currents, tidal amplitude, and salinity levels must be appropriate for the respective target species. Further factors to consider are nutrient supply in the water, water depth, and transparency to maintain beneficial irradiance levels, which may, in the case of shallow water farming, also be influenced by the color and composition of the bottom sediments. Moreover, ideally, grazers should not be found in the vicinity of a farm and the presence of epiphytes or other unwanted macroalgal species competing for light and nutrients should have been tested before a commercial farm is ventured (see also Chap. 11 by Potin).

Since the worldwide demand for seaweeds and their products could not be met by simple collection from natural populations, several decades of effort have gone into farming (Tseng 1984, 1987). A considerable number of technical variations in cultivating seaweeds are presently used depending on species, local conditions, and experience (Pereira and Yarish 2008). Meanwhile cultivation methods comprise not only single species cultures but also integrated multi-trophic aquaculture (IMTA; Chopin et al. 2008; Buschmann et al. 2008).

22.1.3.1 Monocultures of Seaweeds

Basically, seaweeds are either "seeded" on ropes or nets (e.g., *Porphyra)* or thallus fragments are fastened on or pinched into ropes, which are subsequently fixed to various suspended or floating culture structures (e.g., *Gracilaria*). From Chile a system to anchor *Gracilaria* cuttings in the sand is known and has also been successful (Trono 1990; Pereira and Yarish 2008; FAO 2011c: National Aquaculture Sector Overview—NASO). Paddle wheel ponds that keep algae floating and moving are a suitable device to grow the green *Ulva* to large quantities (Chopin et al. 2008; Butterworth 2010).

"Nori" production comprising several species of the genus *Porphyra* is a big business worldwide valued at US$ 1,400 million in 2008 according to the FAO statistical yearbook 2010 (FAO 2010b). After about 300 years of culture efforts dependent on natural seeding, Baker (1949) discovered the conchocelis phase of this genus. Only then could the present-day effective multistage culture system be established (Pereira and Yarish 2008, 2010). *Porphyra* is mainly cultivated in China, Japan, and Korea: Mollusk shells, mostly of oysters, are seeded with diploid carpospores from preselected thalli and kept in large shallow indoor tanks for approx. 5 months until under nutrient, temperature, and light control conchospores are released by the conchocelis filaments. Appropriate spore density and agitation of the suspension facilitate even settlement on collecting nets. After germination, grow-out of the thalli takes place in relatively shallow bays, nets fixed, semi-floating, or floating (Sahoo and Yarish 2005; Pereira and Yarish 2010). Fixed or semi-floating, the alternation of immersion and desiccation with the tide is guaranteed helping to avoid diseases caused by fungi or bacteria, reducing epiphytic diatoms and improving the taste. Floating nets can be kept over slightly deeper water (10–20 m), thereby extending the farming area. However, a nursery system must be included that periodically dries the nets and hardens them (Pereira and Yarish 2008, 2010). It is also possible and even improves the quality of the final product to carefully freeze the nets with young thalli and store them at −20°C for later grow-out (FAO 2005–2011a). Depending on the species it takes 40–50 days at sea, for *P. haitanensis* and *P. yezoensis*, respectively, before the first crop can be attained. Six to eight harvests are possible during 5 months of cultivation (Pereira and Yarish 2010).

The species with the highest production is the brown alga *Saccharina japonica* (formerly *Laminaria japonica*), "kombu." 4.9 million tons of kombu were produced in 2009, 84% of it grown in China, where the species is not endemic, but was introduced in 1927 (Tseng 1987; Lowther 2006). Conventional "2 year cultivation" of *S. japonica* took a period of 18 months at sea with at least another 2 months for "seeding," which resulted in relatively high prices for the product (Ohno 1993). "Cultivation by transplanting" uses natural *Saccharina* sporophytes either washed ashore or manually thinned out. As the activity of the meristem increases in late winter to early spring, new haptera are easily formed and allow a new attachment on ropes during this time. Time from transplantation to harvest lasts 12–18 months (Ohno 1993). Only 12 months are needed for the widely applied so-called forced-cultivation technique (Hasegawa 1971; Ohno 1993; Critchley and Ohno 1997; Sahoo and Yarish 2005). This became possible due to scientific control of the entire biphasic life cycle, where indoor facilities are necessary to manage the labor and cost-intensive "seedling phase" (Tseng 1989; Mc Hugh 2003; Chen 2006). A large independence of naturally available seedstock could be attained by detaching *Laminaria* frond fractions from the meristem (Buchholz and Lüning 1999; see also Lüning et al. 2000; Pang and Lüning 2004). Meiospores are artificially released from sporogenous thalli, germinate to microscopic gametophytes, form zygotes, and eventually produce young sporophytes that stick to ropes. In "the grow-out phase" (Tseng 1989), culture ropes with juvenile sporophytes are transferred to the open sea where they grow to a frond length of approx. 1–2.5 m, depending on the species. If the predicted shift of biogeographic areas becomes true (see also Chap. 18 by Bartsch et al.), aquaculture of *S. japonica,* as an example, may be strongly impaired in that the space and the period for grow-out in coastal waters are reduced. Young seedlings do not tolerate more than 20°C and fronds have to be harvested at ≤21°C, because they start to rot at higher temperatures (FAO 2005–2011b) .

The most common design for grow-out of Laminariales in the open water is a longline system of horizontal ropes parallel to the sea surface with anchoring weights to stabilize the entire system and with buoys to provide flotation. Combining vertical arrangement of seeded culture lines as the first step and later suspension and lifting of these lines into a horizontal position overcomes first overexposure, then shading problems in growing sporophytes, while reducing effects of cross currents and storms on only horizontally attached lines (FAO 2005–2011b). From the various methods (e.g., Holt and Kain 1983; Kawashima 1984; Kain and Dawes 1987; Dawes 1988; Kain 1991; Merrill and Gillingham 1991; Critchley and Ohno 1997; Buck and Buchholz 2004), the locally appropriate one has to be chosen for the special conditions of a given farming site.

Longline systems installed in harsh offshore conditions, to where farms could be expanded, were not robust enough as there is a considerable stress on support material and algae (Buck 2004; Buck and Buchholz 2004). Among the various suggestions for technical structures that have been made (Polk 1996; Hesley 1997; Stickney 1998; Bridger and Costa-Pierce 2003) a ring design did withstand strong currents and wind waves and is still the most promising (Buck and Buchholz 2004). The idea of utilizing the grounding structures of offshore wind generators for the fixation of aquaculture systems is intriguing (e.g., Buck 2002; Krause et al. 2003; Buck et al. 2004) and the first experiments on *Laminaria* species show that adapted to strong currents as young individuals, they grow well at exposed sites (Buck and Buchholz 2005).

The cultivation of seaweeds at sea or in ponds flushed by incoming seawater has lately been supplemented or completely exchanged for land-based tank cultivation for smaller rhodophytes and chlorophytes (see Sect. 22.1.3.2) as well as large kelps. Lüning and Pang (2003) kept free floating sporophytes of laminarians or *Palmaria palmata* circulating in the water agitated by air. The tanks allowed a high cultivation density of 10 kg m^{-2}, since shading was amended by the continuous turnover of fronds toward the light. Uniform exposure to nutrients was likewise facilitated and the infestation with epiphytes was kept very low (Ryther et al. 1979; Bidwell et al. 1985). The Lüning and Pang (2003) system was additionally supported by a continuous short day treatment. The same short day treatment (8 h light) using outdoor tanks with automatic blinds resulted in prolonged growth activity of *Laminaria digitata* that also seemed to deter epiphyte settlement (Gómez and Lüning 2001). The experience gained in tank cultivation is a valuable basis for some of the internationally developing integrated mariculture systems (see citations in Neori et al. 2004, p. 376; Abreu et al. 2011; Pereira et al. 2011).

The world population recently reached the seven billion mark and a sustained or rather growing supply of protein from aquatic animals is highly desirable. Concomitantly there is an increasing concern about the negative consequences of intensive and constantly spreading aquaculture of fish, shrimps, and mollusks. Therefore, the remediation of negative consequences has been a field of intensive research during the last decade. Two ecologically sensible strategies to meet the requirements for more space allotted to aquaculture have been and will continue to be tested: One is the offshore aquaculture that to date seems very expensive and technically demanding, but will allow considerable mass production. The other is the very promising but likewise complicated Integrated Multi-Trophic Aquaculture (IMTA) approach.

22.1.3.2 Integrated Multi-Trophic Aquaculture (IMTA)

Extensive polyculture pond systems with organisms of several species in the same water body have traditionally been applied in Asian countries and were based on trial and error. Only since the 1970s, a more systematic approach has resulted in the development of integrated intensive land-based mariculture systems (Ryther et al. 1979). The aim of IMTA is the creation of a manageable small ecosystem with several species of different trophic levels combined in one system in the right proportions, each utilizing waste products or the biomass generated by another member of the system. All of the individual components must be marketable since the commercial viability is an important factor of any such IMTA design (Chopin et al. 2008). If the benefits for the environment were accounted for, the value of IMTA production systems would be highly increased and political support for the development of these structures would mirror this.

Neori et al. (2004, 2007) argued that seaweed-based integrated aquaculture systems will most probably facilitate the expansion and sustainability of the worldwide aquaculture industry. Nevertheless, the major aim of global aquaculture enterprises is the production of fish, shrimp, or shellfish protein. With the dwindling of wild resources through overfishing there is an ever growing demand for those products. At the same time the demand for certain seaweeds for human consumption or animal feed or else for algal ingredients (mainly phycocolloids) has to be met and is already a large market, worth 22.4 billion US$ in the year 2008 (FAO 2010b).

Since the culture of fed species like fish or shrimp inevitably results in eutrophication of the adjacent waters (Stead and Laird 2002; Fei 2004; Sanderson et al. 2006; Troell et al. 1999, 2003), a bioremedial complementary culture design makes sense for environmentally protective reasons. Simultaneously the biomass of carefully chosen extractive and marketable species could at least partly counterbalance the considerable costs for fish or shrimp feed (Neori et al. 2004; Abreu et al. 2009). Moreover, there are oligotrophic seawater conditions, like in Israel or Australia, that do not allow the growth of algae and it makes sense to try intelligent new aquaculture approaches under these circumstances (Schuenhoff et al. 2003; Butterworth 2010; Neori et al. 2004).

An encompassing review of the multiple IMTA activities is found in Barrington et al. (2009) for temperate and Troell (2009) for tropical regions of the world. Potential candidates for integrated systems are not only the hitherto monocultured and expensively fed fish and crustaceans, filter-feeding bivalve or herbivore mollusks (*Haliotis*), and more than 20 species of seaweeds but also echinoderms and polychaetes. Presently existing IMTA systems usually contain no more than three components at different trophic levels. One is fed fish or shrimp, one extracting organic bound nutrient particles, either feed leftovers or feces, and one, seaweeds, extracting the effluents utilizing inorganic nitrogen and phosphate for growth. In a Sustainable Ecological Aquaculture effort Cascadia SEAfood even integrates sablefish with two species of bivalves, kelp, and sea urchins that feed on the fouling organisms on cages, their gonads being offered to seafood gourmets (Cross 2010; Cook and Kelly 2007). In the case of an abalone farm in South Africa, the resulting seaweed crop of *Ulva lactuca* can partly be used for feeding the abalone (Nobre et al. 2010; Robertson-Andersson et al. 2008). Since it is known that *Ulva* synthesizes more protein (>40% dw^{-1}) with higher ammonia-N in the water, it turns out to be a valuable feed allowing *Haliotis* to grow significantly faster than with Ulva kept in low nitrogen concentrations and containing only 12% protein (Shpigel et al. 1999).

While *Ulva* spp. with their thin thalli and large surface-to-volume ratio are perfect inorganic extractors their biomass does not realize a high price. Therefore, commercially valuable red algae like *Porphyra* (nori), *Gracilaria* (as an agarophyte), and *Kappaphycus* (as a carrageenophyte) are being tested in IMTA systems (Chopin et al. 1999; Abreu et al. 2009, 2011; McVey et al. 2002; Pereira and Yarish 2010; Rawson et al. 2002; Robertson-Andersson et al. 2008; Lombardi et al. 2006). Depending on the region, particularly those with pronounced seasons, seaweeds in IMTAs may have to be exchanged for other species in the course of the year, which requires additional engineering efforts to suit each species' requirements. There are for example different demands of red algae versus brown kelps concerning surface area, water flow rates, and nutrient exchange, etc.

Owners of profitable finfish or shrimp cultures are not necessarily concerned about eutrophication of the environment and have to be convinced that no diseases are introduced by co-cultured organisms (Troell et al. 2003). It needs the owners' consent to use existing fish or shrimp cultures to establish an IMTA system: In open sea, but nearshore systems, different components of an IMTA can simply be placed in each other's vicinity with mutual beneficial effects provided local currents and other water dynamics allow sufficient exchange between them (Abreu et al. 2009; Sanderson 2009; McVey et al. 2002; Chopin et al. 2001; Troell et al. 1999; Petrell and Alie 1996). The alternatives are land-based tank systems or ponds that can be separated from sea water inflow at periods of toxic algal blooms or oil spills, etc. In these systems, fish farm effluents are redirected through a series of tanks containing complementing organisms. The Sea Or Marine Enterprises in Israel integrated gilthead seabream with *Ulva* or *Gracilaria*, with the algae serving as a feed for commercially valuable abalone (Neori et al. 2004). With abalone (*Haliotis midae*) and seaweeds alone, a partial recirculation of the culturing water is feasible (Robertson-Andersson et al. 2008).

To establish a managed small ecosystem, that is adapted to site and region and that in addition sustains stakeholders and environment, is a very complex task, impossible to be tackled by individual farmers. Therefore, Canada has launched a new network CIMTAN (2011). CIMTAN is directed to collect additional knowledge and intensify interdisciplinary as well as multi-institutional information exchange between the experts on aquaculture on both coasts of Canada. Research and development of IMTAs has been conducted in Canada since 2001. The joint goal is to establish an easily adaptable system of IMTA with a set of nutritionally interacting species that mimics the natural condition of a diverse ecosystem, thereby being less vulnerable to e.g., microbial infections or parasite infestation.

At the same time most/all of the systems components should be of commercial value supplementing each other in reaching an acceptable profit for stakeholders and environment. Between January 2010 and December 2014, about 250 people will be involved in 14 projects systematically investigating the various aspects of IMTA from nutrient plumes to microbial interactions, detritivores (such as polychaetes and echinoderms), bivalves, fish parasites, and seaweeds (including *Saccharina latissima,* formerly *Laminaria saccharina*, *Alaria esculenta*, *Palmaria palmata*, and *Ulva* spp.) to infrastructure components, ecosystem modeling, and social implications for coastal communities. With the insights gained it will be easier to promote a sustainable and vibrant aquaculture industry in Canada and probably other temperate regions of the world.

22.1.3.3 Offshore Aquaculture

Aquaculture is continuously expanding in coastal seas and ashore, comprising farming in marine and brackish water environments (FAO 2010a, b). However, coastal waters host a highly competitive group of uses such as commercial shipping, areas exclusively reserved for the navy, extraction or disposal of sand, oil exploration and exploitation, as well as pipelines, cables, wind farms, nature reserves, and other marine and coastal protected areas. Recreational activities and fisheries are additional interests that deserve attention. This massive utilization of marine areas leads to stakeholder conflicts (Buck et al. 2004; Langan et al. 2006; Rensel et al. 2006). Additionally, farming activities may also generate negative environmental impacts on coastal ecosystems at local up to regional scales (e.g., Buck and Krause 2012), thus leaving little room for further expansion of modern coastal aquaculture systems. Locating aquaculture activities further offshore appears as a viable option to avoid stakeholder conflicts and to reduce environmental impacts to the coast (Corbin 2007). The term “offshore” within the context of aquaculture was defined by Ryan (2005) and is based on the moving of farm installations from nearshore sheltered environments to more exposed environments, which are commonly described as “high energy environment”.

Following Troell et al. (2012) and North (1987) considerable controversy has emerged over the proper development of offshore aquaculture, and its actual advantages over existing nearshore aquaculture. In general, many of the challenges for offshore aquaculture engineering involve adaptations of farm installation designs and operation protocols to a variety of physical factors, such as currents and wave actions: The robustness of the aquaculture systems to withstand harsh oceanographic conditions is one challenge, while the difficulties in anchoring and/or submerging structures in deep water is another. Major shipping routes have to be considered as well as migration routes of marine mammals. Logistic difficulties of transport and the operation and maintenance of offshore platforms of any farming enterprise must be evaluated.

Due to the scarcity of space even in the open ocean island territories or countries with relatively short coastlines, the concept of “multiple use” needs to be addressed. Germany is an example where the plans for the massive expansion of wind farms in offshore areas of the North Sea triggered the idea of a combination of wind turbines with installations for extensive shellfish and seaweed aquaculture (Buck 2002, 2004). A combined design of fish cages in the foundation of the turbines in addition to the extractive components of IMTA systems was discussed (McVey and Buck 2008). Offshore wind farms provide an appropriately sized area for farming that is free of shipping traffic. At the same time the infrastructure for regular service support is readily available. Such sites provide an ideal opportunity for devising and implementing a multiple-use concept (Buck et al. 2004; Michler-Cieluch 2009).

Some experimental-scale operations have shown the feasibility of offshore macroalgal farming (for review, see e.g., Buck et al. 2008). The focus of those systems was placed upon the technical design needed to withstand hydrodynamic forces and investigations on cultivation techniques to avoid dislodgement of laminarians (Buck and Buchholz 2004, 2005). Ebeling, Griffin, and Buck (unpublished data) were the first to calculate the economic potential of a seaweed farm (*Saccharina latissima*) within a planned wind farm off the coast of Woods Hole (Massachusetts, USA) in Nantucket Sound and found it being beneficial on a large scale.

22.2 Socioeconomic Aspects

Traditionally, the academic community has tended to approach aquaculture primarily from technological and environmental perspectives (Marra 2005). However, it has been recognized that aquaculture increasingly generates direct socioeconomic benefits through the supply of highly nutritious foods and other commercially valuable products, providing jobs and creating incomes. For example, the FAO reports for the Philippines that seaweed farming is currently the largest and most productive form of livelihood among the coastal population of the Philippines. In 2004, more than 116,000 families consisting of more than one million individuals were farming more than 58,000 ha of seaweed (FAO 2005–2011c). Enough and affordable manpower to maintain the farms is an indispensable prerequisite. Personnel on all levels of skills are required. The benefits for the well-being of coastal communities are reflected in the finding of a recent case study on a South African IMTA farm of abalone and seaweed presented by Nobre et al. (2010). In this study, the impact of direct permanent employment within the South African aquaculture industry on local communities was exemplified: The selected communities were characterized by high unemployment (85.7%), with more than 50% of the labor force being unskilled and semiskilled. It could be shown that employment of a high number of unskilled and semiskilled personnel in the aquaculture sector had a large local impact in previously disadvantaged coastal communities, where any increase in employment is valuable (Nobre et al. 2010). This is particularly relevant where unemployment is not only an economic issue but also a sociopolitical concern.

Thus, in addition to its own economic contribution, aquaculture can also induce, as a spin-off, economic contribution to other sectors that supply materials to aquaculture or use aquaculture products as inputs (ICES 2011). The numbers of people engaged in other ancillary activities, such as processing, farm construction, manufacturing of processing equipment, packaging, marketing, and distribution can be substantial. Indeed, estimates indicate that, for each person employed in aquaculture production, about three other jobs can be produced in secondary activities. The total aquaculture sector, encompassing finfish, shellfish, and seaweed aquaculture, and those supplying services and goods to them, provides employment and livelihoods to a total of about 20 million people (compiled from FAO 2011c).

Despite these positive effects, decisions about aquaculture development are often based on incomplete information, particularly in relation to the socioeconomic dimensions. As a consequence, inadequate accounts for trade-offs associated with different development options are made. Therefore, there is a risk that anticipated and much needed socioeconomic benefits from aquaculture expansion may come at the expense of increased and possible unsustainable pressure on ecosystem goods and services (Naylor et al. 2000), ultimately jeopardizing people's food security and livelihoods.

In contrast to many finfish aquaculture enterprises, there are, however, encouraging experiences made with seaweed aquaculture. An example on the important role of seaweed cultivation for local livelihoods and sustainable development is the introduction of seaweed farming on Zanzibar, Tanzania in 1989. In that year, the seaweed *Eucheuma* was imported from the Philippines and successfully grown on the East Coast of Unguja Island. Today, more than 90% of the farmers are women, which have changed the life in the villages. Not only did the women gain independent economic power, but the number of children suffering from malnutrition has also decreased, which indicates that the health of their mothers has improved. As daily income is secured, children are able to attend schools regularly. Furthermore, seaweed farming has also reversed the trend of rural depopulation, since it fostered self-employment of the village youths (Msuya 1997, 2006; Msuya et al. 2007).

The question remains though, how negative effects on the environment and positive socioeconomic consequences from aquaculture development can be balanced. For instance, although methods of cultivation can be adapted and vary being equally successful, the careful choice of the farming site seems to be essential for any aquaculture success (Trono 1990; Buck and Buchholz 2005). Notwithstanding, the seascapes are increasingly managed for multiple functions and services in addition to provision of food, and this requires the integration of ecological and socioeconomic research, policy innovation, and public education (ICES 2011). The multiuse dilemma has driven many researchers, experts, and policy makers to try and address issues related to the sustainability of aquaculture development from disciplinary/sectoral perspectives. However, aquaculture development raises questions that cannot be addressed in isolation. If it is to bring about the expected benefits, such as in the case of the seaweed farmers on Zanzibar, seaweed farming must address the interactions and functioning within wider ecosystem, social, economic, and political contexts.

A critical question is how to best guide the development of aquaculture that has the potential to support a portfolio of sustainable livelihoods and assist in poverty alleviation and food security (ICES 2011). Broader systematic perspectives on aquaculture, such as the "Ecosystem Approach to Aquaculture" (Soto et al. 2008), may enable analysis of trade-offs and sustainability aspects, especially with respect to net benefits for poorer resource users. Furthermore, local knowledge generated through active bottom-up participation and the application of transparent decision-making processes are some of the building blocks behind improved coordination of all the sector's stakeholders. Strengthening of institutional capacity and resources (including human capacity), both at national and international levels, is needed to enable development of aquaculture for poverty reduction and improved human well-being.

22.3 Direct Seaweed Applications and Bioactive Compounds

22.3.1 Introduction

Following the twentieth International Seaweed Symposium in Ensenada, Mexico, in 2010, several quite encompassing reviews have lately been published comprising various potential uses of seaweeds as functional food, feed supplement, or manure and soil conditioner with biological or pharmaceutical activities. Adding some more the following paragraphs provide an overview of the currently available information in published literature guiding specific interests in seaweed applications to the great number of detailed references collated already.

22.3.2 Seaweed for Food and Medication

Seaweeds have been used as food and for medical purposes since the late Pleistocene as Dillehay et al. (2008) reported from an excavation site at Monte Verde in southern Chile. Nine species of marine algae were recovered, among them edible species (*Durvillaea antarctica*, *Porphyra columbina*, *Sarcothalia crispata*, and *Macrocystis pyrifera*) and two nonedible ones (in the genus *Gigartina* and *Sargassum*). Some are nowadays being used as medical plants by indigenous people of that area and may have served the same purpose 14,000 years ago.

To date the food sector is still the most important field of application for the various species of seaweeds farmed or collected from the wild. While direct consumption is most common in the Asia-Pacific region, algal hydrocolloids are used worldwide in a great variety of food items as emulsifying, gelling, or water retention agents (Indergaard and Østgaard 1991; Murata and Nakazoe 2001; Bartsch et al. 2008). 86,100 tons of hydrocolloids were traded in 2009 comprising

58% of carrageen, ~31% alginates, and ~11% agar (Bixler and Porse 2011). The demand particularly for carrageen could not be met lately mainly due to the increased demands of the Chinese hydrocolloid industry. Moreover, collective quantity does not always suffice, since species as well as geographical location and climate where the seaweeds are grown and the season of harvest determine the chemical characteristics of the hydrocolloids and their quality. Quality is also influenced by the extraction methodology (Bixler and Porse 2011).

Aware of the fact that there is a great variety of chemical compositions and therefore bioactive properties in the different species of seaweeds Løvstad Holdt and Kraan (2011) supply a wealth of current knowledge on bioactive compounds of the most important species in 21 tables comprising the various polysaccharides, proteins, peptides, and amino acids as well as lipids and fatty acids, pigments, vitamins, iodine, phenolic components, and undesirable substances like heavy metals: The vast range of biological activities they listed originated from in vitro investigations up to clinical studies. Most spectacular are the antibacterial and antiviral activities that may partly be responsible for the records on positive effects against tumors and HIV. Important beneficial effects for human health lie also in the reduction of blood cholesterol levels and anti-diabetes and anti-hypertension effects. In addition to direct pharmaceutical uses of algal ingredients, a high-tech medical use of alginate as part of a matrix that can carry protein drugs is being developed. It utilizes the mucoadhesive property of alginate helping to retain the drugs in the gastrointestinal tract for a longer period, thereby improving drug bioavailability and effectiveness in the intestine (George and Abraham 2006). While the list of beneficial effects of seaweeds and their ingredients on humans is long, the process of getting them authorized as food or medical items can be as well (Løvstad Holdt and Kraan 2011).

22.3.3 Seaweed in Agriculture and Animal Diets

The large amounts of minerals, trace elements, vitamins, and iodine among other components render seaweeds, particularly the brown ones, a valuable addition not only to food but also to livestock feed and soil fertilization (lit. in Bartsch et al. 2008; Craigie 2011). Some direct or indirect beneficial effects hold for plants as well as animals of very different classes. An example is antihelmintic properties of seaweed extracts that can help not only mammals but also plants like tomatoes which suffer from nematode infestations in their roots (Løvstad Holdt and Kraan 2011; Craigie 2011). While commercial seaweed extracts have been available for 60 years, only 1% of the current seaweed industrial production goes into agricultural use, even though according to Craigie (2011) "seaweed extracts can modify plant and animal responses at a fundamental level." However, the appropriate utilization of seaweed meal or extracts in agriculture and as feed addition has to be experimentally secured in advance of extensive use. Craigie (2011) reviews the history of seaweed utilization and the development of extracts and the responses of the soil and crops to various applications, e.g., different concentrations of extracts that can decide between inhibition and promotion of germination and growth. Table 12 (in Craigie 2011) summarizes the bioactive properties reported for seaweed extracts in plants and animals. As for plants the choice of algal species and extract concerning its nature and proportion in the feed of the respective livestock has to be carefully tested to avoid detrimental effects and improve overall health and benefit reproduction (Craigie 2011). Addition of 4% *Sargassum* meal to the feed of shrimp cultures reduced cholesterol contents of their muscle tissue by 29%, quite desirable for shrimp grown for human consumption (Casas-Valdez et al. 2006). In the case of cattle there can even be an advantage elicited in the shelf life of steaks, since a short-term feed addition of 2% *Ascophyllum* meal (Tasco) prior to slaughter not only results in a better marbling of steaks but also retains the red color over a longer period. The latter is due to a higher proportion of oxymyoglobin compared to conventionally fed cattle (Braden et al. 2007).

Of the 10 larger and 17 smaller producers of commercial seaweed extracts for agriculture that Craigie mentions, only three are presently located in Asia, that is in China, even though Asia is producing >98% of all seaweeds. The indisputable benefits of seaweed utilization in plant and animal farming excite expectations toward a more extended production and use in the future.

22.3.4 Other Applications of Seaweeds

The phycocolloids agar, carrageen and alginates have long been used for their water binding and thickening properties: While agar is not only known as a neutrally flavored thickener of stews, sauces, desserts etc., it is also indispensable as a solid culture medium in medical bacteriology and microbiological research. Alginates from brown seaweeds are used in printing dyes and for better adsorptivity of textiles. They are together with other seaweed components valued ingredients of cosmetics. Extracts typically found in cosmetics are made from *Ulva lactuca, Ascophyllum nodosum, Laminaria longicruris, Saccharina latissima, Laminaria digitata, Alaria esculenta,* various *Porphyra species, Chondrus crispus*, and *Mastocarpus stellatus* (Cosmetic Ingredient Dictionary 2002–2011).

The latest innovation is a textile fiber named SeaCell®. It is a cellulose-based fiber produced from seaweeds like *Ascophyllum nodosum* and used as a yarn for clothing or for filling duvets (Smartfiber 2010).

Another field of high interest and great demand is the partial replacement of fish meal by seaweeds. Only a small selection of seaweed species will probably be suited. Experiments by Walker et al. (2009) showed positive results with up to 30% *Porphyra* spp. in the diet of juvenile Atlantic cod. If *Porphyra* ("nori") was introduced into the commercial aquaculture of fish, demand and price of the already valuable seaweed would probably rise enormously.

Due to their high carbohydrate content seaweeds can be fermented to methane (biogas) and in many places (mainly beach cast) seaweeds are considered a potential CO_2-neutral and renewable energy supply (lit. in Bartsch et al. 2008; Roesijadi et al. 2008; Chung et al. 2011).

Bioremediation of eutrophic waters has been mentioned above in relation to aquaculture. It would also work for waters supplied with an excess of nutrients from other sources. If the resulting quantity of algal biomass was not good enough to be introduced into a high quality production line, it may still serve as a good feedstock for biofuels.

22.4 Conclusion

Seaweeds have accompanied human history for about 14,000 years. Seaweed research from simple observation to organized experiments has helped to install an extensive aquaculture industry that produced close to 14.8 million tons in 2009, while it was just a few kg in the 1950s. Large and many small enterprises worldwide secure thousands of family incomes and are therefore of high socioeconomic importance. The global "hot spot" of seaweed farming as well as direct use of these macroalgae as food items is Asia. Algal ingredients like the phycocolloids agar, alginate, and carrageenan are in demand by the food industry, medical, and technical applications. The use of seaweed meal or extracts for agricultural applications bears a great potential for expansion. To satisfy the market demand not only for seaweeds but also highly requested protein sources like finfish, shellfish, and crustacea, the relocation of culturing sites to offshore areas is suggested for wind farms at sea as a multiuse concept. Another promising and intensively developing field of aquaculture is the expansion of Integrated Multi-Trophic Aquaculture (IMTA) systems where commercially valuable organisms from different trophic levels, some fed and some extractive, are combined in a culturing system, ideally sustaining each other and with the help of seaweeds even bioremedial for the environment.

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