Seaweed Aquaculture

ARTHUR C. MATHIESON

Gracilaria foliifera, .33 x

Chondrus crispus, .50 x

Gigartina sp., .30 x

Rhodymenia palmata, .30 x

INTRODUCTION

Seaweeds, or attached macroscopic marine algae, are a major source of potential food products in the sea. Today the seaweed industry is rapidly expanding because of the discovery of a variety of new seaweed products, especially those employing phycocolloids. In many cases the demand for seaweed products far exceeds their supply. Future growth of the seaweed industry will depend upon a stable source of high quality raw materials. Hence, many individuals and companies are interested in unialgal cultivation of economic seaweeds. Intelligent programs of conservation and harvesting are also necessary to maintain these valuable resources.

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In this paper the utilization and cultivation of seaweeds are presented in three aspects as follows:

(1) Uses of Seaweeds;

(2) Seaweed Aquaculture—an Overview;

(3) Seaweed Cultivation.

The first section summarizes the major usage of seaweeds throughout the world, and it gives a perspective for the need to cultivate seaweeds. It is abstracted from an earlier paper by the author (Mathieson, 1969). The second part discusses some of the major biological, technological, and sociological problems associated with seaweed cultivation. The Japanese have developed the most extensive systems of seaweed aquaculture; a detailed summarization of their accomplishments is given in the last section. In addition recent activities in other areas of the world are also outlined.

USES OF SEAWEEDS

Many species of seaweeds have been used as a direct source of food since ancient times, particularly in the East Asiatic-Australian region. The most diversified dietary use of seaweeds was developed by the ancient inhabitants of Hawaii, for 75 different seaweeds or "limu" were regularly used as food (Dawson, 1966). The Japanese and Chinese presently make extensive use of seaweeds as food (Bardach, Ryther, and McLarney, 1972).

The red alga *Porphyra*, or purple laver, is one of the major edible seaweeds in Japan. It has been harvested for food since ancient times, and at present it is the basis of a thriving nori[1] industry. *Porphyra* is presently cultivated and harvested on a commercial basis. The harvested material is dried, pressed into sheets, and subsequently packaged for market. The final product is used in soups, sauces, sandwiches, in the preparation of macaroni and various other commodities.

The larger brown algae (kelps) have also been used extensively as a source of food (kombu and wakame[2]) since before the Christian era. In Japan thin slices are used in soups and sauces and with vegetables. In addition they are mixed with meats, steeped in fresh water to make a drink, and, coated with sugar, eaten as a candy. Many of the smaller brown and green algae are also used in salads, as vegetables, garnishes for meats and fish, soups, sauces, and for making jellies (Okazaki, 1971).

The red algae, dulse (*Rhodymenia palmata*) and Irish moss (*Chondrus crispus*) are used as food in parts of western Europe, the Maritime Provinces of Canada, and New England. Dulse is eaten raw, cooked with soups, eaten with fish and butter, and used in a variety of other ways. Irish moss is dried and eaten out-of-hand like popcorn, or used in making blancmanges and soft jellies. The jelling qualities of Irish moss are due to the colloidal material (carrageenan) found within its cells. A soft jelly bread is also made from Irish moss. The Indians of the Pacific Northwest used *Porphyra* and the common sea lettuce (*Ulva*) as a source of food and salt (Scagel, 1961).

In general, seaweeds contain a high percentage of indigestible carbohydrates; in this sense they are comparable to roughage materials such as lettuce and celery. The greatest nutritional value of seaweeds lies in the various vitamins, minerals, and trace elements they contain. The amount of vitamin C in some brown and red algae is equal to or greater than that in a lemon. Most seaweeds are a good source of iodine, which aids in the normal functioning of the thyroid gland, and hence prevents goiter. The low frequency of goiter among Orientals is thought to be due to the large amount of seaweed in their diet.

Marine algae have long been used as fodders in coastal areas (particularly near the North Sea). The livestock in these areas are grazed directly on the seaweeds at low tide, and during the winter harvested seaweed is used to supplement their diet. Several types of meals and powders, which are primarily made from the brown alga, *Ascophyllum nodosum*, are now being used extensively for supplements to dried milk and other rations. They serve as valuable sources of vitamins and trace elements. Seaweed supplements are said to increase the wool production and growth of sheep, as well as to improve the color of egg yolks. Although several beneficial effects of seaweed meal have been recorded, some harmful side effects may result if the proportion of meal is too great.

Seaweeds such as *Ascophyllum nodosum* have long been used as green manures in maritime districts of Europe and North America. The fresh seaweeds were either dug into the ground or spread on the soil surface, and then allowed to decompose. The fertilizing constituents in fresh seaweeds are comparable to barnyard manure, except that they contain more potassium salts and less phosphorous (Scagel, 1961). They are considered to be more effective fertilizers than barnyard manures because they release their nitrogen and phosphorous compounds more slowly, they have more trace elements and growth substances, and there are no weed seeds or soil microorganisms.

Seaweeds were considered of medicinal value in the Orient as long ago as the year 3,000 B.C. The Chinese and Japanese used them in the treatment of goiter and other glandular troubles. The Romans considered seaweeds as useless even though they used them to heal wounds, burns, scurvy, and rashes. The British used *Porphyra* to prevent scurvy on long voyages. Various red algae (particularly *Corallina officinalis*, *C. rubens*, and *Alsidium helminthocorton*) were used as vermifuges in ancient times. Dulse is reported to be a laxative and also to reduce fever. Several red algae (including *Chondrus crispus*, *Gracilaria*, *Gelidium*, and *Pterocladia*) have been used to treat various stomach and intestinal disorders. The algae apparently absorb enough water to relieve constipation and other associated discomforts. One Hawaiian red alga (*Centroceras clavulatum*) was used extensively as a cathartic. The stipes of one large kelp (*Laminaria cloustoni*) have been used to aid in childbirth by distending the uterus during labor. It was also used to open wounds and facilitate healing. Recently a number of species of ma-

[1]*Porphyra* is commonly called "nori" in the orient.—Editor.

[2]The brown algae Laminaria and Undaria are called kombu and wakame; respectively, in the orient.—Editor.

Drying *Laminaria* near the Usu Branch, Hokkaido Central Fisheries Experiment Station, Japan (August 1971).

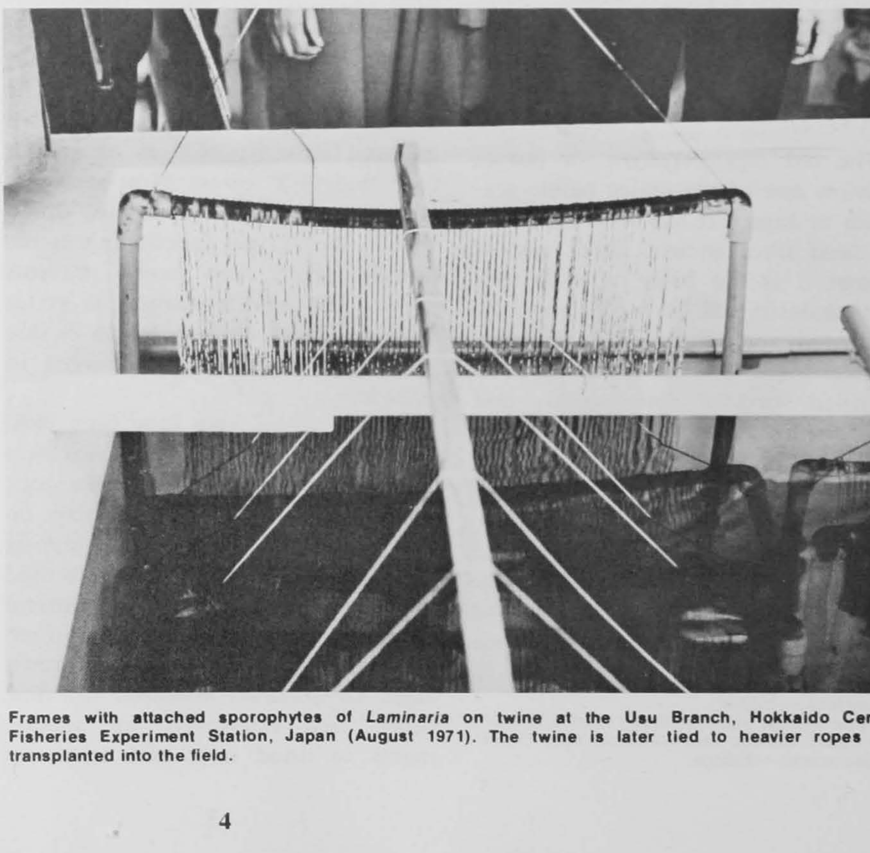
rine algae have been found to have anticoagulant and antibiotic properties. The colloidal extracts (carrageenan) of some red algae may possibly be useful in ulcer therapy, while the colloidal materials of brown algae (alginates) are found to prolong the "rate of activity" of certain drugs.

Phycocolloids, or the naturally occurring storage products (polysaccharides) of seaweeds, are the basis of major industrial utilization of seaweeds. They are also referred to as hydrocolloids, because of their ability to form colloidal systems when dispersed in water. To date, phycocolloids have only been extractable on a commercial basis from the brown and red algae. The principal phycocolloids are algin (from kelps and rockweeds), agar (from *Gelidium* and other related red algae), and carrageenan (from the red algae *Chondrus crispus*, *Gigartina* and related species). Each phycocolloid has characteristics suiting it to particular uses and each can be varied within relatively broad limits by extractive and chemical techniques to adapt it precisely for specific employment.

Algin or alginic acid is prominent in kelps and rockweeds. According to Dawson (1966), it constitutes about 2.5 percent of the total weight in *Macrocystis*. Thus, *Macrocystis* has become the primary source of algin in the United States, because of its ease of harvesting and high content of algin. *Ascophyllum nodosum* and several kelps are used as a source of algin in Europe and other locations.

Several derivatives of alginic acid are known (calcium, sodium, ammonium, potassium, and propylene glycol alginates) and they have a wide variety of uses because of their viscosity and water absorbing properties. Alginates are commonly used as emulsifiers and stabilizers in dairy products, such as sherbets, ice cream, chocolate milk, cheese, puddings, and toppings. They are also used in syrups, sauces, salad dressings, soaps, shampoos, toothpastes, shaving creams, medicines, lipsticks, paints, insecticides, plastics, fireproofing fabrics, and polishes. Some surgical threads are now being made of alginates because they will dissolve after a certain period of time and do not have to be removed. A whole-blood substitute derived from seaweed has been used in emergency transfusions. It is more effective than sugared water or salt water, which are customarily used, because it does not break down in the blood stream.

Carrageenan is another very important industrial colloid. It is primarily obtained from Irish moss and species of *Gigartina*, but it can also be extracted from at least 20 other species of red algae, many of which are found in different parts of the world. At present, Irish moss is one of the major marine resources in New England and the Maritime Provinces of Canada, and it is the basis of an extensive colloid industry. Carrageenan resembles agar chemically (i.e. it is a carbohydrate ethereal sulphate) but it has a higher ash con-



Frames with attached sporophytes of *Laminaria* on twine at the Usu Branch, Hokkaido Central Fisheries Experiment Station, Japan (August 1971). The twine is later tied to heavier ropes and transplanted into the field.

tent and requires somewhat higher concentrations to form a gel.

The colloid extracted from Irish moss constitutes about one-half of the weight of the plants (dry weight basis). Irish moss is worth from 12 to 13 cents per pound, dry weight, but the colloid as extracted, standardized, and blended (i.e. with different carrageenans) costs well over $1 per pound. Despite this relatively high cost, demand exceeds supply. Carrageenan is widely used in the food and pharmaceutical industries because of its thickening, emulsifying, stabilizing, and suspending properties. It is used extensively in milk-based products because of its unique interaction and stabilizing effects with milk protein. Extracts find their way into hundreds of other common household items such as toothpastes, diet foods (the carbohydrate is not metabolized in the human digestive system), hand creams, soups, confectioneries, insect sprays, water base paints, inks, shoe stains, shampoos, and cosmetics. It is also used in the sizing of cloth and thread, in certain printing processes, as a clarifying agent in the production of beer, and as a dental impression compound.

Agar is a gel-forming substance found in certain species of red algae (e.g. *Gelidium*, *Gracilaria* and *Pterocladia*). The name agar is an abbreviation for the Malayan or Ceylonese term agar-agar, which means jelly. A jelly is produced from these seaweeds when they are boiled and the resulting liquid is cooled. Agar was first produced commercially by the Japanese in 1670, and it was the first seaweed product to become an important stable item of commerce. The Japanese are still the primary producers of agar. However, since its acute shortage during the second world war, agar has been produced in substantial amounts by other countries (Britain, Denmark, Australia, United States, Russia, New Zealand, India, and South Africa).

Robert Koch first showed (1881) that agar was an effective culture media, because many microorganisms were unable to decompose it. Thus it has become a standard fixture in most hospitals and laboratories where culture media are required. Agar was

Tanks and culture frames inside the Usu Branch, Hokkaido Central Fisheries Experiment Station, Japan.

early found to be useful for stomach and intestinal disorders. It is a nonirritant bulk producer which absorbs and holds water as well as serving as a mild laxative. It is now employed as a covering for various capsules (antibiotics, sulpha compounds, and vitamins) when a slow release of the medicant is desired at a point beyond the stomach. Agar preparations are sometimes used beneath bandages to heal wounds. In addition it has a variety of other uses: preservation of canned meats, fish, and other easily spoiled foodstuffs; preparation of sizing for fabrics; as an ingredient of waterproof paper, waterproof cloth, and glue; a cleaning media; a clarifying agent in the manufacturing of wines, beers, and coffee; and the preparation of special breads for diabetics in which agar replaces the starch.

As suggested by Scagel (1961) carrageenan and algin have many similar uses. However, they have specific properties which restrict or enhance their use depending on the circumstances.

SEAWEED AQUACULTURE—AN OVERVIEW

Krishnamurthy (1965) gives an interesting account of the principles and problems associated with seaweed cultivation. He emphasizes that cultivation of many species would be desirable in order to maintain adequate supplies of raw materials. A knowledge of the plant's biology and reproduction is fundamental to successful cultivation. Most seaweeds produce an enormous number of spores, and they can be multiplied extensively if proper culture conditions are perfected. For example, over a million swarmers can be produced from a single *Ulva fasciata* plant, while a single *Gracilaria millardetii* plant produces over 60,000 tetraspores and more than 40,000 carpospores (Krishnamurthy, 1965).

In contrast to sporic reproduction, the number of fragments that can be produced from a plant is limited by its size, maturity, and physiological state. According to Austin (1960) there are a variety of adaptive features that allow free-living seaweeds, such as *Furcellaria*, *Gracilaria*, *Gelidium*, *Pterocladia*, *Eucheuma*, and *Hypnea*, to survive in a pelagic state: (1) they can grow without orientation to light and gravity; (2) they are capable of rolling; (3) they can survive burial in mud and/or sand; and (4) they can carry out constant vegetative multiplication, without the loss of clonal vigor. Many of the latter properties should be screened in "seed" stock selection of seaweeds for aquaculture.

Krishnamurthy (1965) lists six major problems which may restrict seaweed cultivation: (1) selection of a suitable environment for growth; (2) engineering of the seashore for farming; (3) protection of the crop from physical and biotic effects; (4) probable pests and parasites; (5) proper transplantation of the young germlings to the field for cultivation; and (6) harvesting.

In Japan most seaweed cultivation is carried out in shallow embayments and inland seas where reduced wave action is present. Sheltered habitats have obvious advantages, for they minimize the structural support needed for culture frames such as "hibi," or the nets and posts employed by the Japanese in nori cultivation. Sheltered habitats will also avoid the dislodging of germlings and other propagules. However, sheltered embayments are often highly polluted in industrialized countries, and they may have wide ranging hydrographic regimes (temperatures and salinities), both of which may restrict the growth of seaweeds. A thorough understanding of the environmental tolerances and optima of seaweeds is fundamental to successful seaweed mariculture. Protection of crops from biological (i.e. grazing) and physical effects may also be a major consideration in seaweed cultivation. Extensive fish and urchin grazing (Randall, 1965; Leighton, Jones, and North, 1966) are known in many areas, and they can easily destroy a large-scale seaweed farm. Other predators, pests, and parasites such as fungi and bacteria could also cause epidemic destruction of unialgal seaweed farms.

Adequate harvesting techniques must be devised for each of the different types of seaweeds. Ideally one would like to maintain a farm with a continuous supply of "seed" material. Seaweed farming from vegetative fragments has many potential advantages, if successful crops can be harvested and residual "seed" material is retained for further regeneration and growth. In sporic propagation of seaweeds, advantage should be taken to maintain peak populations. The effects of differential levels and times of harvesting should also be determined for each species in order to maintain peak productivity of seaweeds. In addition, breeding and selection studies will be fundamental to successful seaweed mariculture programs. Specific examples would be genetic studies to enhance disease resistance or to select specific properties (Suto, 1963).

A precaution of major significance is to avoid careless handling of "foreign" seaweed strains, to prevent the introduction of less exotic species of algae and/or animals (Hanic, 1973). Examples that can be cited are the recent introduction of *Sargassum muticum* to the Pacific Northwest (Scagel, 1956) and to Great Britain (Farnham, Fletcher, and Irvine, 1973; Anonymous, 1973), as well as the recent transfer of *Codium fragile tomentosoides* to the northeastern coast of North America (Coffin and Stickney, 1966). Presumably both of the latter seaweeds were introduced with shellfish from other geographical areas.[3] *Codium fragile* is a major pest, for it has destroyed many of the commercial oyster beds in New York and New England. Hanic (1973) emphasizes that adequate precautions will be expensive and time consuming, because "foreign" strains must be quarantined until they are decontaminated. All waste seawater involved in such impoundment cultures should obviously be sterilized to prevent contamination of local waters.

Calhoun (1968) gives an interesting account of the systems approach to food production from the sea. He emphasizes that one should take advantage of all natural opportunities available, and attempt to adjust nature to increase yields. Calhoun cites nutrients as a means of increasing yields. The enhancement of seaweed growth by supplying nutrient-rich deep water should be cited as a possible application in aquaculture. Roels, Gerard, and Bé (1969) give a detailed account of artificial upwelling and its application to shellfish mariculture. In addition Roels has suggested its applicability to seaweed mariculture (O.A. Roels, Lamont-Doherty Geological Observatory, Palisades, NY 01964, pers. commun.).

In the continental United States, legal and sociological considerations would appear to be two of the major hindrances for active seaweed aquaculture. The concept of multiple use and public ownership must be thoroughly integrated into any successful program of seaweed mariculture. Kane (1970) gives a detailed review of ocean law and its applicability to aquaculture. Claims and decisions

[3]The means by which *Codium* was introduced into New England waters is disputed by the scientist responsible for introducing the European oyster, *Ostrea edulis*, (Introduction of *Codium* in New England Waters, V. Loosanoff, Fish. Bull. 73:1, Jan. 1974. In press.). Loosanoff points out the detailed precautions taken to prevent introduction of foreign organisms with the European oysters and speculates that *Codium* was introduced during World War II via European freighters heavily encrusted with marine fouling organisms (as much as 2-3 ft thick) in which *Codium* was both present and visible. —Editor.

Poles suspending shells with conchocelis, inside the Usu Branch, Hokkaido Central Fisheries Experiment Station, Japan.

involving riparian landowners, navigation, fishing, recreation, and water quality are discussed.

SEAWEED CULTIVATION

Nori

Porphyra, or nori as it is commonly called in the orient, was first cultured in Tokyo Bay in 1736 by positioning well-branched trees or bamboo in the sea bottom to capture the spores (Okazaki, 1971). Subsequently, other "culture" methods have been perfected by the Japanese, such as blowing up rocks on the sea bottom, the introduction of rocks and oysters in the ocean and in tanks, and the seeding of nets attached to poles (i.e. "hibi"). The discovery of the microscopic conchocelis stage of *Porphyra* (Drew, 1949, 1954) initiated a rapid development of nori cultivation. Thus, in 1952 16,000 acres of nori were under cultivation in Japan, while in 1959 over 155,000 acres were cultivated (MacFarlane, 1968). At present the nori industry employs over 300,000 Japanese (Neish, 1968).

MacFarlane (1968), Bardach et al. (1972), and Tamiya (1959) give detailed accounts of modern nori culture in Japan. Cleaned oyster shells are primarily used as spore (carpospore) collectors from the leafy thallus of *Porphyra*. The shells are suspended for a few days in shallow trays with *Porphyra* plants. Subsequently they are allowed to incubate for 7-8 months (March through September), during which time the carpospores attach and produce the microscopic conchocelis stage. In October the conchocelis stage usually produces conchospores (monospores), which are buoyant; the conchospores are transferred to the hibi and allowed to adhere. After a month the nets are transferred into the ocean and allowed to grow from about November to March. The hibi are usually placed at the mouths of estuaries where the waters are nutrient-rich. Sometimes the conchospores are collected in the field by placing conchocelis-bearing shells beneath the collecting nets and allowing them to set. *Porphyra tenera* is the most important commercial species of nori. However, four other species (*P. angusta*, *P. kunieda*, *P. yezoensis*, and *P. pseudolinearis*) are also cultivated. The seasonal cycle and growth of the five species are somewhat different, as well as their preference for open coastal versus estuarine habitats (Boney, 1965).

According to MacFarlane (1968) there are three critical periods in the life history of nori: (1) adhesion of the conchospores to the hibi; (2) the initial stage of growth after "budding" of the conchospore; and (3) the initial period of harvest. Temperatures of about 21.7°C are optimal for adhesion of the conchospores. In contrast temperatures of less than 13.1°C are critical for the "budding" of the conchospores. Boney (1965) states that water motion is also very important in determining spore attachment, for currents greater than 7 cm/second will inhibit attachment of conchospores.

A variety of spore-collecting machines have been produced to disperse the buoyant conchospores from a drum onto nets (MacFarlane, 1968). The nets are typically 4 × 60 ft, with from 6- to 10-in meshes. Particular attention is paid to reduce crowding, for crowded plants are more susceptible to fungal (e.g. *Pythium*) and bacterial diseases. Thus, 10-50 conchospores/cm is about the ideal number of spores; higher numbers are associated with fungal and bacterial diseases. The vertical positioning of the hibi can also reduce disease. Typically the plants are positioned for 3-4 hours of exposure/day. Higher intertidal exposure periods have been found to decrease fungal diseases. However, too much exposure may reduce growth and toughen the thallus, making it unsuitable for food (Bardach, et al., 1972).

A variety of fertilizer pellets (90 percent nitrogen and 10 percent potassium) are now being developed to provide fertilization of nori populations (MacFarlane, 1968). The pellets are placed in porous containers in amounts to provide 10-14 days of fertilization. Fertilization is also being used in some areas in preharvest periods to increase coloration.

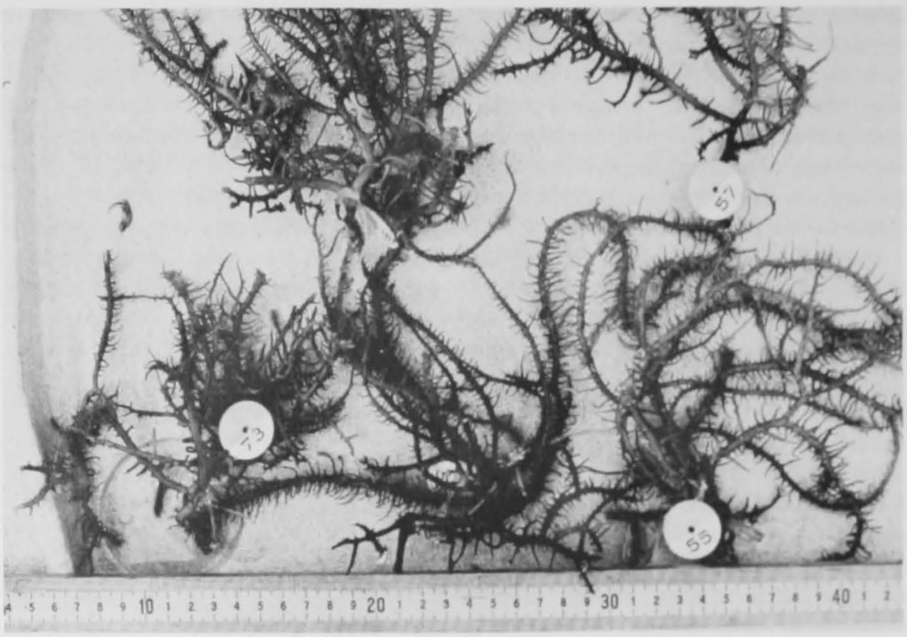
According to Okazaki (1971) young leafy thalli of *Porphyra* 2-3 cm long can be stored for nearly a year if they are freeze-dried (to 20-30 percent of original water) and refrigerated to −20° or −30°C. If they are put back into seawater they can produce a crop in about 1½ months. In 1970, one-half of all culture nets were refrigerated. The phasing of cultures has obvious advantages of prolonging the harvesting season of good quality nori. Another method of major interest is the photoperiodic control of conchospore liberation from conchocelis. Several experiment stations in Japan control (phase) the liberation of conchospores to control the yields of nori (MacFarlane, 1968). According to Bardach et al. (1972) about 70 percent of the commercial production of nori in Japan is based on artificial production of monospores (conchospores) by various prefectural and municipal laboratories.

Breeding experiments have been initiated to enhance the edible properties of nori (Suto, 1963). On the whole these have not been very successful (Boney, 1965).

Bardach et al. (1972) have given an economic evaluation of the nori industry in Japan. Typically an 18-m culture net produces from 35 to 105 kg of nori annually. In some areas as many as 100 nets/hectare can be found that are capable of producing about 750 kg/hectare during the 6-8 month growing season. Since 1960 the annual production of nori in Japan has averaged about 120,000 metric tons; the supply seldom equals the demand. Imada, Saito, and Teramoto (1972) state that the annual sales of nori during 1970 were about US$140 million (based on the then-prevailing currency exchange rate). This is higher than any other marine product in Japan. Inshore pollution is a major problem limiting the production of nori, and the Japanese are seeking foreign sources of *Porphyra*.

Wakame and Kombu

The brown alga *Undaria*, or wakame as it is commonly called, is one of the most important edible seaweeds in Japan. Three species of *Undaria*, *U. undarioides*, *U. peterseniana* and *U. pinnatifida*, are cultured in Japan. In the early 1960's over 60,000 tons were produced (Okazaki, 1971).



Samples of Florida *Eucheuma* sp. employed by C. J. Dawes in growth and transplant studies, Florida Keys, November 1971.

MacFarlane (1968), Okazaki (1971), and Bardach et al. (1972) give detailed accounts of wakame propagation in Japan. "Stone planting" and "rope cultivation" are the two major methods of culturing. With the first method stones or concrete blocks are deposited on the sea bottom for the attachment of kelp zoospores and the subsequent growth of sporophytes. The method is most successful in areas where large quantities of *Undaria* are growing.

The concrete blocks are cylindrical in shape, with a basal opening and a well-shaped depression at the top. The basal opening lessens the shifting of the blocks due to wave action, while the upper depression provides increased surface area and shelter for the growth of young germlings. The blocks are harvested after a year and replaced by new ones. The Japanese government has subsidized the production of the blocks in some northern sections of Hokkaido.

The rope cultivation techniques were first perfected at Onagawa, in the Sendai region of northern Honshu (Bardach et al., 1972). The techniques are currently employed at various prefectural and municipal laboratories, as well as by private growers throughout Honshu. *Undaria* is a cold-water alga, hence, it can only be cultivated where persistent cold water conditions are prevalent (i.e., northern Honshu), or when winter temperatures are below 22°C i.e., in southern Honshu.

Typically the twine or rope is immersed in seawater tanks with fertile kelps during April and May The zoospores are allowed to settle for 2-3 hours, or until about 100 spores/cm of twine have adhered. Populations with higher densities tend to suffer from fungal or bacterial diseases. After spore attachment, the twine is lashed to frames and retained in deep seawater tanks—until about September to November. The young sporophytes are then transported into the field. The twine, with its attached sporophytes, is wound around heavy gauge "growth" ropes, which are about 3 m long. The "growth ropes" in turn are attached to a horizontal bamboo pole, which is kept afloat by buoys and anchored at the bottom. Cultures of *Undaria* can be grown at any depths to 6 m (Bardach et al., 1972). Pearl culture rafts may also be employed to culture wakame. The young kelp sporophytes can be harvested by mid to late winter.

Bardach et al. (1972) summarize a variety of production data for wakame cultivation. For example one bamboo raft, 3.6 × 1.8 m, can produce about 1 ton wet weight of *Undaria*. The annual production of wakame in Japan is presently estimated to be about 60,000 metric tons. According to the same authors there is some conflict of interest between the oyster and wakame industries, because they both employ similar types of environments.

Okazaki (1971) describes two other cultural techniques for wakame production besides "stone planting" and "rope cultivation." The first is the removal of miscellaneous seaweeds by divers or specialized machinery. Chapman (1950) also describes the "weeding" of Japanese kelp beds to reduce unwanted species. A second method of enhancing wakame growth is by exploding the sea bottom with dynamite. By this method new rock surfaces appear to which zoospores of *Undaria* can adhere.

The brown alga *Laminaria* or "kombu" is another major edible seaweed in Japan. In addition it is also a source of alginic acid. *Laminaria japonica* is the major source of kombu in Japan, but several other species of *Laminaria* are also employed. "Stone planting" and "rope cultivation" are the two primary means of propagating kombu. MacFarlane (1968) gives a complete account of *Laminaria* cultivation in Japan. The techniques employed are similar to those of wakame described previously. Two to three year old plants are considered suitable for harvesting. In some areas rock ledges are blasted with dynamite in order to produce new surfaces for *Laminaria* growth.

Artificial propagation of *Laminaria japonica* in China has been enhanced by detailed ecological studies (Bardach et al., 1972). Light studies have shown that the young sporophytes grow best at 1,000-2,000 m-candles or 0-1.5 m below the surface. Nitrogen appears to be a major factor determining the growth of *L. japonica*, for it flourishes naturally in enriched habitats (i.e., those with more than 5 mg N/m^3 of nitrate-nitrogen). Hence, fertilization with nitrogenous fertilizers is an integral part of the cultivation procedures. *Laminaria japonica* is a cold-water species that grows successfully at temperatures as high as 21.5°C. An understanding of the temperature requirements and the development of warm water strains, called "Hai-Ching #1," have made it possible to grow *L. japonica* in southern China during the spring and winter months. The development of long-range shipping techniques, employing low temperatures (5°C), aeration, and complete darkness, have also allowed the transportation of young, mature, and reproductive sporophytes.

Cheng (1969) and Bardach et al. (1972) give a detailed account of *Laminaria japonica* propagation in China. Prior to 1943 "stone planting" or simple bottom culture techniques were employed. Since 1949 a variety of raft culture techniques have been developed as follows: (1) basket rafts with five or more cylindrical bamboo baskets are tied in a row for cultivation; (2) a single line tube raft is constructed of bamboo or rubber tubes and tied end to end; and (3) a double line tube raft is constructed from bamboo tube to form a ladder-like structure. Ropes bearing young sporophytes are attached to the rafts. The ropes are either attached perpendicular to the water, parallel or upright. The latter method provides maximum access to the sunlight. In most cases the plants are established in the field from February to March. By mid-June they are large enough (3 m or larger) to harvest.

A porous earthenware cylinder containing fertilizer is attached to each of the culture rafts. The fertilizer becomes dispersed in the water and it is absorbed by the sporophytes. In some cases the young sporophytes are immersed in a solution of ammonium nitrate prior to being outplanted; immersion in a fertilizer solution may also be carried out weekly to enhance growth.

The single line tube raft is the most popular type of cultivation method for *L. japonica* because it produces the highest yield of seaweed/kg of fertilizer, i.e., 3.75 kg of algae/kg of fertilizer. As many as 72,000 to 134,000 kelp plants/hectare can be cultured on the single-line tube rafts.

The original "stone planting" techniques in China simply provided additional substrate for naturally produced zoospores. The zoospores are now allowed to attach to the stones prior to deposition. In many areas 3,800-4,200 stones/hectare are planted for the growth of *Laminaria japonica*.

According to Bardach et al. (1972), bottom cultures in productive areas yield about 2.4 metric tons/hectare. Yields for raft cultures are not available, but they must be higher than those on the bottom. As of 1960, 3,000 to 5,500 hectares of coastal waters were utilized for the cultivation of *L. japonica* in China.

Monostroma and *Enteromorpha*

The green algae *Monostroma* (Hetoegusa), *Enteromorpha* (Aonori) and *Ulva* (Aosa) are the most important edible green algae in Japan (Okazaki, 1971). *Monostroma* is extensively cultivated, while *Enteromorpha* is grown to a lesser extent (MacFarlane, 1968). *Ulva* is only occasionally used as a food source, and it is rarely cultivated. *Monostroma* commands the highest price of any seaweed in Japan (Bardach et al., 1972). The cultivation techniques for each of the three green algae are basically similar to those of *Porphyra*. That is, they are grown on "hibi," which are positioned in the intertidal zone of shallow seas and estuaries. According to Boney (1965) the origin of *Monostroma* cultivation appears to lie in the plants growing as contaminants on the *Porphyra* "hibi." *Monostroma* is presently grown by itself, or mixed with *Porphyra*, *Enteromorpha*, and/or *Ulva*. Certain of the *Monostroma* culture grounds are called "taneba," for these sites are where the fixed spores and germlings appear in appreciable quantities in early autumn (Boney, 1965). According to Segi and Kida (1960) the position of the "taneba" is linked to the direction of the main surface currents of the flood tides. As many as three crops of *Monostroma* are harvested from a net before it is replaced (Bardach et al., 1972).

Gelidium, *Pterocladia*, and *Gracilaria*

As suggested previously, Japan is the primary producer of agar. *Gelidium amansii* is the principal agar source in Japan, but a variety of other species of *Gelidium*, *Pterocladia*, and *Gracilaria* are also utilized. Most of the latter seaweeds are obtained by dredging and diving in natural beds. The Japanese also propagate *Gracilaria* on nets and ropes in sheltered embayments such as Tokyo Bay. Branches of the plant are placed at intervals in the twists of the ropes, and they are in turn suspended in the nutrient-rich waters. Later the ropes are pulled up and harvested.

Greenhouse culture tanks with *Furcellaria fastigiata* (first tank) and *Chondrus crispus* (second and third tanks) at the National Research Council of Canada's Research Facility at Fink Cove, Nova Scotia, Canada (summer 1971).

The regenerative properties of *Gelidium amansii* and related forms have been utilized as a means of increasing the natural yields of the plants. Basically small fragments of the plants are scattered in bays where they are allowed to regenerate new fronds. The latter technique has been employed for many decades (Okamura, 1911). More recently "rope concrete cultivation" has been used for the propagation of *Gelidium amansii* (MacFarlane, 1968). Basically the concrete structures are similar to those employed by the Japanese for wakame cultivation, except that they are pyramidal rather than cylindrical in shape and they have a series of eyebolts embedded at different elevations. Ropes are pulled through the eyebolts to retain the fragments. Again the regenerative properties of the plants are employed to "culture" the plants on the concrete blocks. According to MacFarlane (1968) a variety of fertilizer pellets containing urea, phosphates, and indole acetic acid are now being developed to enhance the growth of *Gelidium* and other agarophytes.

Chondrus

The Atlantic Regional Laboratory of the National Research Council of Canada in Halifax has recently initiated an extensive program of marine Irish Moss cultivation (Neish, 1968). The experimental site is located about 18 miles from Halifax. It consists of several greenhouses, huts, and tanks (outdoor and indoor) with a constant stream of water. Studies of seaweed growth, reproduction, and stock selection have been initiated.

Neish and Fox (1971) describe a variety of greenhouse experiments on vegetative propagation of *Chondrus crispus*. Detached plants (i.e., plants lacking holdfasts) are capable of continuous growth when held in greenhouse tanks supplied with flowing seawater. Growth rates were assessed under different light intensities, aeration, photoperiods, as well as varying concentrations of several nutrients. Nutrients (calcium nitrate, urea, diammonium phosphate, and superphosphates) were supplied by pulse feeding with different fertilizers or by the slow addition of nutrients in plaster of paris pellets. Calcium or sodium nitrate and ammonium nitrate stimulated growth and enhanced pigmentation. Urea was a poor source of nitrogen. Continuous illumination and high temperatures (15-20°C) gave the fastest rate of growth. Growth was exponential with doubling times occurring in 2-3 weeks.

A selection of rapidly growing strains was initiated by Neish and Fox (1971). One strain (T-4) not only grew faster than others, but it was less susceptible to epiphytization, which was a major problem in some experiments. Pieces of fronds from a large plant (T-4) typically showed an enhancement of growth until the plant became quite large. Neish and Shacklock (1971) studied the successional development of a clone from the T-4 strain. A single clone was grown from 4.5 g on 1 May 1970 to a total biomass of 1 ton by September 1972. Typically the detached plants assume a dense spherical shape and they remain vegetative. The larger plants spontaneously fragment, particularly when phosphorous is limiting.

Further experiments on vegetative propagation of Irish moss strain T-4 are described by Neish and Shacklock (1971) and Shacklock, Robson, Forsyth, and Neish (1973). The effects of differential flushing rates, combinations of fertilizers, population densities, additions of carbon dioxide, and light quality are summarized. Of particular interest was the finding that the chemical composition of cultured plants could be altered by changes in culture conditions. Thus, plants growing rapidly in nitrogen-enriched seawater have a low content of total solids and carrageenan, and a high content of nitrogenous materials. When nitrogen-enriched plants are transferred to unenriched sea water there is a rapid increase in percent carrageenan and total solids and a decrease in nitrogen compounds. Thus, a "ripening" or "fattening" period with no nutrients should be incorporated in any aquaculture program with *Chondrus crispus*. Wild plants growing *in situ* also go through these same changes during the summer when nitrogen is low (Fuller and Mathieson, 1973). Temperature also has an effect on these changes, for the temperatures which produce the best growth with fertilizers give the best carrageenan yields (Shacklock et al., 1973).

Chen, McLachlan, Neish, and Shacklock (1973) have recently shown that kappa carrageenan is found in the gametophytic plants of Irish moss, while lambda carrageenan is present in the sporophytic phases. Kappa carrageenan is the major gel fraction from Irish moss (Stancioff and Stanley, 1969). As suggested by Shacklock et al. (1973) "seed" selection of differential phases would provide a uniform and consistent supply of the different carrageenan fractions.

Neish and Fox (1971) discuss the application of their work to commercial cultivation of Irish moss. They state that it would not be profitable as a greenhouse crop, nor in a system employing supplemental artificial illumination. However, cultures in outside impoundments might be profitable from May to September at their latitudes. Adequate nutrients (particularly nitrogen sources), controlled access to sea water, temperatures greater than 10°C, and the availability of superior strains would be essential.

Macrocystis

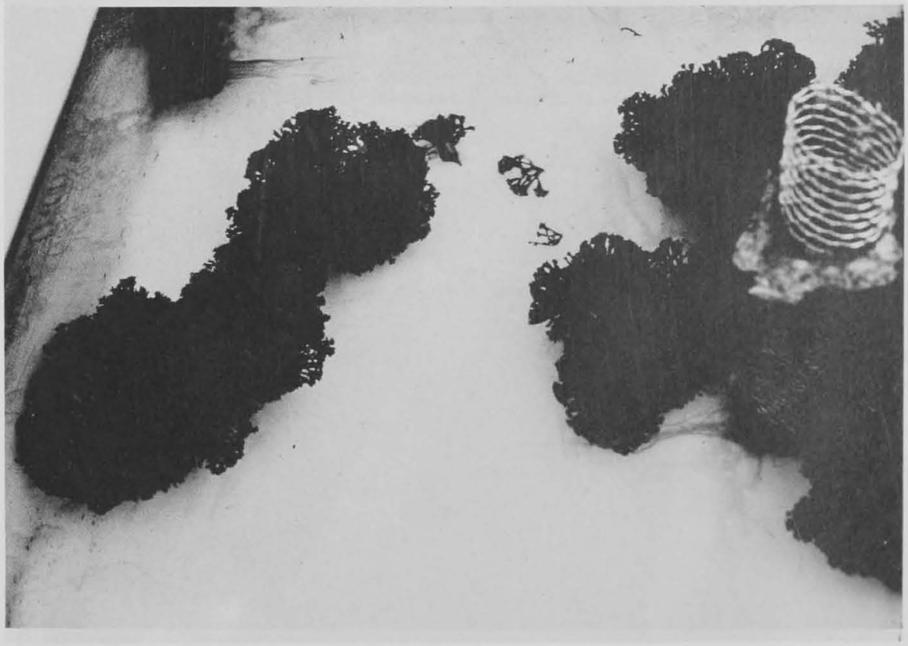
Macrocystis pyrifera is one of the most important natural resources on the California coast, for it is a major source of algin as well as a significant component of the nearshore kelp bed community (North, 1971). A rapid deterioration of kelp beds has occurred in southern California since 1940, and it has caused considerable concern for the welfare of this valuable resource. An intensive study was conducted by North and his associates from 1956 to 1962 to determine the cause of the kelp decline (North, 1971). One of the major findings was that excessive grazing by sea urchins (*Strongylocentrotus purpuratus*) was destroying many beds. The urchins were so numerous that reforestation was not occurring; the imbalance of urchins was primarily due to the absence of an important predator, the sea otter. In 1962 a new project, "The Kelp Habitat Improvement Project," was initiated in order to control urchin populations and to restore the vanishing kelp beds.

Close-up photo of *Chondrus crispus* in the greenhouse at the National Research Council of Canada's research facility at Fink Cove, N.S. Note the spherical, compacted shape of the plants.

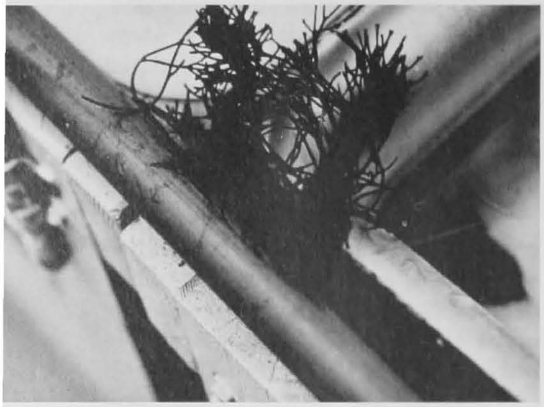
North (1972, 1973) gives a detailed description of *Macrocystis* cultivation and the habitat improvement studies since 1962. A natural evolution of mariculture techniques has developed. Initially transplant techniques were attempted with large *Macrocystis* plants (North, 1964). It was hoped that a natural "seeding" of adjacent areas would occur and that the beds would be "reforested." The transplants were very laborious and the plants were rapidly eaten by resident urchins and/or fish populations. Direct killing of urchins by hammers was attempted to reduce urchin populations and allow new colonization of *Macrocystis* plants. This was a very time-consuming operation, and ultimately quicklime was used prior to transplanting, for it kills urchins immediately upon hitting their tests. Some restoration of beds ultimately occurred by transplantation and continual application of quicklime.

Ultimately mass culture techniques were evolved and microscopic sporophytic stages were used as "seed" for natural "reforestation" (North, 1972). The embryonic sporophytic stages of *Macrocystis* have a "sticky" exterior; thus, they are cultured until they exhibit a sticky outer surface. Then the cultures are scraped free and dispersed in the sea. Quicklime is again used to kill the sea urchins prior to "seeding." The results of a "seeding" operation are not evident until 3-4 months after their dispersal. Six to nine additional months must elapse before a juvenile kelp develops sufficient surface canopy to be visible.

A variety of other dispersal techniques were attempted (North, 1972, 1973). In some cases the "sticky" sporophytes were bathed with lead particles to aid with dispersal and to provide negative buoyancy. Mass cultures have also been initiated on a substrate of glass cloth. The cloth is 18 inches wide and of varying lengths up to 30 feet. A dense spore suspension is introduced to the holding aquarium and allowed to settle on the cloth for several days. After being well established the cloth is maintained in a chilled, filtered, and ultraviolet sterilized flowing seawater tray. After 1-2 weeks the embryonic sporophytes are visible. Their surfaces are sticky at this time and they can be dispersed into the sea. Dispersal involves scraping the tiny plants off the cloth near the bottom by a scuba diver. Recently an attempt has been made to grow kelp juveniles on plastic (PVC) rings, with a ¼- to 12-inch diameter. Ultimately, the rings with their attached embryos are glued by an epoxy resin to a rocky bottom. The latter method was not very successful, because several starfish were attracted to and ate the epoxy, as well as the kelp sporophytes. North (1973) gives a detailed account of the kelp culturing system his group has developed for mass culture of "seed." The transplants of kelp embryos on strips of glass cloth are similar to the "rope culture" techniques developed by the Japanese for wakame and kombu.



Close-up photo of *Chondrus crispus* in tanks at the National Research Council of Canada's research facility at Fink Cove, N.S.



Close-up photo of *Furcellaria fastigiata* at the National Research Council of Canada's research facility at Fink Cove, N.S.

Fish and urchin grazing often restricted the transplantation and "reforestation" of kelp plants. According to North (1973), about 2,000 adult plants are needed to stabilize and survive grazing, as well as to overcome stress conditions associated with storms. An attempt was made to reduce fish grazing by establishing a "kelp nursery" enclosed within a tent. A 4-inch mesh was employed. The nurseries were only partially successful, for they did not exclude the smaller fish. A 1½-inch mesh is now being employed. Estimations of fish grazing showed that three adult kelps/fish was a relatively stable condition. It was estimated that a biomass increase of about 600 kg/day of kelp was needed to prevent fish depletion. The transplantation of large *Macrocystis* plants was found to attract many herbivorous fish and urchins. Even so it was found that fish grazing was more important in certain areas than urchin grazing.

North (1973) emphasizes that he is attempting to develop "seeding" techniques which are economically feasible for use in the United States—i.e., with its high labor costs. He estimates that an average survival rate is 1/100,000 with their present techniques. Thus, their culturing techniques are being developed to produce billions of embryos at a very inexpensive price.

Another major area of *Macrocystis* work has been an attempt to select heat-tolerant strains, for abnormally high temperatures can cause kelp decline. Heat-tolerant strains appear to exist, particularly in more southerly areas, and they show good potentials as transplants (North, 1971).

Eucheuma

The tropical red algal genus *Eucheuma* is another major source of the phycocolloid carrageenan. According to Doty (1970, 1973) the genus can be divided into groups; the *cottonii* types that contain iota carrageenan in their cell walls and the *spinosum* types that contain kappa carrageenan. Iota carrageenan disperses quickly into cold water, and it does not form as rigid a gel as kappa carrageenan. Iota carrageenan has many industrial applications. The major source of *Eucheuma* is in Southeast Asia and the demand for its extracts, particularly iota carrageenan, exceeds the supply. Overharvesting and variability of wild-crop procurement have encouraged the development of *Eucheuma* mariculture.

Doty (1973) and Parker (1974) give detailed accounts of *Eucheuma* farming in the Philippines and Micronesia. Successful farms were evolved after a variety of different propagation methods, growth studies, and environmental investigations were conducted on *E. striatum* and *E. spinosum*. Grazing by fish and sea urchins was a major factor restricting direct planting on reef bottoms. Thus, constant-level plant techniques were developed, where the plants were held at a constant distance from the bottom. "Seed" or pieces of fronds weighing 50-150 g are tied to the mesh intersections of monofilament nets with soft polyethylene strips. The nets measure 2.5 × 5 m, and they have a mesh size of 25 cm^2. The nets are tied to mangrove poles, which in turn are supported by galvanized wire. The system of nets and poles is very similar to the Japanese "hibi," except for the dimensions and the monofilament lines. About 10 kg of *Eucheuma* are planted on a single net. Typically the nets are arranged in four modules with 800 nets each; the four modules make a 1-hectare farm.

According to Doty (1973) the cost for installing and operating a 1-hectare farm in the Northern Sulu Sea area of the Philippines is about US$3,126/year based on a 3-year amortization. Other costs (i.e., overhead) are variable depending on the location and personnel. About 10 tons of dry weed/hectare has been produced at Tappan, leaving 50-100 g of live weight of each thallus for "seed." It is estimated that 30 tons is reasonable on a well kept farm. Clean *Eucheuma* yields about $250-$300/ton (dry) FOB Manila. Thus, Doty (1973) states that "on a given area, *Eucheuma* farming can provide more than three times the dollar return that sugar brings."

Close-up photo of tank and *Chondrus* plants inside the greenhouse at the National Research Council of Canada's research facility at Fink Cove, N.S.

SEA GRANT PROJECTS

A variety of Sea Grant projects are currently being conducted in order to provide basic information for enhanced industrial utilization and mariculture of economic seaweeds. Doty's and North's projects have been discussed in an earlier section and they need not be reviewed. The accomplishments of several other investigators are relevant to our discussion of seaweed aquaculture.

Dawes and his associates at the University of South Florida in Tampa (Dawes, Mathieson, and Cheney, in press; Dawes, Lawrence, Cheney, and Mathieson, in press; and Mathieson and Dawes, in press) have conducted a variety of detailed autecological studies of Florida *Eucheuma* species, particularly *E. isiforme*. As suggested previously, the latter genus has great economic potential as a source of iota carrageenan. Thus, Dawes, Mathieson, and Cheney (in press) have evaluated the feasibility of its culture in Florida, because of the more stable socioeconomic climate in Florida than in the Indo-Pacific area. H. Humm has initiated a variety of culture studies of agar (*Gracilaria*) and carrageenan-producing species (*Hypnea*) of the West Florida area (H. Humm, University of South Florida, St. Petersburg, Fla., pers. comm.). Specifically he has attempted to increase the amount of solid substrate for "seeding" economically important species. In addition he has attempted to develop culture techniques for the production of loose algae in impounded areas. Studies by M. B. Allen and C. P. McRoy at the University of Alaska have attempted to determine the feasibility of cultivating *Porphyra* (or nori) in Alaska. A good market would exist for nori in Japan and other oriental countries.

Waaland (1973) has summarized a series of ecological studies on the Pacific Northwest carrageenophytes *Iridaea cordata* and *Gigartina exasperata*. He describes the development of a simple transplantation method, as well as the results of laboratory findings on optimal light and temperature conditions for sporeling growth. He emphasizes that such information is fundamental if the plants are to be successfully cultivated. Norris and Kim (1972) give a detailed account of thallus development in some of the Puget Sound Gigartinaceae. A thorough understanding of harvesting effects and regrowth potential is basic to successful management of an economic marine crop such as *Iridaea cordata*. Mathieson and associates at the University of New Hampshire have also evaluated the ecology, physiology, reproductive biology, biochemistry and optimal environmental factors for the growth of *Chondrus crispus* and *Gigartina stellata* (Mathieson and Burns, 1971; Burns and Mathieson, 1972a, b; Fuller and Mathieson, 1972; Mathieson and Prince, 1973). Both of these species are harvested in mixed lots as a source of carrageenan in the North Atlantic. An economic evaluation of the Irish moss industry, including its potential for aquaculture, has been outlined by Patell (1972).

Interior of greenhouse at the National Research Council of Canada's research facility at Fink Cove, N.S. showing tanks, lights, and paddlewheel system for aeration.

Neushul and his associates at the University of California at Santa Barbara have initiated a wide variety of studies of seaweeds, in order to increase their available supply and utilization (M. Neushul, University of California at Santa Barbara, Santa Barbara, Calif., pers. comm.). Detailed studies of spore ecology have been conducted, including the determination of settling rates and the effects of water motion on germination and growth of spores (Charters, Neushul, and Coon, 1972; Coon, Neushul, and Charters, 1972; Neushul, 1972). A resource management study of the agarophyte *Gelidium robustum*

Exterior culture tank at the National Research Council of Canada's Fink Cove, N.S. research facility, showing the concrete foundation and paddlewheels for aeration.

has been conducted (Barilotti and Silverthorne, 1972) to determine optimal time of harvesting, regrowth and reproduction potential after harvesting, and seasonal agar production. Detailed economic studies (e.g. Silverthorne and Sorensen, 1971) have also been initiated in order to determine the needs for seaweed products, public policy implications of mariculture, and the enumeration of the most favorable seaweed cultivation industries in southern California.

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