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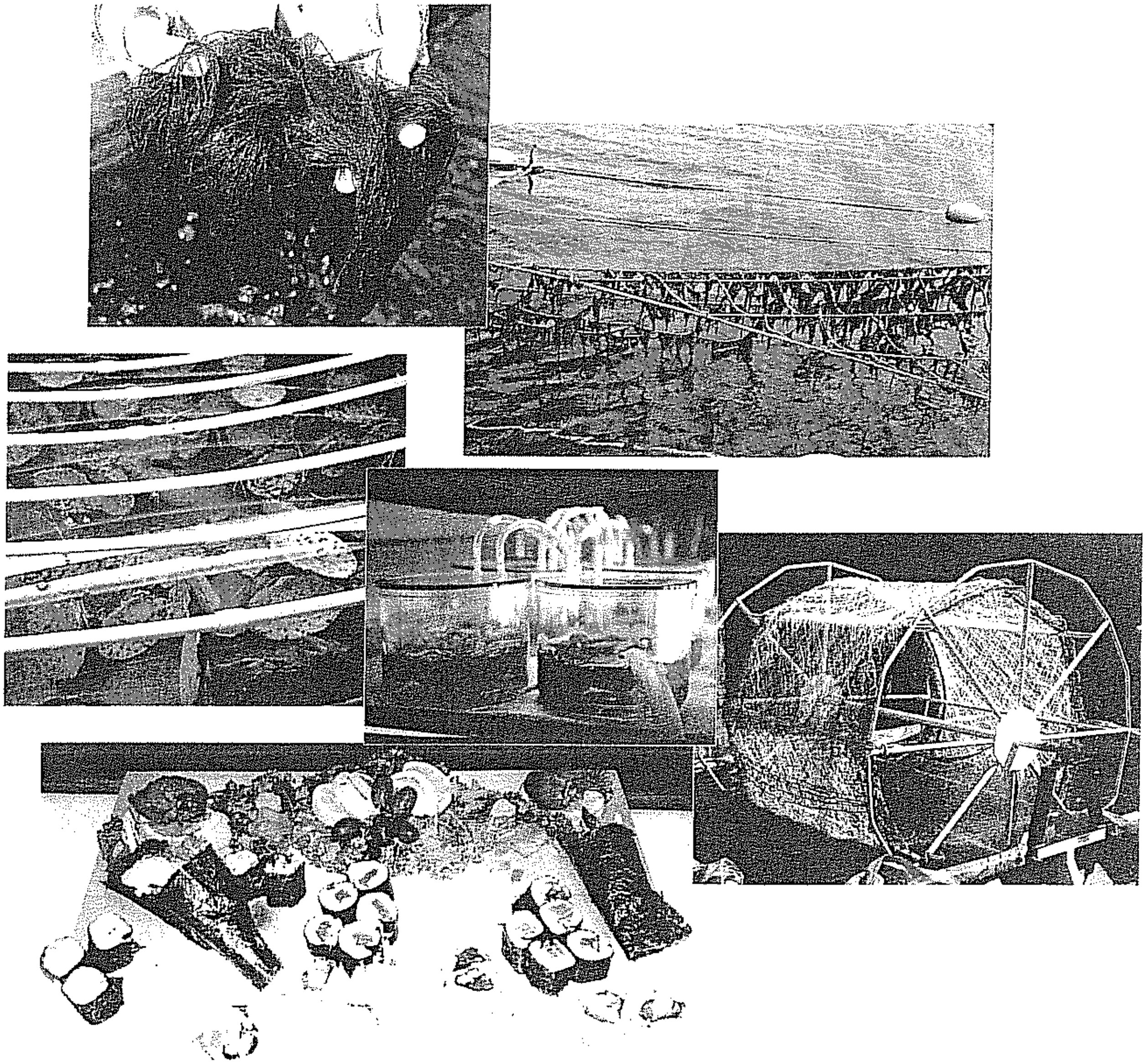

SEAWEED

MOVING TO THE FOREFRONT IN AQUACULTURE

Seaweed cultivation: global trends

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When one thinks of aquaculture, the organisms that first come to mind are usually fish or shrimp or maybe shellfish. Macroscopic algae, usually called macroalgae or seaweeds, are often overlooked despite their enormous global market. The worldwide commercial harvest of seaweeds is ~7.8 million metric tons (mt)[4]; 87 percent of this amount, or ~6.8 million mt, is cultivated[3], rather than being harvested from wild populations. The value of these cultivated seaweeds is ~US$5.9 billion.[3] Both the value and the amount of production have doubled over the last 10 years (Fig. 1).

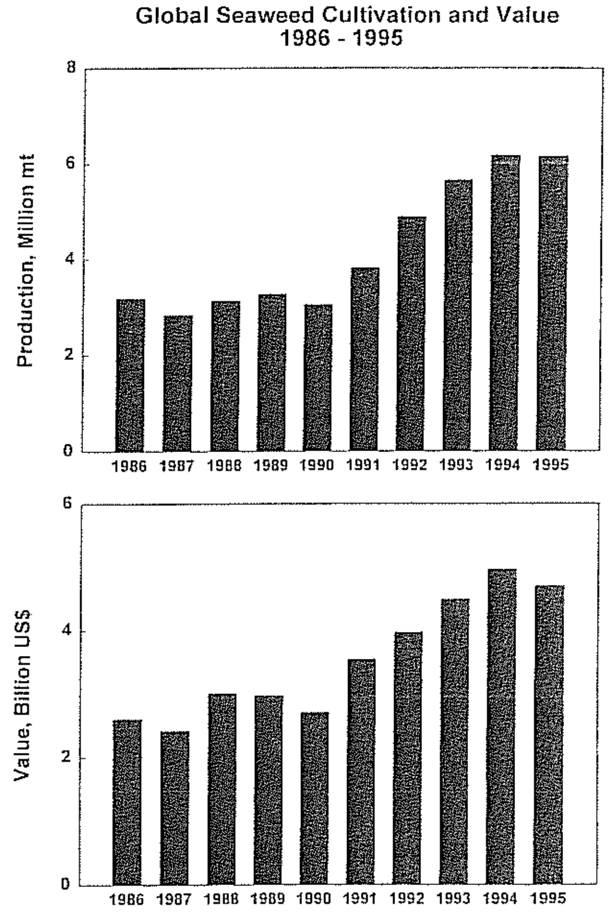

Fig. 1. Global seaweed cultivation and value, 1986-1995. Source: FAO (1997a)

Despite the magnitude of seaweed aquaculture, it is often hard to appreciate the degree to which seaweeds are utilized. We all use seaweed products every day, usually without knowing it. For example, seaweed extracts are in ice cream, puddings, chocolate milk, pie fillings, canned meats, jellies, cosmetics, soaps, shampoos, and paints. Seaweeds are eaten by people in various parts of the world, fed to domesticated animals, and used as fertilizers, soil additives and medicines.

Seaweeds have been harvested from natural populations throughout historic times in many parts of the world, but natural populations are no longer adequate to meet the demand for seaweed. As with other organisms, seaweed aquaculture permits higher production of a better product, and hopefully more economically, than natural harvests. Industry prefers a greater stability in both the quantity and quality of raw material.

The first known record of seaweed cultivation is in 1623, when Japanese fisherman planted nori (the red alga *Porphyra*, familiarly known today for its use as a wrapper in sushi) on bamboo twigs in the intertidal zone. Cultivation of kombu (the brown alga *Laminaria*) began in 1730, again in Japan, where fishermen deployed stones to enhance the recruitment of this kelp and its subsequent harvest. Both nori and kombu were originally cultivated for direct human consumption for food, which, even today, remains the greatest, and most valuable, use of cultivated seaweeds.

Currently, ~5.5 million mt of edible seaweeds are cultivated worldwide, at a value of ~US$4.5 billion (Table 1). Significant cultivation of edible seaweeds is limited to three genera. The most valuable fishery and aquaculture species in the world are kombu and nori, with values of ~US$2.9 and ~US$1.5 billion per year, respectively. More than 3.8 million mt per year of kombu are harvested from nearshore farms in China, with smaller quantities cultivated in Japan and Korea. The same three countries are responsible for the world's cultivation of nori (~0.9 million mt per year), with Japan the largest producer (~0.4 million mt per year).

After human food consumption, the next most valuable commercial use of seaweeds (Table 2) is as raw material for the extraction of phycocolloids (agars, alginates, and carrageenans). These polysaccharides, with a global market value of ~US$583 million, are used in many industries for their gelling, emulsifying, and stabilizing properties in an increasingly diverse array of industrial and biotechnical applications.

Historically, before the widespread use of synthetic fertilizers, seaweeds were important as soil additives and fertilizers, a use which still occurs to some extent today. Seaweed meal is an ingredient of animal feeds. Emerging uses of seaweeds, but not yet significantly realized at the commercial scale, include pigments, pharmaceuticals, waste water treatment, and

Table 1. World-wide Economic Value of Seaweeds Cultivated for Food Consumption

Product	Value (10^6 US$)	Raw Material (mt)	Raw Material (UA $/mt)	Product (mt)	Product (US $/mt)
Kombu (*Laminaria*)	2,866	4,055,027	707	~1,014,000	2,826
Nori (*Porphyra*)	1,464	909,122	1,610	~91,000	16,088
Wakame (*Undaria*)	229	495,390	462	~33,000	6,939
Totals	4,559	5,459,539		~1,138,000	

Source: FAO (1997a)

Table 2. Worldwide Economic Value of Seaweeds Used for Industrial Consumption.

Product	Value (10^6 US$)	Raw Material (mt)	Raw Material (UA $/mt)	Product (mt)	Product (US $/mt)
Carrageenan	~240	~400,000	600	~25,000	9,600
Alginate	~211	~460,000	459	~23,000	9,174
Agar	~132	~125,000	1056	~7,500	17,600
Soil Additives	~10	~550,000	18	~510,000	20
Fertilizers	~5	~10,000	500	~1,000	500
Seaweed Meal	~5	~50,000	100	~10,000	5,000
Totals	603	~1,595,000		~576,500	

Sources: Lobban and Harrison (1997), Porse (1998)

Table 3. Top Five Cultivated Seaweed Genera in the World (1995)

Product	Value (10^6 US$)	Raw Material (mt)	Raw Material (UA $/mt)
Laminaria	2,866	4,055,027	707
Porphyra	1,464	909,122	1,610
Undaria	229	495,390	462
Eucheuma	42	441,665	95
Gracilaria	31	71,533	433
Totals	4,632	5,972,737	

Source: FAO (1997a)

bioconversion for alternative energy production.

The economic values of kombu and nori (Table 3) are an order of magnitude higher than the next most valuable and most cultivated seaweed (the brown seaweed *Undaria*, or wakame) and nearly two orders of magnitude higher than the next most cultivated genera, the red algae *Eucheuma* (cultivated for carrageenan, primarily in the Philippines) and *Gracilaria* (cultivated for agar, with the most significant producer currently Chile).

While the consumption of seaweeds, especially for industrial uses such as phycocolloids, is a truly global phenomenon, significant commercial cultivation of seaweeds is restricted to only a few regions of the world, where there has been a long historical use of seaweeds and/or where favorable growing and economic conditions now exist. Nearly all of the world's cultivated seaweed can be accounted for by only ten countries (Table 4). The top three seaweed-producing countries are China, Korea, and Japan, where most of the world's edible seaweeds (i.e., kombu, nori, and wakame) are grown. Most of the remaining top seaweed-producing countries are also in Asia, but produce seaweeds primarily for industrial consumption (i.e., phycocolloids), rather than for food. One notable geographical exception is Chile, which has had quite a success story in seaweed cultivation, especially for *Gracilaria*, during the last 15 years (discussed further, below).

Most of the increase in cultivated seaweed in recent years has resulted from scientific and technology breakthroughs, as well as finding stable economic situations for seaweed industries to develop and prosper. The cultivation of nori was greatly enhanced during the 1950s and 1960s following the elucidation of its life cycle by the British phycologist Catherine Drew. This important, basic scientific discovery had profound practical applications to the development of the nori industry. Selection of gametophytes and the environmental control of spore release from high-quality strains resulted in an enormous increase of nori farming in Japan, and subsequently in China and Korea.

Similarly, the currently huge kombu

Table 4. Top Ten Countries for Seaweed Cultivation (1995)

Country	Production (mt)	Major Genera
China	4,807,066	*Laminaria, Porphyra*
Korea	779,599	*Undaria, Porphyra, Laminaria*
Japan	569,489	*Porphyra, Laminaria, Undaria*
Philippines	466,054	*Eucheuma*
Indonesia	108,000	*Gracilaria*
Chile	49,183	*Gracilaria*
Taiwan	8,261	*Gracilaria*
Viet Nam	8,000	*Gracilaria*
Russia	6,560	Brown Algae
Italy	5,000	*Gracilaria*
Totals	6,807,212	

Source: FAO (1997a)

industry in China was non-existent in 1949, when an extensive research program began on the cultivation of the kelp *Laminaria japonica,* first introduced accidentally from Japan in the 1920s. Under the leadership of C.K. Tseng, Chinese phycologists developed an entire industry for growing this species from spore to harvest, including methods for the indoor cultivation of kelp sporelings under controlled environmental conditions and for the cultivation and harvest of gametophytes in China's coastal waters. Using classical genetic approaches, significant strain improvements in the wild *L. japonica* were made, including a considerable increase in its thermal tolerance, which lead to a large increase in the geographical area that could support *Laminaria* farms.

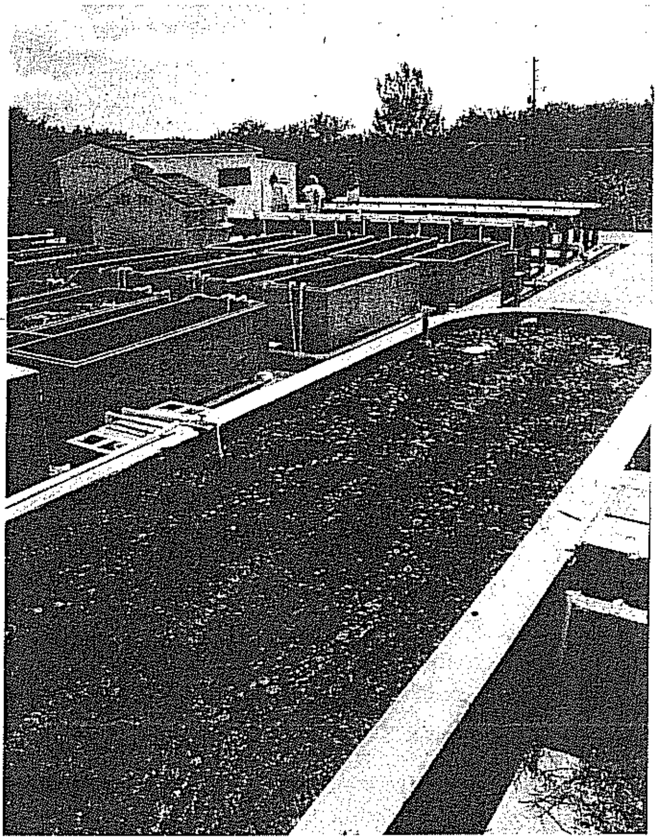

Fig. 2. Experimental marine botany cultivation facility at Harbor Branch Oceanographic Institution (HBOI), Fort Pierce, Florida

A major stimulus for the successful cultivation of phycocolloid-bearing seaweeds was the dwindling and uncertain wild stocks of red algae which became apparent during the 1960's. Significant research efforts, including partnerships between phycologists and private industry, lead to a much greater and stable production of these seaweeds. Two notable examples are *Eucheuma* in the Philippines and *Gracilaria* in Chile. *Euchuema* cultivation improvements, initiated by the late phycologist Max Doty, resulted in the Philippines becoming the largest producer of carrageenophytes and *Eucheuma* becoming the major source (85 percent) of the world's supply of carrageenan; carrageenan production in the Philippines increased from 500 mt in 1971 to 25,000 mt in 1996. In Chile, over-harvesting of wild stocks of *Gracilaria* in the 1980's lead to increased research by Chilean phycologists to develop aquaculture methodologies for this agaro-phyte. The amount of *Gracilaria* cultivated in Chile[3] increased over 10 years from 5,000 mt (1985) to 66,000 mt (1994); Chile is now the major producer (Ç40%) of the world's agar supply.[3]

In most of the Western world, seaweed cultivation has not advanced much beyond the experimental phase, most of which has occurred during the last 25 years. There is now renewed interest in incorporating macroalgae into integrated polyculture systems, something which has long been practiced in China and in other parts of Asia. Integrated polyculture was the focus of macroalgal cultivation efforts begun in 1971 by John Ryther and his associates at Woods Hole Oceanographic Institution in Massachusetts and at Harbor Branch Oceanographic Institution in Florida (Fig. 2). Early success with rapidly growing strains of the red alga *Gracilaria* (Fig. 3), as well as the existing commercial harvesting of the brown alga *Macrocystis* in California, lead to the development of research programs (~1975-1985) that explored the feasibility of using marine biomass (seaweed) as an alternative energy source. While the economics of raising seaweeds for bioconversion was not favorable in the 1980s, this period of time was probably the most productive in terms of advances in macroalgal cultivation.[2]

The recent renewed interest in seaweeds as components of polyculture

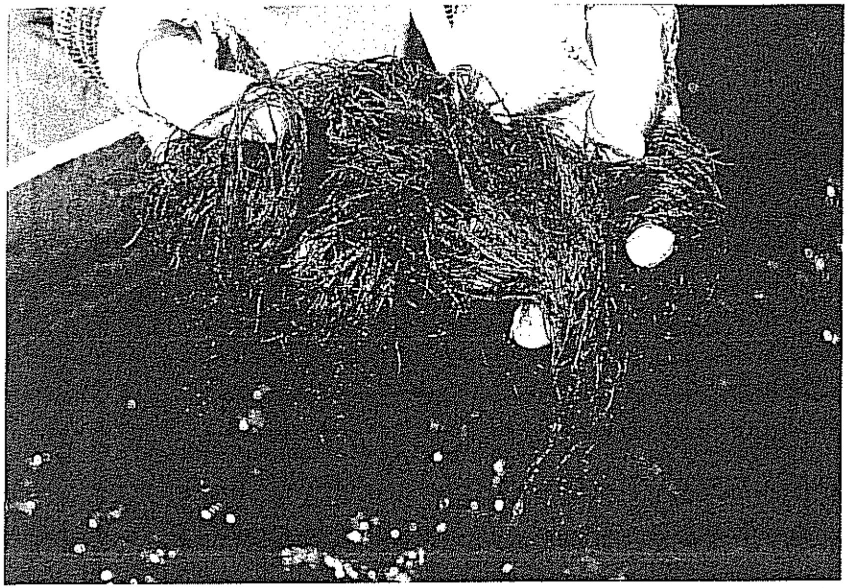

Fig. 3. Gracilaria *(G16-S), a seaweed developed and patented by HBOI for its improved agar characteristics.*

systems is largely due to concerns over the aquaculture of animals that can result in serious coastal eutrophication problems. Seaweeds can be successfully used as "nutrient scrubbers" of seawater in association with the mariculture of fish and crustaceans, either before or after the water is used by the animals. When the value added for the service of improving water quality is combined with that of the principal crop (the animals), seaweeds may significantly improve the success of a mariculture operation. Moreover, the most efficient use of cultivated macroalgae may very well be in the diets of other aquaculture organisms, either those in the same polyculture system or elsewhere. In this way, the trophic interactions within an aquacultural environment mimic those in the natural environment, where energy flows through the system, but nutrients cycle within it.

In addition to changing economic conditions, the future of macroalgal cultivation will largely depend on "understanding the organism" and incorporating its needs into larger integrated systems that take advantage of the high rates of productivity and nutrient uptake inherent in many macroalgae. Significant advances in seaweed aquaculture are likely to continue over the next decade. Better selection of naturally available strains for specific applications, innovative culture technologies, and advances in biotechnology, such as those presented elsewhere in this special issue, will provide improved strains and will lead to higher yields, better quality products, and greater economy of money and natural resources. Increased use of seaweed in integrated polyculture systems will reduce the environmental impacts of animal aquaculture, increase the economic returns for both animal and seaweed components, increase the geographical cultivation of seaweeds, and promote the development of niche markets for seaweeds. Continued success and growth of food and industrial uses, including novel uses and new markets, are likely to keep the value of seaweed products relatively high, even as production increases.

A yet-to-be-realized development that could occur in the next decade or two is the successful large-scale, open-ocean commercial farming of seaweeds. While such open-ocean farming had been proposed back in the 1960s and 1970s with the goal of "energy farming" (i.e., growing marine biomass for bioconversion into fuels such as methane and methanol to replace the consumption of fossil fuels), economic and political realities resulted in such farms being an unfilled vision. Cultivating seaweeds for the purposes of bioconversion and other bioremediation will become more feasible as concerns about anthropogenic causes for global environmental degradation increase, as illustrated by the recent Rio and Kyoto accords. One mechanism which will greatly facilitate the development of marine biomass farming will be "carbon taxes". Such taxes on fossil fuels or on carbon emissions would subsidize the development of fossil-fuel alternatives as a mitigation effort to reduce global warming.

If large, open-ocean sea farms are developed in the near future, there undoubtedly will be many biological, technical, social, and political issues that will need to be resolved. But it is hard to imagine that such farms would not be conceived and developed without also incorporating the aquaculture of other organisms, particularly fish. The sooner the mariculture community learns to optimize the efficiency of its overall operation at the relatively small scale that exists today, by cultivating animals side by side in the same system, the sooner the large ocean farms of tomorrow will become a reality.

Notes and References

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