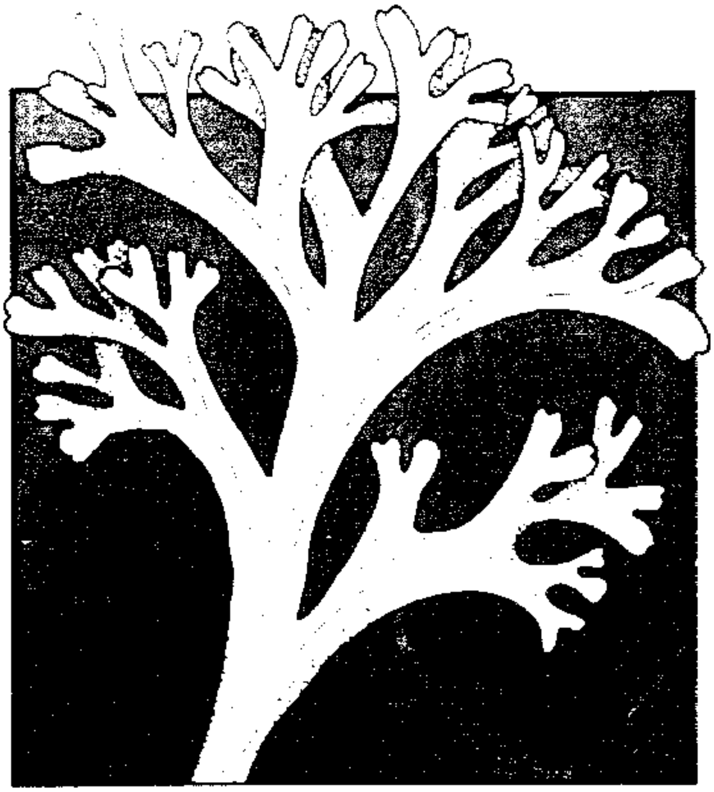

Mariculture of Red Seaweeds

Judith E. Hansen
Julie E. Packard
William T. Doyle

Report #T-CSGCP-002

A California Sea Grant
College Program Publication

SEA GRANT
CALIFORNIA

This book is being sent to you compliments of the California Sea Grant College Program.

We hope you find it useful and welcome any comments or suggestions.

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Cover drawing: *Chondrus crispus* Stackhou

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The California Sea Grant College Program is a statewide, multi-university program of marine research, advisory services, and education, administered by the University of California Institute of Marine Resources. Through the research it sponsors, Sea Grant contributes to the growing body of knowledge about our coastal and oceanic resources and aids the solution of contemporary problems in the marine sphere. Through its Marine Advisory Program, Sea Grant transfers information and technology developed in its research efforts to a wide community of users in California, the Pacific region, and the nation. Sea Grant also supports a range of educational programs for students, teachers, and the general public to promote the wise use of our coastal and oceanic resources by this and future generations

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Traditional nori cultivation, Matsushima Bay, Sendai, Japan. (Courtesy of T. Mumford)

Preface

For the last 10 years, the California Sea Grant College Program has supported research to increase what we know about red seaweeds--a group of marine plants probably unfamiliar to the layperson but well known and much needed by food processors and biomedical researchers.

The food industry has long used carrageenans from red seaweeds to make ice cream and other food products that require gelling; the biomedical community requires a certain kind of high-quality agar from the seaweed to culture bacteria and other organisms. These two groups rely heavily on imported seaweed stocks, which are often unreliable in quality, exhorbitant in cost, and subject to supply fluctuations due to political turmoil in the countries where the seaweed grows. As new applications for using red seaweed have developed, the demand for red seaweed has increased, to the point where commercial harvesting techniques now need to be developed to lessen our dependence on wild seaweed stocks.

In this book, the authors trace the history of red seaweed use as a food in Asia, Polynesia, Europe, and North America. They document the seaweed's nutritional value and use as animal fodder, as "nutrient scrubbers" to clean contaminated water, and as biomass for energy. Using some of their own research, the authors describe attempts to manipulate seaweed habitat using artificial substrates, live storage, and vegetative propagation.

By relating red seaweed mariculture—in both its historical and political perspectives—to the development and recent successes of red seaweed research, the authors provide a picture of the evolving development and potential of red seaweed mariculture. We hope that this book clearly presents the challenge awaiting those individuals who can see the potential for developing the mariculture of red seaweeds.

James J. Sullivan
Program Manager

Acknowledgements

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Introduction

Seaweed cultivation for food and useful products is so new to Westerners that its full scope is hardly described by the prevailing term, *aquaculture*. The U.S. Department of Commerce suggests that aquaculture is "the culture or husbandry of aquatic animals or plants by private industry for commercial purposes or by public agencies for augmenting natural stocks" (NOAA, 1977). The National Academy of Sciences (1978) calls it "the human controlled cultivation and harvest of both freshwater and marine aquatic species."

Although the above definitions are applicable to both plants and animals, they are frequently used to cover animals alone, as public attention has focused on farming of familiar and sought-after delicacies such as prawns and lobsters. Given the current state of the art, however, these species can only be farmed as luxury items, whereas seaweed crops could be tailored to existing markets at prices that are competitive in the world marketplace.

Based on finances alone, American seaweed cultivation is on the verge of change and recognition. The term *mariculture* is more appropriate in the context of this discussion and refers here to the managed cultivation and harvest of marine plants, whereas the broad term aquaculture refers to the cultivation of all submerged plants, both marine and freshwater (e.g. watercress).

Seaweed cultivation in the eastern world is well established and highly successful. In Japan—a country famous for its culture of shrimp, eel, abalone, and other fin and shellfish for food—seaweed is a high-ranking mariculture crop in dollar value (figure 1). In the People's Republic of China, recent American visitors have applauded the dramatic advances made in culturing, breeding, and harvesting a variety of seaweeds. The success of mariculture in Japan and China is intimately tied to the use of the cultivated species for food. This food is consumed within those countries and also offered for export.

Most seaweeds used by Westerners are not consumed directly as food. But seaweed extracts—the phycocolloids—are used in a wide variety of foods, household items, and biomedical products. As clearly as seaweed foods have become part of Eastern cultures, so have seaweed extracts found their way into nearly all facets of Western everyday life. For example, we use them daily in toothpaste, cosmetics, shampoo, pet foods, baby foods, milk products, and many other foods. It is perhaps the American desire for "convenience foods" that has led to the advancement of the American seaweed industry.

Figure 1. Nori retail counter in Tokyo department store, Japan. (Courtesy of T. F. Mumford)

Figure 2. Bacteria cultures plated on agar-based medium. (Courtesy of F. Chapman)

At present, the uses for emulsifying, blending, and otherwise making food products more attractive and time-saving far outstrip the early primary use of seaweed colloids—as a gelling agent for microbiological media (figure 2). However, the already limited world supply of high-quality gel for the latter purpose has been strained in recent years. Today there is a demand for even higher quality gel for cell cultures and molecular genetics research and for sophisticated chemical techniques such as gel-electrophoresis and gel chromatography. With this increasingly specific application comes the requirement for phycocolloid stability and purity.

As demand for phycocolloids has increased, pressure has been put upon the world's seaweed resources. Over time, the easily accessible seaweed beds have become overharvested, and polluted coastal waters have deteriorated habitats in several areas. While industry has not been slow in exploiting every part of the world's oceans for a supply of appropriate seaweeds, labor and shipping costs have risen substantially. Thus, ties to supply, however sound, must be reexamined for cost effectiveness. Moreover, political conditions in certain countries have at times reduced or stopped supplies. In many countries there has been a changeover from producing dried seaweed to processing and exporting a finished product. This has made both supplies and product quality less certain.

In conjunction, little advance has been made toward synthesis of phycocolloid alternatives to meet today's industrial and biomedical needs. Because there are formidable chemical barriers to developing synthetics to match the effectiveness and versatility of phycocolloids, we continue to rely on our native seaweeds.

These collective pressures (economic, political, biological, and technological) have generated the recent and rapid development of red algal mariculture. This expansion in mariculture research and technology clearly reflects the urgent need for dependable sources of raw material, a cost-effective industry, and the promise of financial rewards. The rewards of successful commercial seaweed cultivation have been realized in the eastern Pacific. In the Western world, commercial seaweed mariculture is poised on the threshold of economic feasibility. The changeover from dependence on natural seaweed populations to mariculture is concurrent with exploration of the use of algae for nutrient-scrubbing purposes and for biomass conversion to meet energy needs.

Red Algae As Food

History and Current Practice

Red seaweeds have been relished by people as food staples and delicacies for thousands of years. *Gracilaria* is mentioned in Chinese *Materia Medica*, and, in a volume dating to 600 B.C., we find the statement, "Some algae are a delicacy fit for the most honorable guest, even for the king himself" (Porterfield, 1922). In China, Japan, and the Indo-Pacific region, several dozen species of red algae are used.

Usage in Europe and North America has developed to a lesser extent and has centered around a few genera. In Iceland's earliest-known law book, reference is made to rights involved when collecting *Palmaria*, or 'dulse'. Perhaps the best-known edible Atlantic seaweed, dulse has been eaten in Iceland since about 960 B.C.

Worldwide, seaweed consumption has been especially important to island cultures, where arable land is scarce. Johnston (1966) notes that "many islands edaphically unsuited for the culture of land vegetables may be encircled instead by a ring of seaweeds—the marine equivalent of terrestrial vegetables." Although peoples around the globe have developed their own red algae cuisines, the algae are generally prepared in one of three ways: (1) washed and eaten raw, (2) cooked or dried as a vegetable, or (3) boiled and sweetened to make a jelly or custard, which is thickened by the algae's natural colloids—carrageenan and agar.

In Asia and Polynesia

Edible red algae have been most appreciated by Eastern cultures. The Japanese are the principal users of red seaweeds for food, and today one can still find several species included in a single meal. *Porphyra*, or 'nori', is by far the most popular and is usually processed into dried sheets. The algae are collected and washed in fresh water to remove debris, then chopped and spread on frames to dry. The thin, dried sheets are peeled from the frames and sold as a finished product known as 'hoshi-nori'. Nori is commonly toasted over a flame and sprinkled in soup or rice, or rolled around flavored rice with fish or vegetables to make a popular luncheon snack called 'sushi'.

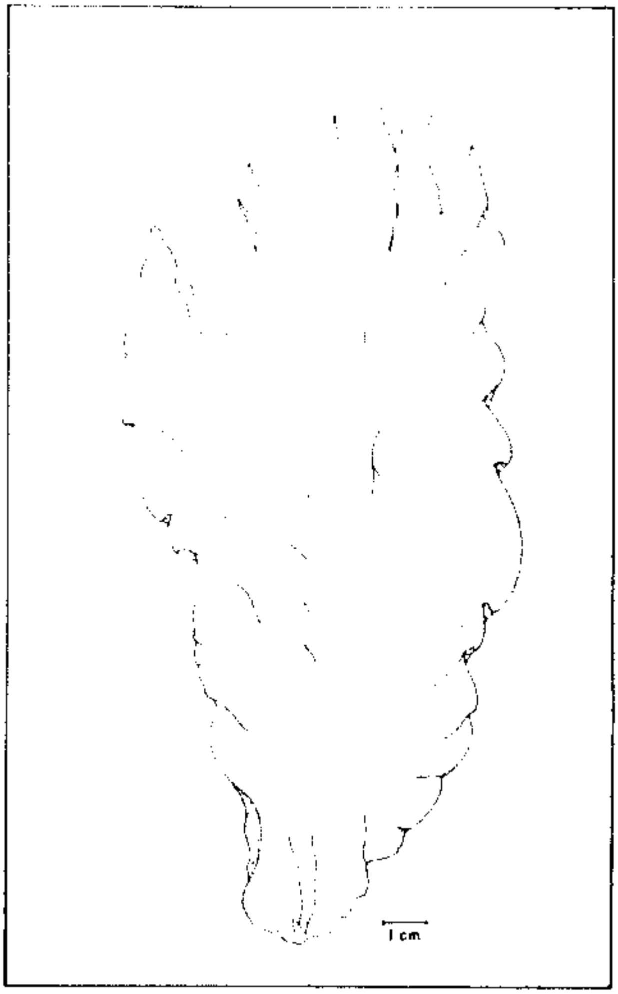

Figure 3. *Porphyra yezoensis* Ueda

Although several species are still collected wild, *Porphyra* has been cultivated since 1570 (Tseng and Chang, 1955), and today Japan's seaweed cultivation is the most advanced in the world. The nori industry is based mainly on *Porphyra tenera*, 'amanori', and *P. yezoensis*, although up to seven other species have been cultivated in Tokyo Bay in the past (Chapman, 1970)

In addition to cultivated crops, several wild species of *Porphyra* are collected for food. Other red algae such as *Nemalion, Eucheuma, Chondrus, Acanthopeltis, Grateloupia, Gigartina*, and *Carpopeltis* are locally collected and prepared. Most of these seaweeds are eaten as vegetables, in soups, or prepared as sweetened jellies.

On the neighboring mainland, South Korea boasts a large *Porphyra* industry using cultivation methods similar to those of Japan. The majority of Korean *Porphyra* products are prepared for export, although they are also consumed locally.

Red algae continue to be a significant food in China, although much of the natural Chinese coastline is

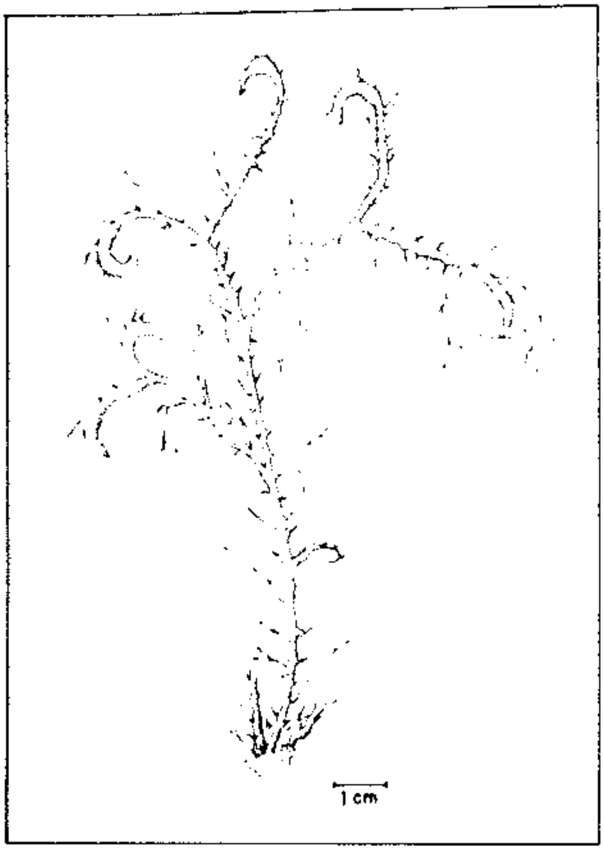

Figure 4. *Hypnea musciformis* (Wulfen) Lamouroux

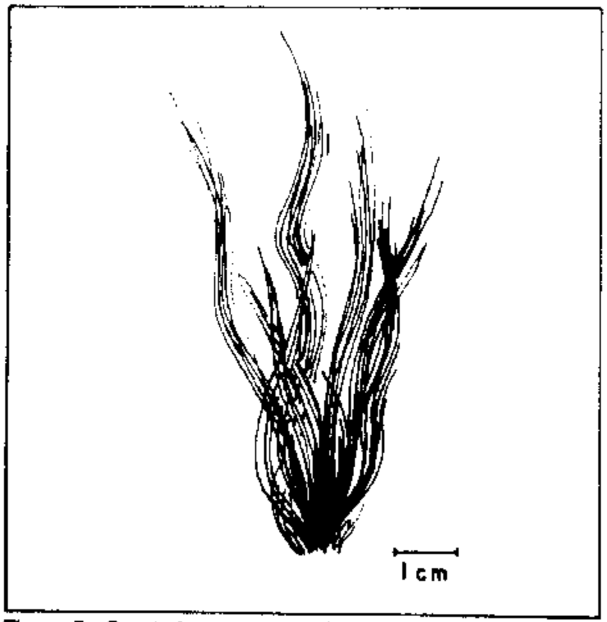

Figure 5. *Bangia fusco-purpurea* (Dillwyn) Lyngbye

unsuitable for algal growth because of high water temperatures and turbid river runoff. As a result, most edible red algae were imported for many years, primarily from Japan.

Contrary to some reports, however, there is a considerable amount of local collection and consumption along the coastlines and neighboring islands of China (Tseng, 1933, 1935). Coast dwellers of Kwangtung Province and Hainan Island, southern China, have collected *Hypnea musciformis*, *H. cervicornis*, *Grateloupia*, *Acanthophora*, and *Porphyra* species for food. *Gelidium* is also eaten in Amoy, southern China, while *Gloiopeltis* species are used in northern China. The gelatinous red seaweeds are most commonly prepared as a sweetened jelly, which is served in the summer months for a cooling treat. Other species are cooked as a vegetable.

In the past two decades, China has developed an impressive seaweed cultivation program. Although it is primarily based on production of the edible brown alga *Laminaria japonica*, *Porphyra* and *Gracilaria* are farmed as well. *P. haitanensis* and *P. yezoensis* are grown on nets using methods similar to those used by the Japanese. The harvest is used in soups or toasted in sheets and eaten alone (Tseng, unpublished interview, 1978). The current accelerated research efforts on mariculture in China (Earle, 1978; Ryther, 1979a) indicate that *Porphyra* and probably other red seaweeds will be increasingly important in the Chinese diet.

Porphyra and numerous other red seaweeds are eaten in Taiwan and neighboring islands. *Bangia fusco-purpurea* is used by local people in a famous marine vegetable dish called 'tou mau tsai', and *Nemalion pulvinatum* is gathered by women and children and sold fresh in Keelung. The Taiwanese generally eat *Porphyra* in soup and rolled in rice balls, while *Gracilaria* spp., *Hypnea* sp., *Chondrus ocellatus*, and *Gigartina intermedia* are eaten with meat or soup. In Taiwan, three species of *Gracilaria* are cultivated in ponds; from a production total of 2500 dry metric tons in 1973, 31 percent was consumed directly for food (Shang, 1976).

In Hong Kong, algal food usage is restricted to *Porphyra* species. Women and children harvest the weed by hand along the exposed south and east coasts of Hong Kong and nearby islands. As on the southern China coast, harvest is limited to a few months in winter, the shoreline being relatively barren during the rest of the year (Chiu, 1958). On the Botel Tobago Island, the Yami tribe commonly utilizes several other species, including *Dermonema gracile*, *Halymenia durvillaei*, *Carpopeltis formosana*, *Acanthophora* sp., *Laurencia* sp., and *Chondria armata* (Fan, 1953).

Red seaweed consumption is widespread in other areas of the South Pacific and Indian Oceans, where modes of preparation are varied. Coast dwellers in Indonesia and the Philippines collect *Gymnogongrus*, *Gracilaria*, *Hypnea*, and *Laurencia*. These are sold fresh in the vegetable market and are eaten raw or after blanching. *Eucheuma*, 'gusu', and *Caulerpa*, 'lato', are the most commonly eaten seaweeds in the Philippines. They are prepared mostly with vinegar and spices as a salad (I. Neish, pers. comm.). *Porphyra* is cultivated in the Philippines, using methods similar to the Japanese. The harvested *Porphyra*, or 'gamet', is marketed when partially dry and is blanched before being served with soy sauce or as a salad (Sulit et al., 1954).

In Java, *Asparagopsis sandfordiana* is soaked in water to mellow its pungent flavor and then cooked with meat. On the island of Bali, *Hypnea cervicornis* is collected and prepared with palm sugar and grated coconut as a sweet jelly, and *Gracilaria* is used raw in salads (Johnston, 1966). Inhabitants of India and

Burma eat *Bostrychia* and *Gracilaria*. The Burmese also eat *Catenella* raw in salads or prepared as a spicy dish with oil of *Sesamum*, salt, powdered *Capsicum* fruit, fried ginger, onion, and garlic. Throughout the South Pacific and in Thailand the gel forming genera are used with coconut in a pudding. A few red seaweeds such as *Porphyra columbina* are consumed in New Zealand, however, little seaweed is eaten in Australia.

Perhaps the most diverse food usage of seaweed has been by the Hawaiians. In the early twentieth century they were reported by Reed (1907) to have used up to seventy-five different species of edible algae, called 'limu', and these included thirty species of red algae. The most choice of these were cultivated in royal "limu gardens," which were tended by weeding out the more common, less desirable species.

Although limu consumption has fallen during this century, red algae (e.g., *Laurencia, Asparagopsis, Gracilaria*, and *Grateloupia*) are still a part of the Hawaiian diet and may be found in markets there. In the past these algae were a welcome addition to the Hawaiian diet of fish and poi. Today they are still prepared with fish, invertebrates, and raw liver (Abbott and Williamsen, 1974). Supermarkets in Hawaii currently sell approximately 80,000 lbs of *Gracilaria* spp. annually (Abbott, pers. comm.).

In Europe and North America

In contrast to the diversity of species eaten by Asian and Polynesian cultures, red algal food usage in Europe and North American has centered around three genera: *Porphyra* or 'laver', *Palmaria* or 'dulse', and *Chondrus* or 'Irish moss'.

Porphyra has been extensively used in the British Isles, where it is known as 'laver'. It was a highly recommended diet for whaling boat crews in the eighteenth century. It was exported from Britain in the early 1900s, but trade has slowed since that time.

Currently, the miners of Southern Wales are said to be the major laver consumers and 200 tons wet weight are consumed annually in this region. Most of the raw material is imported from England, Scotland, northern Wales, and Ireland, while a small amount is collected and processed locally. In the past, it was prepared and sold by fishermen's wives in many areas. The algae are washed in fresh water, boiled for several hours, minced, and eaten after warming in fat. Laver is served for breakfast—spread on toast or baked into oatmeal-covered 'laverbread'. In Ireland it is also made into a jelly when heated with water.

Porphyra has been utilized in North America to a lesser extent. It is thought to have been eaten by American Indians since ancient times. The Kwakiutl Indians of British Columbia prepared it in elaborate ways, including prolonged rotting and storage. Indians still collect it from Numas Island, although most buy it in four-gallon cans (Turner and Bell, 1973).

Apart from Indian usage, little *Porphyra* consumption has occurred in North America, although *P. perforata* was collected in California and exported to China and other countries through the 1960s. This species is still marketed in Hawaii as "California seaweed" (Abbott, pers. comm.).

Several other red algae are still collected by Asian inhabitants of San Francisco, including *Polyneura latissima* (Madelener, 1977). In addition, *Gracilaria verrucosa* is collected from West Coast bays and estuaries during the herring spawning season. The herring eggs-on-seaweed are salt-cured and exported to Japan, where they are considered a delicacy (Hardwick, 1973; Ness, 1977).

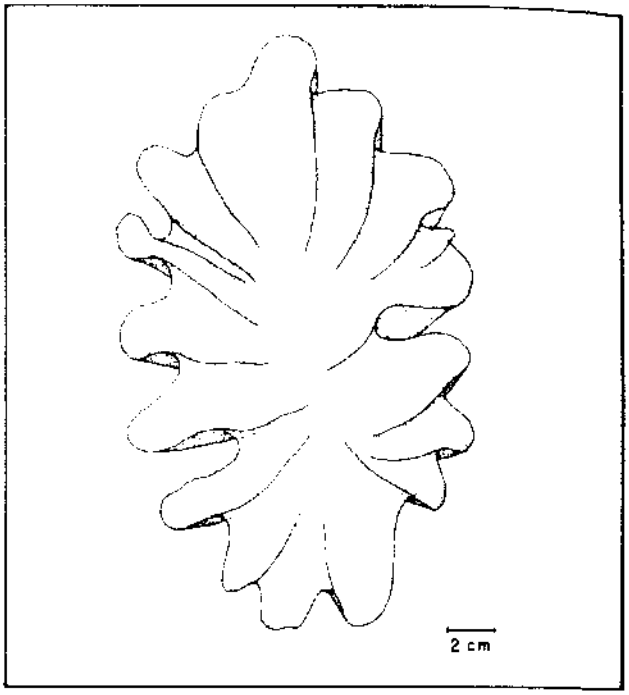

Figure 6. *Porphyra umbilicalis* (L.) J. Agardh

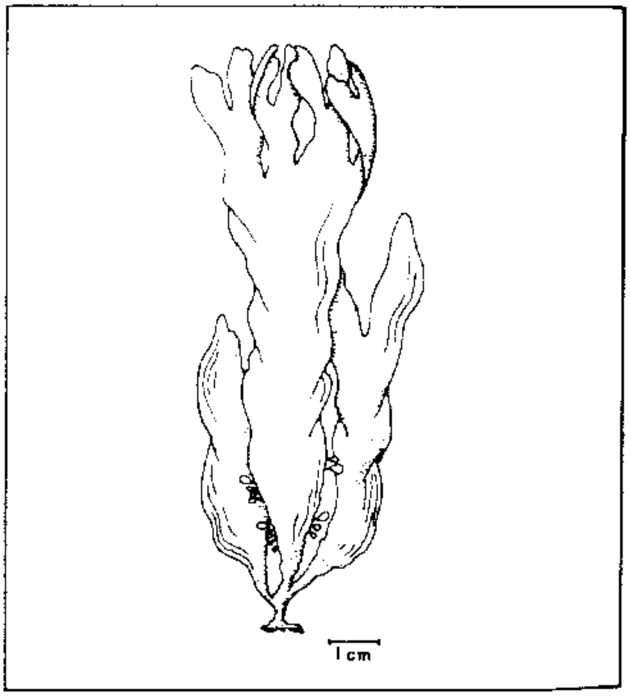

Figure 7. *Palmaria palmata* (L.) O. Küntze

Palmaria palmata (= Rhodymenia palmata) was gathered and eaten by Vikings in ancient times and has been widely used in Scotland, Ireland, and Iceland. In Scotland and Ireland it is known as dulse or 'dillisk', and it is eaten fresh or dried, or may be cooked as a vegetable or in sweetened puddings. In Scotland it was said that "he who eats of the Dulse of Guerdie

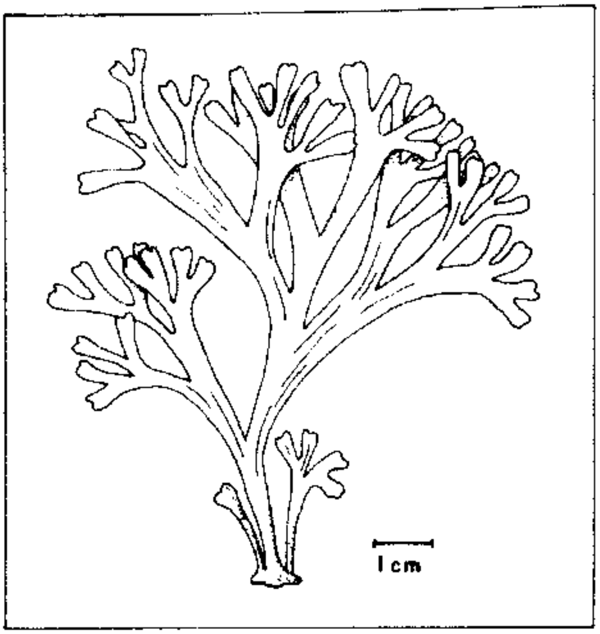

Figure 8. *Chondrus crispus* Stackhouse

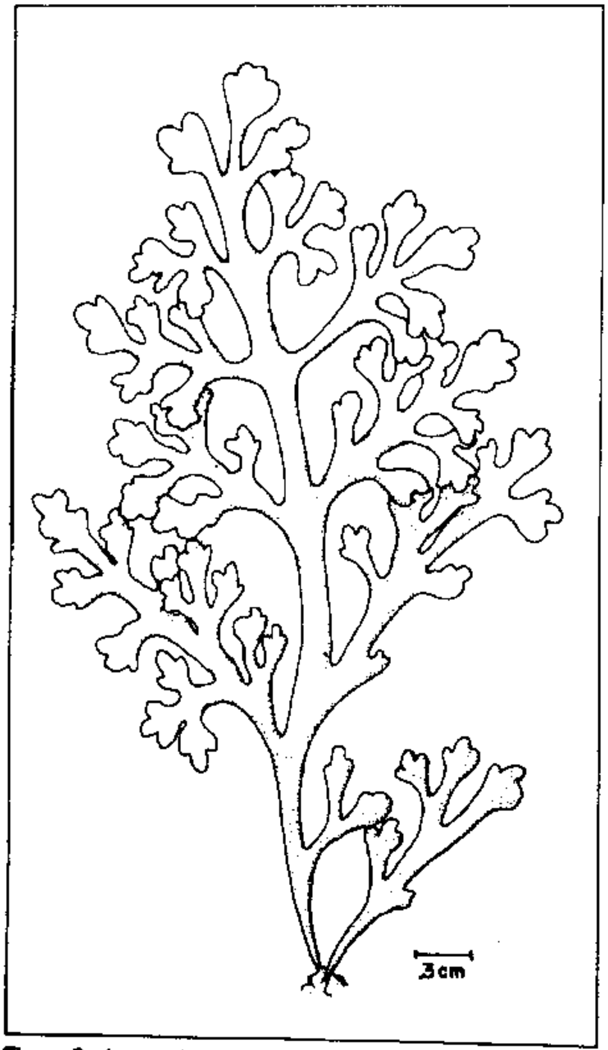

Figure 9. *Laurencia pinnatifida* (Gmel.) Lamouroux

and drinks of the wells of Kildingie will escape all maladies except the Black Death' (Major, 1977).

No commercial trade exists in these areas today; however, personal collection still occurs. *Palmaria*, or 'sol', has been eaten in Iceland since the eighth century and was a trade item in the twelfth to nineteenth centuries. Today it is only used on the south coast, where it is eaten with fish, in puddings, baked in bread, and is used like a chewing tobacco.

An active *Palmaria* trade still exists in Canada, where 40-50 tons of dried *P. palmata* are marketed each year (Dixon, 1973). The weed is gathered in the Bay of Fundy and on Nova Scotia shores. It is commonly eaten as a snack in taverns. Utilization has centered around Nova Scotia, but has more recently been introduced into British Columbia. In Alaska, dulse is chewed like tobacco. Farther afield, it has been used on the Kamchatka Peninsula, U.S.S.R., to make an alcoholic beverage.

The most important edible red alga used extensively in Europe and North America is Irish moss, also known as carragheen (carrageenan) or 'goémon blanc'. Although *Chondrus crispus* is the specific plant referred to as Irish moss, the related plant *Gigartina stellata* is often included in the collections and used in the same manner. After being bleached and dried, Irish moss is typically cooked with milk to make blancmange, a pudding flavored with sugar and citron. The thickening agent is now known to be the sulfated polysaccharide carrageenan.

Numerous other red algal species have been used in the British Isles; an estimated twenty species have had local names in Ireland, Scotland, and Wales. Among these are *Laurencia pinnatifida*, or 'pepper dulse', which is used as a condiment; and *Dilsea carnosa* (= *Iridaea edulis*), which was eaten after being pinched between two hot irons. In addition, *Dilsea carnosa* is eaten on the west coast of Europe. However, Dixon (1973) comments that

> ...the general texture of *Dilsea* resembles most closely a heavy-duty inner tube and the claims of its use most likely represent an old taxonomic misidentification of the species of laminate red alga which was widely eaten.

The early European colonists in South Africa utilized *Suhria vittata* to make a sweetened jelly flavored with sugar, lemon, and brandy or sherry. Consumption of other species in North America only occurs in the West Indies. *Gracilaria* is used to make jellies in Trinidad and Jamaica, and *Eucheuma* is eaten in Antigua. Little is known about South American seaweed foods. *Porphyra columbina* is eaten in balls mixed with *Ulva lactuca* in Chile (Ohmi, 1968), but further use of red algae there is unknown.

Animal Fodder

Use of red seaweeds for animal fodder has centered around Europe, although brown algae have had more widespread use for this purpose. Livestock are allowed to graze on the shore in Iceland, Scandinavia, Britain, and France. *Palmaria palmata* appears to be a favorite of goats, cattle, and sheep; the animals actively select it over other species. At Roscoff, it is known as 'goémon á vache', or cow seaweed. In some coastal areas of Ireland and Scotland, cattle and sheep feed exclusively on the red alga *Palmaria* and brown

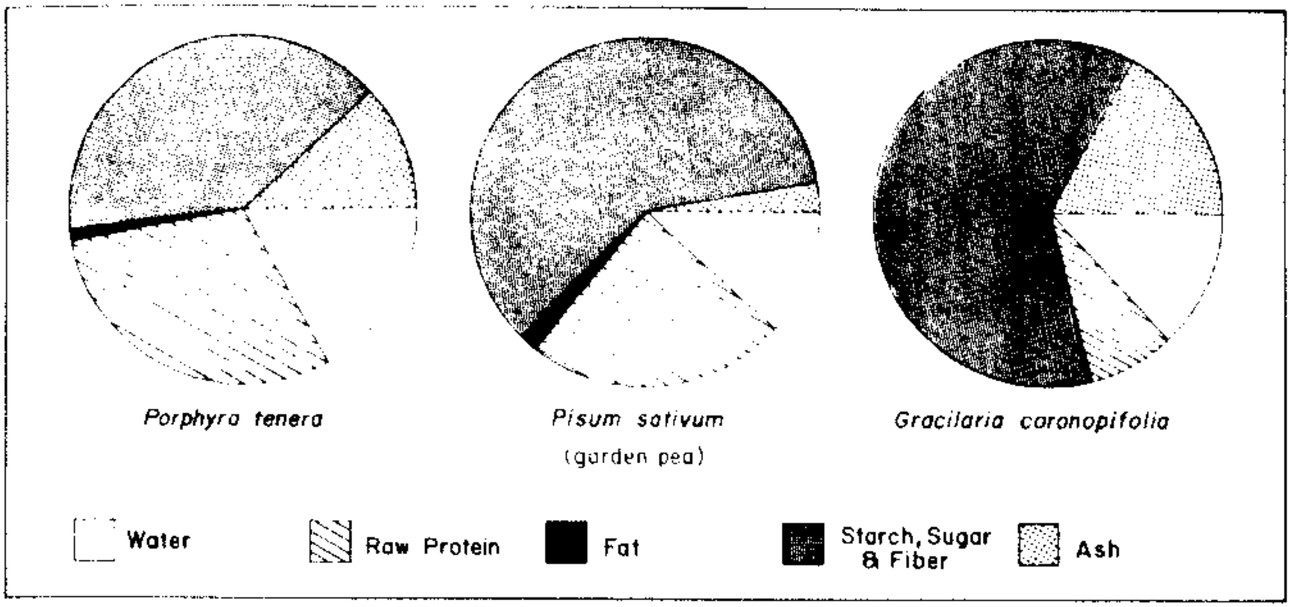

Figure 10. Nutritional composition of seaweeds (% of dry weight) (Tressler, 1923, Spector, 1959)

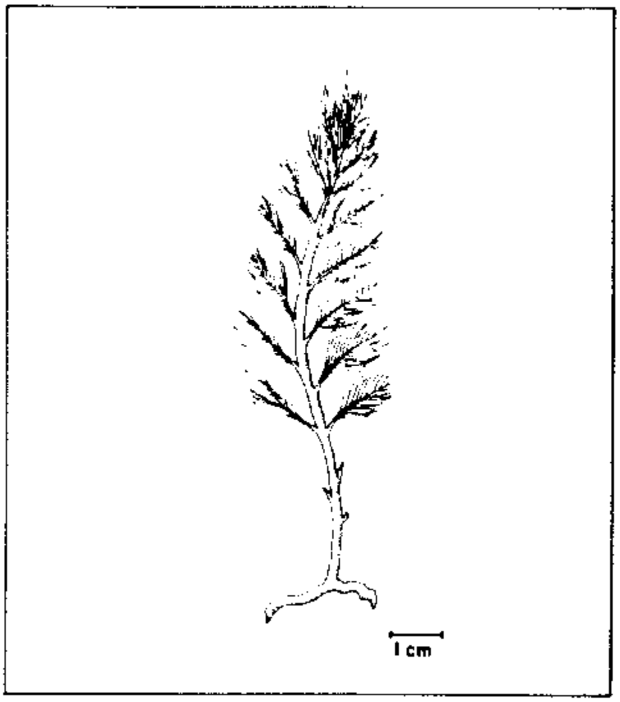

Figure 11. *Asparagopsis taxiformis* (Delile) Collins et Harvey

alga *Alaria* with no apparent effect on milk or meat (Dawson, 1966). Red algae have also been used in winter stall-feeding in Iceland and northern Europe.

There are few reports of red algal animal fodder in the East. The Chinese have used *Hypnea* for pig feed, and *Gracilaria* is used as fish pond feed in the Philippines.

Nutritional Value

Nutritional analyses of red algae have shown them to be mainly composed of carbohydrates, with small amounts of protein, fat, and ash, which is primarily sodium and potassium (figure 10). Most of the carbohydrates are not easily digested by humans because we lack appropriate enzymes. Experiments have shown that the human utilization of carbohydrates in red algae averages lower than for common food carbohydrates—less than 60 percent. Results vary as different authors study different seaweeds; however, Swartz (1914) reported 100 percent utilization of dulse carbohydrates by humans, while only 6 percent was utilized from Irish moss.

Compared to animal sources, red algae are generally low in protein. However, some species compare favorably with more conventional plant foodstuffs: *Porphyra* contains more protein than garden peas on a dry weight basis. The digestibility of red algal protein is generally low, although humans are apparently able to digest 75 percent of the protein in nori (Schachat and Glicksman, 1959). Combined with its relatively high protein, this digestibility makes *Porphyra* the only red alga thus far that could be considered a good protein source.

Fat content is very low in members of the Rhodophyta. The *Porphyra* species that have been analyzed only contain 0.2 percent to 0.8 percent fat on a dry weight basis.

Among the minor elements required in human nutrition, iodine is perhaps the most notable element found in red algae. Iodine obtained from seaweed consumption has been suggested as the cause for the low incidence of goiter in Japan. Other elements in red algae include Na, K, Mg, Ca, Fe, P, Al, S, Si, and As (Okazaki, 1971).

Beta-carotene, the precursor of vitamin A, is present in all seaweeds. Thus, vitamin A can presumably be obtained from most red algae; however, few specific values are known. Several B vitamins are present, including thiamin, riboflavin, niacin, and vitamin B_{12}. Vitamin C is present in *Porphyra* in concentrations greater than in oranges, although the vitamin C content of red seaweeds varies considerably with season (Chapman, 1970).

Porphyra fulfills an important need in the Eskimo diet by providing the major source of vitamin C. Loose

Table 1

Selected Vitamin and Mineral Contents of *Palmaria palmata* and Other Foods (mg/100 g edible portion)

		Minerals				Vitamins			
	Water (g)	K	Ca	Mg	Fe	A(IU)	B_1	Niacin	C
Palmaria palmata, dried	trace	7,000	560	450	50.0	26,000	0.39	3.8	
Apples, dried	20		24		1.4	0	0.05	0.5	6.00
Peas, dried	10	880	73	140	6.0	370	0.87	3.0	2
Potato chips	3	880	30	–	1.9	50	0.18	3.2	11
Peanuts, roasted	5	740	74	167	1.9	360	0.30	21.6	0

(Morgan, et al., 1980)

(1966) has calculated that 100 grams of amanori provides 30 g protein (45 percent of the daily adult requirement); 100 percent of vitamins A, B_2, and B_{12}; and 67 percent of vitamin C. This quantity of amanori would also supply the daily requirement of sodium, potassium, and magnesium. A comparison of selected vitamin and mineral contents of *Palmaria* and other more conventional foods is shown in table 1.

Clearly, more definitive information is needed about red algal nutrient content. In general, it appears that some red algae are rich in vitamins and minerals, but most are a poor source of protein and carbohydrates because of low concentrations or poor digestibility. It is noteworthy that in Japan the seaweed is often left to rot for a period of time before consumption. This allows fungi and bacteria to break down some of the algal carbohydrates and may render them more available to human digestion. It has also been suggested that prolonged seaweed consumption may promote the buildup of an intestinal flora to digest the algal carbohydrates more easily (Johnston, 1966).

Despite possible nutritional benefits, red algae today provide only a minor contribution to the human and animal diet. The majority of seaweeds are consumed in Japan and other oriental countries. Seaweed consumption in the North Atlantic has been negligible for 50 to 100 years, with the exception of carragheen (carrageenan), laver, and those types used in Iceland (Chapman, 1970), but local use in Asia and the South Pacific is still widespread.

Recently there has been renewed interest in edible seaweeds from an ethnobotanical standpoint, as evidenced by the publication of books on food algae in Hawaii (Abbott and Williamson, 1974; Fortner, 1978) and North America (Madelener, 1977). In the Western world, gathering edible seaweeds is presently on a scale close to that of collecting mushrooms. But red seaweed consumption is safe! To the authors' knowledge, there are few poisonous species. Even the genus *Asparagopsis*, from which toxic compounds have been isolated (Fenical, 1976) is first soaked and then eaten by the peoples of Java and Hawaii.

Industrialization of Red Algae

Many small businesses based on seaweeds have boomed for a short time and then collapsed. A few seaweed industrial ventures have prospered. These few either have markets with broad applications or are located in regions with a stable source of low-priced labor. Among the red algae, *Porphyra* is one of the few food crops for which demand has warranted commercial-scale production, whereas numerous species of red algae are commercially harvested and processed for their extracts or phycocolloids.

Porphyra

One of the first red seaweeds to be industrialized was *Porphyra*, perhaps because it is universally appreciated as a food (e.g., 'amanori'—Japan, 'tsu-tsai'—China, 'laver'—Britain, 'slack'—Scotland, 'sloke'—Ireland, 'limu'—Hawaiian Islands). The Japanese have cultivated *Porphyra* on a large scale since 1570. As a result of the industrial promotion policy of the Japanese government (1876-1909), instruction in culturing methods was provided, and *Porphyra* farms developed in nearly every suitable bay in Japan. Each major breakthrough in cultivation methodology doubled industrial production.

During the 1930s a transition was made from growing the plants on leafless bamboo brush or oak branches to horizontally hung nets. Between 1949 and 1954, the British phycologist K. M. Drew discovered *Porphyra*'s filamentous spore-producing "*Conchocelis*" stage. This major discovery led to the development of methods in the 1950s of artificially sporulating nets.

Refrigerated storage (-20°C) of the nets was developed during the 1960s. By the end of that decade, floating net cultivation was introduced, allowing the small farms to extend farther out to sea. This slow yet progressive improvement in Japanese *Porphyra* cultivation resulted in an industrial production of about 860 million sheets of nori/year between 1938-1947, rising to 6 billion in 1970. By 1975, 7.1 billion sheets (278,127 tons wet wt) were produced, with an estimated value of $380 million in the U.S. (Kurogi, 1975).

Porphyra cultivation in Japan has been threatened by a rapid development of heavy industry and subsequent discharge of pollutants into the bays. Dredging and filling of the nearshore areas to construct seaside industrial lands has damaged the existing *Porphyra* cultivation grounds around the estuaries in bays and inland seas. This has stimulated further refinement of the floating net technique that made it possible to use the offshore waters 25-50 m deep as cultivation grounds (Miura, 1975a). This conflict of traditional industry with seaside industrial expansion is an increasing political and governmental problem.

The Phycocolloids

Seaweed extracts collectively termed phycocolloids (Gr. 'phykos' meaning seaweed, 'kollodes' meaning glue-like) underlie the most important and diverse of the seaweed industries. A colloid is a jellylike substance that cannot easily pass through a membrane (e.g., gelatin). These colloids are grouped into two major families—the agars and carrageenans—which have distinct differences in molecular configuration and in some physical properties.

Agar

The first phycocolloid to be commercialized was agar. The term comes from the Malayan 'agar-agar' meaning jelly; however, it most likely referred to the carrageenophyte *Eucheuma* (Tseng, 1944). The use of agar as a food by oriental peoples certainly occurred long before recorded history. Okazaki (1971) reports that the Chinese instructed the Japanese people in the use of seaweed gel for food sometime around 970.

Until then, the method of dried agar production had not yet been discovered, and the coagulated gel was used as food among upper-class people and priests. Another source states that "agar was originally produced in China and introduced into Japan in 1662" (Chapman, 1970). The authors, however, have been unable to trace the history of agar production and use in China.

Development of the still-used freeze-thaw method of agar manufacture took place in Japan sometime during the mid-1600s (Horiuchi, In Tseng, 1944). Subsequently, its use spread rapidly. However, it was still referred to as "seaweed jelly" and not as agar until the 1800s.

Seaweeds that yield an extract (agar) with the following characteristics may be termed agarophytes.

> Agar—a sulphuric acid ester of a linear galactan insoluble in cold, but soluble in hot water; a 1.0% solution should set to a firm gel between 32-39°C and not melt below 85°C. (Tseng, 1945; Chapman, 1970). Some examples are: *Gelidium, Pterocladia, Ahnfeltia*—one species, *Gracilaria* spp.

The concept that agar is composed of a neutral "agarose" and a nonionic "agaropectin" is an oversimplification. On the agarose backbone—the basic repeating unit of agar (figure 14)—sulfate ester, methoxyl, ketal pyruvate, and carboxyl groups can appear in an almost infinite number of combinations. The conditions used for separation determine in which fraction specific molecules appear (Guiseley and Renn, 1975). Agarose is "...that mixture of agar molecules with the lowest charge content and, therefore, the greatest gelling ability, fractionated from a whole complex of molecules called agar, all differing in the extent of substitution with charged groups" (Yaphe and Duckworth, 1971). Sulfate is an important constituent of native agars, but because it appears to interfere with gelation it is generally regarded as a nuisance in agar of commerce (McCandless and Craigie, 1979).

Extracts of other seaweeds that are chemically different or form weak gels at the above concentrations (e.g., *Chondrus crispus, Iridaea, Gigartina, Gloiopeltis, Phyllophora,* and *Gracilaria*—some species) have been

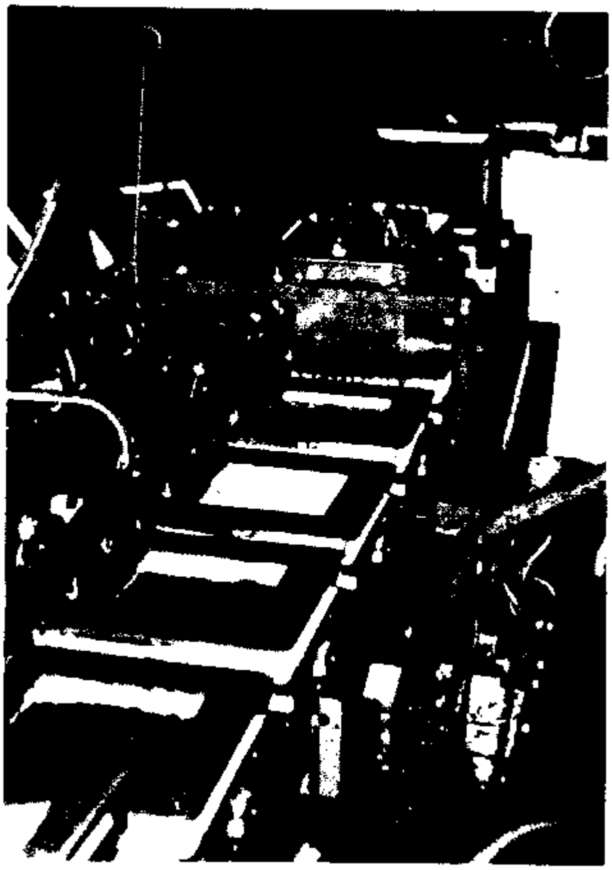

Figure 12. Nori sheet manufacturing machine. (Courtesy of T. F. Mumford)

Figure 13. Nori auction in Sendai, Japan. (Courtesy of T. F. Mumford)

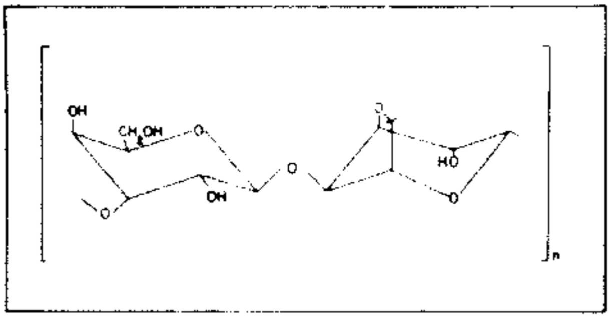

Figure 14. Basic repeating unit of the seaweed colloid agarose

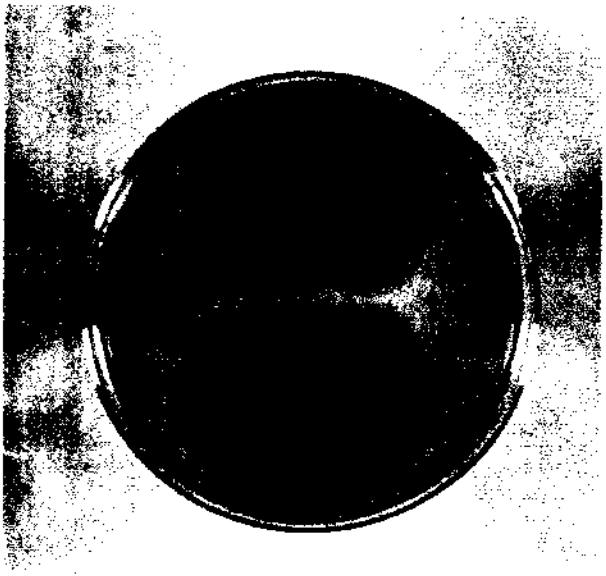

Figure 15. Agar-based culture medium with colonies of the mold. *Aspergillus versicolor* (Vuill.) Teraboshi (Courtesy of R. Phillips)

described collectively as "agaroids." Many of these contain the phycocolloid carrageenan. During commercial extraction processes, many times "agarophytes" and "agaroids" are mixed together, producing an amorphous "agar" of unknown seaweed source and of great chemical variation. These mixes are the agars of commerce and are used worldwide for meat canning and preserving, making dental impressions, jam making, candy making, brewing (to remove solids), printing, coating medicines, and sizing fabric.

High quality agar (primarily from *Gelidium*) finds its most important use today as a culture medium for growing cells and microorganisms. Agar-based media (figure 15) are employed routinely throughout the world in hospitals, public health agencies, colleges, and research institutes. Frau Fanny E. Hess suggested this use for agar to her physician-husband, who used it successfully in 1881. However, the discovery is usually credited to their associate Robert Koch, who went on to use agar as the medium for his famous experiments on tuberculosis bacteria (Hitchens and Leikind, 1939).

Currently, agar for culture media is, on the average, 60 percent higher in price than food-grade agar because of the greater degree of purification required (Guiseley, 1968). Much more recently, the agar derivative agarose is increasingly used in immunology and gel chromatography.

Prior to World War II, Japan had a near monopoly on the production of agar, with a volume exceeding 2,000 dry tons/year. With the outbreak of the war, supplies of Japanese agar were immmediately cut off. Agar became one of the first commodities to be designated as "critical war material" (Humm, 1947) by the War Production Board (1942), and all agar use in the United States was restricted to microbiological culture media. As a consequence, research on local agarophytes and agaroids began and spread worldwide, with agar extraction plants popping up nearly overnight.

In the United States a small agar industry that had begun in California was revived and expanded (American Agar and Chemical Company of San Diego). By 1945 there were eight additional companies in production. Today only American Agar (Difco) remains; it processes seaweed from California, Mexico, South America, Africa, Spain, and Portugal. However, Marine Colloids of FMC now manufactures the agar derivative agarose (Guiseley and Renn, 1977).

Not all coastlines have a preponderance of *Gelidium* species, and therefore a search ensued for alternative agarophytes and other red seaweeds with agar-like extracts. A considerable effort was given to agarophytes such as *Ahnfeltia plicata* (Russia), *Gracilaria* (Australia, U.S., Africa), and *Pterocladia* (New Zealand). Similarly, active work began in Britain on the "agaroids," or carrageenophytes *Gigartina stellata* and *Chondrus crispus* (Marshall, et al., 1949), and on *Hypnea* in India.

After World War II, Japan immediately regained the lead in agar manufacture, followed by Spain and—to a much lesser extent—Morocco, Korea, China, Portugal, and the United States. In Japan, the main agarophytes of commerce are *Gelidium* and *Gracilaria*. Use of *Gracilaria* agar became much more important in the 1950s owing to the development of an NaOH, alcohol pretreatment to convert L-galactose-6-sulfate moities to 3,6-anhydro-L-galactose (Japan Patent 7676, 1960) and the subsequent removal of excess sodium ions (Japan Patent 3505, 1963). This process significantly enhances gel strength.

Japanese seaweed from natural populations is harvested by hand or dredge between summer and autumn, and is dried and sold to part-time (winter) agar manufacturers located in the mountains within the freezing zone. Okazaki (1971) reported that 500 such small farm-plants were manufacturing agar by the natural method. In addition, about 36 plants in Japan produce agar by both the refrigeration and pressure methods. The amount of Japanese seaweed processed for agar in 1935 was approximately the same as in 1975 (Okazaki, 1971; Kurogi, 1975). However, over 50 percent of the 1970 crop was imported, reflecting a deterioration in the status of Japanese sources.

There have been few substantial changes in agar production from the original method developed in Japan in the 1600s. However, improvements in the United States have led to increased efficiency in the agar extraction process (Guiseley, 1968). Considerable progress is being made in the extraction and use of agarose (Marine Colloids, 1977a). Agarose is gradually replacing agar in areas where its nonionic nature

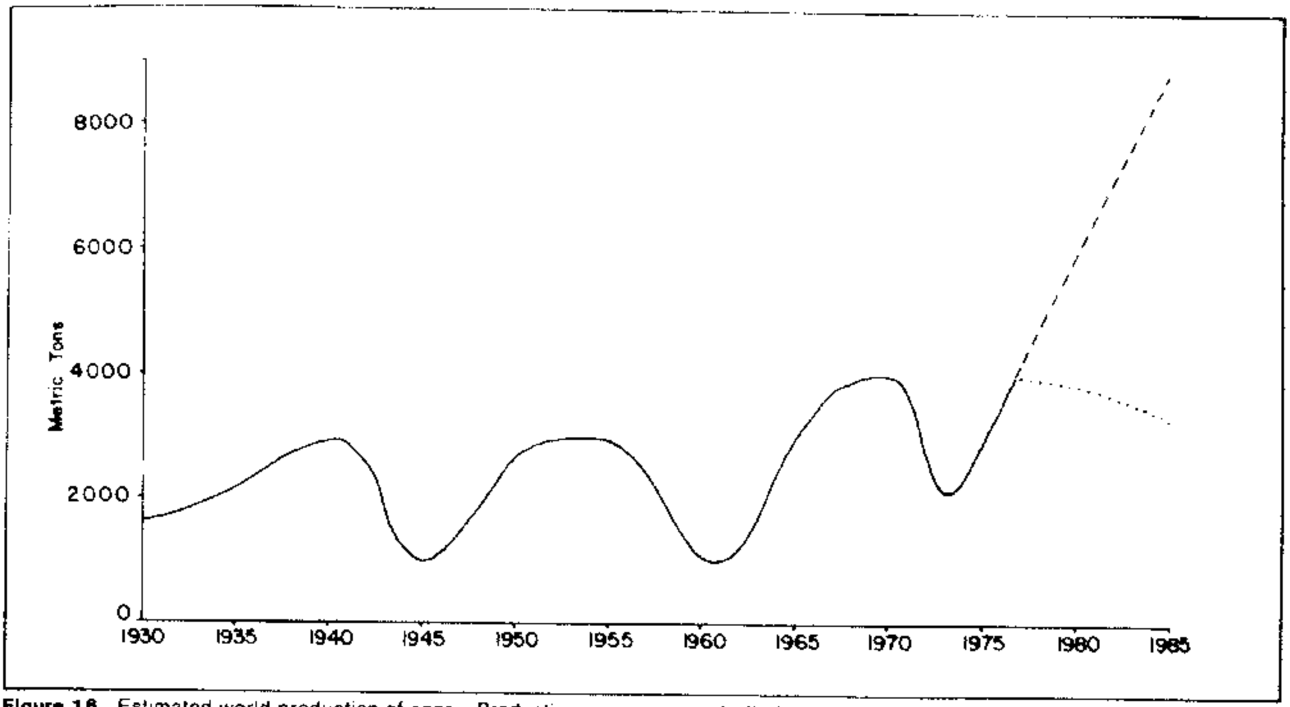

Figure 16. Estimated world production of agar Production assuming controlled culture of seaweeds (----); production based on wild sources only ( ). (Reproduced from Moss, 1977)

and ability to form strong gels at low concentrations are desirable (Guiseley, 1968).

The overall agar industry has a history of devastating, yet predictable boom-and-bust cycles (figure 16) (Moss, 1977). These have led to the inception and collapse of numerous small endeavors. The cycles are in part due to the biology of the plants themselves. Many of the species that produce high-quality agar for microbiological use are perennial and slow growing. During a year of preponderant growth, or when luxuriant beds are found, the species are invariably overexploited. This results in a "bumper crop" for that year, which affects the price based on supply.

Of greater consequence is the paucity of crops in the next few years, probably because of slow regrowth rates. Given the current harvest methods, pollution, and economic problems, the price of microbiological-grade agar (approximately 15 percent of the world agar market) (Moss, 1977) has been rising steadily in the past five years to $125/Kg (Difco, 1980), while retail agarose costs $250-780/Kg (Marine Colloids, 1977a).

In addition, food-grade agar, worth only 40 percent as much as agar for media-making purposes, will most likely be replaced by other colloids if production fluctuations cannot be stabilized. Studies were undertaken in California to determine the feasibility of using high-quality kappa carrageenan as an agar substitute for microbiological purposes (Abbott and Chapman, 1981). Kappa carrageenan from *Rhodoglossum affine* (Harvey) Kylin, with modifications, is comparable to Difco agar-based medium.

It is apparent that the economics of this important and lucrative group of agar-bearing seaweeds will stabilize only with the development of mariculture. The alternatives are dramatic price fluctuations based on wild crop harvests or partial replacement by other colloids of varying effectiveness and stability.

Carrageenans

The carrageenans, a collection of colloids from a larger number of red algae that produce agar, have been at the forefront of active phycocolloid research for the past twenty-five years. The name 'carrageen', coined by E.C. Stanford, is derived from the coastal town of Carragheen, Ireland, and refers to *Chondrus crispus*, also called 'Irish moss' (Tseng, 1947). The suffix for sugar, "-an," was added later.

The earliest use of carrageenan was in jellies and custards. Colonists brought the Irish moss industry to the United States around 1835. They paid $1-2/lb to import this seaweed for desserts until it was found to grow in abundance along the rocky shores of Massachusetts (Humm, 1951). Carrageenan was first isolated from *Chondrus crispus* in 1844 (Schmidt, 1844). Subsequently, carrageenans have been extracted from over eighty algal species, and commercial usage has expanded and diversified to over two hundred applications.

Knowledge regarding the chemical characteristics of carrageenan molecules has undergone a rapid evolution as more species are studied and new techniques are developed. In a broad sense, carrageenan is defined (Marine Colloids, 1977b) as

> ...that group of galactan polysaccharides extracted from red algae of the Gigartinaceae, Solieriaceae, Hypneaceae, and Phyllophoraceae families, and that have an ester content of 20% or more and are alternately α 1-3; β 1-4 D-glycosidically linked.

As recently as 1955, O'Neill determined the basic structures of kappa and lambda carrageenan, and Rees (1963) identified a third type called iota (figure 17). Several other carrageenan molecules have been found or hypothesized. Based on the sulfation and subsequent desulfation of the hypothetical molecule,

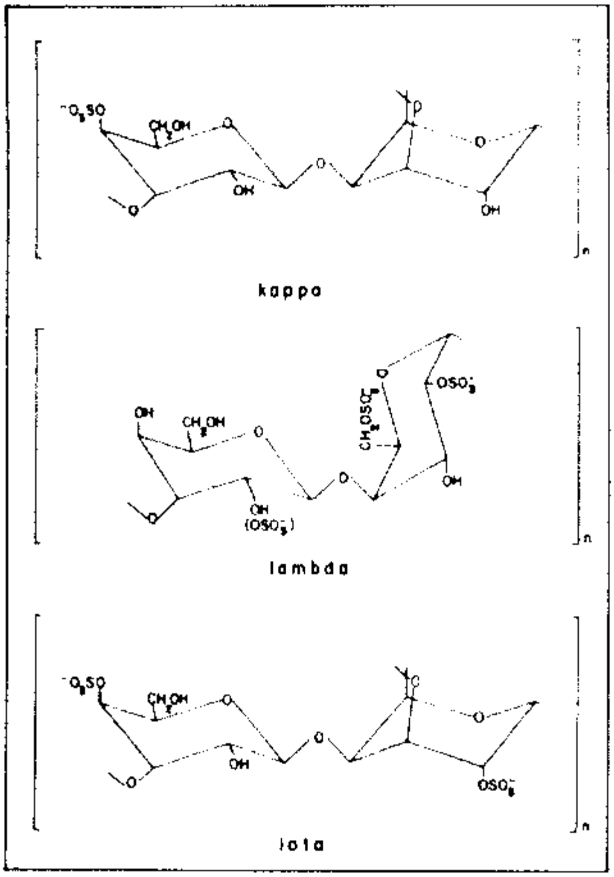

Figure 17. Chemical structure of kappa, lambda and iota carrageenan. (Reproduced from Santos, 1980)

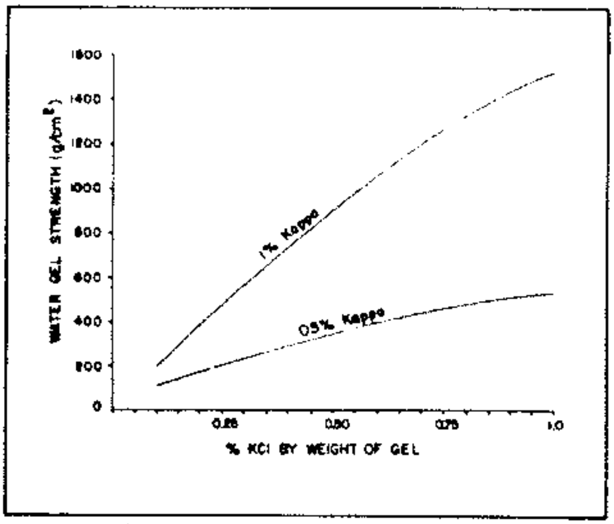

Figure 18. Cation effect on gel strength of kappa carrageenan (0.5%, 1.0% on weight/weight basis). (Reproduced with permission from Marine Colloids Div. of FMC)

families of carrageenans can be divided into those which are esterified with sulfate at the 4-position (the kappa-family) and those which are not (the lambda-family). The kappa-family includes iota- and kappa-carrageenans which contain 3,6 anhydro-D-galactose and gel in the presence of K^+ as well as the theoretical mu- and nu-carrageenans. The lambda-family includes lambda-, xi-, and the pyruvate-containing pi-carrageenans, all of which do not gel and are very viscous. The partly methylated, sulfated D-galactans from the Cryptonemiaceae also appear to be carrageenans (McCandless and Craigie, 1979).

Carrageenans have been extracted from many related genera and species, yet each has its distinct set of characteristics. In some species, these may be quite disparate. As common properties, though, all carrageenans are soluble in water (some may require heat) and in water-miscible solvents (e.g., alcohol, propylene glycol, glycerine), insoluble in organic solvents, and precipitated by cationics (proteins, amines). The gel strength and viscosity of carrageenans are highly influenced by molecular weight, pH, and the addition of salts (K^+, Ca^{++}, NH_4^+) (figure 18).

With the progressive discovery and refinement of these characteristics, combined with industrial innovation, commercial applications for carrageenans have surged and diversified. In the United States (the largest single producer), about 70 percent of all carrageenan products are used in the food industry. The two major categories of applications are: (1) use in liquid systems—i.e., water gels (table 2); and (2) use in protein systems—i.e., milk reactivity (table 3). The remaining industrial applications are in pharmaceuticals and cosmetics (table 4).

Carrageenan was first extracted from *Chondrus crispus* on a small scale by Krimco Dairy, in Massachusetts, for making ice cream. Full-scale manufacture of carrageenan was pioneered by Sea Plant Corporation, New Bedford, Massachusetts, in 1937. Sea Plant and Algin Corporation of America, in Maine, joined forces in 1959 to form Marine Colloids.

Marine Colloids, currently the largest producer of carrageenan in the world, is now a division of FMC Corporation, Chicago (1977). This company received an impetus during World War II, when carrageenans were substituted for food-grade agar. From 1960-1970 carrageenan sales brought Marine Colloids approximately $6-8 million/year. Through innovation in techniques, new source material, and expanded applications, sales grew to a production of some 8 million lbs/year, valued at about $20 million/year, by 1976. The primary source material for this sales growth is *Chondrus crispus*, followed to a lesser extent by *Iridaea, Gigartina, Rhodoglossum,* and *Eucheuma.*

Other major carrageenan manufacturers are Copenhagen Pectin/GENU (Denmark, Canada), Prona (Spain, Portugal, Argentina, Chile), Ceca (France, Africa), Takaragen and Nitto (Japan), and Gomez-Marinas (Spain). Moreover, new processing plants are being established as new source material is discovered (e.g., in the Philippines, Norway, Brazil, Argentina, Japan) (Neish, I.C. pers. comm., 1979).

The carrageenophyte *Furcellaria* (Danish agar) is harvested and processed by Litex Corporation in Canada and Denmark (figure 19). *Furcellaria* carrageenan, or furcellaran, is extracted much like agar. The resultant products are used primarily in making jams, preserves, and icing for pastries. Other uses in foods are similar to those outlined for carrageenans in table 2.

Growth of this industry is limited by an inadequate supply of *Furcellaria*, and sales based on this source are relatively small (Moss, 1977). However, Litex is diversifying; it is processing a considerable amount of

Table 2

Typical Water Applications of Carrageenans

Use	Function	Carrageenan Type
Dessert gels	Gelation	Kappa (K) + Iota (I) K + I + locust bean gum (LBG)
Low calorie jellies	Gelation	K + I
Pet foods (canned)	Fat stabilization, thickening, suspending gelation	K + LBG
Fish gels	Gelation	K + LBG, K + I
Syrups	Suspension, bodying	K, Lambda (L)
Fruit drink powders and frozen concentrates	Bodying, pulping effects	Sodium K, L, potassium-calcium
Relishes, pizza, barbecue sauces	Bodying	K
Imitation milk	Bodying, fat stabilization	I, L
Imitation coffee creams	Emulsion stabilizer	L
Whipped toppings (artificial)	Stabilize emulsion, overrun	K, I
Puddings (non-dairy)	Emulsion stabilization	K

Reproduced with permission from Marine Colloids of FMC (1977)

Table 3

Typical Milk (Dairy) Applications of Carrageenans

Use	Function	Carrageenan Type
Milk gels:		
Cooked flans or custards	Gelation	Kappa (K), K + Iota (I)
Cold prepared custards	Thickening, gelation	K, I, Lambda (L)
Puddings & pie fillings (starch basel dry mix cooked with milk	Level starch gelatinization	K
Ready-to-eat	Syneresis control, bodying	I
Whipped products:		
Whipped cream	Stabilize overrun	L
Aerosol whipped cream	Stabilize overrun, stabilize emulsion	K
Cold prepared milks:		
Instant Breakfast	Suspension, bodying	L
Shakes	Suspension, bodying, stabilize overrun	L
Acidified milks:		
Yogurt	Bodying, fruit suspension	K + Locust bean gum
Frozen desserts:		
Ice cream, ice milk	Whey prevention, control meltdown	K
Pasteurized milk products:		
Chocolate, egg-nog, fruit-flavored	Suspension, bodying	K
Fluid skim milk	Bodying	K, I
Filled milk	Emulsion stabilization, bodying	K, I
Creaming mixture for cottage cheese	Cling	K
Sterilized milk products:		
Chocolate, etc.	Suspension, bodying	K
Controlled calorie	Suspension, bodying	K
Evaporated	Emulsion stabilization	K
Infant formulations	Fat and protein stabilization	K

Reproduced with permission from Marine Colloids of FMC (1977)

Table 4

Use of Carrageenan in Cosmetics and Pharmaceuticals

Application	**Function**
Antibiotics (liquid)	Suspension, activity stabilization
Lotions and creams	Bodying, slip, rub out
Hydroalcoholic lotions and creams	Bodying, emolliency, rub-out
Shampoos	Foam stabilization, thickening gelling
Toothpaste	Bodying, foam stabilization
Ulcer products	Protein reactivity
Cough proparations	Coating
Salves	Bodying
Chewable tablets	Reduce chalkiness
Medicinals (milk magnesia)	Suspension of insoluble ingredients
Laxatives (liquids)	Oil in water emulsion stabilization

Reproduced with permission from Marine Colloids of FMC (1977)

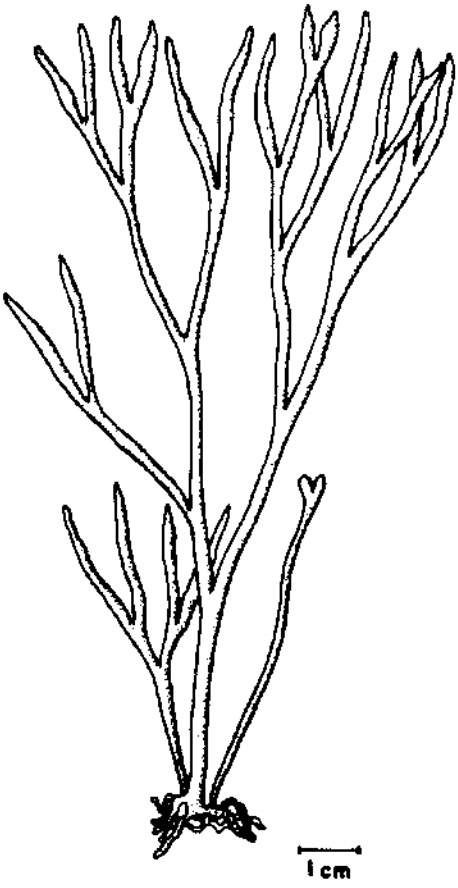

Figure 19. *Furcellaria fastigiata* (Hudson) Lamouroux

Eucheuma cottonii (Neish, I.C., pers. comm. 1979)

The industrial production of carrageenan in the last decade surpassed the older, established agar industry sometime during the 1960s. This development was stimulated directly by the wartime shortages of agar and the resulting intensive research on carrageenan. With postwar return of agar to the world marketplace, carrageenan became important in its own right. Research on new products, exploration for additional seaweed sources, resource development and management, and—more recently—development of mariculture were begun.

This rapid research and development, coupled with an active market, has stimulated somewhat of a run on seaweed resources. Development of new seaweed resources abroad has been followed by the building of small, local processing factories. This is partly due to raw material export restrictions (e.g., those in Argentina, Mexico, Korea). As a result, seaweeds which in the past were gathered and shipped to existing factories are no longer available to these factories.

This trend, which began in the 1960s, has resulted in further partitioning of the world's carrageenan resources (Neish, I. C., pers. comm., 1979). The resulting market slump is somewhat reminiscent of agar's boom-and-bust cycle, rather than an exponential increase in wild crop production as predicted by Moss (1977). Stringent resource management of natural populations, coupled with successful mariculture practices, could produce dependable supplies.

Other Industries

A seaweed glue has been used and refined in Japan ('funori') since 1673 and in China ('hailo') (Chapman, 1970). The polysaccharide from the prime source material *Gloiopeltis furcata* (Cryptonemiales, Endocladiaceae) may be a sulfated analog of agarose (Stancioff and Stanley, 1969). The small alga grows high in the intertidal zone and is hand-picked. Suitable substratum and crops are extended by placing boulders at the appropriate tidal level and artificially "planting" them with spore stock.

The seaweed is air-dried for transporting, treated with either a weak acid solution or by fermentation to facilitate cell breakdown, and processed into sheets similar to paper. The sheets are alternately moistened and dried to further cellular breakdown and bleaching. The final product is a yellowish paper-like material, 100-225 g/sheet (figure 21).

Some 44 processing plants handle approximately 208,000 lbs of *Gloiopeltis furcata*/year (Okazaki, 1971). The highest quality material is used for sizing in Japanese silks. Other species of *Gloiopeltis* are mixed with *Ceramium*, *Gracilaria*, and *Chondrus* and used as a textile paste. The pastes are also used in bleaching material for washing, binding material, and in making cosmetics and pigment.

The Japanese use similarly derived algal pastes for stucco (wall plaster) and tile cement in house building. The primary source materials are the carrageenophytes *Iridaea*, *Chondrus*, *Grateloupia*, *Rhodoglossum*, and *Gigartina*. All totaled, seaweed paste production in Japan amounts to somewhat more than 1.1 million lbs/year (Okazaki, 1971).

A small industry is based on the edible red alga *Palmaria palmata* (= *Rhodymenia palmata*), or dulse. As discussed earlier, this broad, flat plant has been used for centuries in Ireland and Scotland ('dillisk' 'crannough') in bread, as a vegetable or garnish, and for flavoring or thickening stews, sauces, soups, and gravies (Major, 1977). It is also eaten in some Mediterranean countries and in Iceland, where its use is extended to cattle feed (Chapman, 1970). In Canada approximately 100,000 lbs/year of dried dulse is prepared by Atlantic Mariculture Ltd., New Brunswick, and packaged for food (Atl. Mariculture, pers. comm., 1978).

The coralline red algae which produce hard lime (calcium carbonate) coverings have long been used in the 'maerl' (France) or 'marl' (Britain) industries. Extensive beds of "loose-lying" coralline algae occur from 2-21 m below extreme low water along parts of the Mediterranean and the west coast of Europe (Dixon, 1973). The beds are composed principally of *Phymatolithon (Lithothamnium) calcareum* and *Lithothamnium corallioides* (Cabioch, 1969; Adey and McKibbin, 1970).

Massive deposits of bleached coralline algae give beaches a sparkling white appearance. The maerl, or coralline sand, is collected from the beached deposits or by dredging, and is applied to acidic or peat soils along much of the European coast.

Use of marl in Britain has diminished in this century, owing in part to abandonment of marginally productive coastal lands and in part to replacement by more convenient sources of lime, but its use has accelerated in Spain (Dixon, 1973).

A novel use for *L. calcareum* in France may revive the maerl industry. In addition to its use to improve acidic soils, it is now used to treat acidic drinking water. Untreated, acidic water dissolves metals from the water distribution system. When such water is filtered through *L. calcareum*, the pH is raised to 8.3. At this pH, lead, copper, and zinc ions are precipitated. Other undesirable ions are eliminated through adsorption or ion exchange (including radioactive elements) (Neveu, 1961).

Algae as "Nutrient Scrubbers"

Eutrophication of aquatic systems has many causes, including upwelling, agricultural land runoff, sewage disposal, or animal mariculture. Each results in an excess of nutrients in the particular system. This can lead to a favorable increase in primary production, a change in community composition and structure, or an unfavorable development of anoxic conditions and eventually to an abiotic environment.

The concept of using plants as "nutrient scrubbers" for the removal of excess nutrients from aquatic systems is not new. It is a logical extension of basic agricultural practices. As early as the fifth century, fish aquaculturists in China used plants for a dual purpose: as nutrient scrubbers and as fish food (Ling, 1977). Fertilizers for such polyculture systems are primarily low-cost manures.

Today, many enterprising Chinese families operate an integrated culture or polyculture system that includes the central fish pond with aquatic, vascular

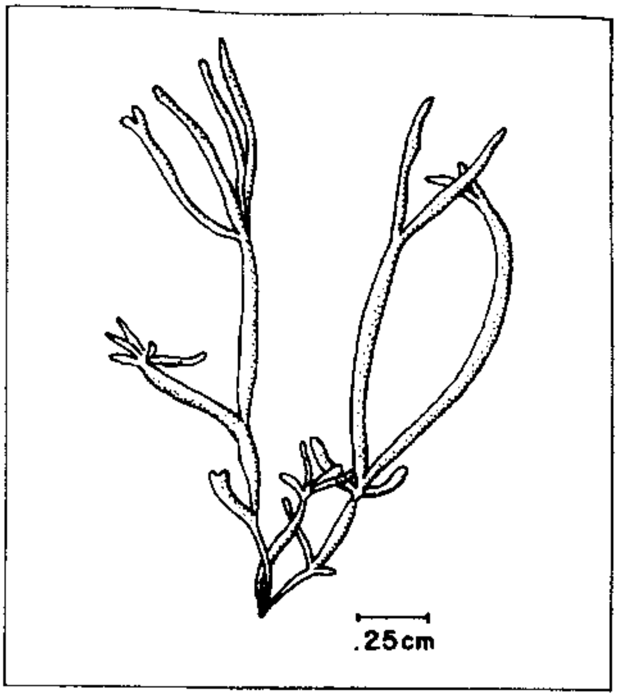

Figure 20. *Gloiopeltis furcata* (Postels & Ruprecht) J. Agardh

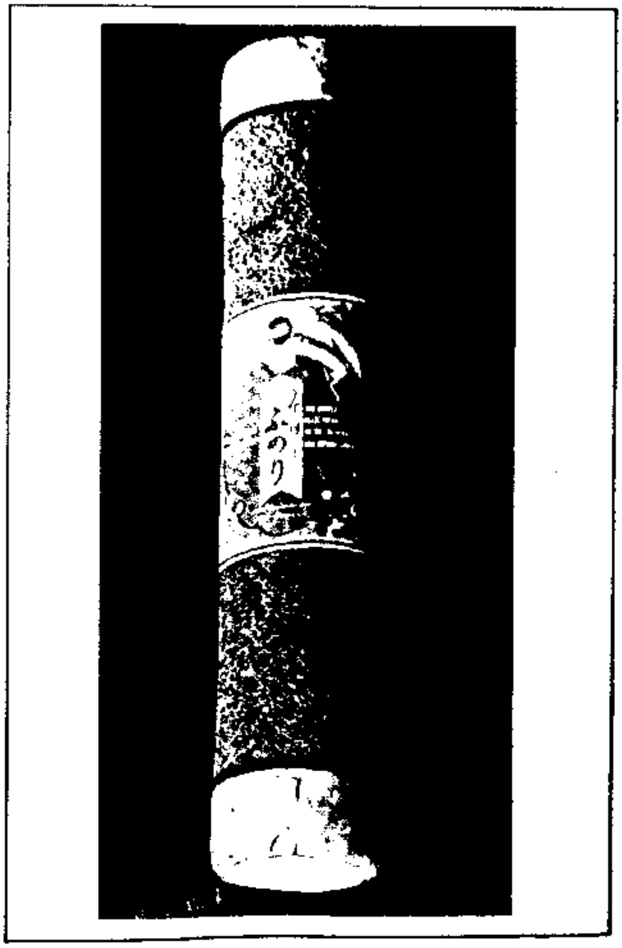

Figure 21. A commercial package of funori (*Gloiopeltis*) 3' long, 6-7" in diameter (Smith, 1904). When boiled the dried seaweed is converted to a starch, glue or paste commonly used in Japan.

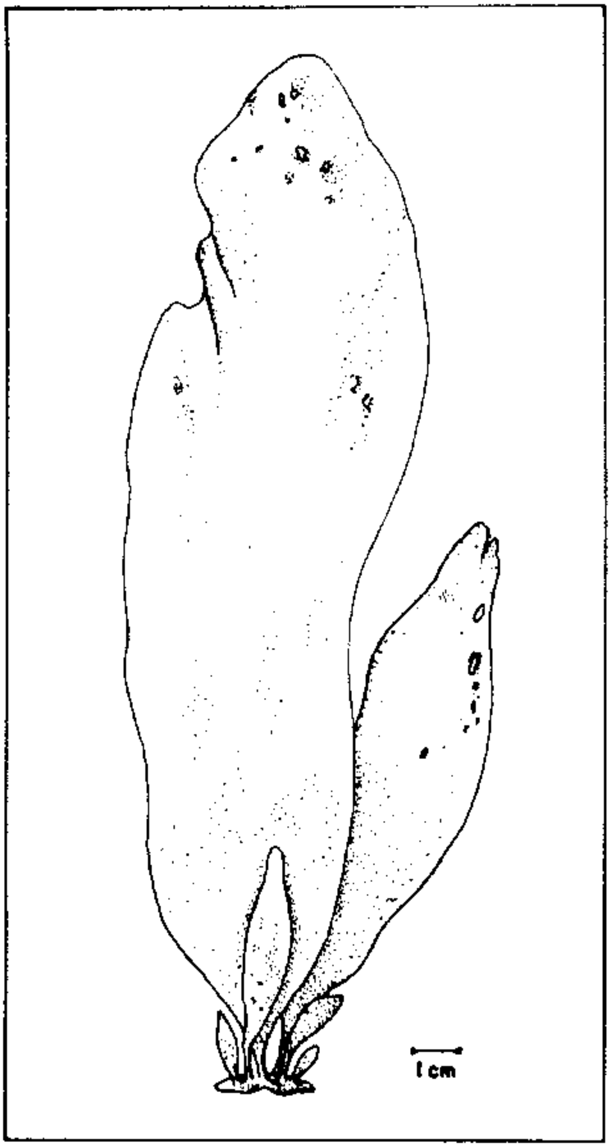

Figure 22. *Iridaea cordata* (Turner) Bory

plants and algae; a vegetable garden or fruit trees that are irrigated with wastewater; and a chicken coop, pig sties, or ducks to fertilize the pond plants. A large-scale system might also include silk production; the necessary mulberry trees require nutrient-rich wastewater (Ibid., 1977).

As "night soil" and other manures are utilized in China, so secondarily treated sewage effluent has become a fertilizer for aquaculture systems in the Western world. Freshwater microalgae have long been used as nutrient scrubbers in sewage treatment ponds or more recently in sewage ponds associated with livestock feedlots. The nutrient-rich algae harvest can then be used directly as a fertilizer or recycled back as livestock fodder (figure 23).

In recent years great strides have been made in the aquaculture of animals in enclosed systems. These practices have rapidly evolved into polyculture with the addition of algae for food and for removing excess nutrients excreted by the animals. From an economic standpoint, red algae of commercial value have been the choice for nutrient scrubbers in both mariculture and sewage-related systems.

In the United States, Ryther, et al. (1975) pioneered such systems. Commercially important red algae such as *Gracilaria* sp. and *Hypnea musciformis* have been nutrient scrubbers for secondary-treated wastewater and oyster effluent (LaPointe, et al., 1976). *Chondrus crispus*, *Neoagardhiella baileyi*, and *Gracilaria foliifera* have also been integrated into waste recycling-polyculture systems (Ryther, et al., 1975; DeBoer and Ryther, 1977; Ryther, 1979b; Ryther, et al., 1979). Haines and Wheeler (1978) developed a multifaceted approach to studying the carrageenophyte *Hypnea musciformis* in St. Croix. Nutrient scrubbing capacity of *Hypnea* was assessed in clam mariculture effluent, artificially upwelled water, and seawater enriched with either domestic sewage or chemical fertilizers (Ibid., 1978; Langton, et al., 1977).

Domestic sewage can harbor varying amounts of metals, which may be accumulated in animals under such mariculture conditions. Ryther and Mann (unpublished) included *Gracilaria* and *Neoagardhiella* in a waste recycling aquaculture system for the purpose of removing metals (e.g., Cd, Cr, Cu, Hg, Ni, Pb, Zn).

The refinement and expansion of animal mariculture is likely to encourage the large-scale integration of red algae for purposes of nutrient scrubbing and ultimately for the lucrative phycocolloids. Cultivation of algae for such purposes is, after all, less expensive and may be the only way to prevent discharge of some kinds of wastewater containing noxious elements.

Algae as Biomass for Energy

Perhaps the most revolutionary application suggested for red algae in recent years has stemmed from the concept of "biomass energy." Plant cells can be viewed as millions of tiny solar collectors, trapping atmospheric carbon and converting it to organic compounds via photosynthesis. Using conventional methods, this plant biomass can be converted to fuels such as methane, providing a clean and plentiful alternative to fossil fuels. Several other useful products result from the processing.

Primarily because of the low efficiency of photosynthesis, the sun-to-plant-to-fuel conversion on land is only 1 percent efficient; thus, 1.5 million square miles of land would be required to supply the nation's energy, or 20-100 percent of our currently farmed land (Hall, 1977). Meanwhile, a growing population will cause ever-increasing demands on usable land for food, space, and natural resources.

To alleviate this massive land requirement, researchers have looked to the sea. The oceans cover a vast area of currently undeveloped space. It is estimated that 60 to 70 percent of the ocean surface is potentially arable. Unfortunately, most of the open ocean is too deep and dark for attached plants to grow, and surface waters are often poor in nutrients. As a result, generating adequate biomass for conversion to fuel will require farming on vast artificial substrates near the lighted ocean surface. Deep, nutrient-rich water will have to be artificially upwelled to fertilize the plants; it is hoped that this pumping can be driven by

Figure 23. An algae production system using wastewater from a hog feed lot (Kansas). The resultant high protein algae slurry is the basic component of the hog feed (lower right).
(Courtesy of M. Aitken, Algae Processes, Inc.)

wind or wave power. Since this system requires no fresh water or arable onshore land, it will have minimal impact on our dwindling terrestrial resources.

Once the biomass is generated, several processing options are available. If the algal material is tough, the harvest will be chopped and ground. However, this is not necessary for the red alga *Gracilaria*, which requires no processing prior to digestion (Ryther, pers. comm. 1980). The solids are pressed out and converted to methane via anaerobic digestion. Other chemical methane production processes are being considered as well.

The effluent liquid will contain valuable extractable salts such as potassium chloride and nitrogen. The remaining water will either be recycled as cooling water, used to fertilize land crops, or returned to the marine farm to supply nutrients. The solids remaining after the digestion process will be used for fertilizer or animal feed. These conversion processes are fairly well understood and considered feasible.

In contrast, the large-scale farming of plants in the sea presents many unknowns and obstacles to overcome. Which plants are the candidates for culture? The ideal plant for cultivation in the system described above would have a rapid growth rate, be easily cultivated and harvested, regrow vegetatively or via a perennial portion after harvest, and produce useful and marketable by-products. The brown and red algae are likely the only marine plant groups to meet these criteria adequately.

To date, research on ocean energy farming has centered around the brown alga *Macrocystis*. Its large size, rapid growth, and history of harvest on the Pacific coast have made it an obvious choice. With government and industrial support, researchers at the Naval Undersea Center and the California Institute of Technology have been investigating large-scale farming of *M. pyrifera* for food, fuel, fertilizer, methane, and industrial chemicals as part of a program known as the Ocean Food and Energy Farm Project.

A pilot one-acre structure was tested in 1975 (figure 24). It consisted of structural members strung with polypropylene line to which kelp plants were attached. A current project sponsored by the American Gas Association and U.S. Department of Energy included implementation of a quarter-acre module (QAM) of similar design offshore of San Diego, California, in 1978. Long-term plans are to establish a 100-acre farm by 1981, and a large-scale 100,000-acre farm by 1990.

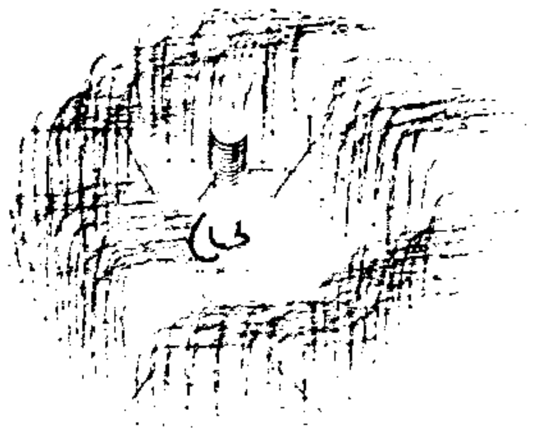

Figure 24. Diagram of *Macrocystis* cultivation on an offshore structure. (Courtesy of V. Gerard)

Considerable progress has been made on growing kelp and determining optimum requirements for growth. However, major engineering problems with the module design present formidable obstacles to these long-term speculations.

Unfortunately, *Macrocystis* is restricted to cool, temperate waters. For this reason, it cannot be depended upon to supply the world's energy. It is possible to upwell cool deep water in some tropical regions, but this is prohibitively expensive. In addition, the introduction of a nonnative species around the world may have far-reaching effects on local marine ecosystems; the experimental cultivation of *Macrocystis* on the north coast of Brittany several years ago met with an uproar of opposition from neighboring phycologists (International Seaweed Symposium 8, 1974). As a result, many other species of algae will have to be considered for ocean farming.

In 1977, a feasibility study was published for marine biomass energy in Hawaii. The study presents a model based on literature then available; it has not yet been tested. As *Macrocystis* was not a feasible crop for several reasons, the native brown alga *Sargassum* was proposed for cultivation on polypropylene grids. The model plantation would cover 23 square miles off the southwest coast of Molokai Island, and would produce the following annually: 1) enough methane to supply 35 percent of Oahu's 1975 pipeline gas sales, 2) 10 million pounds of alginates, 3) 56,000 tons of livestock feed supplement, and 4) an unknown quantity of potassium chloride and sodium sulfate (Murata and Kelly, 1977).

The algal biomass energy concept is only in its fledgling stages. To date, *Macrocystis* and *Sargassum* are the only known seaweeds that have been seriously considered. As research proceeds, more species will be evaluated, and among them will be many red algae.

Overall, the culture of red algae is perhaps better known than that of brown algae. Net culture techniques were born with *Porphyra* cultivation in the East, and research on phycocolloid-producing red algae has increased elsewhere in the past few decades. Red algal colloids are also increasingly valuable on the world market, spurring increased efforts to cultivate carrageenan- and agar-bearing seaweeds on nets and in tanks, and giving us baseline information for larger-scale projects. Further, although no red algae grow as large as giant kelp, many of them are perennial or grow well from vegetative fragments.

The major drawbacks of red algal ocean farms are the difficulty in harvesting small thalli and the biomass production rates, which are less than kelp production rates. The first problem could surely be overcome by modifying current harvesting barges. Smaller growth rates would have to be weighed against other desirable aspects of the species in question, such as value of chemical composition and ash content. These characteristics can also be optimized by genetic selection of desirable stock.

Already the red alga *Eucheuma* has been suggested as a potential source of biomass from marine plantations (Bryce, 1977; Murata and Kelly, 1977). It is one of the more robust forms of red algae, growing to 2 meters in length at a rate of 3 to 5 percent per day, and it is the only red alga that has been successfully cultivated in the open ocean and harvested for phycocolloids on a large scale. *Eucheuma* farming occurs in the Philippines, and as Doty (1977b) points out, more economical methods for cultivation must be sought if farming is to succeed in more developed countries. Cultivation in enclosed pens, in hollows on the natural substrate, and by placing fragments under wires stretched on the sea botttom are promising alternatives that allow mechanical harvest and growth rates often exceeding 5 percent per day (Doty, 1977b).

Ryther's (1979b) experiments on another candidate, *Gracilaria*, offer encouraging results. Methodology has been developed for the anaerobic digestion of *Gracilaria* to methane using bacteria from anaerobic marine sediments. Ryther now has two *Gracilaria* digesters in operation, and preliminary results indicate a gas production range of 0.2 to 0.4 liters/g *Gracilaria*, of which 60 percent is methane. In addition, the process recovers about 75 percent of the *Gracilaria* nitrogen, which is then recycled back to the seaweed culture facilities as fertilizer (Ryther, pers. comm., 1980).

Many species of red algae are candidates for producing biomass energy. First, major research is needed on cultivation, substrate engineering, harvest, processing, market feasibility, and many other aspects. In addition, as Doty (1977b) points out, "the physical environment and the biological characteristics of algae may not be the severe barriers to economic seaweed production that the bureaucratic and socio-political ones are." It will take decades or longer, but seaweed power may be on the wave of the future.

Mariculture of Red Algae

Criteria for Selecting an Algal Species

Mariculture of red algae is at a crossroads. Seaweed-based industries have relied nearly completely on harvesting unmanaged natural seaweed resources. As needs increase for higher quality and greater stability and quantities of certain species, innovative industrialists and far-sighted governmental agencies look toward managed cultivation, or mariculture, as an answer.

Development of red algal mariculture has progressed at an imperceptibly slow pace compared to land-based agriculture. The few developments made within the past decade have, however, established criteria for selecting an algal species for mariculture.

The basic criterion is *product need.* For example, expanding applications and use of carrageenan provided a major impetus for the recent rapid advances in carrageenan research and cultivation.

Trial-and-error cultivation quickly leads to the criterion of *growability.* Some red algal species grow especially well by means of vegetative propagation, whereas others grow best or solely from spores. Knowledge of the chemical and physical requirements for best growth—e.g., irradiance/daylength, temperature, nutrients, stocking density, and water movement—is necessary for each species. An adequate prescription should also discourage serious pathogens and pervading epiphytism problems.

Satisfaction of the growability criterion requires careful research on the ecology and physiology of the species of interest. This clearly involves a major time commitment and risk in the overall development of mariculture procedures. The risk may be high, since the results may be negative; either the species is highly sensitive and cannot be cultivated effectively, or prescribed conditions are too costly or presently not feasible.

A third criterion is *location.* Can the species in question be cultivated cost-effectively at sea or in enclosures on land? Presuming that the prescription for maximum algal growth is feasible, the mariculture system designed should make the most efficient use of surroundings for minimum energy utilization. For example, irradiance/daylength and, subsequently, growing period are greatest at the lower latitudes. Location for the most efficient use of ambient seawater is a further consideration. Required nutrients such as nitrogen and phosphorus are at least temporally high in areas of upwelling and in bays and estuaries and where excessive land runoff occurs. Further, if the system is highly labor-intensive, cost of labor on location gains importance as well as transportation costs to the nearest processing plant.

To complete this list of species selection criteria are the *governmental regulations and requirements* to be met before implementing a mariculture system. Additional mariculture development in regions of the world where cultural modes easily accommodate mariculture (e.g., Japan, China), or where fishery regulations encourage such practices (e.g., Philippine Archipelago) will find few governmental encumbrances. However, in Europe and North America substantial maritime laws (international, federal, state, local, and special district) predate mariculture and require serious and costly deliberation. It is of some reassurance that in both Canada and the United States efforts are being made to simplify both federal and state procedures for obtaining permits.

In the broad sense, plant mariculture can be described as the managed cultivation and harvest of marine plants. In this context five forms of mariculture have been developed thus far for the red algae.

Managed Harvest of Natural Populations

The simplest form of mariculture is the managed harvest of *in situ* algal populations. Until very recently, this has been the state of the art for nearly all red algae of commerce, except *Porphyra*. This type of mariculture can be practiced by anyone who can successfully identify all morphological forms of the species of interest. The management aspect incorporates regulations on harvesting season, location, and tools. Mariculture of this type has been quite successful, for example, for *Gelidium* and other agarophytes in Japan and carrageenophytes in Canada and the United States.

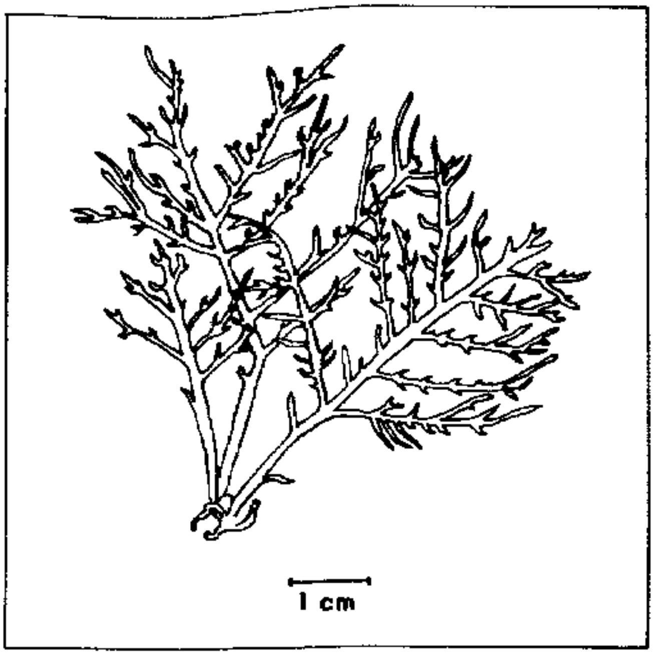

Figure 25. *Gelidium amansii* Lamouroux

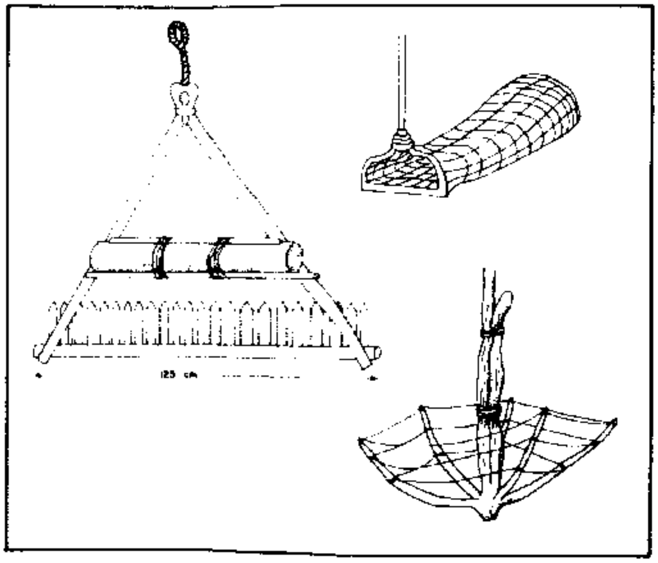

Figure 26. Tools for harvesting *Gelidium* in Japan (Okazaki, 1971).

In Japan

Agar-producing seaweeds have been harvested in Japan for centuries. Moreover, Japan has been and continues to be one of the world's major producers of agar used for microbiological culture media, foods, brewing of beer, manufacture of wines and coffee, cosmetics, candy, and pharmaceuticals. Applications for the phycocolloid have been steadily increasing in the past few decades, but harvesting methods remain virtually unchanged and highly labor intensive (figures 26, 27).

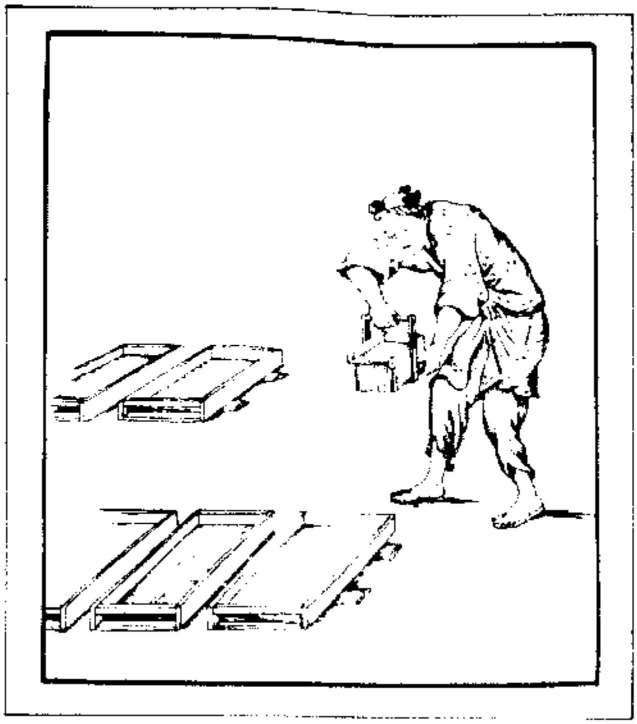

Figure 27. A Japanese woodcut (by Masanobu Kanai depicting the pouring of Kanten (agar) extracted from tengusa (*Gelidium*) into cooling trays. (Reproduced in Smith, 1904)

Numerous genera encompassing some eighty species are harvested in Japan for the agar industry, of which *Gelidium* spp and *Gracilaria* spp constitute the greatest biomass (Okazaki, 1971). The *Gelidium* harvesting season opens May 1 and continues through October. Long before the season opens, the richest and largest seaweed beds (seaweed biomass > 1.5 kg/m^2) are located, and appropriate preparations are made. Harvesting is done by hand (either in the intertidal zone or by free diving), by airhose divers, from a boat (using hand tools), and by trawls (figure 26). By far most seaweed is harvested by airhose divers and by trawling with motor boats.

Management of agarophyte resources is a responsibility of local seaweed cooperatives. Examples of such a management program come from Miyake Jima, one of the seven Izu Islands south of Tokyo Bay, where the majority of Japanese *Gelidium* is harvested. There is a definite harvesting season, and the shallow waters surrounding this island are open only to free diving, swimming, and shoreline harvesters. Airhose divers and boats may harvest only in deep waters of 45 m or more.

The seaweed cooperative selects the areas and the days when harvesting can take place. Another measure to prevent overharvesting is prohibition of scuba tanks, which would greatly increase diver mobility while harvesting. Daily, the harvesters deliver the freshly gathered seaweed to the cooperative, where it is dried, rolled into bundles, and shipped to buyers in Tokyo (Cuyver, 1978).

Approximately 73 percent of the agar production costs go to harvesters for purchase of the raw seaweed material. Agar is subsequently extracted and purified via the natural method, which began about 350 years ago, or industrially by the refrigeration or pres-

Figure 28. Harvesting (a) and processing (b) the red seaweed *Gelidium* in Japan from which agar will be extracted and refined (c). (Courtesy of A. M. Nonomura)

sure methods, both of which started in 1946 (Okazaki, 1971). Other agar-extraction methods such as electro-osmosis, autovapor evaporation, spray drying, and direct heat drying have been used in Japan, but are now considered uneconomical.

The managed harvest of natural agarophytes has provided the base of the commercial Japanese raw seaweed and agar industries from its inception. Despite the apparent success of this type of mariculture, there has been a progressive decline in the annual *Gelidium* crop to approximately one-half of the biomass produced in 1935. While the total amount of seaweeds used for making agar has remained nearly constant between 1935-1975 (omitting WW II years), the difference has been made up by importing seaweed, primarily *Gracilaria*.

In North America

Commercial harvesting of carrageenophytes in the eastern United States and Canada began in the middle 1800s. The mainstay of the harvest has always been natural populations of *Chondrus crispus* (figure 29), though small but varying amounts of *Gigartina stellata* and *Furcellaria lumbricalis* (Danish agar) are included. During the earliest years of commercial use, the dried seaweed was sold for its gelling properties for making certain desserts. Later, carrageenans were extracted from the harvested crops for Krimco Dairy to use in ice cream (Neish, I. C., pers. comm., 1979). Since that time millions of kilograms of *Chondrus* have been harvested from Atlantic nearshore waters for extraction of carrageenans. Harvesting methods and management practices have changed very little (figure 30).

Chondrus populations commonly span a vertical range from the intertidal zone to somewhat deeper than -20 m, but maximum and therefore economically harvestable populations grow between the midintertidal zone and -6 m depth (figure 31). *Furcellaria* occupies much the same range as *Chondrus*, while *G. stellata* is found primarily at the upper end of the range. Collectively, these carrageenophytes have been harvested throughout their growing range, and from beach drift. They are gathered by hand-picking with rakes of various design, by trawls, and experimentally by mechanical harvesters.

Approximately 45.5 million kg wet weight (roughly equivalent to 10 million kg dry weight) of *Chondrus* are harvested annually from the eastern coastal waters of North America. Ninety to 95 percent of the harvest comes from Canadian waters (Nova Scotia, Prince Edward Island, Newfoundland, New Brunswick), employing some 1,371 harvesters (Pringle, 1976); the remainder comes from the United States (Maine and Massachusetts).

Traditionally *Chondrus* is harvested from small dories (about 4.6 m) using a long-handled rake (figure 32).

> Two and a half hours before low tide, the mosser puts on oilskin overalls and rubber boots and sets out in his dory equipped with pulling rake and a bottle of cod-liver oil to smooth the water. The moss is bleached on the beach where the successive stages in the process, deep purple, dark red, pink, light brown and finally yellowish white, turn the shore into a gigantic patchwork quilt. The moss is washed in salt water, dried,

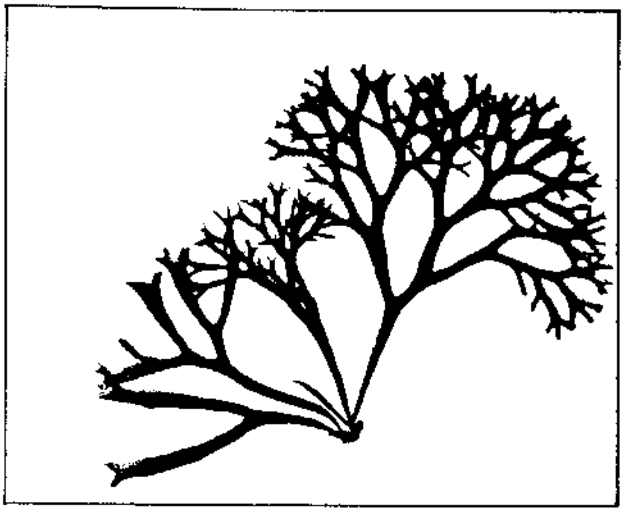

Figure 29. *Chondrus crispus* with six fronds from a single holdfast differing in stage of growth and branching pattern. (Courtesy of C. MacFarlane)

Figure 30. Transporting harvested *Chondrus* by horse carts in Nova Scotia, Canada. (Courtesy of C. MacFarlane)

Figure 31. A dense bed of *Chondrus crispus* in Halifax Co., Nova Scotia, Canada. (Courtesy of C. MacFarlane)

> packed in barrels and shipped to the market (Chase, 1941).

This description depicts the *Chondrus* harvesting industry as it is today, except the cod liver oil is no longer used, and the dories now unload the raw seaweed directly into trucks or at drying stations. Until the recent oil shortages, most drying was done mechanically. Presently, beach drying of *Chondrus* is done wherever possible to save energy costs.

The commonly used hand rake is made of tempered steel with closely-spaced triangular tines about 15 cm in length on a 39 cm rake head. The handle (3-4 m) is fastened at approximately 45° so that the raking face will lie flat on the bottom when extended forward. In shallow water, the harvesters may rake standing in the water.

The seaweed is usually harvested for a four-hour period with an average yield of 455 kg wet weight (Patell, 1972). Marine Colloids Division of FMC (Rockland, Maine) estimates the mechanical efficiency of the rake to be about 67 percent. These determinations were made by quantifying the remaining seaweed biomass in experimental areas after they had been raked.

Harvesting *Chondrus* by raking supposedly removes primarily the larger, older, upright blades—leaving the holdfasts and smaller blades to continue growth for subsequent harvests. In certain areas drag rakes are employed (figure 33). One type has baskets on the front and back to catch the plants. These are much heavier than the hand rakes and not only scour or scrape the bottom, but remove holdfasts on 31 percent of the harvested plants. Hand raking removes about 5.6 percent plants with holdfasts (Environment Canada, 1976). As a result, basket drag raking has been banned in Canada. Furthermore, a preliminary study (Pringle, 1979) indicates that drag raking removes 2,000 mm^2 holdfast/kg of *Chondrus* harvested, while it takes two years for *Chondrus* to attain a holdfast size of 4 mm^2.

Use of the drag-rake method has also stimulated complaints from the lucrative lobster fishery. *Chondrus* beds provide a natural habitat for lobsters, and even though the animals are highly mobile, it is known that the rakes impale a portion of the shallow-

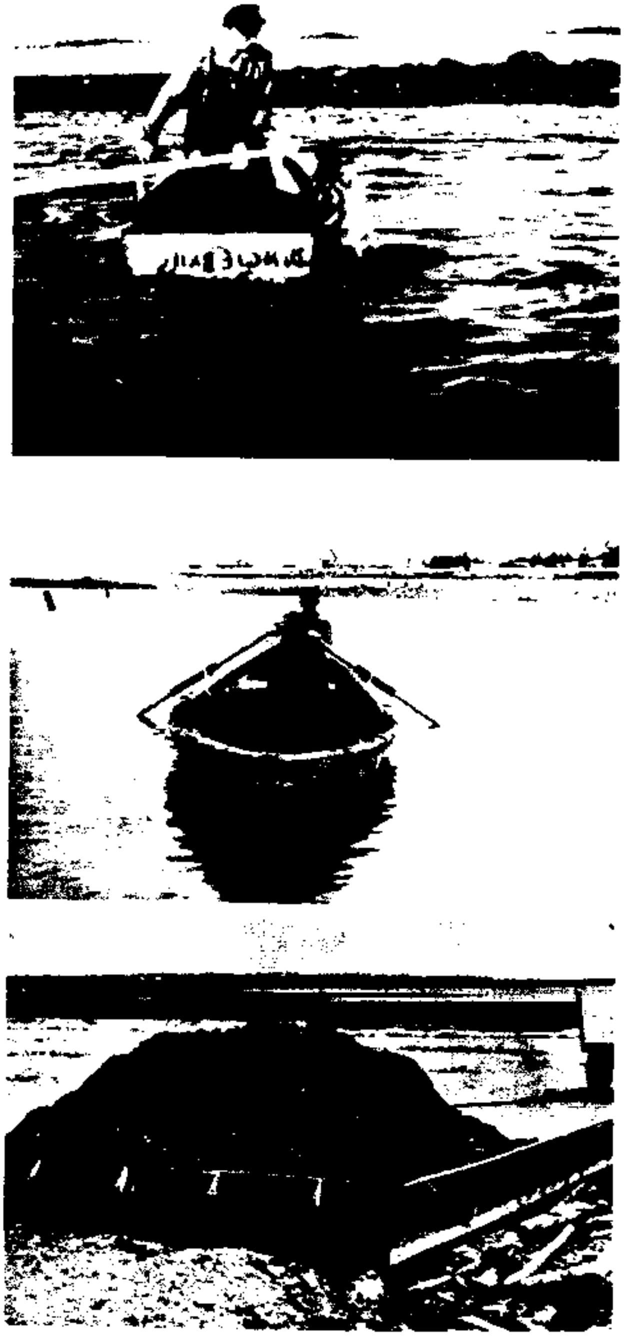

Figure 32. *Chondrus crispus* harvesting in Nova Scotia, Canada: (a) hand raking, (b) transporting harvested *Chondrus* in 1950, (c) seaweed on a drying platform (rows of bleached *Chondrus* in background). (Courtesy of C. MacFarlane)

water population. Drag rakes may kill an estimated 1-6 percent of the "exposed" lobster population in shallow waters, and the toll is taken mainly from the 7.6-10.0 cm size class (Scarratt, 1971).

Inevitably, the next step in the industrialization of *Chondrus* harvesting was the mechanical harvester. Several harvesters have evolved to the field-testing stage. Marine Colloids (Neish, I. C., pers. comm.) invested a substantial amount of time and money into a diver-operated unit. The harvester is pushed or pulled along by a diver. The rotary cutting head, powered by a 3 hp hydraulic motor, is approximately 30 cm wide with a cutting blade similar to that of a rotary lawnmower. There are four lines to the surface: the eductor hose, two hydraulic lines, and the diver's air hose. The cut algae are sucked to the surface via the eductor hose. The power plant for the total unit is a 30 hp engine.

Even though the harvester proved to be effective in the field-testing stage, an economic assessment showed that relatively industrious hand rakers could harvest more *Chondrus* per day and could work unhampered during a greater variety of sea conditions. The greatest economic drawback of the mechanical harvester is that it requires a team of trained divers. The outcome is that while the unit operated fairly well mechanically, it is presently "in storage."

Another harvester was developed by Resources Development Corp. (Bath, Maine). This is an air-lift unit for collecting drift algae. The device pumps loose *Chondrus* out of holes where it collects. Such holes have been known to contain 2,250 to 22,700 kg (wet weight) of fair quality *Chondrus*. A diver moves the hose around the sea bottom like a vacuum cleaner, and water and algae rush to the surface and onto a sorting table. The major economic obstacles were the high cost of divers and crew in relation to the low unit price for the algae.

Other mechanical harvesters have been developed: for example, by Marine Plants Experimental Station, Miminegash Harbor, for the flat-bottom conditions characteristic of the Prince Edward Island (Canada) *Chondrus* beds; and by Sea Harvest Inc., New York. Both are diver-operated.

Until a significantly higher price for *Chondrus* is assured, prospects for an economically feasible mechanical harvester are poor. One assessment is optimistic regarding further refinement of the harvester developed to collect drift algae and also of an improved hand-operated rake (Patell, 1972).

Management practices for *Chondrus*, *Gigartina*, and *Furcellaria* in the Atlantic United States and Canadian waters were poorly defined, and harvesting was virtually unregulated until 1974, when formal regulations were drafted (Pringle, 1976). At that time *Chondrus* harvests ranked second (at 12.84%) in total weight of marine organisms landed in eastern Canadian provinces, and ranked fifth (at 5.16% of total) in value (Pringle, 1976). Through the persistent efforts of Constance MacFarlane and many others, management practices and harvesting regulations have been formalized for the Canadian provinces through the Fisheries Act, Atlantic Coast Marine Plant Regulations (P.C. 1976-2316 as amended by P.C./C.P. 1977-1974; 1977-2635; 1978-3462) (Fisheries & Environ. Canada, 1978). These regulations apply to harvesting of *attached* algae from all Atlantic Coast provinces.

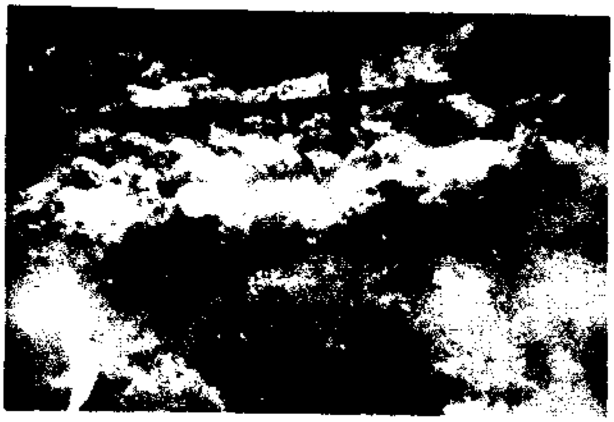

Figure 33. Drag rake harvesting of *Chondrus* in Canada (1960) (Courtesy of C. MacFarlane)

The harvesting of red algae requires a license, and the season, method, and gear are specified in some areas. Depending upon the harvesting district, the *Chondrus* harvesting season begins June 6 - July 15 and ends November 1. Drag rakes cannot be used in certain parts of Prince Edward Island because of the friable nature of the sandstone substratum. Basket drag rakes are also banned from areas of P.E.I. and Nova Scotia because of the deleterious effect on both substratum and lobsters. In one harvesting district, the distance between the tines of hand rakes must be greater than 5 mm to decrease removal of the small plants and holdfasts. A rake with more closely spaced tines acts more like a hoe and scours the substratum. In addition, development of cutting-type mechanical harvesters is not recommended (MacFarlane 1968b).

Harvesting carrageenophytes from eastern United States and Canadian waters will likely always use traditional means to some extent, as it is a part-time occupation for lobster fishermen and others. Similarly, populations of *Gelidium*, *Gracilaria*, *Eucheuma*, *Furcellaria*, *Hypnea*, and numerous other taxa will continue to be harvested around the world as long as it is economically feasible. The resources will remain viable if management programs such as the Japanese *Gelidium* program become well established. Without such management, resources will be overharvested, resulting in unstable crops and unit prices. However, new prospects lie ahead for *Chondrus*, *Gracilaria*, *Gelidium*, and *Eucheuma* with the advent of pond- and sea-based mariculture.

Habitat Manipulation

The first efforts to increase wild seaweed harvest involved manipulating natural habitats to favor the desired species. In this way existing algal beds could be expanded and new ones created where no suitable substrate was available. Common means of habitat manipulation involved weeding rocks of undesirable species, placing concrete boulders on the sea floor, breaking up and exposing rock with explosives, and cementing over existing rocks (Kurogi, 1963). Most important, totally artificial substrates could be introduced at the desired location, tidal level, and season.

Several red algae have been cultivated using these methods. The "limu gardens" kept for Hawaiian royalty are examples of seaweed cultivation by weeding out undesirable species. The placement of rocky sub-

Figure 34. Japanese woodcut prints (by Masanobu Kano) depicting original nori cultivation techniques: (a) preparing and (b) planting brush as a substratum for *Porphyra* spores (Kode, 1877; reproduced in Smith, 1904).

strates at specific depths is still the basis of *Gloiopeltis* (funori) cultivation in Japan, although spore suspensions are artificially provided to establish the plants. *Gloiopeltis* only occurs in a narrow tidal level range, and thus its habitat may be considerably extended by filling in low crevices with boulders to create a large flat shelf at the appropriate level (Chapman, 1970). Similarly, in the tropics, substrate has been provided for growth of *Gracilaria* and *Eucheuma* by spreading dead coral over barren sandy bottom areas (Neish, 1976b). Concreting of rocks has been used in the cultivation of certain types of amanori (*Porphyra*).

Artificial Substrates for *Porphyra*

Growth on artificial substrates is the basis of the nori (*Porphyra*) industry in Japan and Korea; this industry is the most highly evolved example of habitat manipulation in seaweed culture and certainly exceeds most forms of terrestrial agriculture in its complexity.

In the early 1700s, *Porphyra* harvests began to decline at the Sumidagawa River mouth because of changing sea-floor conditions. As a result, methods were developed to provide it with substrate where it otherwise could not grow.

The earliest means of providing habitat consisted of affixing bundles of oak brushwood or bamboo—called 'hibi'— to the muddy sea bottom in shallow bays and estuaries (figure 34). These bundles were assembled onshore and transported to the growing area by boat. A wooden tool with long handles was used to force a hole into the mud where the hibi was then placed in 10 to 15 feet of water. The hibi was set out in autumn, and a coating of diatoms developed on the bundles soon after. This diatom film helped to "catch" *Porphyra* spores floating in the water column.

Although the above culture methods are still used in Korea, in the past two decades Japanese growers have largely replaced brushwood with other substrate materials. These include blinds made of split bamboo bound with rope or, more commonly, nets. Hibi nets are made of hemp palm, coconut palm, or synthetic fibers woven into twine approximately 3 mm diameter. The net is knotted to form a 15 by 15 cm mesh, and is usually 18 or 36 m by 1 to 2 m in overall dimension. The various net materials differ in drying characteristics and other aspects; factors such as presence of silt or fouling algae are considered in determining the suitable net for a given area (Miura, 1975a).

The hibi nets are supported by poles or by a floating frame system moored with anchor ropes. The specific method depends on tidal range, current, and bottom conditions. The pole system consists of affixing the nets to bamboo poles at a specific unchanging level (fixed type) or with floats attached so that the nets move up and down with the tides (lift type). The floating system can be used in deeper water (e.g., more than 10 m).

By this method, the nori nets float on the surface at all times, supported by buoyed ropes moored on the sea bottom (figure 35). These methods have considerably enlarged the range of growing areas. The floating net system described above has allowed nori farming in areas of small tidal range (30 to 40 cm) as well as deep water (40 to 50 m).

Traditionally, nori nets are outplanted in autumn at a level that allows exposure 4 to 4.5 hours/day. Initially, several nets are placed on top of one another in the seeding area, which is usually an area of high salinity. The time of month is considered to be crucial, as noted by Kurogi (1963): "Hibi spread on the second to fourth day after the first or fifteenth of the lunar month catch the largest number of spores." Several species of *Porphyra* result from this natural net sporulation, the most common being *P. tenera*.

After a month, young plants are evident, and the nets are separated. At this point they may be transplanted to an area of lower salinity to mature; for example, near a river mouth where nutrients are plentiful. The nets are maintained at approximately the same level as at seeding. In another two weeks, the plants are 15 to 29 cm in length, and harvest begins. This early harvest is prized as the most choice amanori, although several successive harvests are made until March, when the nets are picked clean.

During the growing season, the nori habitat is further manipulated in many ways. The nets may be raised or lowered to optimize temperature conditions or control outbreaks of *Porphyra* diseases. The beds may be fertilized by using ceramic pots containing slow-release fertilizer pellets or by spraying. Fertilization may be carried out during the growing season or just prior to harvest to insure good color in the crop (MacFarlane, 1968b).

"*Conchocelis*" Cultivation

Prior to the early 1950s, *Porphyra* cultivation on nets depended almost solely on spores naturally present in the water column. This often resulted in variable spore cover on the nets, as well as yielding a mixed harvest, which often included less choice species. Some advantage was taken of the accessory reproduction of *Porphyra* thalli to alleviate this problem. Fresh nets were placed over existing ones bearing young thalli to catch any asexual spores. However, it was Kathleen Drew Baker's discovery of the shell-boring "*Conchocelis*" stage of *Porphyra* in 1949 that led to major breakthroughs in improving nori cultivation (figure 36).

Foremost of these breakthroughs was the development of a dependable supply of spores for net seeding in autumn. Once "*Conchocelis*" was recognized as the source of *Porphyra* spores, methods were developed to culture it in tanks during the summer months. Today, this is done in the regional fishery experiment stations or by fishermen in their homes (Kurogi, 1963).

"*Conchocelis*" cultivation begins in March or April when *Porphyra* carpospores are available, and seawater temperatures have risen above 10°C. *Porphyra yezoensis* is most commonly used. Oyster or scallop shells are spread over the bottom of shallow tanks containing seawater. A suspension of carpospores, obtained by release from fertile *Porphyra* thalli or filtration of pulverized *Porphyra* fronds, is introduced into the tanks. Following spore settlement, the shells are transferred to larger tanks, where the "*Conchocelis*" filaments are allowed to grow through the summer months.

Conchospore release begins in the autumn and lasts through December. During this time the hibi nets are seeded by one of two methods. Ocean seeding is accomplished by placing the "*Conchocelis*" shells in bags or nets around the layered nets at the growing areas, where conchospores are released and attach to the hibi. Alternately, the hibi nets may be placed in the "*Conchocelis*" culture tanks, where spore dispersal and settlement on the nets is enhanced by agitation of the water or the nets.

Several hours after conchospore seeding, the nets are spread in the sea in layers of up to 50 nets. When spore attachment is certain, the seeded nets are separated. Cultivation proceeds as for naturally seeded nets. Today a portion of the one-month-old "nursery nets" are transferred to cold storage and maintained at -6 to -30°C. The juvenile thalli on these nets remain viable for several months and are kept as

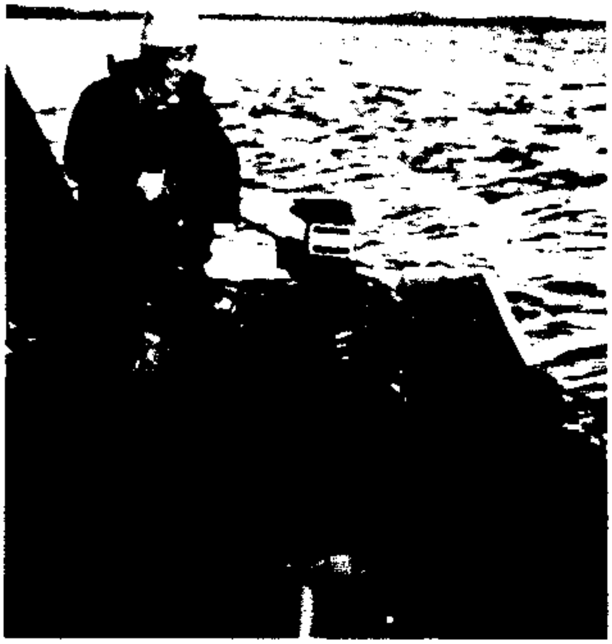

Figure 35. Harvesting nori from floating nets in Japan. (Courtesy of T. F. Mumford)

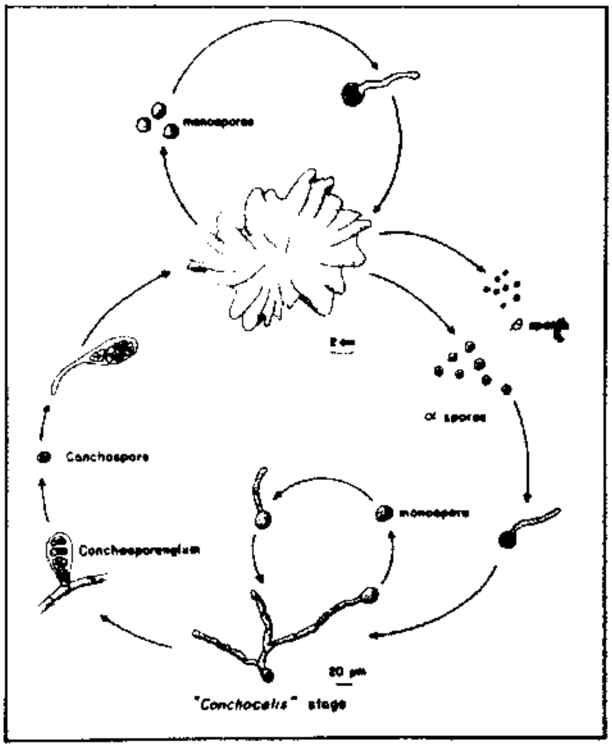

Figure 36. *Porphyra* life history

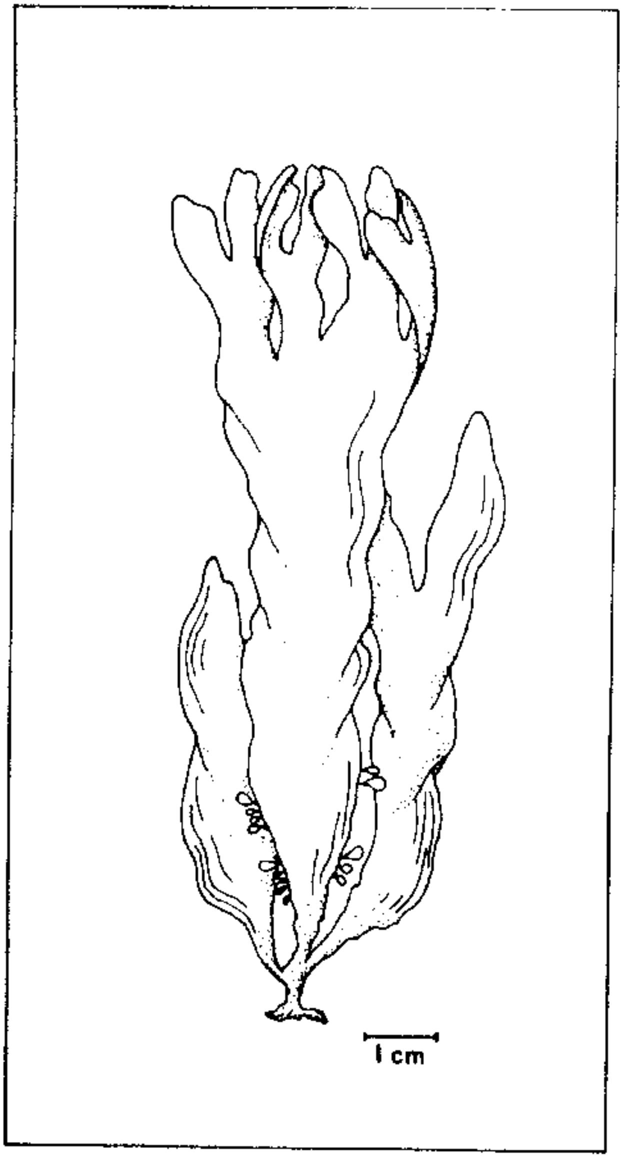

Figure 37. *Palmaria palmata* (L.) O. Küntze

a reserve for outplanting in case the season's crop is damaged by pathogens or bad weather.

Artificial sporulation from cultured "*Conchocelis*" insures a heavy spore set. In addition, manipulation of the "*Conchocelis*" culture environment (temperature, photoperiod) induces spore release earlier than in nature, lengthening the nori growing season and increasing annual production. Perhaps the most important long-term result of *Porphyra* cultivation will be selection of new desirable strains. Already *Porphyra* growers have selected a high-yield strain of *P. yezoensis* from cultured "*Conchocelis*."

In recent years, methods have been developed for cultivation of nori in totally artificial environments onshore. The "*Conchocelis*" is grown in freeliving culture, and monospores are allowed to germinate on nylon string or a fibrous substratum. After 20 or more days of "string culture," the young *Porphyra* fronds are removed to grow in agitated tanks. *Porphyra* cultivated in the above system grows as rapidly as in nature, and manipulation of the system could step up growth rates even higher (Imada et al., 1971).

Currently, much of the coastal nori farming areas in Japan are jeopardized by pollution. Onshore cultivation provides one solution to this problem, especially when it is based on totally synthetic seawater. The large-scale industrialization of artificial culture is currently held back by the cost of electricity (Imada et al., 1971), and limited land availablity will certainly be a hindrance in the future. Some farming of specific strains of nori may occur far removed from Japan's seas. However, commercial *Porphyra* agronomy in Japan represents the highest technological level to date in red algal mariculture. It is certain that this culturally based seaweed industry will overcome pollution-induced cultivation difficulties through technological advances or socio-political pressure.

Live Storage of Wild Stock

Methods for prolonged live storage of wild seaweed stock have been developed only in the past decade. These research efforts have been centered in the northeastern United States and eastern Canada, where holding of *Palmaria palmata* (= *Rhodymenia palmata* or dulse) harvests prior to processing became desirable (figure 37). Today, the majority of dulse is eaten in Britain and Canada. It is commonly eaten with fish and in puddings, baked in bread, used like a chewing tobacco, and eaten as a snack in taverns.

It is estimated that the dulse harvest could be doubled if drying and packaging procedures were improved (Chenard, 1971). Wet summer weather often ruins crops during the drying process. In addition, a significant standing crop of dulse is left untapped in autumn when uncertain weather conditions preclude low-tide harvests.

Development of mechanical dehydrators, one solution to the problems, has been a special challenge. Unlike seaweed harvests prepared for extraction of phycocolloids (e.g., *Chondrus, Gelidium*), *Palmaria* must retain its palatable qualities to remain marketable. Unfortunately, improperly dried dulse rapidly loses its flavor, and poor packaging renders much of the commercially available product soggy and gummy by the time it reaches the consumer (*Ibid.*).

Several dehydrators have been tested by the industry, and Applied Marine Research, Ltd. tested the range of available drying devices in 1975. It was concluded that a belt-type drier produced an acceptable product, but that annual dulse production would have to be stepped up by other means to make dehydrating economically feasible (Applied Marine Research, 1975).

Live storage of dulse harvests has also shown promise as a means to increase annual production. Impounding the fresh harvest offers several advantages. In areas where plants are dried in the open air, the harvest can be accumulated and stored between good drying periods (i.e., favorable weather conditions). Where harvests are dried artificially with dehydrators, holding facilities provide a different benefit. The dulse harvest is limited to very low tides in the spring and summer, resulting in intermittent and heavy loads on the dehydration and processing facilities. Impounding the crop allows increased control and efficiency in processing plants.

Traditionally, dulse harvests are stored in net bags, where they will remain in good condition for three to five days. In the early 1970s Atlantic Mariculture, a division of Marine Colloids, Inc., initiated research on impoundment of Canadian dulse harvests for more prolonged periods. The plants are kept in tanks specifically designed to promote as much water movement as possible. Air lines running along the apex of a V-shaped tank bottom keep the plants in constant motion, promoting nutrient exchange and light penetration (Neish, 1972).

Using this method, *Palmaria* harvests may be stored for a few days to several months. Following a low-tide harvest, the plants are cleaned of dirt, invertebrates, and epiphytes and placed in the tanks at the appropriate densities.

Although these methods were developed for mere storage of wild seaweed harvests, a secondary benefit was realized which is far more significant to the red seaweed industry: when held in these tanks, the plants grow. *Palmaria* has shown more than 60 g dry weight/m^2 tank surface/day yields in tanks stocked with 10 kg fresh weight/m^2 (Neish, 1976a). *Chondrus* has also been successfully maintained in a similar system (Neish, A.C. and Shacklock, 1971).

Impoundment experiments have now been conducted on several other commercially important seaweeds. In 1975, month-long impoundment trials were carried out in September and June with four seaweeds, including the red algae *Palmaria palmata* and *Porphyra umbilicalis* (Sharp and Neish, 1976). The holding system consisted of a plastic-lined, 12-section plywood tank 15 m long, 2.5 m wide, and 1.2 m deep. A 5 cm pipe lying on the V-shaped bottom supplied air to continuously agitate the plants. The seawater turned over three times per day and was fertilized once a week with ammonium nitrate.

The *Palmaria* and *Porphyra* both showed good growth in the summer trial, while autumn-stocked crops showed a weight loss. *Porphyra* gained weight up to 15 percent per day in the 5-week summer trial, and all species tested were maintained successfully for 4 to 5 weeks with negligible deterioration for holding purposes. Stocking density and season during which stock is obtained were important factors in controlling epiphytism. The red algae tested appeared to be the best candidates for impoundment using these methods, as the kelps are too bulky for tumble tanks, and the green algae tend to fragment when agitated (Sharp and Neish, 1976).

Today, the only commercial impoundment of seaweed harvests is carried out with dulse crops on Grand Manan Island, New Brunswick. Results of the experiments described above indicate that *Porphyra* harvests could also be successfully held in tanks, although no commercial harvest of *Porphyra* currently takes place in the eastern United States or Canada. In general, live storage of seaweed harvests is a requirement peculiar to crops that must remain as fresh as possible or for which drying and processing are inefficient.

Presently, there is a ready market for increased dulse production, but costly large-scale impoundment and dehydration facilities are not feasible now because of low-level harvesting. It is more likely that the unique system of "tumble culture" will find a future in mariculture of other commercially important red seaweeds.

Vegetative Propagation

Red algal mariculture has made prominent advances recently, through the development of vegetative propagation. Impetus for this development has its roots in the expanding phycocolloid industries. In the last decade uses for phycocolloids have been escalating and diversifying into highly specific applications. With specificity comes the requirement for higher and more stable quality in seaweed crops, brought about by controlled cultivation.

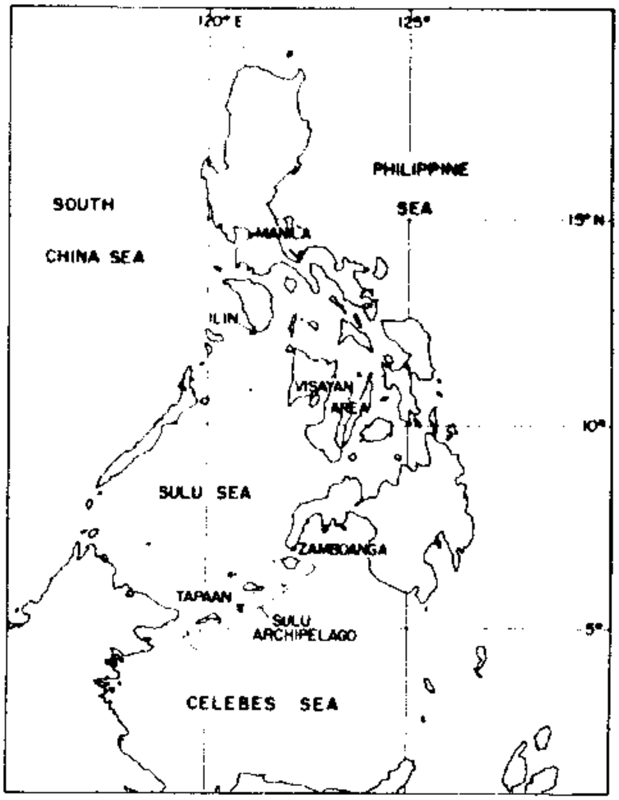

Figure 38. Map of the Philippine Archipelago.

Some species of red algae have an apparent boundless affinity for vegetative propagation. They can be grown detached from the holdfast from "cuttings," either freefloating in enclosures or secured to an artificial substratum at sea. The most prominent examples of successful mariculture of this type involve the genera *Eucheuma*, *Chondrus*, and *Gracilaria*. Cultivation of all three genera has undergone recent development for phycocolloids, and the *Gracilaria*, additionally, for use as a food crop.

In Open Ocean: *Eucheuma*

Eucheuma mariculture made its debut in the Philippine Archipelago (figure 38). Prior to mariculture, *Eucheuma* had been harvested sporadically throughout the area with either no management or "common-sense" management (pick some, leave some) and was controlled by the weather: no harvesting or drying took place during the typhoon season (Doty, 1973). Crops characteristically underwent boom-and-bust cycles with radical price fluctuations. Stabilization and predictability of the unique *Eucheuma* crops are of prime significance to the phycocolloid industry.

Like *Hypnea* and *Furcellaria*, *Eucheuma* species have the inherent property of producing either kappa

Table 5

The Better-Known Carrageenan-Containing *Eucheuma* Species Used Commercially

Kappa Carrageenan **("*cottonii*" types)**	**Iota Carrageenan** **("*spinosum*" types)**
E. cottonii (= *E. okamurae*)	*E. spinosum* (= *E. muricatum*) (= *E. denticulatum*)
E. striatum (= *E. nudum*) (= *E. edule*)	*E. isiforme* (= *E. acanthocladum*)
E. procrusteanum	*E. unicinatum* (= *E. johnstonii*)
E. speciosum	

The scientific names in parentheses are probable synonyms of those under which they are indented (Doty, 1973)

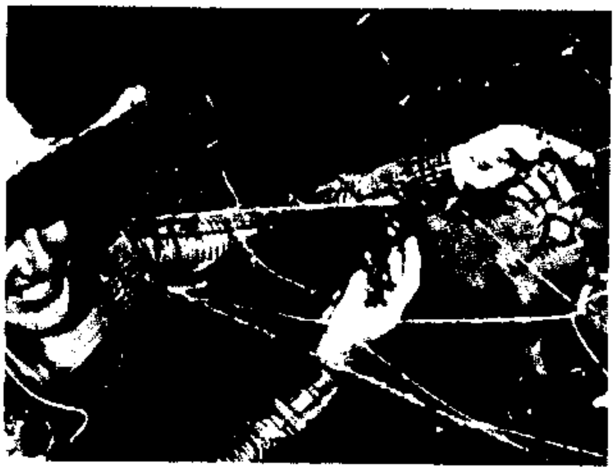

Figure 39. M. S. Doty (Univ. of Hawaii) at a *Eucheuma striatum* farm in the Philippines. Each stocking thallus shown weighs 50-100 grams.

or iota carrageenan in both life history stages. Both carrageenan types are highly valued by industry for their different gelling properties. Other carrageenophytes available in commercial quantities synthesize kappa and lambda (viscous) carrageenans in different life history stages (gametangial and sporangial, respectively). These must be morphologically or chemically separated to obtain the "pure" colloid of choice (McCandless, 1978).

Since 1958, Maxwell S. Doty and others had been interested in the productivity of *Eucheuma* (figure 39). The practical application of *Eucheuma* came to Doty's attention when a political collapse in Indonesia led to a cut-off in *Eucheuma* supply to the United States. This political mishap led Marine Colloids of FMC (Rockland, Maine) to initiate farsightedly a marine agronomy program for *Eucheuma* in Southeast Asia.

Recognition of the mariculture potential for Philippine *Eucheuma* species eventually led to a consortium of efforts by the University of Hawaii, Marine Colloids, Inc. (Philippines), and the Philippine Bureau of Fisheries and Aquatic Resources (BFAR). The consortium directed its efforts towards *Eucheuma* research and ultimate development for the various species. Principal financial support was initially provided by Marine Colloids, Inc. and later by the U.S. Sea Grant Program, NOAA (Doty, 1973). The consortium initiated research on *Eucheuma* in 1967 near Zamboanga, Philippines.

From a commercial viewpoint, the genus *Eucheuma* may be divided into two distinct groups: species that produce kappa carrageenans and those that produce iota carrageenans ("*cottonii*" and "*spinosum*" types of commerce, respectively, figure 40). Experiments were carried out on one species selected from each carrageenophyte group (table 5), *E. striatum* and *E. spinosum*, to develop information of agronomic value. Parallel work was undertaken on different physical techniques for possible use in farming. Experimental results revealed that the brighter the light, the faster *Eucheuma* grows; any dessication is detrimental, and variations in seawater temperature normally anticipated in fully marine conditions in the Philippines seem to be of little significance (Doty, 1973).

In growth experiments, the *Eucheuma* planting or "seed" material consisted of vegetative fragments of the thalli. These cuttings have been broadcast on favorable sea-bottom areas, lashed to stones, semiconfined in open baskets, or tied to stakes, nets, and lines at different constant distances from the sea bottom, or suspended below the surface on floating systems. The last two techniques are referred to as constant-level or constant-depth plantings or farms (Doty, 1973). Bottom plantings suffered from grazing to a varying degree, and mariculture efforts were focused on above-bottom plantings. However, bottom plantings of *Eucheuma* are used extensively along the east coast of Hainan Island, China, where they cover 500 hectares (Tseng, unpublished interview, 1978).

Successful *Eucheuma* mariculture resulting from the Philippine experimental farms was developed through the consortium's efforts and funds during 1967-1970. Eventually, privately-owned farms for *E. striatum* were established on the northern Sulu Sea and in the Sulu Archipelago. In the latter area, where storms are rare, the farms produced well (figure 41).

Constant-level plantings were positioned just below low-tide level and at least 0.5 m off the bottom. Nylon monofilament nets (80 lb test) were used, and "fist-sized" *Eucheuma* fragments were lashed at the mesh intersections by a 1 cm x 30 cm soft polyethylene strap (figure 42). The net system used was much like the hibi nets used for cultivating *Porphyra* in Japan. Farming modules were developed to hold 200 nets, and four such 2,500 m^2 modules comprised a 1 hectare (= 2.5 acre) farm, which could be managed by an enterprising family (Doty, 1973). *E. striatum* growth rates averaged from 1.5 to 5.5%/day. When thalli were harvested, 50-200 g (wet weight) of each plant was left as "seed" material. Reports on production ranged from 10 to 30 tons dry wt/ha/yr (Dry weight assumes approximately 45 percent water.) (Neish, I.C., pers. comm., 1980).

The experimental *Eucheuma* plots were expanded into pilot farms in 1971, and eventually Marine Colloids began instructing Philippine workers in standard cultivation procedures in 1971-1972. By mid-1972 it was concluded by the consortium of research interests that *Eucheuma* mariculture could be profitable for Filipino families (Parker, 1974). The training of farmers to manage their own *Eucheuma* farms consisted of assistance with site selection, demonstration of cultivation techniques, provision of continuing scientific and practical research results, and the guarantee to buy all *Eucheuma* produced by farming families (*Ibid.*).

Eucheuma farming is a labor-intensive operation. Efficient and regular maintenance is the key to high productivity (figure 43). Parker (1974) outlines the four basic processes involved: (1) weeding (i.e., removal of epiphytes by brushing the nets with a scouring pad and picking epiphytes off the growing *Eucheuma* plants), (2) careful observation of the plants, which involves harvesting of slow-growing or unhealthy seedlings and substituting with a better strain, (3) repair of the nets and moorings and cropping of eelgrass around the farm, and (4) control of predators, primarily sea urchins.

Periodically, the farmer harvests the crop—the most satisfying aspect of farming. When the plants attain an average size of 800 g (about 2 months after planting) they are pruned back to 200 g again. To harvest, the farmer breaks off the *Eucheuma* branchlets and loads them onto a canoe or raft to be air-dried on shore (Parker, 1974).

By 1974, following nine years of persistent research and development by the original consortium and innumerable farmers, *Eucheuma* farming had proliferated rapidly and had become an accepted livelihood for local Filipinos. The 1973 farm harvest of *E.* "*cottonii*" was about 500 tons (dry); in 1974 the harvest skyrocketed to over 10,000 tons. This boom in production was accompanied by 40 percent of the harvest remaining in storage at source while the price of the dried seaweed plummeted from U.S. $0.40/kg to U.S. $0.04/kg. A slow recovery followed; however, farming methodology evolved rapidly.

A new cultivation system utilizing monolines was developed and is now used by 99 percent of the *Eucheuma* farmers (figure 44). Monofilament lines are commonly 150-180 lb test and 10 m in length, with about 50 cuttings/line (Ricohermoso and Deveau, 1979). Further progress involved disease prevention. Crop losses due to disease were nearly overcome when successful strain selection programs produced a rapidly growing, disease-resistant type, the Tambalang strain (Doty and Alvarez, 1975).

Farming of iota carrageenophytes, *E.* "*spinosum*" of the trade, also underwent significant expansion. Development in 1977 produced some company farms dedicated to improving crop production and farming technology through fertilizer use, increased planting density, improved cultivation techniques, pest and disease control, and containment of fragmenting plants. This latter problem can account for as much as 30 percent of crop loss.

Through such mariculture improvements, a goal of supplying 50 percent of the world carrageenophyte market with high-quality seaweed was envisioned (Richohermoso and Deveau, 1979). Could such successful seaweed mariculture have been introduced in Europe or North America in this same decade? Most likely not. Farming of from 1.5 to 3.0 kg of algae/man-hour in the Philippines is economically rewarding, for it interferes little with the normal subsistence efforts of the farmers. This is especially true in countries where the family income of the local people is about $50.00/year (Doty, 1977a).

But, at the same time, can the industries of importing nations afford to subsidize mariculture development in areas with radically fluctuating political and socioeconomic conditions? After all, *Eucheuma* farming developed out of a political collapse in Indonesia. The danger of seaweed production monopolies and unpredictable cutoffs in source material has led to *Eucheuma* farming attempts or plans for farming in

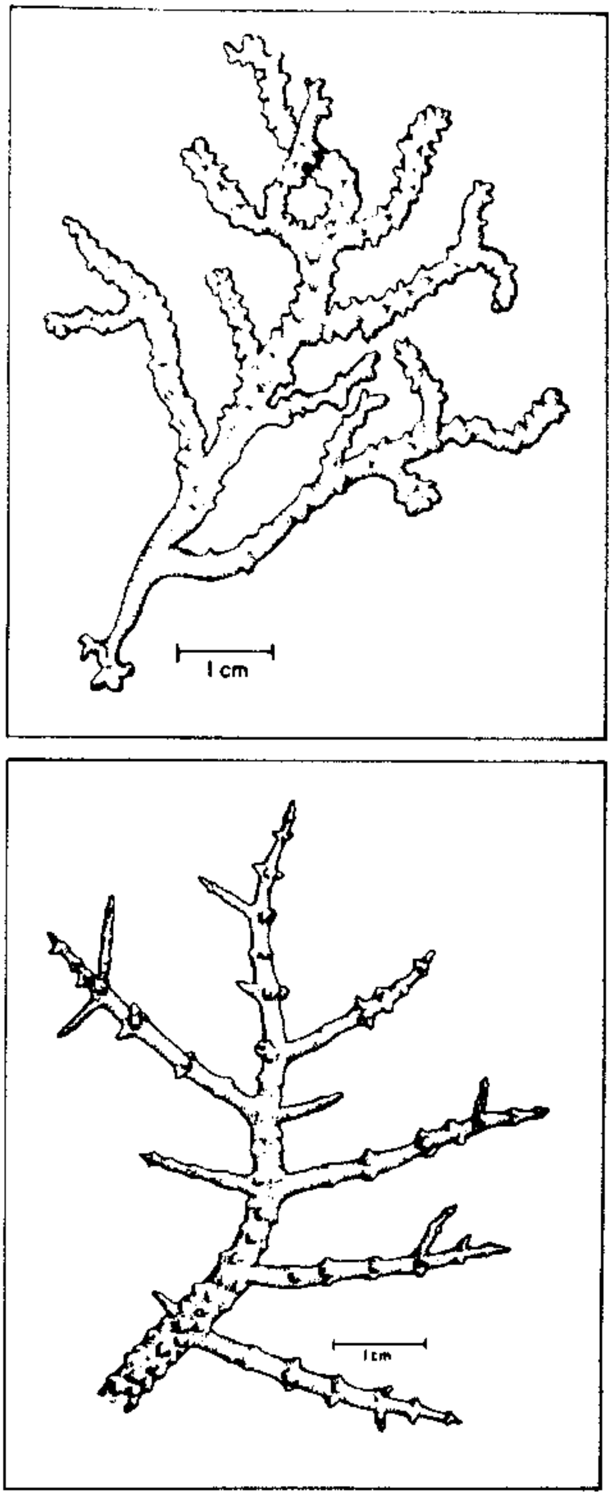

Figure 40. *Eucheuma striatum* ("cottonii" of commerce) (a); *E. spinosum* (b) (Doty, 1973).

Figure 41. *Eucheuma* farm in the Philippines. (Courtesy of I. C. Neish)

Figure 42. Monoline cultivation of *Eucheuma* in the Philippines. (Courtesy of I. C. Neish)

Figure 43. *Eucheuma* farm maintenance in the Philippines. (Courtesy of I. C. Neish)

several new areas: Society Islands, the Line and Gilbert Islands, Micronesia, Guam, both Samoas, the Hawaiian Islands, and Sabah, Malaysia (Doty, 1977a, 1977b). As the need for carageenans increases, it is hoped that *Eucheuma* will come from some of these islands as well as from Southeast Asia.

Recognizing the requirement for less time-consuming and tedious cultivation methods for profitable mariculture in the Western world, Doty experimented with new *Eucheuma* cultivation methodology on his home grounds in Hawaii. This research was a "bird of a different feather," as *Eucheuma* is an introduced species to Hawaii. Thus, a considerable amount of research was required on the life history of the species and experimentation on its growth pattern and requirements in the cooler Hawaiian waters.

Culminating a major research effort, the results proved positive: the Tambalang strain of *Eucheuma*, a kappa-carrageenan producer, grew extraordinarily well in "lawn," "hollow," and "pen" plantings off Oahu Island. All of these plantings could be mechanically harvested (Doty, 1977b). The strain grew so well, in fact, that an environmentalist outcry resulted over the concern that unconfined *Eucheuma* would deleteriously affect native marine species. However, it was quickly demonstrated that the unconfined thalli died when they were washed over the reef into deeper water (Doty, 1977b).

Subsequently, the *Eucheuma* strain has been employed on a small scale as a nutrient scrubber in a Hawaiian animal mariculture system (Glasgow, J., pers. comm., 1979). Newly designed experiments (Doty and Marine Colloids, Div. of FMC Corp., pers. comm.) are presently under way at these same facilities in Hawaii. Other attempts at experimental mariculture of the genus have been carried out in Florida by Dawes (1974), and Marine Colloids (unpublished).

Development of *Eucheuma* mariculture spans barely more than a decade, yet major scientific strides have been made despite socio-economic and political uncertainties both abroad and on home ground. The entire story of *Eucheuma* development should be carefully studied, as it contains both pitfalls and promises for the future of seaweed mariculture. The inherent achievements and problems that surfaced during the cultivation attempts will certainly provide a model for future endeavors in the vegetative propagation of red algae.

In Enclosed Systems: *Chondrus crispus* and *Gracilaria*

An alternative strategy for vegetative propagation of red algae has evolved with the use of enclosed systems (e.g., an excavation on land, a diked area in the sea, or a floating enclosure). Although the techniques are not yet widely used commercially, a considerable amount of research effort has been devoted to the enclosed-system approach. Such systems are more flexible than open-ocean cultivation and therefore have a broad spectrum of objectives and applications.

Enclosed systems have been developed to cultivate edible algae, fodder, and selected species for industrial use. Other objectives are to cultivate algae as nutrient scrubbers in sewage effluent treatment and for recovery of valuable or hazardous effluent compounds. Commercial developers of polyculture systems are finally recognizing the virtues of integrating algae for the dual purpose of nutrient scrubbing and providing an additional cash crop.

Prominent examples of the enclosed system strategy for vegetative algal propagation feature *Chondrus crispus* and *Gracilaria*.

Chondrus has been commercially harvested from natural populations along the Atlantic coasts for nearly a century. As a result, extensive surveys of *Chondrus* populations have been carried out (e.g., MacFarlane, 1952; 1966; 1968a; Taylor, 1971), as have numerous studies regarding basic biology of the species. Most of these have been summarized by Harvey and McLachlan (1973). The resultant substantial backlog of information provided a springboard for launching an active program to develop *Chondrus* mariculture.

The strategy for vegetative propagation of *Chondrus* can be characterized as intensive rather than extensive, as described for Philippine *Eucheuma* mariculture. The Western world's economic structure does not permit extensive use of labor or shorefront space, and climate limits growing period. Thus cultivation techniques have developed through a large investment of capital for sophisticated technology and environmental control systems (Neish, 1976a). This approach ultimately involved a cooperative effort among colloid industries (Marine Colloids, GENU Products), research institutes, and government agencies of Canada (NRCC; NSRF) and the United States (National Sea Grant College Program, NOAA of the Dept. of Commerce).

Pioneering this work was the late A.C. Neish of the Atlantic Regional Laboratory, Nova Scotia (NRCC), who demonstrated in 1969-1970 that *Chondrus* could be vegetatively propagated in suspended culture (Neish and Fox, 1971; Neish and Shacklock, 1971; Shacklock, et al., 1973). A *Chondrus* strain selection program was an early component in these studies and produced the vigorous T4 isolate. The clone propagated from this plant grew from 4.5 g (May, 1970) to a total biomass of approximately one ton by September 1972 (Shacklock, et al., 1973). T4 grows continually and fragments spontaneously, instead of producing massively spherical plants. It has not been observed to regenerate holdfasts.

The vigorous T4 strain has been the focal point for further development of enclosed system mariculture. The results from many long-term experiments describe the optimum irradiance, photoperiod, temperature, pH, plant density, water movement, and nitrogen regimes for best growth and carrageenan yield of *Chondrus* T4 (Shacklock, et al., 1973; Shacklock, et al., 1975; Neish, et al., 1977; Simpson, et al., 1978; Simpson, et al., 1979; Neish and Knutson, 1979; Neish, I., 1979).

The resultant prescription for *Chondrus* growth in an enclosed system with flowing seawater is not static, but requires a state of flux. This requirement is due primarily to the interactions among thallus carrageenan and nitrogen and seawater nitrogen in the cultivating enclosures, known as the "Neish Effect" (Shacklock, et al., 1974). *Chondrus* growth is enhanced when the seawater is enriched with NO_3-N or NH_4-N, while there is a parallel drop in carrageenan level. This is a reversible relationship, and nitrogen levels can be manipulated to stimulate either high growth rates or high carrageenan yield. Additional basic physiological data regarding *Chondrus crispus*, summarized by Buggeln and Craigie (1973), has facilitated further refinement of the prescription for optimum *Chondrus* cultivation in enclosed systems.


Figure 44. *Eucheuma* crop on a monoline farm in the Philippines. (Courtesy of I. C. Neish)


Figure 45. V-shaped enclosure designed for *Chondrus* cultivation. (Courtesy of I. C. Neish)


Figure 46. *Chondrus* T4 cultivation in earthen enclosure using the paddlewheel technique at Marine Colloids Div. of FMC. (Courtesy of I. C. Neish)

A transition point in *Chondrus* mariculture, and ultimately in carrageenan processing, stemmed from the discovery that specific carrageenan type is associated with life history stage: gametangial stages yield kappa, whereas the tetrasporangial stage yields lambda carrageenan (Chen, et al., 1973; McCandless, et al., 1973). This association was later found to be true for all other species tested in the family Gigartinaceae (McCandless, 1978). Recently, it has been found that the kappa-carrageenan-producing *Chondrus* T4 clone is a male (Enright, C., pers. comm., 1980).

Figure 47. Weighing cultivated *Chondrus* T4 at Marine Colloids Div of FMC (Courtesy of I C Neish)

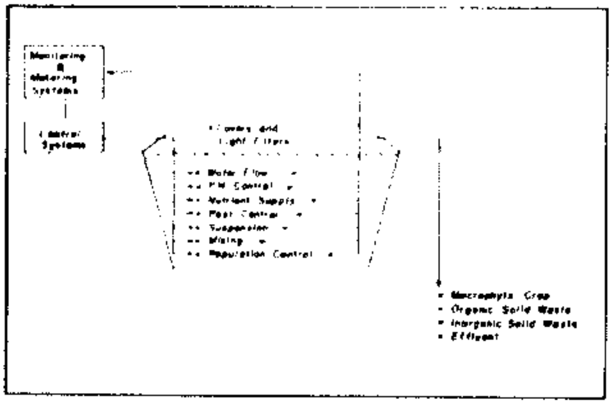

Figure 48. *Chondrus* cultivation in an enclosure system indicating factors that require precise control (Neish, 1979).

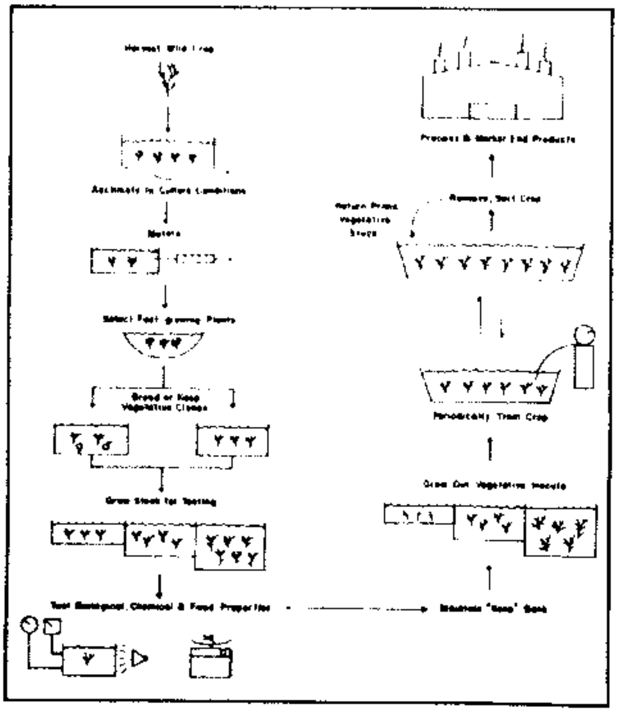

Figure 49. An approach to *Chondrus* selection and propagation for large-scale mariculture (Neish, 1979).

The accumulated scientific information directly pertinent to *Chondrus* agronomy provided industry with an optimistic outlook and a solid foundation to build large-scale *Chondrus* cultivation programs. Between 1973 and 1976 two East Coast Canadian firms, Marine Colloids, Ltd. and GENU Products Canada, Ltd., began development of enclosed system *Chondrus* mariculture. Neish (1976a) had projected that both companies would be cultivating *Chondrus* commercially by 1986. However, this projection has been at least temporally modified in light of the world's oil and energy situation.

In order for the energy- and capital-intensive *Chondrus* mariculture programs to continue at the current developmental pace, new energy sources must be found. Marine Colloids is exploring the feasibility of solar energy conversion (Neish, I.C., pers. comm., 1980). *Chondrus* mariculture at Marine Colloids has advanced to the pilot-farm stage (figures 45, 46, 47). *Chondrus* T4 and several other kappa-carrageenan-producing clones are being experimentally cultivated in eight 100 m^2 enclosures. GENU (Canada) and CECA (France) have similar, but smaller pilot cultivating programs in operation.

In order to attain such pilot-farm stages, a prodigious amount of experimentation is required, as exemplified by the research on *Chondrus crispus*, one of the world's most highly studied red algal species. Such studies identified the factors requiring the most precise control for *Chondrus* cultivation (figure 48) (Neish, I.C., 1979).

However, control in *Chondrus* cultivation is a final step down a precarious road of unknowns. Neish (1979) diagrams the complex selection process required to establish a species in enclosed-system mariculture (figure 49).

Despite the fact that vegetative propagation of *Chondrus* in enclosures has considerable potential and raises intriguing scientific questions, it remains in the pilot-farm stage. To date, the estimated cost of cultivating *Chondrus* in enclosures (based on Huguenin, 1976), exceeds costs for the major commercially-utilized carrageenophytes harvested from natural populations, such as *Chondrus crispus* (Canada), "Gigartina radula" (of the trade from Chile), and cultivated *Eucheuma* species (Philippines).

Unlike propagation of *Chondrus*, vegetative propagation of the agarophyte *Gracilaria* (figure 50) evolved quite rapidly, and in Taiwan the agarophyte is proving commercially successful. The reasons for success are: 1) agarophytes command a much higher market price than carrageenophytes, 2) labor costs are relatively low where *Gracilaria* is presently cultivated, and 3) *Gracilaria* is being integrated into existing mariculture facilities.

Until the early 1960s, *Gracilaria* made a relatively minor contribution to agar industries. Thereafter, use of several *Gracilaria* species surged, and the agarophyte presently accounts for a major portion of the commercial agarweed biomass. Additionally, *Gracilaria* species are important as food items in Micronesia, parts of Southeast Asia, and the Far East. Because *Gracilaria* species now form an important agarweed resource for industrial and food uses, and because of the adaptability of some species to enclosure cultivation, mariculture of this genus has blossomed.

Gracilaria cultivation in Taiwan was done on a very small scale between 1962-1970, but by 1971 it had become a widespread means of livelihood for farmers, as it now is in mainland China (Ryther, 1979a). This change was due to declining harvestable populations, a significant price increase for the dried seaweed, and improvements in culturing techniques.

Three species of *Gracilaria* are cultivated in Taiwan: *G. gigas*, *G. lichenoides*, and *G. compressa* and *G. confervoides*, the latter two species being synonomous with *G. verrucosa* (Hudson) Papenfuss (Ohmi, 1968). *G. verrucosa* is used most extensively because of its adaptability, high growth rate, and agar gel strength (Shang, 1976).

Gracilaria is vegetatively propagated in tidal enclosures formerly used for milkfish production. Shang (1976) describes the tidal ponds as generally one hectare in area. The water is 20-30 cm deep from March to June and 60-80 cm deep after June to compensate for seasonally high temperatures. The plants thrive in waters of about 25 ppt salinity and at temperatures between 20-25°C (Lin, 1970). For best *Gracilaria* growth, the following criteria should be considered (Chen, 1976):

1. Fresh water should be available for diluting seawater where evaporation causes increased salinity.
2. Wind should not move the plants from their fixed locations in the enclosures.
3. Sufficient tidal movement is necessary to facilitate exchange of pond water.
4. Pond substratum should be sandy loam.
5. Seawater pH should be between 6 and 9 (optimum = 8.2-8.7).

Typical *Gracilaria* cultivation, as described by Shang (1976), begins in April. About 5,000 g fresh weight/ha of *Gracilaria* "cuttings" are broadcast on the pond bottom and are held in place by a fishnet cover or by bamboo poles. Pond water is exchanged every two to three days to maintain proper salinity and to replenish nutrients. The crop is weeded at least three times a year. Milkfish and *Tilapia* are stocked in the same pond to graze on the blue-green and green algae that epiphytize *Gracilaria* at the rate of 300-400 fish/ha. However, the fish must be removed before they begin to eat the *Gracilaria*.

The ponds are fertilized with urea (3 kg/ha/wk), or fermented pig manure (120-180 kg/ha/2-3 days) (Edwards, 1977). The crop is harvested from June to November every ten days, washed and sun-dried; 7 kg of fresh *Gracilaria* equals about 1 kg dry weight. The plants grow very little between December and March, when temperatures fall below 8°C in Taiwan.

Gracilaria is also reared in polyculture with grass shrimp (*Panaeus monodon*) and crabs (*Scylla serrata*) to provide additional profits. Plant density is somewhat lower. Direct production cost of *Gracilaria* in such polyculture systems accounts for only about 11 percent of the total operating cost.

Estimates for financial returns of *Gracilaria* mariculture in Taiwan (Taiwan Fisheries Bureau, 1973; Chen, 1976) are based on the average annual production rate of 10 t (dry) *Gracilaria*/ha/yr for monoculture and 9 t/ha/yr for polyculture. The major operating costs for monoculture are in labor (58%) and seed stock (18%). Labor includes seeding, weeding, harvesting, drying, and management, all of which requires about 132 working days/ha/yr. In 1973 the yield gave an income of $2,750/ha, providing a 50 percent profit return. The annual profits for *Gracilaria* in polyculture are 1.7 times greater than those for monoculture.

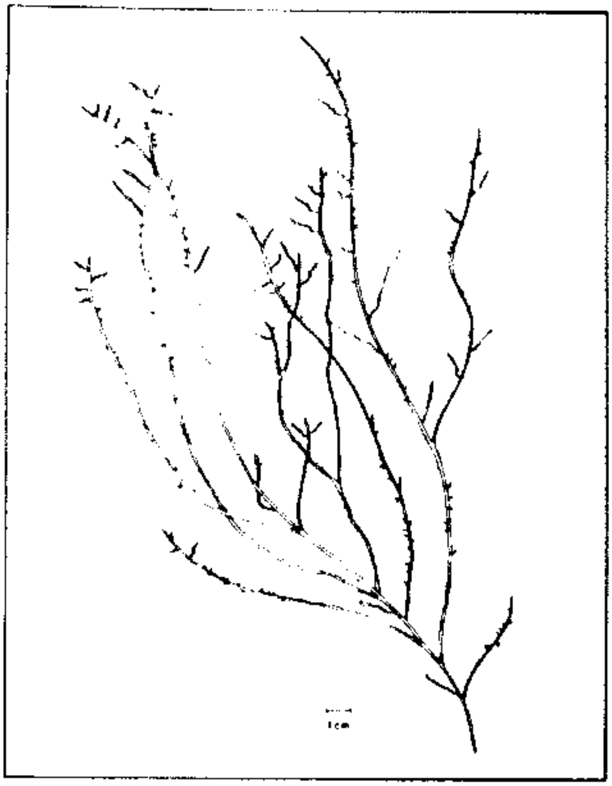

Figure 50. *Gracilaria verrucosa* (Hudson) Papenfuss

Commercial *Gracilaria* mariculture in Taiwan has increased dramatically; by 1973, 250 hectares were producing about 2,500 dry metric tons, and by 1974 the cultivated area had doubled (Chen, 1976). Approximately 31 percent of the crop is used domestically for food (Shang, 1976). The low cost of labor, use of existing cultivation facilities, and the increasing value of agarophytes are the basis for successful *Gracilaria* mariculture in Taiwan.

Research teams in the United States and Canada have investigated high-production enclosure mariculture techniques for *Gracilaria* and several other red algal genera (e.g., *Neogardhiella*, *Hypnea*, *Iridaea*, *Gigartina*, *Gelidium*, *Chondrus*), the results of which are summarized in table 6. The experiments have been conducted in a wide variety of enclosure shapes and sizes, from greenhouses to concrete raceways. In all cases the mariculture systems are capital intensive and attempt to provide near optimum growing conditions for the alga under study.

This approach, initiated by A.C. Neish for *Chondrus* mariculture in Canada, was expanded upon by J. Ryther at Woods Hole, Massachusetts, and in Florida. Ryther and his associates have explored mariculture of red algae in monoculture and using tertiary-treated sewage effluent in polyculture (DeBoer and Ryther, 1977; Ryther, et al., 1979). Studies of this group have concentrated on the nutrient scrubbing capabilities and growth rates of *Gracilaria* sp. and *Neoagardhiella* in the Woods Hole waste-recycling seaweed-mariculture project (figure 51).

In these experiments unattached *Gracilaria* and *Hypnea musciformis* (LaPointe, et al., 1976) were grown in concrete raceways 12.2 m x 1.2 m, or in rectangular, plywood tanks. Sloping bottoms provided

Table 6

Production Rates of Red Algae in Mariculture Systems

Species	Location	Growth Rate	Stocking Density (wet wt)	Production (dry wt)	Reference
Chondrus crispus	Nova Scotia Canada	2-4.5%/day	4-6 kg/m^2	25-35g/m^2/day	Neish, I. C. (pers. comm. 1980)
Gigartina exasperata	Washington	$\bar{X}$ = 3%/day	2.4-4.8 kg/m^2		Waaland (1977)
Gracilaria	Taiwan			10t/ha/yr	Shang (1976)
Gracilaria	Woods Hole, Mass.	5-10%/day	1.8-2.8 kg/m^2 (winter)		Ryther, et al. (1979)
Gracilaria	Florida		2.8-4.5 kg/m^2 (Sp.-S)		Ryther, et al. (1979)
Gracilaria	California	$\bar{X}$ 8%/day (spring)	2-4 kg/m^2		Hansen, in prep.
Gracilaria	Nova Scotia	13.9%/day	1.8 kg/m^2		Edelstein, et al. (1976)
Gracilaria	B.C., Canada	1.37%/day	8.3 kg/m^2		Whyte and Englar (1979)
Gracilaria	B.C., Canada	4%/day	0.5 kg/m^2		Saunders and Lindsay (1979)
Gracilaria & Neoagardhiella	Florida			$\bar{X}$ = 34.8 g/m^2/day	La Pointe and Ryther (1978)
Neoagardhiella	Florida	5-10%/day	2.8-4.5 kg/m^2 (Sp.-S)		Ryther, et al. (1979)
Eucheuma striatum	Philippines	1.5-5.5%/day		10-30t/ha/yr	Doty (1973)
Eucheuma spinosum	Africa	5.4%/day (max.) 5.3%/day (spring) (min.) (end autumn)			Braud and Perez (1979)
Gelidium coulteri	Hopkins Marine Station, California	2.5%/day	2.5-3.2 kg/m^2	17g/m^2/day	Hansen (1980)

depths ranging from 0.6 m to 1.5 m. The seawater was mixed and plants were agitated by aeration. In the polyculture experiments, production rates of the seaweeds were high in spring and summer and lower in autumn and winter and were correlated with water temperature and irradiance. *Gracilaria* production stopped in winter.

Other attempts at vegetative propagation of *Gracilaria* in enclosures on the east and west coasts of Canada have expanded our understanding of the basic growth requirements and potentials for the genus. Edelstein, et al., (1976) investigated greenhouse cultivation of *Gracilaria* in Nova Scotia within a seawater temperature range of 15-28°C (25-28°C optimum) and an extended photoperiod of 16 h enhanced growth. The plants thrived in 30-31 ppt salinity but deteriorated completely at 10 ppt. *Gracilaria* cultivated in effluent from halibut-holding tanks in British Columbia showed a relatively low growth rate (Whyte and Englar, 1976). The purified agar from cultivated plants was of higher quality than that of the natural stock, but not high enough to meet pharmaceutical grade standards.

On the west coast of Vancouver Island, B.C., *Gracilaria* sp. was cultivated in polyethylene bags with an open surface area of 6 m^2 and depth of 1.2 m, all supported by a floating raft structure (Saunders and Lindsay, 1979). Air-lift pumps were used to provide aeration, water circulation, and filtration. Seawater turnover rate was 1.6 times/day, and growth rate was fairly low. It appears that an increase in both the seawater turnover rate and stocking density would most likely enhance the *Gracilaria* growth rate in this innovative, *in situ* cultivation system.

In California, Hansen and Abbott (Hopkins Marine Station) initiated a project, sponsored by the California Sea Grant College Program, to develop mariculture of *Gracilaria* on monolines for the purpose of increasing seaweed substratum for herring spawning activities—the basis of the lucrative herring-eggs-on-seaweed fishery. A dual objective of the program was to experiment with pilot-scale *Gracilaria* mariculture in tidal enclosures (figure 52). Techniques for growing *Gracilaria* on monolines have been developed and growth rates are high. Such a crop was transplanted to San Francisco Bay, California, during winter 1980. The herring spawn that occurred on this crop was of commercial quality (Hansen and Phillips, in prep.).

Further enclosure cultivation experiments on the West Coast involve both carrageenophytes and agarophytes. Waaland (1977) has vegetatively propagated *Gigartina exasperata* in Washington. A fast-growing strain has been isolated which reaches rates of 4.3%/day. Waaland's (1977) experiments with *Iridaea cordata* show even greater growth rates, but the species did not vegetatively propagate well and was therefore not suited for such an enclosure system.

The enclosure strategy has been shown valuable in

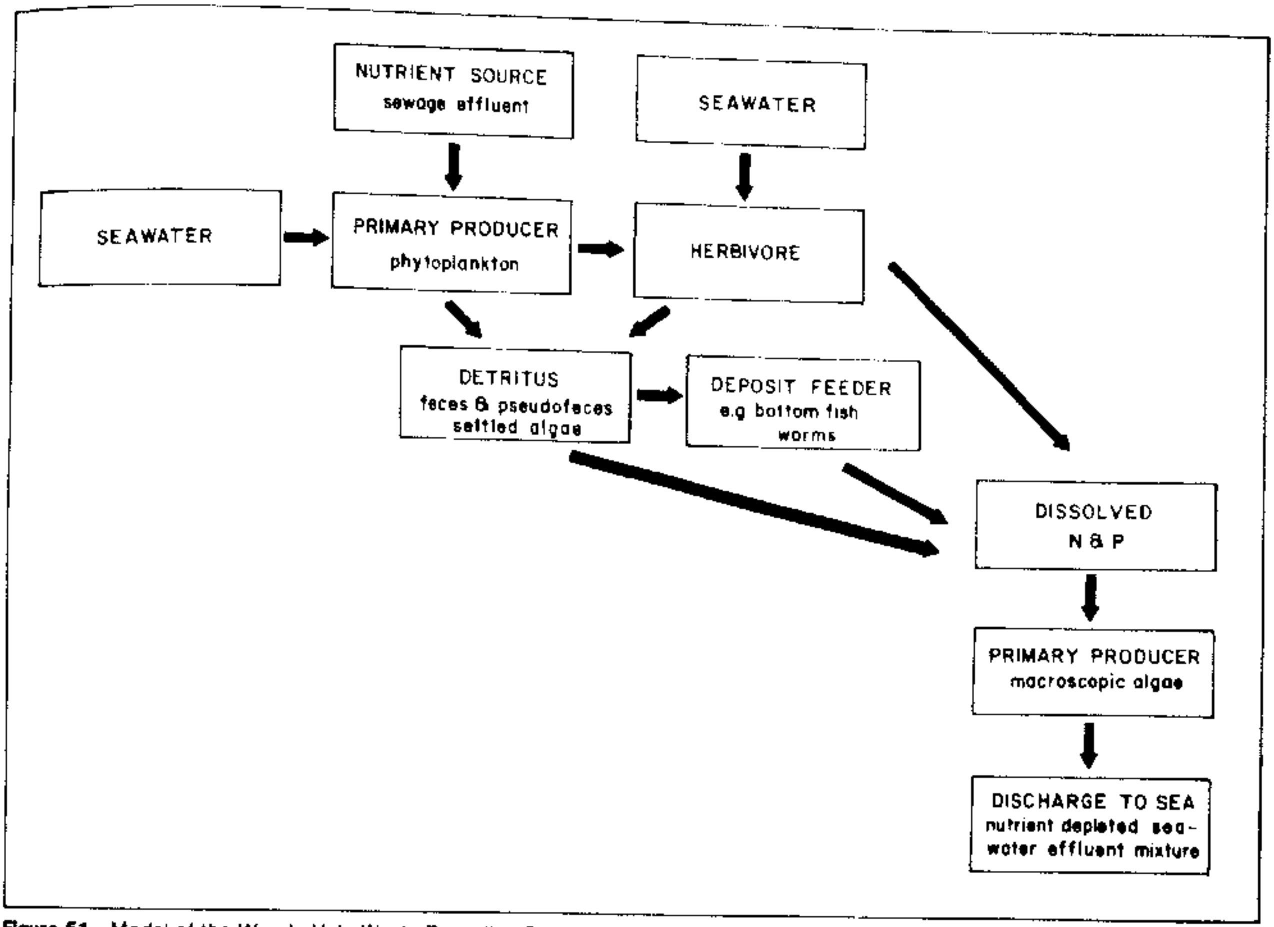

Figure 51. Model of the Woods Hole Waste Recycling Polyculture System (Ryther, 1975).

providing a nursery situation for "seeding" nets with *I. cordata* spores and grow-out of juvenile plants before planting at sea (figure 53). Such methods, developed specifically for growing only male and female plants on nylon seine nets, were developed and implemented on an experimental scale at Hopkins Marine Station, California (Doyle and Hansen, 1977). This methodology has been refined and expanded in Puget Sound, Washington, by Mumford (1979). Currently this project is at the pilot-farm stage. Since the nets are "seeded" with tetraspores or carpospores, this method should produce a male and female or a tetrasporangial crop yielding solely kappa carrageenan or lambda carrageenan, respectively (Mumford and Waaland, 1980).

In California, experiments on the physiology and vegetative propagation of the agarophytes *Gelidium* and *Gracilaria* and carrageenophyte *Rhodoglossum* are under way (Hansen, 1980; Hansen, in prep.). Free-floating plants, agitated by aeration, are grown in slope-bottom, wooden tanks. Growth rates of cultured populations are approximately ten times greater than growth *in situ* (table 6; figure 54). Optimum seawater temperature for photosynthetic rates of the three species is between 20-25°C and rates in air are approximately 33 percent of those when the plants are submerged (Hansen, in prep.).

Highly controlled vegetative propagation of potentially important red seaweeds is developing throughout the world. Further refinement in cost effectiveness of enclosure mariculture should bring it within the commercial realm because of enclosure mariculture's broad applicability in industry, polyculture, wastewater treatment, and biomass energy conversion. The success of *Gracilaria* mariculture in Taiwan and China is an auspicious beginning. However, except for *Gracilaria*, to date all commercially successful mariculture operations using vegetative means prosper at sea (e.g. *Eucheuma*), under less controlled conditions using a low capital/high labor strategy.

Spore Selection

Following in the footsteps of horticulture, a necessary step in red algal mariculture is the development of desirable strains for improved algal cultivation. Features such as rapid growth, disease resistance, and appropriate timing of reproduction can increase seaweed crop yields just as they have for terrestrial food crops. Progress is already being made in this area (West, 1979), not surprisingly on *Porphyra*, the red alga for which cultivation techniques are the most highly evolved.

Although nori farming has become increasingly scientific in recent decades, there are still many variables in the process. Widely divergent growth rates of cultured species and sporadic outbreaks of disease contribute to uncertain yields. Attempts to obtain *Porphyra* stock with exceptional quality have centered around the two approaches taken by traditional horticulturalists: crossbreeding and selection.

With the advent of successful laboratory cultivation of *Porphyra*, hybridization experiments have been initiated in Japan. Thus far, these research efforts have not yielded results of direct commercial use. Suto

Figure 52. Raceway (10 × 30 m) for cultivation of *Gracilaria* at Moss Landing, California. (Courtesy of R. Phillips)

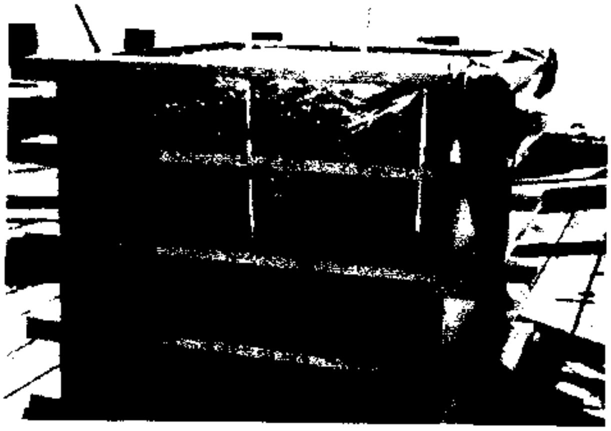

Figure 53. Artificial tank "seeding" of nylon nets with *Iridaea cordata* spores in Washington for outplanting. (Courtesy of T. F. Mumford)

pioneered work on artificial hybridization of *Porphyra* and determined that interspecific crossings do occur. He concluded, however, that selecting desirable strains would probably be more practical for increasing yields and quality (Suto, 1963).

Selective breeding has been carried out by individual nori cultivators ever since "*Conchocelis*" nets were artificially seeded. Net-grown nori populations that were exceptionally productive or yielded a high-quality product were segregated and retained for further net seeding.

Laboratory experimentation has also shown this to be a promising route to improved nori cultivation. By selecting exceptionally long-growing fronds of *Porphyra tenera* and *P. yezoensis*, Miura (1975b) established two new forms that are taxonomically distinct from their predecessors. Average *P. tenera* and *P. yezoensis* fronds grow to 10-15 cm in length; the new *P. tenera* reached 1 m and *P. yezoensis*, 60 cm. Conchospores from these strains produce equally long fronds, and successive populations of long, linear fronds continue to form in culture. This shape leads to more yield per unit length of netting. In addition, both forms grow rapidly and exhibit retarded production of reproductive cells. This latter trait is desirable, as reproduction leads to disintegration of and damage to the fronds.

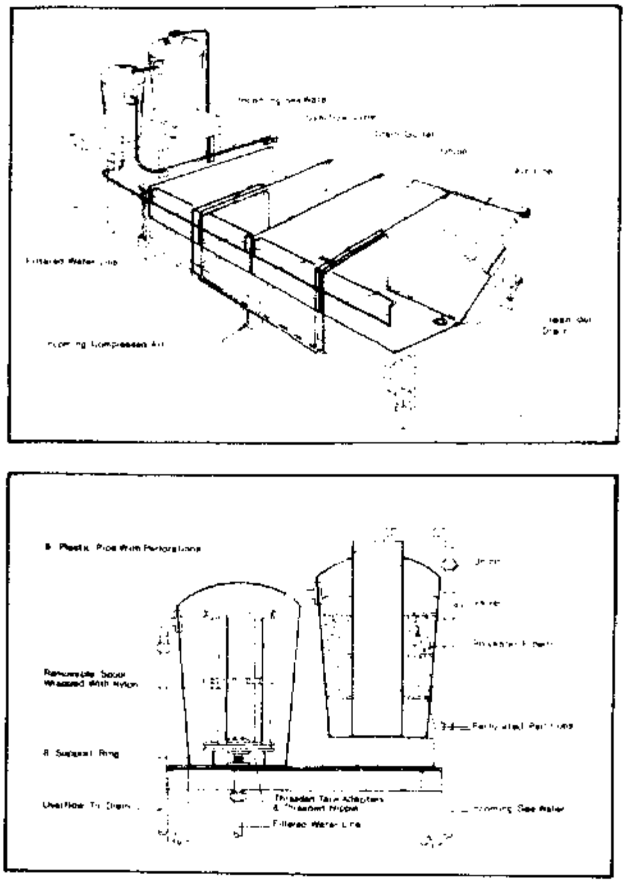

Figure 54. Slope-bottom tanks for culture of free-floating *Gelidium* and *Rhodoglossum*, Hopkins Marine Station, California (a); detail of filter system for a flow-through seawater source (b). (Courtesy of R. Phillips)

Based on laboratory cultivation, it was estimated that yields from these two strains could be three to five times higher than those of conventional *Porphyra* strains (Muira, 1975b). Recent field cultivation of one of these strains looks promising. Transplants of *Porphyra tenera* forma *tamatsuensis* Miura were established in Sinan and cultivated for three years. Results indicated that this form could be harvested 14 to 17 days earlier than *P. tenera* or *P. yezoensis*, and it grows 5 to 21 cm longer than the latter two species. Division and growth of neutral spores in cultivated populations of *P. tenera* f. *tamatsuensis* were more rapid. Overall, production was 38 percent to 84.6 percent higher than the conventional *P. tenera* harvests. The product was rated as good quality for export but inferior to some other laver sources (Chung et al., 1977).

Genetic selection experiments with the carrageenophyte *Gigartina* have been directed towards development of high-yielding, fast-growing isolates (West, 1976-79). Though the isolates generated have not yet been employed in commercial mariculture, the hybridization and selection techniques that were developed will be invaluable for red algal crop improvement in the future.

Additionally, culture and selection experiments with *Eucheuma* (Polne, et al., 1980) and *Gracilaria* (Hansen and Glasgow, unpublished) and attempts at tissue culture of commercially important red algae are in pro-

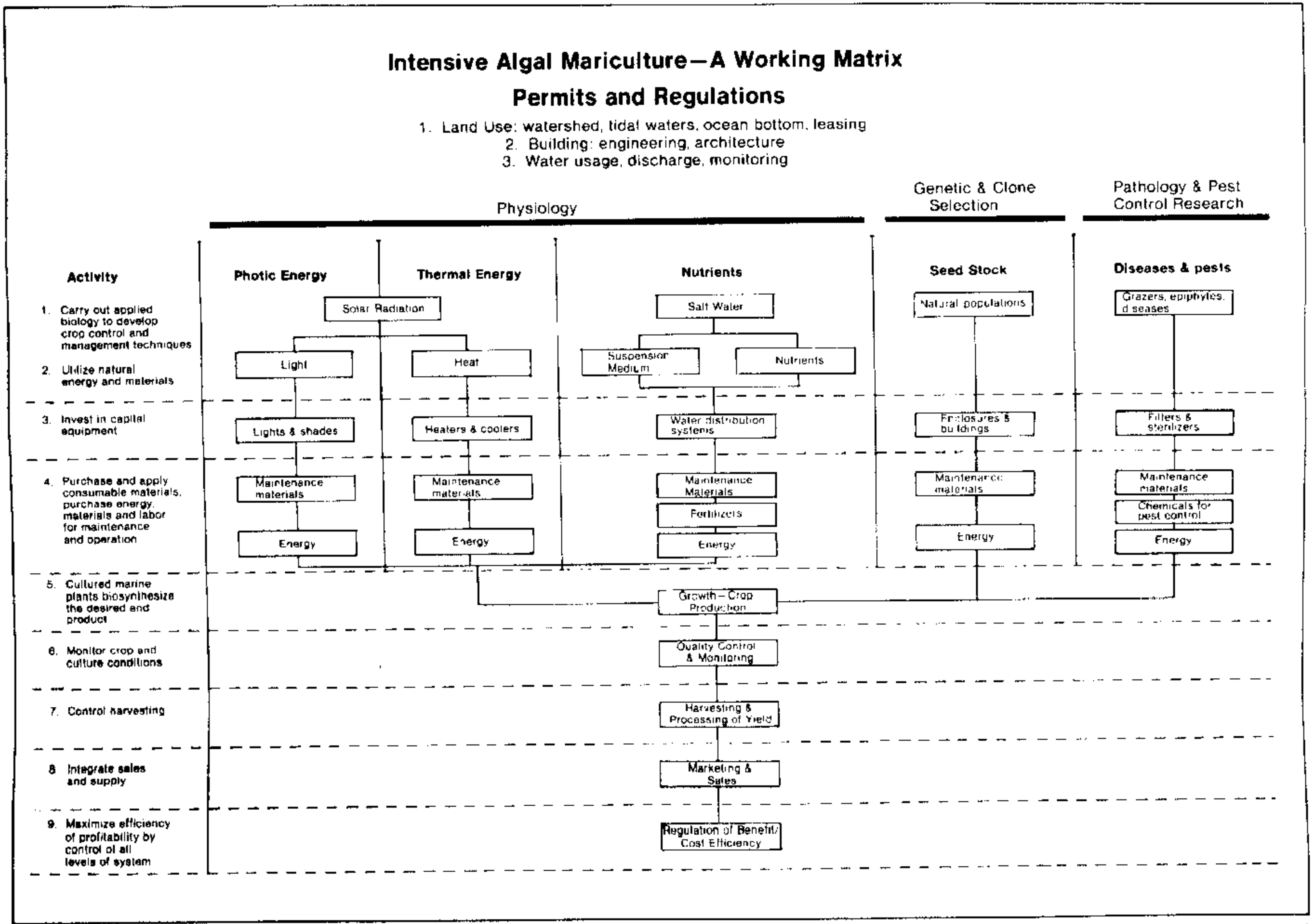

Figure 55. A matrix of activities and considerations that must be integrated for the successful mariculture of an alga.

(Modified from I. C. Neish, 1979)

gress (Gibor, 1980; Polne, in prep.).

Clearly the time has arrived for strain selection to improve mariculture yields of sexually propagated red algae. Historically, such research has been hindered by a general lack of information on culture techniques and life histories of the plants. The principles of modern vascular plant genetics must be further adapted to seaweeds if the mariculture of sexually reproducing red algae is to progress via crop improvement.

The Future

What lies ahead for seaweed mariculture? People of many coastal nations consume seaweed regularly, and, until recently, native seaweed populations have provided adequate resources. In the unindustrialized sectors of the world, these replenishable seaweed supplies remain adequate.

In technologically advanced nations such as Japan, where seaweeds have long been an integral part of a cultural cuisine, a different picture has emerged. Reclamation of bays and estuaries and strong competition with industry for use of near-shore waters have reduced the amount of coastal waters available for algal mariculture. At the same time, demand for cultivated algae has increased.

Collectively, these pressures have motivated scientists and marine agronomists to make major breakthroughs in *Porphyra* mariculture. These advances have centered on genetic research and technological changes directed toward using deeper, offshore waters for cultivation grounds.

On the other hand, Western countries do not have long-established markets for seaweeds as food; hence mariculture of edible algae is not crucial. Yet it is something of a triumph of industry and marketing that these countries have found and continue to find an increasing number of uses for seaweed by-products. Recent developments in red algal mariculture have transpired from a demand for stable sources of phycocolloid-bearing red algae for industry. These efforts regarding the large-scale, near-shore, enclosure, or polyculture cultivation of carrageenophytes and agarophytes were the debut of a new progressive era for mariculture. The strategies are either extensive and based on a large labor force, or intensive and based on a high capital investment.

The success of both approaches has come from cooperation among phycologists, agronomists, engineers, industrialists, and politicians. Today such cooperation is imperative for intensive seaweed mariculture. The highly integrated activities and diverse array of expertise must be considered in a broad matrix in order to mesh effectively. Such a matrix, modified from Neish (1979), is outlined in figure 55.

The problems generated by an intensive seaweed mariculture endeavor can be staggering, yet a successively planned and smoothly run system will yield financial rewards. The major hurdles begin with site location. In industrialized nations competition for shorefront/tidal land and concern for water quality are great. Therefore, time devoted to governmental regulations and permits is high. Simultaneously, basic and applied research regarding the seaweed of interest must be completed, and the results must be applied to the design, engineering, and economics of the mariculture system. If the system is plausible, and the chosen species successfully adapt to large-scale cultivation, then improvements, marketing, sales, and new applications will insure financial rewards.

Work toward the development of intensive mariculture systems began around 1973, and it appears that such systems today can produce about 30-80 tons (dry weight)/ha/yr (Neish, 1979), with crops generally worth $250-1,600 U.S./ton. Huguenin (1976) estimates that to generate a 14 percent (pretax) return on the overall investment (a fair business return), 100 metric tons/ha/yr must be produced at a price of $1000 U.S/ton, and the water turnover rate must be low (1 turnover/10 days). To achieve such efficiency, the present technology of seaweed mariculture must be significantly improved. Advancements in genetics and clone selection research would improve species adaptability, production, and quality. Further in-depth research on algal physiology could promote the needed refinements in cultivation technology.

An additional strategy to increase cultivation efficiency would be to include the algal species in polyculture, a technique that has proved successful for *Gracilaria* culture in Taiwan. The major advantage of integrating a seaweed into an animal culture facility is reciprocal. The algal population provides nutrient scrubbing capabilities, while the animal excreta fertilize the seaweed. In addition, the seaweed provides a renewable cash crop.

Our assessment of red algal mariculture indicates a general success of even small-scale systems when an algal species is cultivated for food in countries where algae are used routinely. Extensive mariculture of phycocolloid-producing seaweeds such as *Eucheuma*, done in near-shore waters and utilizing a high labor strategy, has also proved successful. This required ten years for development.

Intensive mariculture of red algae in enclosed systems is poised on the threshold of commercialization. Progress awaits technological and biological improvements in cultivation efficiency. Active work on enclosed systems began around 1973; in terms of general management principles (Francis, 1977), technological developments of this complexity can be expected to take at least seven years.

Based on this prediction and on progress to date, we will likely see the beginnings of commercial mariculture/polyculture of red algae adjacent to or in coastal waters sometime in the early 1980s. We project that successful mariculture of this type in the industrialized nations will first develop where the need is critical. Of the seaweed uses described, the necessity for a stable, high-quality colloid for biomedical purposes such as bacterial, viral, and cell culture media is foremost. Although they require a relatively small percentage of red seaweeds produced today, these needs must be met, for no substitutes are known. As a result, mariculture of agarophytes and appropriate carrageenophytes under the intensive conditions described will be most promising.

The maturation of seaweed mariculture is an innovative extension of agricultural practices to include marine plant crops. Simultaneously, it is a technological advancement in marine fisheries. If the institution of seaweed mariculture is accepted from this combined point of view, the impact on industries competing for shorefront lands, other commercial fisheries, real estate, and recreational land use will be significantly less, promoting the favorable development of these renewable resources—the marine algae.

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