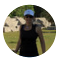
Tropical seaweeds for human food, their cultivation and its effect on biodiversity enrichment

Article *in* Aquaculture · October 2014

DOI: 10.1016/j.aquaculture.2014.10.032

Ricardo Radulovich
University of Costa Rica
44 PUBLICATIONS **458** CITATIONS



Schery Umanzor
University of Connecticut, Stamford
9 PUBLICATIONS **42** CITATIONS

Aquaculture 436 (2015) 40–46

Contents lists available at ScienceDirect

Aquaculture

journal homepage: www.elsevier.com/locate/aqua-online

Tropical seaweeds for human food, their cultivation and its effect on biodiversity enrichment

Ricardo Radulovich *, Schery Umanzor, Rubén Cabrera, Rebeca Mata

Dep. of Agricultural Engineering, University of Costa Rica, San José, Costa Rica

ARTICLE INFO

Article history:
Received 9 September 2013
Received in revised form 30 May 2014
Accepted 21 October 2014
Available online 31 October 2014

Keywords:
Aquaculture
Coastal rural development
Macroalgae
Mariculture
Sea farming

ABSTRACT

As a response to growing land and freshwater shortages and climate change, the use of seaweeds as food, their cultivation at sea and its effect on biodiversity are being researched on both the Caribbean and Pacific coasts of Costa Rica. Native species, more plentiful on the Caribbean coast, were collected and pre-selected based on existing information and on criteria including ubiquity, abundance, growth and palatability. These species were then evaluated as food and subjected to floating long-line cultivation using vegetative propagules. After establishing postharvest procedures, use as food involved many preparations to be eaten fresh or after drying, including a dry-ground meal. Ten of these species, which had nutrient contents within expected values including 9.8% crude protein on a dry weight (dw) basis and high iron, were considered adequate as food, both directly and as part of recipes in quantities not exceeding 20% dw of a given dish. Higher concentrations either 'overwhelmed' traditional recipes or their taste was rejected by tested consumers. Near-coast cultivation was in general a simple matter, easily transferred to artisanal fishers. To a great extent due to herbivory and theft of ropes, yield (ranging from 51.7 to 153.2 t ha^{-1} yr^{-1} on a fresh weight basis) was quantified for only five species with a mean of 9.3 t ha^{-1} yr^{-1} dw, equivalent to 0.91 t ha^{-1} yr^{-1} of crude protein—very similar to yields of two grain crops per year. Species of *Codium*, *Gracilaria*, *Sargassum* and *Ulva* were considered adequate both for use as food and cultivation. Cultivated seaweed plots rapidly attracted biodiversity, including a significantly larger number of fish species and individuals than nearby control areas. Based on this we postulate the need to further explore a 'biodiversity enrichment' service from seaweed cultivation and any effect of this on fisheries enhancement. While noting areas in which further research and international collaboration are needed, it is concluded that tropical seaweeds, besides their many other uses, can at this stage substitute up to 15% of food on a dry weight basis, their cultivation is simple, and effects on biodiversity are a previously undocumented advantage. Given the lack of experience in most of the world excepting some Asian countries, the agriculture-like approach followed here may be of use to others in tropical developing countries who wish to explore seaweed cultivation at sea, for food and other products and for environmental/biodiversity services.

1. Introduction

Needed increases in world food production are hindered by growing land and water shortages and by climate change (Falkenmark et al., 2009; OECD/FAO, 2012; UNU, 2012); however, at sea space abounds and food production does not require any freshwater (Radulovich, 2011). The use of seaweeds (macroalgae)—the only existing choice for primary production at sea—for human food and other applications, has grown to ~21 million tonnes (Mt) on a fresh weight basis annually, of which ~20 Mt are cultivated at sea, the rest is from natural harvests (FAO, 2012, 2013). It is considered that 76% of world seaweed production and 88% of its value are for direct food consumption (Chopin, 2012). However, 99.8% of cultivated production happens in only nine countries, of which eight are Asian (four of them tropical: Indonesia, Philippines, Malaysia and Vietnam), and one African (Tanzania, particularly Zanzibar); the remaining 15 tropical countries with some cultivation reported produce a combined yearly total of only ~32,000 t (FAO, 2012).

Although tropical seaweeds have amply demonstrated 'cultivability' and productivity, and their nutritional adequacy and edibility as human food have also been shown, at least at the laboratory level (e.g., Black, 1952; Matanjun et al., 2009; McDermid and Stuercke, 2003; Reed, 1907; Robledo and Freile, 1997), most of the limited cultivation experience outside Asia is for hydrocolloid uses, as it is, e.g., for Zanzibar (Msuya, 2011). In all countries of tropical Latin America, the Caribbean and most of Africa seaweeds are essentially an ignored resource, and scant or no cultivation is reported for any purpose much less for food (FAO, 2012).

Given the overarching opportunity this may represent, it was considered convenient to evaluate seaweeds as a food source, including their cultivation and effects on biodiversity in Costa Rica, a country

---

* Corresponding author. Tel.: +506 8315 0613.
E-mail address: ricardo.radulovich@ucr.ac.cr (R. Radulovich).

http://dx.doi.org/10.1016/j.aquaculture.2014.10.032

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). Since there is a generalized lack of proven methodology to follow, it was necessary to establish and implement an agriculture-like protocol to conduct this work, thus expanding aims into generating specific experience which can be of use in the context of coastal tropical developing countries seeking solutions at sea to their food-production limitations.

2. Materials and methods

Work was conducted in Costa Rica from early-2011 through mid-2013 in the near-shore waters of the Cahuita/Puerto Viejo region of the Caribbean coast and in the Gulf of Nicoya, Central Pacific and Cuajiniquil, North Pacific coast. Since it was considered essential to use only native species, at least at this early stage, the procedure followed consisted of prospecting for seaweed species, pre-selecting species, evaluating pre-selected species as food and for their cultivability, and final selection.

2.1. Prospecting and pre-selection

Prospecting for seaweed species by scouting different areas on or near the sites throughout the year required seeking, collecting and identifying specimens of different species. Species were pre-selected according to cultivation and nutritional properties as described in the literature, as available, and their characteristics like ubiquity, abundance, vigorous growth and perceived advantages of using them—something that included observing preference of herbivores and eating the raw seaweed *in situ*.

Noting that for some species final taxonomic classification is in progress, after pre-selection seaweed species were subjected interactively to both a variety of postharvest treatments and uses as food, and to cultivation.

2.2. Uses as food

For pre-selected seaweeds harvested either from the wild and/or cultivated, postharvest treatment consisted of thorough washing with freshwater, cleaning away debris, small fauna and epiphytes, while removing unwanted parts like holdfasts and damaged tissue. After that excess surface water was removed by agitation. Those to be consumed raw were used or bagged and refrigerated. Others were oven-dried at 60 C for 24 h, time that proved sufficient for constant dry weight (which was established for 23 species at a mean of 9.7% [± 1.6%] of dry weight over fresh weight). After drying and allowing to cool down to room temperature, seaweeds were packed in polyethylene bags which were sealed after expelling excess air by hand, and stored in the shade at room temperature.

A variety of cooking methods and recipes were tried following in every case standard culinary practice and using regular house kitchens, appliances and tools in order to simulate real-life applications. While the detailed description of this is beyond the scope of this paper, and is presented elsewhere (Radulovich et al., 2013), the major types of food preparations used seaweeds:

a) Fresh (raw): as part of salads; blended with fruit and vegetable juices; whole or chopped to be cooked into a variety of specific food preparations (dishes) like rice and/or beans, similar to spinach and as a beverage; baked to crispy; and, fried in a variety of manners including a recipe similar to green beans covered with egg batter;
b) Rehydrated after drying: whole or chopped into a variety of dishes like rice and/or beans; and,
c) Dried, ground to different levels of coarseness: as partial substitute of wheat and maize flour in the preparation of a variety of recipes like cookies, fried chips, grissinis and spaghettis; as a meal or a powder to be sprinkled liberally on or into different recipes, including fruit juices and scrambled eggs; and, encapsulated to be consumed as a dietary complement.

Food preparations were first preliminarily evaluated by panels composed of project personnel considering appearance, taste/palatability, color, smell, consistency, after-eating effects, ease of use for cooking and perceived departure from typical/traditional control recipes that did not include seaweeds. After preliminary evaluation, selected recipes and modes of use were further evaluated with groups of people through 25 informal food tasting panels. Panels were composed of from 5 to 43 participants, mostly urban dwellers though some were conducted with only coastal rural inhabitants. The main acceptability criteria considered were quantities consumed, including repeating, as well as comments on appearance, flavor, odor, texture and others as expressed by participants during and after tasting. This food preparation and testing process was iterated seeking improvements, including trying recipes with different species or with combinations of species. A third step consisted of evaluating postharvest treatment and packaged storage, both dry and refrigerated-raw.

Eight of the seaweed species selected due to advantages in both use as food and cultivation were subjected to bromatological analyses to determine content of fat, crude protein, total dietary fiber and iron on a dry-weight basis. All analyses were conducted in certified laboratories of the University of Costa Rica following quantitative Association of Official Analytical Chemists (AOAC) methods. Results are presented aggregated because these are exploratory determinations for only one harvest time, and due to the fact that in some cases the final taxonomic classification of some of the species is lacking.

2.3. Cultivation

Pre-selected seaweed species were subjected to floating long-line cultivation in waters 1.5 to ca. 10 m deep. Sites used were chosen through a combination of accessibility and local conditions, avoiding the rougher waters yet attempting to represent prevailing conditions for a potential future expansion. Long lines were spaced 1 m apart and, depending on the species, vegetative propagules of 4 to 30 g each were tied to ropes (4 mm thick) spaced on average 0.3 m between them. Plots were placed in different locations ranging from rocky/coralline and seaweed prairie flats to barren sandy bottoms on the Caribbean and above muddy flats on the Gulf of Nicoya and rocky sandy bottoms in Cuajiniquil. Plot size varied from a few lines occupying ca. 50 m^2 to the largest occupying 1200 m^2 (20 m wide × 60 m long) off the Puerto Vargas beach at the Caribbean site. Sand-filled burlap sacks were used as anchors and reused plastic bottles and jugs as floats.

Main cultivation parameters evaluated were growth and survival rates, as well as other characteristics such as fouling, epiphytism, sediment accumulation, herbivory and relations of the cultivated plots with their surroundings, including biodiversity and responses to currents and waves. Yield data were obtained from weekly to monthly rates. Data presented on a per hectare and yearly basis were extrapolated from at least three monthly fresh weight measurements of 5 to 10 m of line per sample. Some of this cultivation work was conducted with local fishers.

2.4. Biodiversity considerations

Biological diversity, defined as the number of species and of individuals present at a site, was evaluated through time for some of the Caribbean cultivation plots as compared to surrounding areas, identifying and counting selected groups of species and approximating their numbers for time intervals ranging from a few to up to 12 weeks.

Biodiversity data presented here are mainly for the larger plot at the Puerto Vargas beach, Caribbean site, which is in a protected area with no fishing allowed and exhibits very low native biodiversity having a sandy and almost barren floor, save for some rocks at its shallowest end. The plot, with an area of 1200 m^2, was established beginning at 120 m from the shore, immediately past wave breaking point, with a bottom depth ranging from 3 to 6 m. Fish numbers and species, as represented by individuals of a size >0.05 m (visible and identifiable with naked eye at one meter distance within water), were counted while establishing the plot and biweekly thereafter for 12 weeks by two marine biologists snorkeling together over and under the complete cultivated plot area, then moving to two nearby areas (control plots) of equivalent size each, located beginning 50 m away at each side of the cultivated plot, repeating the procedure. Higher taxa of invertebrates identifiable with naked eye out of the water and an approximation to their numbers, as well as vegetation (seaweeds and cyanobacteria) growing voluntarily on ropes, were also identified and counted. Thus no evaluation was conducted of microscopic biodiversity or of the myriad fish larvae and fingerlings ≤ 0.05 m long. Results for the two control plots are averaged together as they both represent the area surrounding the cultivated-seaweed plot. Statistical significance for all biodiversity comparisons was determined by paired *t*-test at the 99% confidence interval.

It was not possible to conduct thorough biodiversity evaluations at the Pacific sites since, due to theft, plots were short-lived. At the Gulf of Nicoya, biodiversity evaluation at the one site with prolonged cultivation proved extremely difficult due to murky waters and only some observations and short tests are reported.

3. Results

3.1. Prospecting and pre-selection

Prospecting on the Caribbean coast proved very rewarding, where a variety of brown, green and red seaweed species were easily collectable in most places sampled, with banks of the smaller species growing on rocks and corals while sizable and often dense ‘prairies’ of the larger ones (with up to 1.0 m tall often ‘bushy’ individuals of *Bryothamnion* spp., *Dictyota* spp. and *Sargassum* spp.) could be found growing on some sandy shallow bottoms. This abundance left the more complicated searches to specific species being sought. Also, arrivals of floating masses of *Sargassum* spp. and of other genera are common on the Caribbean coast.

On the Pacific coast the search proved more difficult since in the inner Gulf of Nicoya seaweeds are not at all abundant (attributable to decades of sediment, inorganic nutrients and organic matter input from land creating muddy bottoms and murky waters—though effects of bottom trawling cannot be discarded). Benthic seaweeds, in particular *Codium* sp. and *Acanthophora spicifera* Børgesen, were found in the outer third of the Gulf. Two filamentous species, however, a green, *Chaetomorpha* sp., and a brown, *Ectocarpus* sp., are ubiquitous and oftentimes grow abundantly on the surface of floating objects such as logs, ropes, fish cages and cultivated seaweeds, to the point that *Ectocarpus* sp. is considered a severe fouling pest. This relative absence of benthic seaweeds required searches in the more pristine environments of Cuajiniquil in the northern Pacific coast, where after some effort abundant banks of *Sargassum liebmannii* J. Agardh and *Ulva lactuca* Linnaeus were found, sometimes associated with each other and with other less abundant species that remain to be identified and tested.

In all, 38 species (33 from the Caribbean and 7 from the Pacific; with *Ulva lactuca* present on both coasts) were pre-selected for further consideration as food and 21 for cultivation (17 from the Caribbean and 5 from the Pacific). After a process of several food and cultivation tests, only 10 species (7 from the Caribbean and 4 from the Pacific) were finally selected as the most promising ones (Table 1).

Three exceptions to this seaweed selection process should be noted. Although only a small specimen of *Eucheuma isiforme* J. Agardh was eventually found in the Caribbean after extensive search, its prolific grow-out was fully lost to herbivory during cultivation and thus no results for this very promising species are shown. *Bryothamnion triquetrum* M. Howe, extremely ubiquitous and naturally abundant in the Caribbean, and a fast grower in cultivation as well, was discarded from being used as food for a variety of reasons, beginning with its harsh texture and taste and its complex chemical composition. Two species of *Halimeda* in the Caribbean, very abundant and ubiquitous, showed promise as potential calcium supplement or for other uses such as scrub in cosmetics, but were not considered for direct use in or as food nor for cultivation.

3.2. Uses as food

As seen in Table 1, there was a variety of uses as food for the selected species. Of these, the tender-most one (*Caulerpa racemosa* J. Agardh) was only consumed fresh in salads, whereas *Codium* spp. and *Chaetomorpha* sp. were only used or cooked fresh, being added whole or chopped into a variety of dishes, due to undesirable changes from drying. For convenience, all other species, though equally useful when cooked fresh, were normally dried and used after rehydration, whether whole, chopped or ground. The latter process, grinding to different coarseness, proved very useful allowing the finer material to be used as substitute for wheat and maize flour, something that was considered adequate up to a maximum of 20% for the different species tested, particularly *Sargassum* spp. and *Ulva lactuca*, beyond which the recipe began losing main characteristics such as consistency or appearance. Seaweed material ground to coarser fineness, in occasions consisting of a mix of up to 80% *Sargassum* spp. plus *Ulva lactuca* and *Gracilaria cervicornis* J. Agardh was used both liberally sprinkled atop a

Table 1
Selected tropical seaweed species with main uses as food and cultivation specifics. Yield data are mean and (standard deviation); N/A indicates no conclusive yield data available.

Species	Coast	Selected uses as food	Yield (t ha^{-1} yr^{-1})
Green			
Anadyomene stellata	Carib.	Cooked fresh or dried; as flour or meal	Not cultivated, harvested from rocks
Caulerpa racemosa	Carib.	Fresh in salads or as appetizer	N/A; fragile–needs protected cultivation; heavy herbivory
Chaetomorpha sp.	Pacif.	Cooked fresh similar to spinach	N/A
Codium taylorii	Carib.	Cooked fresh; fresh; fried with egg batter	153.2 (48.6)
Codium sp.	Pacif.	Cooked fresh; fresh; fried with egg batter	92.9 (36.5)
Ulva lactuca	Carib.Pacif.	Cooked fresh or dried; as flour or meal; fried; baked	51.7 (12.9); herbivory; requires frequent harvests
Brown			
Dictyota ciliolata	Carib.	Cooked fresh or dried; as flour or meal; fried; baked	N/A
Sargassum liebmannii	Pacif.	Cooked fresh or dried; as flour or meal; fried; baked	N/A
Sargassum platycarpum	Carib.	Cooked fresh or dried; as flour or meal; fried; baked	104.8 (23.6)
Red			
Gracilaria cervicornis	Carib.	Cooked fresh or dried; as flour or meal; fried; baked	76. 0 (11.9); heavy herbivory
Combination			
Sargassum + *Ulva* + *Gracilaria*		Ground dry in capsules; as flour or meal sprinkled on foods and beverages	

variety of preparations, including fruit juices before blending and also encapsulated to be used as a dietary complement.

As determined by food-tasting trials, many products were liked and easily consumed. The most widely accepted ones were: *Caulerpa racemosa* and to a lesser extent *Codium* spp. served fresh as part of salads; *Codium* spp. fried fresh covered with egg batter (a tasty dish that was very much liked by coastal inhabitants); *Sargassum* spp. pieces cooked after rehydration together 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); *Chaetomorpha* sp. cooked and served in a manner similar to spinach; thin baked grissinis and fried tortilla chips substituting wheat and maize flours respectively with 15% *Sargassum* spp. flour on a dry weight basis; the coarsely ground mixture of three species sprinkled liberally on top of different dishes including blended into fruit and vegetable juices; and, the encapsulated mixture of the same three species. The two latter modes of use were liked very much, to the point of receiving many requests for more from over 50% of panel participants, even months after the trials (which for these cases lasted 30 days at 1–4 g d^{-1}).

An interesting and recurrent comment during tasting panels was "I did not expect seaweeds to taste good", reflecting a natural resistance that nonetheless was removed after tasting. The most recurrent comments for requesting more of the ground material used powdered, sprinkled or encapsulated, were: 'feelings of well-being', 'good taste' and 'help against constipation'. The most recurrent comments for dislike or even for no acceptance were 'fish-like smell and taste', 'uncommon taste' and, in some cases, 'hard pieces'. Of all species tested, and only as an organoleptic perception from the panels, *Sargassum* spp. and *Codium* spp. showed the least 'fish-like' smell and taste while *Ulva lactuca* and *Anadyomene stellata* C. Agardh had strong smell and taste even after drying and cooking.

Storage of bagged fresh material in the dark at room temperature was adequate mainly for *Sargassum* spp. and for up to two weeks refrigerated for most species excepting *Caulerpa racemosa* which lasted only up to five days. Storage of packaged dried seaweed proved adequate, with no obvious decay and apparently keeping their properties, for up to at least nine months in the dark at room temperature. As determined by organoleptic perception, neither drying nor storage reduced to any considerable extent the 'fish-like' smell and taste.

The pooled nutritional content of eight of the most promising of the selected seaweeds is shown on Table 2. On average, these were 1.4% fat, 9.8% crude protein, 29.5% total dietary fiber and 151.9 ppm iron (Fe). Although there was considerable variation in values, variability was highest in fat content, with over 20-times larger value between the highest (*Dictyota ciliolata* Kützing, as expected) and the lowest. Content and variability of Fe were also high. In general, however, values were within expected ranges indicating the basic nutritional adequacy of consuming these seaweeds, including high dietary fiber. However, and perhaps due to discrepancies when identifying species or to environmental or other variations, large differences in content found in the literature for specific nutrients (e.g. for amino-acids) and minerals for apparently the same seaweed species discouraged at this point the nutritional analysis of the main recipes.

3.3. Cultivation

After minor adjustments of the long-line cultivation technology to better-fit local conditions, cultivation proved simple and effective. For species that were eventually selected (Table 1), short term growth rates were within 2.8 to 7.2% d^{-1} while survival rates averaged 84.3% (52.1 to 100%; not counting recurrent complete die-off of *Ulva lactuca*). In many occasions, however, theft of some or all of the ropes, on both coasts, did not allow to consistently obtain yields on a per area basis. Theft also discouraged continuation on the part of participant fishers, although they easily and gladly understood the usefulness of seaweeds and mastered the basic cultivation techniques after short explanations. Differences through time in both survival and growth rates were related to biofouling, accumulation of sediment and herbivory, mostly as observed from parrot fish (Scaridae) and surgeon fish (Acanthuridae). Herbivory proved extreme for several of the cultivated species (like *Eucheuma isiforme*, *Gracilaria cervicornis* and *Caulerpa racemosa*) while negligible for others (particularly for *Sargassum* spp. and *Codium* spp.). For these reasons yields for only some species are reported, while only an indication is given for the other selected species, including comments on some other related factors (Table 1). These conditions also precluded determining differences between the Caribbean and the Pacific.

Table 2
Pooled nutritional composition on a dry weight basis of eight selected tropical seaweeds (same as Table 1 excepting *Anadyomene stellata* and *Sargassum liebmannii*).

	Lipid (%)	Crude protein (%)	Total dietary fiber (%)	Fe (ppm)
Mean (s.d.)	1.4 (1.2)	9.8 (2.5)	29.5 (13.3)	151.9 (135.0)
Range	0.2–3.5	5.4–12.8	18.0–53.8	17.4–316.9

Of these species selected (Table 1), only *Anadyomene stellata* was considered inadequate for cultivation of this sort, yet due to its abundance and ubiquity it was selected since harvest from the wild can be a very valuable form of use. *Caulerpa racemosa* required to be grown inside some rustic cages or 'pouches' made of net to decrease damage from currents and waves as well as to protect it from herbivory. *Ulva lactuca* would die-off cyclically or attributed—by observation only—to large and rapid changes in water temperature and/or salinity, something that required frequent harvesting, bi-weekly to monthly, in order to avoid complete losses. Overall, the several *Sargassum* spp. tried in different modalities exhibited the highest tolerance to epiphytism, fouling and herbivory.

In spite of the above limitations, yields around or over 100 t ha^{-1} yr^{-1} on a fresh weight basis were obtained for *Codium* and *Sargassum*, while the yields of *Gracilaria* and *Ulva*, though lower, 76.0 and 51.7 t ha^{-1} yr^{-1} (Table 1), were quantifiable in spite of high herbivory and recurrent die-off, respectively. While yields averaged 95.7 t ha^{-1} yr^{-1} on a fresh weight basis, when converted into dry weight through the 9.7% ratio established earlier, an average of 9.3 t ha^{-1} yr^{-1} on a dry weight basis was obtained. Using the 9.8% average crude protein content (Table 2), a specific yield of 0.91 t ha^{-1} yr^{-1} of crude protein can be obtained at this stage, using no fertilizer nor freshwater. This annual yield can be compared very favorably with that of two sequential crops per year of, e.g., bean and maize in tropical developing countries.

3.4. Biodiversity considerations

Biodiversity, as measured in number of fish species and individuals for several plantings in the Caribbean, was significantly larger in most cases as compared to control areas for both the surface on or around cultivated seaweeds and within the water column under the seaweed plots. The exceptions were two small plots nearby some shallow coralline formations with abundant native biodiversity, where no differences were detected between cultivated and uncultivated areas.

The difference in biodiversity was most evident when comparing the effect of establishing a relatively large (1200 m^2) experimental plot planted to selected seaweed species on the Caribbean above a barren sandy bottom, where very low animal and seaweed biodiversity are normally observed. As seen in Fig. 1, number of fish individuals and species identifiable with the naked eye in water (>0.05 m long) was very low throughout the complete 12-week period in the two control areas, where only one species of grunt (*Anisotremus* sp.) and one of sardines (*Harengula* sp.) were observed, besides some jelly fish (Cnidaria phylum) and small crabs (Majidae and Portunidae families). The third fish species observed during week 12 was a spotted eagle ray (*Aetobatus narinari*), really moving in and out of the water column under the cultivated seaweeds. Under the cultivated seaweed plot,

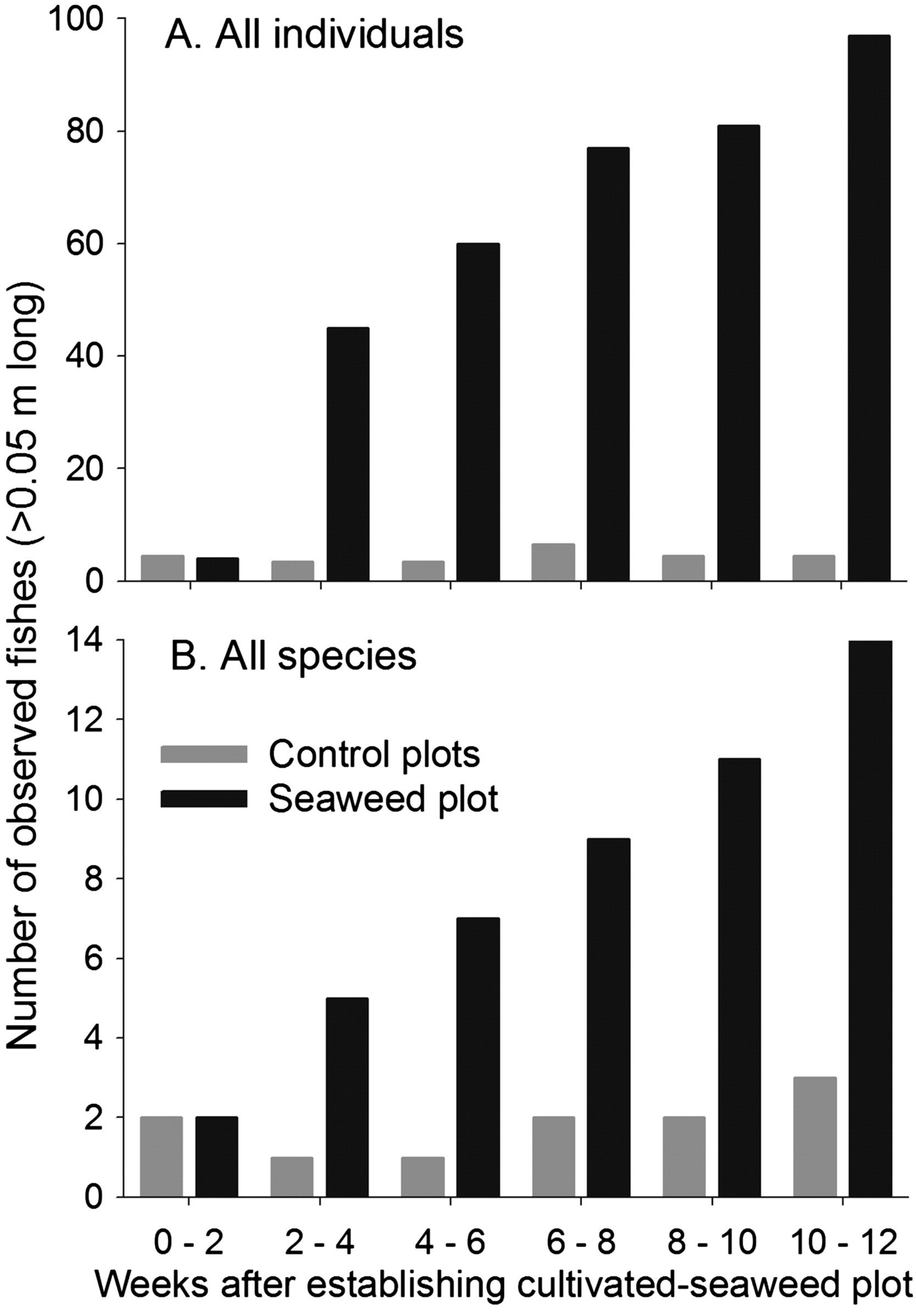


Fig. 1. Number of observed fish individuals (A) and species (B) with individual sizes >0.05 m in the water column under a 1200 m^2 cultivated-seaweed plot as compared to two equivalent control areas off the Puerto Vargas beach, Cahuita National Park, Caribbean coast, Costa Rica.

however, observable fish individuals and species increased from four and two during establishment to 97 and 14 at week 12, respectively (Fig. 1). Differences in number of fish individuals and species between control and seaweed plots were highly significant ($p \leq 0.01$) starting at week 3 after establishment.

Interesting aspects were that soon after establishing that large seaweed plot, during week 1, both sardines and grunts were seen moving within the water column instead of only close to the bottom or hidden in crevices as they continued to do in the control plots. Also, besides omnivorous fish species and two species of herbivores, namely parrot fish and surgeon fish, by week 6 two medium-sized adult barracudas (*Sphyraena barracuda*) arrived and stayed as residents under the cultivated seaweeds, leaving immediately after harvest in week 12. By week 10 several sharks (*Carcharhinus falciformis*) and a spotted eagle ray became common sights until harvest. A bottlenose dolphin (*Tursiops trocantus*) was also seen in week 10 but, of course, was not counted. While grunts and sardines never numbered over five in any of the control plots, these numbers rose significantly to over 20 and over 10, respectively, at every counting time under the cultivated seaweed plot. Additionally, larger individuals of grunts and sardines were regularly seen under the seaweeds than in control areas. Particularly abundant under the seaweed plot (>30 individuals regularly) was the sergeant major fish (*Abudefduf saxatilis*).

Invertebrate biodiversity recorded for this cultivated-seaweed plot in comparison with its surroundings, where only a few jelly fish and some small crabs were seen throughout the 12-week period, were: flat worms, brittle stars, isopods, sipunculid worms, ring worms, hermit crabs, amphipods, bryozoans, sponges and Turbinidae gastropods, all of them around or on the seaweeds and ropes. In particular, Turbinidae gastropods and small Emerald crabs (*Mithraculus sculptus*) were seen very abundantly feeding on seaweeds. Isopods were very numerous, more so evidenced by their biting, while amphipods regularly attempted to enter ear and nose canals. Overall, the effect of biodiversity enrichment was such that one of the data-takers wrote on her report for week 10: “Seaweed plot area is like a marketplace compared to nearby sites!” Also, the protected-zone manager at Cahuita said that sharks had not been seen for years in these waters during their regular patrolling.

Voluntary seaweeds (i.e., ‘weeds’), of different species than the ones cultivated, *Cladophora* sp., *Dictyota* sp., *Ectocarpus* spp. and *Padina* spp., as well as long filaments of the cyanobacterium *Lyngbya* sp., were found established on the ropes or on some of the cultivated seaweeds from weeks 8 through 12.

Observations for some plantings on the Gulf of Nicoya, a Pacific site, also indicated increase in biodiversity yet this was not formally quantified. In particular, spotted snappers (*Lutjanus guttatus*) were often attracted to seaweed plantings. To test this further, three lobster cages were baited only with pieces of *Codium* sp. and placed for five separate 24 h periods over muddy bottoms near seaweed plots. The most common and abundant catch every time was this species of snappers. Also, adding floating lines with *Codium* sp. inside shrimp (*Penaeus vannamei*) cages kept the seaweed significantly ($p \leq 0.01$) cleaner from fouling and epiphytism with *Ectocarpus* sp. (measured as % surface covered) as compared with those grown outside the cages, pointing to a trophic interaction with shrimp.

4. Discussion

Although prospecting for different seaweed species was relatively easy in the Caribbean given the abundance of species and individuals, this was not the case for the Pacific, where searches in different locations and seasons were needed to obtain sufficient material of a few promising species. Even then, this is a continuing line of work since several key species both in the Pacific and the Caribbean remain to be found, and cultivation and replenishment from wild material is often needed for some of the species. Of course, this process should lose importance as, with time, the best species will have been identified, domesticated, made available even on an international context and improved through selection, breeding and genetic engineering—analogous to the process that has been followed through millennia with agricultural crops.

While the use of seaweeds for food at this experimental stage can be considered in many ways successful and many recipes that use up to 15% of seaweed on a dry 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. The experience in tropical Asian countries with a long time tradition of tropical seaweed consumption, as well as that reported for other places (e.g., for Hawaii, see McDermid and Stuercke, 2003; Reed, 1907) would be most useful. 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 complicated and expensive.

Yet different strategies based on this experience can be implemented as first approaches, like using seaweeds that have less ‘fish’ smell and taste like *Sargassum* spp. and *Codium* spp., particularly after cooking into recipes that help ‘mask’ flavors through other ingredients. 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 perception can be easily altered. This allows thinking that acceptance of seaweeds as food and/or of food products containing them may be easier after the appropriate marketing efforts, 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, is a valuable 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 over-emphasized. Suitable ‘cultivability’ must be matched with suitable use for food and momentum must be gathered 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.’

On cultivation and use as food, these innovations were easily transferred to fishers and their families, who were eager to implement them. Nonetheless, it was clear on the Pacific coast that the understanding about seaweeds by fishers, including lobster divers, was very limited. For example, efforts had to be made to clarify the difference between seaweeds and some coralline formations. Another limitation was the recurrent theft of all ropes, which, attributable to risk aversion, frustrated continuation of all but one of the pilot seaweed farming efforts with fishers. This limitation, together with vandalism, has been noted for previous sea farming startups on the Pacific coast of Costa Rica (Radulovich, 2010). Solutions are generally related to scaling-up in order to afford care.

The fact that cultivated-seaweed plots attracted/promoted biodiversity has at least three implications. The first one, which originally led us to evaluate this effect, was that working in the water within and below plantings turned into a hazard far beyond the annoying bites of isopods when barracudas and sharks became common. The second one is that, given the excessive losses to herbivory, herbivorous fish and other animals could be the focus of caged animal farming, replacing costly feed with seaweeds produced in situ. The third and perhaps most far-reaching implication is that thanks to its role in attracting biodiversity, seaweed farming can be conceptualized within more encompassing schemes, not only as a complement to fish farming, as it is often considered (e.g., Chopin, 2012; Kapetsky et al., 2013). For example, their biodiversity enrichment role in recovering and enhancing fisheries and wildlife may be a most relevant yet previously unconsidered service of seaweed farming. The generally accepted concept that “marine biodiversity is higher in benthic rather than pelagic systems” (Gray, 1997) may simply be due to the lack of adequate habitats in the epipelagic zone. Extensive floating tropical seaweed farming may come to change this, at least locally.

An important aspect that remains to be elucidated is if floating (as opposed to off-bottom) seaweed plots, whether cultivated as the present experiments or natural as in the Sargasso Sea (e.g., Fine, 1970; Hoffmayer et al., 2005) or the East China Sea (e.g., Komatsu et al., 2007) act only as fish aggregating—or attracting—devices (FADs, originally known as the Philippine ‘payao’), which is a widely used and analyzed technique in fishing (e.g. Anderson and Gates, 1996; Castro et al., 2002; Girard et al., 2004), or go beyond that by promoting more vigorous trophic chains than those provided by floating inert material over which, nonetheless, limited trophic relations are established based on fouling. The abundance in the Caribbean plantings of vertebrate and invertebrate herbivores, and of omnivores like the sergeant major fish, known to eat benthic algae (Randall, 1996), points to trophic interactions based on abundant seaweed material serving as feed. Regarding the role of floating *Sargassum* masses on the Sargasso Sea, Fine (1970) indicated that "high diversity values were related to an equitable distribution of species resulting from a stable environment and an area low in productivity". Komatsu et al. (2007) have compared drifting *Sargassum* masses on the East China Sea to oasis in deserts, adding that commercially important pelagic fishes spend their juvenile period accompanying these drifting masses.

It is indeed an exciting challenge to attempt to establish a new epipelagic approach to marine management, based on implementing large areas of floating seaweed farming integrated with fisheries and optionally with animal aquaculture for a complete set of products, and with environmental considerations (including bioremediation) and biodiversity relations for services. This can be a new and very important paradigm for coastal rural development in the context of dwindling fisheries and continuously degrading coastal ecosystems.

In particular, it seems necessary to realize that if marine aquaculture is to become a major mean of food production (which is defined as primary production through biosynthesis), seaweed farming is so far the only option analogous to agricultural crop production. Also, borrowing experience from agriculture should prove beneficial, as it was done here. For example, it was considered important to make an effort to quantify and report yields on a per hectare and time basis, not only as a percentage of growth on a daily basis. Tonnage produced per area and per time is the important variable, particularly as reported on a dry-weight basis—for which there are no agreed-upon standards. Of course, particular components, such as protein or antioxidant contents, may require specific considerations, yet in the end everything is reduced to yield concepts, whether in relative or absolute terms. Also, waters high in nutrients should be prioritized over others in order to fully avoid the use of fertilizer while cleaning those waters from excess nutrients. Growing seaweeds in high-nutrient waters increased their protein content by several percentage points (Msuya and Neori, 2008).

Given the magnitude of the effort required to consolidate seaweed farming and their use as food, integrated with other uses such as for hydrocolloids or bioenergy, future work similar to this should be expanded in scope and to a larger variety of conditions, so that more opportunities as well as limitations are rapidly identified and taken advantage of. Of course, commonality of objectives among researchers, in order to produce results that can be shared adequately, and public funding, even as a small fraction of what is allocated to agricultural research, are needed in order to advance into turning seaweed farming in a significant source of food, considering as indicated above other products as well as services, forging a new paradigm to everybody's satisfaction.

Considering the vast potential of coastline and sea areas for offshore mariculture recently quantified by FAO (Kapetsky et al., 2013), together with facts like that close to 40% of the world's population live in coastal areas (UNEP, 2006) and 49 of 79 countries with moderate to extremely alarming global hunger indices have coasts (Welthungerilfe, 2012), many with nutrient-rich waters as well as plenty of impoverished fishing communities, it makes sense to begin to emphasize widespread seaweed cultivation and use as food and for other products and services, literally attempting to establish it as a second agriculture at sea, completely independent of freshwater limitations.

Acknowledgments

Funding for this work was provided by a Grand Challenges grant (OPP1045878) from the Bill and Melinda Gates Foundation to the University of Costa Rica. Early stages of this work were funded by a Development Marketplace grant from the World Bank (141-07) through the 'Sea Gardens' project. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript. Thanks are given to the Ministry of Environment and Energy of Costa Rica for granting permission to work on the Cahuita protected coastal area of the Caribbean.

This article is based on a paper presented during the 21st International Seaweed Symposium, Bali, Indonesia, April 2013.

References

Anderson, J., Gates, P.D., 1996. Fish Aggregating Device (FAD) Manual—Volume 1, Planning FAD Programmes. South Pacific Commission, Coastal Fisheries Programme. SPC/UNDP/AusAID/ODA, Noumea, New Caledonia.

Black, W.A.P., 1952. Seaweeds and their value in foodstuffs. Proc. Nutr. Soc. 12, 32–39.

Castro, J.J., Santiago, J.A., Santana-Ortega, A.T., 2002. A general theory of fish aggregation to floating objects: an alternative to the meeting point hypothesis. Rev. Fish Biol. Fish. 11, 255–277.

Chopin, T., 2012. Seaweed aquaculture provides diversified products, key ecosystem functions. Part II. Recent evolution of seaweed industry. Glob. Aquac. Adv. 14 (4), 24–27.

Falkenmark, M., Rockström, J., Karlberg, L., 2009. Present and future water requiring for feeding humanity. Food Sec. 1, 59–69.

FAO, 2012. The State of World Fisheries and Aquaculture 2012. FAO, Rome.

FAO, 2013. Global Aquaculture Production Statistics for the year 2011 [on line]. FAO Fisheries and Aquaculture Department, Rome (ftp://ftp.fao.org/FI/news/GlobalAquacultureProductionStatistics2011.pdf).

Fernández-García, C., Riosmena-Rodríguez, R., Wysor, B., Tejada, O.L., Cortés, J., 2011. Checklist of the Pacific marine macroalgae of Central America. Bot. Mar. 54, 53–73.

Fine, M.L., 1970. Faunal variation on pelagic *Sargassum*. Mar. Biol. 7, 112–122.

Girard, C., Benhamou, S., Dagorn, L., 2004. FAD: Fish aggregating device or fish attracting device? A new analysis of yellowfin tuna movements around floating objects. Anim. Behav. 67, 319–326.

Gray, J.S., 1997. Marine biodiversity: patterns, threads and conservation needs. Biodivers. Conserv. 6, 153–175.

Hoffmayer, E.R., Franks, J.S., Comyns, B.H., Hendon, J.R., Waller, R.S., 2005. Larval and juvenile fishes associated with pelagic *Sargassum* in the northcentral Gulf of Mexico. Gulf Carib. Fish. Inst. 56, 259–269.

Kapetsky, J.M., Aguilar-Manjarrez, J., Jenness, J., 2013. A global assessment of potential for offshore mariculture from a spatial perspective. FAO Fisheries and Aquaculture Technical Paper No. 549. FAO, Rome.

Komatsu, T., Tatsukawa, K., Filippi, J.B., Sagawa, T., Matsunaga, D., Mikami, A., Ishida, K., Ajisaka, T., Tanaka, K., Aoki, M., Wang, W.-D., Liu, H.-F., Zhang, S.-D., Zhou, M.-D., Sugimoto, T., 2007. Distribution of drifting seaweeds in eastern East China Sea. J. Mar. Syst. 67, 245–252.

Matanjun, P., Mohamed, S., Mustapha, N.M., Muhammad, K., 2009. Nutrient content of tropical edible seaweeds, *Eucheuma cottonii*, *Caulerpa lentillifera* and *Sargassum polycystum*. J. Appl. Phycol. 21, 75–80.

McDermid, K.J., Stuercke, B., 2003. Nutritional composition of edible Hawaiian seaweeds. J. Appl. Phycol. 15, 513–524.

Msuya, F., 2011. The impact of seaweed farming on the socioeconomic status of coastal communities in Zanzibar, Tanzania. World Aquacult. 42 (3), 45–48.

Msuya, F.E., Neori, A., 2008. Effect of water aeration and nutrient load level on biomass yield, N uptake and protein content of the seaweed *Ulva*. J. Appl. Phycol. 20, 1021–1031.

OECD/FAO, 2012. OECD-FAO Agricultural Outlook 2012. OECD Publishing, Paris and FAO, Rome.

Radulovich, R., 2010. Cage production experiments conducted with shrimp in Costa Rica. Glob. Aquac. Adv. 13 (4), 82–83.

Radulovich, R., 2011. Massive freshwater gains from producing food at sea. Water Policy J. 13, 547–554.

Randall, J.E., 1996. Caribbean Reef Fishes, Third ed. TFH Publications, New Jersey.

Reed, M., 1907. The Economic Seaweeds of Hawaii and their Food Value. Cornell University Library Digital Collections, Ithaca, N.Y.

Robledo, D., Freile, Y., 1997. Chemical and mineral composition of six potentially edible seaweed species of Yucatán. Bot. Mar. 40, 301–306.

Radulovich, R., Umanzor, S., Cabrera, R., 2013. Algas Marinas: Cultivo y Uso como Alimento Humano. Versión 1(http://www.maricultura.net) University of Costa Rica, San Jose.

UNEP, 2006. Marine and coastal ecosystems and human well-being. SynthesisUNEP, Nairobi.

UNU, 2012. Science-Policy Bridges over Troubled Waters. United Nations University, Institute for Water, Environment and Health, Hamilton, Canada.

Wehrtmann, I.S., Cortés, J. (Eds.), 2009. Marine Biodiversity of Costa Rica, Central America Monographiae Biologicae 86. Springer, The Netherlands.

Welthungerilfe, 2012. Global hunger index. Welthungerilfe/IFPRI/Concern Worldwide. D+L Printpartner GmbH, Bocholt, Germany.