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Outdoor cultivation of sea vegetables

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Summary The outdoor cultivation of sea vegetables is carried out on a large scale in the Orient, mainly in Japan, China, Taiwan, Korea and the Philippines. Food crops are the most important among the sea vegetables cultivated, with Porphyra and Undaria being the more important in Japan and Laminaria in China. Eucheuma, an industrial crop containing the phycocolloid carrageenan, is cultivated in wide areas of the Philippines. The cultivation of the major food crops, which developed quickly over the past 30 years, is largely based on the results of research, especially with regard to seeding procedures, which have reached a certain level of sophistication.

The major crops of sea vegetables are cultivated attached to ropes or nets located in a suitable site and habitat. Crops of limited economic value, however, are still cultivated by the old, primitive method of planting on stones on the ocean bed and other similar means. The location and timing of farming are selected with regard to the requirements of the plants for light, temperature, water movement, exposure to air (for the intertidal species), *etc.* Cultivation of seeding material of the three food crops and seeding of ropes and nets is carried out indoors under more or less controlled conditions. When the sporelings become established they are transferred to cultivation grounds in the ocean. When the plantlets grow too densely (in Laminaria) they have to be separated and replanted at the correct distances. This is done several weeks after transplantation to the ocean, when they are large and sufficiently strong. Eucheuma and other industrial crops are propagated vegetatively, using cuttings and fragments as planting material. Where seawater is lacking in nutrients, fertilizers are applied to guarantee a higher yield. The harvest is carried out manually, except for Porphyra, for which mechanical harvesters are used. Sea vegetables are attacked by pathogens that may cause severe damage to the crops. Diseases caused by improper growing conditions are also known. Grazers may also inflict losses. In all major crops the strains cultivated have been selected. In a few cases hybridization and other genetic techniques have been used to obtain domesticated varieties that can grow and yield far beyond the limits of their wild-type parents.

Despite the fact that some mechanization has been introduced into the cultivation of sea vegetables, it is still by and large a highly labor-intensive enterprise. Nevertheless, it competes well with terrestrial crops in the Orient from the economic point of view.

Interest in the cultivation of sea vegetables is widespread in the West and much experimental work aimed at its materialization has been underway during the last *ca.* twenty years.

Introduction

Outdoor cultivation of desirable marine macroalgae, the sea vegetables (this term is used in the extended meaning embracing all cultivated seaweeds, not just food crops), has been practiced in Japan at least since the beginning of the 17th century[98] and in China for about the last 200 years[87]. It developed from previous utilization of the natural resources and started as the mere provision of new suitable surfaces for settlement of useful algae. The first alga to be cultivated was Porphyra (nori in Japanese, zicai in Chinese), which is economically the most important cultivated alga to this day. Until the fifties of our century, cultivation of sea vegetables has slowly expanded geographically, additional edible algae have been included, and techniques have been slowly improved and developed.

A purely scientific achievement, the clarification of details of the life history of the European *Porphyra umbilicalis*[24], inspired studies by Japanese scientists, and the subsequent study by Kurogi on the life history of *P. tenera*, published in 1952 and 1953[42], set the Japanese nori industry on the course to modernization. A similar development took place in China, with studies by Tseng being published in 1954–56 and translated into practice in the early sixties[87]. The development affected the studies and cultivation of other food crops as well, chiefly Laminaria (cultivated in Japan since early in the 18th century[34] and in China from 1943[14]) and Undaria (cultivated in Japan since 1960[2] and in China since 1935[87]).

The last three decades have seen a tremendous development in sea vegetable cultivation, due to achievements such as breeding warmth-tolerant strains of Laminaria and developing the technique of summer seeding in the sixties and seventies[8, 14], which opened a new era in the cultivation of this crop in China. The area farmed is thus expanding rapidly; a continuously growing number of species useful for a number of purposes is being incorporated; new methods and techniques are being introduced; and additional regions of the world are becoming involved. Nowadays the cultivation of sea vegetables is widespread, mostly in the countries where it was initiated – Japan and China – and to a lesser extent in Korea, the Philippines and Taiwan. Intensive experimental work is underway, aimed at its establishment in many other parts of the world.

Cultivation of industrial crops was started rather recently, but has developed relatively rapidly. In the early seventies, cultivation of the carrageenophyte Eucheuma became established in the Philippines, where it is farmed on a considerable scale[42]. In China, however, where its cultivation was begun in 1960, it has not developed much[48]. The agarophyte Gracilaria is widely cultivated in Taiwan, usually in polyculture with other marine organisms.

The production of marine algal biomass for energy conversion or for the removal of excess nutrients entering the marine environment in sewage water is still at the experimental stage *cf.*[75, 93]. Practically all of the commercial cultivation of sea vegetables is carried on out-of-doors. However, some crucial phases, namely the cultivation of seeding material and the seeding process itself are done under controlled conditions indoors. Experimental work on crop cultivation indoors is underway, mainly in North America. Neither topic will be dealt with here in detail.

Despite the marked differences between the natures of the terrestrial and the marine environments, and those of the organisms involved, many of the problems and activities associated with conventional agronomy have equivalents in practical thalassonomy (lit. management of the sea, the art and science of marine crop production, 'marine agronomy'). Some are, *e.g.* the choice of crop, site selection, 'bed' preparation, sowing, weeding, fertilizing, pest and disease control, and harvesting. Equivalents of other agricultural practices, such as soil tillage, are not yet practiced in the commercial cultivation of sea vegetables, although they have been tested in experimental systems.

The differences in environment, however, naturally necessitated modifying some accepted agricultural techniques or devising entirely new ones to cope with the demands of the marine environment and conform with the nature of the marine plants. One example is the manner of planting, which is totally different with the sea vegetables. Since the plants require only physical support from their substrate, and extract their nutrients from the surrounding seawater, they may be grown on an artificial firm substrate at a level where light conditions are at their best, no matter how deep the ocean bottom is at the site. When cultivated at sea, sea vegetables are therefore always cultured attached to a substrate; when grown in ponds on land, however, they may be cultivated in the unattached state.

Here commercial cultivation out-of-doors will be emphasized, while experimental cultivation will be mentioned only briefly. The major questions concerning sea vegetable cultivation will be discussed, with the similarities and dissimilarities between it and the cultivation of terrestrial crops borne in mind.

Crops cultivated

Only a few sea vegetables are commercially cultivated, only four of them on a relatively large scale (Table 1). Three of these, Porphyra, Laminaria (kombo or konbu in Japanese, kunbu in old Chinese, haidai in modern Chinese), and Undaria (wakame in Japanese, quandai-cai in Chinese), are food crops, cultivated mainly in Japan and China[4] and to a lesser extent in Korea[60]. The fourth, the industrial crop Eucheuma, a source of the phycocolloid carrageenan, is cultivated in the Philippines[19,20,66] and on a small scale in China[48,87]. Its yields are claimed to have recently met the world demand for Eucheuma carrageenan[42,46].

Other sea vegetables are cultivated on a much smaller scale. These

Table 1. Sea vegetable crops cultivated, world-wide farming areas and estimated yields (year in parentheses)

Crop	Species cultivated (* = most important in cultivation)	Countries	Area cultivated (10^3 hectares)	Yield (10^3 MT dry weight)	Reference
PORPHYRA			75 (1978)	30 (1978)	55, 87
	* *P. tenera*	Japan, China			4, 87, 98
	* *P. yezoensis*	Japan, China			4, 87, 98
	P. kuniedai	Japan			4, 87, 98
	P. angusta	Japan			4, 98
	P. pseudolinearis	Japan			4, 87, 98
	* *P. haitanensis*	China			87
	P. seriata	Japan			87
	P. arasaki	Japan			87
	P. guangdongensis	China			87
LAMINARIA			50–60 (1979)	300 (1979)	87, 97
	* *L. japonica* (inc. var. *ochotensis*)	Japan, China, Korea			36, 87
	L. angustata	Japan			35
	L. religiosa	Japan			35
UNDARIA	* *U. pinnatifida*	Japan, China, Korea	18 (1979)	25 (1979)	55 86, 87, 98
	U. undarioides	Japan			55, 66
	U. peterseniana	Japan			55
EUCHEUMA				20 (1979)	
	* *E. denticulatum* (= *E. spinosum*)	Philippines			42, 48, 87
	* *E. striatum*	Philippines			45, 87
	E. cottonii	Philippines			45, 87
	E. gelatinae	China			86, 87

Table 1 (*continued*)

Crop	Species cultivated (* = most important in cultivation)	Countries	Area cultivated (10^3 hectares)	Yield (10^3 MT dry weight)	Reference
GRACILARIA			0.3 (1979)	12 (1979)	15
	* *G. verrucosa*	Taiwan, China, Japan			5, 15, 81, 86 87
	G. gigas	Taiwan			15, 81
	G. lichenoides	Taiwan			15, 81
	G. compressa	Taiwan			78
	G. coronopifolia	Taiwan, Hawaii			4, 21
	G. bursapastoris	Hawaii			21
GLOIOPELTIS	*G. furcata*	China, Japan		0.3 (1979)	4, 87
MONOSTROMA			1.5–7.5 (1979) (includes Enteropmorpha)	1–2 (1972)	87
	* *M. nitidum*	Japan			66, 78
	M. latissima	Japan			78
ENTEROMORPHA			included in Monostroma		87
CAULERPA	*C. racemosa*	Taiwan			4
GELIDIUM		Japan	very little		5, 60, 66
GELIDIELLA	*G. acerosa*	India	very little		49, 58, 59

include the edible green algae Monostroma, Enteromorpha, Ulva and *Caulerpa racemosa*, the red agarophytes Gracilaria, Pterocladia and Gelidium, and the red alga Gloiopeltis, cultivated for human consumption as well as for the production of glue[4] and a sizing material for the textile industry[87]. Fresh Gracilaria is also used to feed small cultured abalone (Haliotis)[15]. These sea vegetables as well are cultivated mainly in Japan, China and Taiwan[4,17,52,60,78,81,87].

Selection of farm location and preparation of site for cultivation

For cultivation out-of-doors, where the possibility of controlling the environmental conditions is rather limited, the selection of the right site is crucial for the success of the crop. Different crops, naturally, have different requirements for cultivation conditions. For example, for Porphyra, Yoshida and Akiyama[98] stated that it is most important to select a site that is protected from severe currents or waves that may destroy or damage cultivation gear, a site where the tidal range during spring tide is no less than 1–1.5 m and the current speed about 20 cm s^{-1} (10 when the seawater is rich in nutrients, 30 when it is poor). Where currents are too strong or waves too large, the construction of wave-breakers or weirs may make a site suitable for nori cultivation[98]. Undaria, on the other hand, requires strong currents[55]. It grows best above a sandy seabed with scattered rocks and pebbles. *Eucheuma spinosum* requires a depth of 1–3 m, rather cool water, and a strong enough current (Neish in[21]).

Gracilaria pond sites in Taiwan are selected where a supply of fresh water is available to compensate for evaporation losses, where winds are not so strong as to dislodge the plants from their places, where tidal fluctuations are large enough to enable periodic exchange of water in the pond, where the bottom is sandy loam, and where fluctuations in pH are preferably only between 8.2 and 8.7 but no more than between 6 and 9 (ref. 80).

Setup of sea vegetable farms

The vast majority of sea vegetable farms are located in the sea. Cultivation in ponds or tanks on land is carried out to a much smaller extent.

At first, cultivation in the sea amounted to merely providing the desirable algae with substrates not naturally at their disposal. This was done in many ways; in China, by clearing rocks of other algae and sessile animals, by scraping and then spraying with lime the next day[87], at the right time of the year, which was the reproduction period of the particular alga. In Japan this was done by planting stones or concrete blocks on the seabed, by blasting reefs[36], by anchoring plastic floats at various depths[4] in the subtidal zone, or by sticking brush in the mud in the intertidal area[98]. These methods have largely given way to more efficient ones for the major crops in both countries, but for some less important crops like Gloiopeltis or Gelidium and for the major crops in Korea, they are still in use[4,87].

A variety of fixed or floating nets, ropes and rafts were next used as substrates for the algae. They were first made of natural fibers – hemp, coir or palm fibers, which require long soaking before use to leach out harmful substances – and then, in about 1960, of synthetic ones. Mariculturists in China and Japan developed a variety of specialized methods to suit the particular crop and region. Nevertheless, for some crops in some places rather simple methods are still used, such as those for Eucheuma cultivation in China. There, it is cultivated on rocky bottoms by inserting fragments of the plants into crevices in natural reefs, by spreading them on the bottom and holding them in place by stones, or, mostly in recent years, by tying fragments to coral branches and having divers arrange them on the bottom[87].

One group of cultivation supports includes different types of nets. Vertical nets and bamboo screens, common in the past for nori cultivation in Japan, are hardly used now. Horizontal nets are almost exclusively used for Porphyra cultivation in Japan and China[87,98] and give the highest yields of Eucheuma in the Philippines[21]. The nets used for Porphyra have 15 x 15 cm openings, whereas those used for Eucheuma have openings of 25 x 25 cm. The nets may be tied to poles inserted in the seabed at a fixed level in the intertidal zone (where the tidal range is no more than 1–2 m) for Porphyra, or in the subtidal zone *ca.* 50 cm above the reef-flats for Eucheuma in the Philippines. This is the so-called 'fixed-net' method. Where the tidal range is 3–6 mm, Porphyra is grown in the intertidal zone on so-called 'raft-type'[98] or 'lift-type'[87] nets. These are tied to poles with longer ropes and are equipped with floats. Thus, their level changes with the tidal fluctuations within a certain range controlled by the length of the ropes. The semi-floating net is an improvement, where the nets are equipped with short legs or a wooden frame that rests on the bottom during low tide, thus keeping the nets at a fixed lowest level which is above the low water level. Hence, during low water the nets are left exposed for a certain length of time, which may be adjusted by the length of the legs. With the rising tide these nets become submerged and then float. The 'floating culture'[98] or 'floating method'[87] is used in deep water. Here the nets are never exposed. The development of the intertidal Porphyra on these nets is not as good as on exposed nets, the young stages being the most susceptible to continuous immersion. Therefore, nets are transferred from the intertidal zone to the deep water only when the plantlets are big enough to stand continuous immersion (1–3 cm long). Monostroma is grown similarly[4].

Another group of cultivation constructions are the various arrangements of ropes and 'rafts.' Laminaria and Undaria are grown in China and Japan on such ropes[36,87], and for Eucheuma this is the most popular method in S.E. Asia[21]. The cultivation ropes may be arranged horizontally, in which case great lengths may be stretched between two poles inserted in the bottom or tied to anchors and floated at a desired depth. Ropes may also hang vertically from horizontal lines or from floats. Several such bamboo floats tied together form a 'floating raft'[14,87]. For Laminaria and Undaria, which are often grown together, horizontal lines may be kept at various depths, depending on the transparency of the water, from just below the surface to a depth of several meters. Cultivation of these two sea vegetables is more common on vertical ropes in China, whereas in Japan horizontal cultivation ropes are more popular. For Eucheuma, the ropes are tied between low poles about 50 cm above the reef-flat, as for nets.

Vertical cultivation ropes may be up to five meters long (usually they are 1–1.5 m long in China and longer in Japan) and may be located where the water is 10–15 m deep. They are kept in position by weights attached to their lower ends. Each may carry up to 30 plants. Since the plants at the upper part of the rope receive more light than those on the lower part, the cultivation ropes must be inverted, usually twice during the growing season[85]. The depth of the plants also needs to be adjusted from time to time according to their phase of development and the changing environmental conditions, especially the transparency of the water.

A variety of raft forms has been devised in China[14], but in recent years the single-line floating raft has been used in most cultivation grounds[87]. This type is better able to withstand strong currents and heavy waves.

An attempt was made to grow Gracilaria as well on floating rafts in China[44]. However, it seems that it is more successful on rafts fixed at certain levels[73]. In Japan, Gracilaria is grown on horizontal ropes[5].

Cultivation of Laminaria on sandy seabeds in Japan started by planting stones on the bottom for the settlement of spores, as had been done in rocky areas. Later, specially designed, fenestrated cylindrical concrete blocks were used. Both had some disadvantages. They gradually sank into the sand and the fronds were injured by the stones or blocks. Attempts were made to overcome these problems using concrete 'legs' and plastic pipes, and partial success was achieved in experiments[85].

In Taiwan Gracilaria and *Caulerpa racemosa* are cultivated in shallow ponds by evenly scattering algal fragments to grow unattached, usually in sites selected in areas that are not windy. Caulerpa will root itself, but winds may dislodge Gracilaria, which is sometimes covered with old fishing nets to keep it in place[81]; or, if the ponds are too big, a line or two of bamboo windbreakers are constructed to divide them and decrease the wind effect[15]. Gracilaria is often grown in polyculture with milkfish (Chanos), shrimp (Penaeus) or mangrove crab (Scylla)[15,81] to improve the profitability of the ponds.

Inoculation of farms

In Japan and China, the three major food crops, Porphyra, Laminaria and Undaria, are artificially seeded indoors by spores produced, released and settled under more or less controlled conditions. Seeding is performed in tanks containing fertile plant material induced to sporulate, into which the cultivation substrates (ropes, nets, etc.) are dipped. After the spores settle, the sporelings obtained are allowed to establish themselves before they are transplanted into the sea. Previous studies of the life histories of the various crop species and the environmental requirements of each phase enabled the sophistication of the seeding techniques for these crops. Both Porphyra on the one hand, and Laminaria and Undaria on the other, have microscopic, delicate vegetative phases in their life histories. In Porphyra this is the sporophyte, the so-called conchocelis phase; in Laminaria and Undaria it is the gametophyte. These are cultured indoors to maturation and fertility and serve as seeding material (the details of this indoor cultivation are out of the scope of this account). In addition, in some Porphyra species like *P. yezoensis* and *P. kuniedai*, the leafy, crop phase may produce neutral spores. These may be seeded on the nets either in indoor tanks or in the sea[87,98] and develop directly into the leafy phase.

Artificial induction of reproduction in Laminaria and Undaria enabled seeding of the cultivation substrates 2–3 months ahead of the natural reproduction season, and consequently, early transplantation of seeded ropes into the sea. This resulted in prolongation of the growing season and a much earlier harvest, compared with naturally seeded substrates. It also gave the crop plants an advantage over weed species[3,35,87]. In Porphyra, techniques involving the freezing of seeded nets (after partially dehydrating the young plantlets) enabled transplantation into the sea at any desired time and the replacement of depleted or infected nets[98].

With Laminaria, two transplantations are required. The spores settle on the seedling cords very densely and the sporelings, when grown, compete with and thus weaken each other. Therefore, the seeded cord transplanted to the sea is either cut into small pieces *ca.* 5 cm long, each with a few sporelings, which are inserted into the cultivation ropes at the correct intervals, or it is left in the sea until the young sporophytes reach the length of 10–15 cm. The sporophytes are then detached from the seeded cords and attached to (or usually twisted into) the cultivation ropes and transplanted again, this time over a wider area.

Natural seeding by spores produced in the sea, from either natural or cultivated populations, is still in use for some minor crops such as Gloiopeltis or for the major crops in areas where phycoculture is not much developed, such as Korea[87], where they are grown by the old methods on stones and rocks. Monostroma is also naturally seeded on nets placed in the sea, where spores are released, and subsequently transferred to suitable growing areas[78].

The important industrial crops, Eucheuma and Gracilaria, are propagated vegetatively from plant fragments. Fragments may be stuck in crevices in natural reefs or held in place on the bottom by stones, as is the practice with *Eucheuma gelatinae* or Gracilaria in China[87]. They may be held in place by short, split bamboo sticks pushed into the soft bottom[81,87] or may be tied to nets or ropes, as in the wide Eucheuma farms in the Philippines, or twisted into ropes (Gracilaria in Japan[5]).

Gracilaria and *Caulerpa racemosa* ponds in Taiwan are seeded by spreading vegetative plant fragments evenly over the pond, where they remain unattached[15].

Successful experimental cloning of Porphyra gametophytes by mechanically disintegrating thalli and culturing individual cells to mature plants makes it possible to obtain a large number of genetically identical plants[101]. Successful experimental cloning of Laminaria gametophytes and the ability to keep them for long periods in a vegetative state[26] make it possible to seed ropes and transplant Laminaria at any desired time. Both techniques will probably be used in commercial cultivation in the future.

Fertilization

Seawater usually contains all the nutrients required by marine plants for adequate growth. However, in some areas the nitrogen concentration may limit growth and affect the yields of commercial crops. This has occurred in some farmed areas in Japan and China. Nitrogenous fertilization increases the yields in these cases, and therefore such Laminaria and Porphyra farms are regularly fertilized in both countries[14,87,98]. According to Tseng[87], fertilization is imperative when the inorganic nitrogen concentration in the seawater is below 3.5 μM. When it is around 7.1 μM, the addition of nitrogen improves the quality of Porphyra product, and when it is 14.2 μM or more there is no need to fertilize. Gracilaria ponds in Taiwan also are often fertilized[15,81]. Seawater may become deficient in phosphate as well, but this does not occur in the existing marine farms.

At the present time, the most commonly used fertilizer is ammonium sulfate[87], but other fertilizers have been used as well, such as sodium nitrate[14], ammonium nitrate[4,14], urea, or fermented pig and chicken manure[15,81]. Fertilizers are usually applied by spraying larger farms with concentrated solutions (10%–15%), either from boats[87] or, in Japan, sometimes from helicopters[91]. The older method of hanging porous earthenware bottles containing fertilizers among the plants[14] to gradually dispense the nutrients is still used in some smaller farms. They have, however, largely been replaced by finely perforated plastic bags as slow dispensers of fertilizers[86,87]. For young sporophytes of Laminaria 'pulse' fertilization is employed[4,14,55,86]. This is periodic immersion of the plants in concentrated fertilizer solutions. This method is especially important just before placing the young sporophytes in the sea to give them a good start in their new environment[14,87].

Fertilization experiments are usually carried out in the laboratory or in greenhouse-kept tanks. A few, however were conducted in outdoor tanks[6,96]. Fertilization in natural populations of Macrocystis, to enhance its growth, involved the use of both nitrogen and phosphate sources that were distributed by helicopters[65]. The yield was increased compared with that of nearby beds, although the natural supply of nutrients was relatively high during the period of the study. Other experiments utilizing macronutrient-rich deep water[30] showed that this may sometimes be deficient in some micronutrients and therefore would be best utilized mixed with surface water[64]. The use of nutrient-containing plaster 'pellets' that release nutrients slowly was also tested successfully[49].

Weeding

Weeds may become a severe problem in all sea vegetable farms. The weeds appearing in different farms, however, vary with the habitat and geographical region. Weed control is based on knowledge of the environmental requirements or responses of both the crop and its particular weeds and on manipulating the farms so as to shift competition between the two in favor of the former. Herbicides are not used in commercial sea vegetable farms.

Several techniques of weed control are used for the different crops. The most serious weeds in Porphyra farms are the green Monostroma and Enteromorpha[87], which are also intertidal algae, but which are better adapted to lower levels of the intertidal zone than Porphyra. Therefore, the most common procedure in their control is to tie the fixed horizontal nets so that they are exposed for about 4–5 h daily during daytime, which is too long for the weeds[98]. This necessitates moving the nets up and down on the poles every few days, according to the changes in the tidal levels[98]. With the shift to the floating net culture technique this is no longer practical, and when weed-cover on these nets becomes too dense so that it interferes with the growth of Porphyra, the nets are exposed to the air for hours or even days[87]. This harms the weeds more than it does the Porphyra. Thus, the right exposure period results in considerably lowering the density of weeds without damaging the crop. It should be noted, however, that both green algae are utilized in Japan as food and in some cases are not regarded as weeds but are harvested as by-products[5]. Sometimes they are even encouraged to grow with the Porphyra[4]. After the last harvest of Porphyra in the spring, these green algae are left to develop and are later harvested[87]. Monostroma obtains the highest prices of any sea vegetable in Japan[4]. Other techniques aimed at decreasing competition by weeds are dense seeding and care in handling of culture nets, so as not to expose the substrate for settlement of weeds[87].

In Laminaria farms, other weeds cause problems. In China, Ectocarpus, Licmophora and Enteromorpha, among others, used to settle on ropes carrying autumn sporelings and overgrow the tiny gametophytes. Thus, they prevented the development of the resulting young sporophytes until mid-winter, when the weeds matured and disintegrated, allowing the Laminaria sporophytes to resume growth[14,87]. This delayed their maturation by a few months. The problem was solved by development of a method to obtain sporelings in the summer to produce plantlets 2–3 months ahead of the usual season and then to maintain them at low temperatures indoors for transplantation into the sea in the fall, when the sea temperatures drop enough for them to grow. Under such conditions young Laminaria sporophytes have an advantage over settling spores of weeds and therefore can compete successfully with them. This method was developed in Japan in 1966[35,36], and in

China it is now the only method used[8,87]. Obtaining the right density of sporophytes on culture substrates also helps keep the weeds low. For Laminaria the right density is '2–30 seedlings per field at 400 × magnification'[99]. With Porphyra, attempts are made to ensure that spores settle as densely as possible[87].

In Eucheuma farms in the Philippines no weeding is done[74], since Eucheuma usually outcompetes the weeds under favorable conditions.

In China the 'fixed-raft method' was developed for the cultivation of *Gracilaria verrucosa*, primarily to cope with the severe weed problem that hindered Gracilaria cultivation on floating rafts[73]. The fixed rafts, which stay at the same level, get less light during high water, which deprives the weeds of the high light they require and allows Gracilaria, which needs less light, to grow better.

In Taiwan the main weeds in Gracilaria ponds are Enteromorpha, Chaetomorpha and Ectocarpus[15]. Here fish are used to control the weeds. Milkfish (*Chanos chanos*) and Tilapia are stocked in the ponds at a density of 300–400 individuals per hectare[81] (about 1000 according to Chiang)[87]. When the weed populations decrease, the fish are removed to prevent damage to the crop[81]. According to Chiang[87], Penaeus and Scylla grown with the Graciliaria do the same thing.

A few experiments focused on chemical or biological weed control have been conducted. Cui *et al.*[16] reported the use of citric acid to counter the growth of epiphytes, especially Enteromorpha, in Porphyra farms. The use of various invertebrates to check weeds has also been reported (*e.g.* the isopod *Idotea baltica*[80]; the amphipod *Gammarus lawrencianus*[80]; the snails *Trochus niloticus*[61], Lacuna, Calliostoma and Mitrella[58]; and the opistobranch *Stylocheilus longicauda*[61]). Fish such as *Acanthurus triostegus* have been used experimentally for the same purpose[61], but they also eat the tips of crop plants.

In Hawaii, Gracilaria outplanted on reefs is kept free of epiphytes by the shifting sand in the habitat[21].

Harvesting

In most places most crops are usually harvested manually. The harvest, hand-picked from the nets, lines or ropes attached to rafts, is collected in shallow boats, with the harvesters either in the boats or wading in the water, depending on the crop, method of cultivation, season, geographical location and water depth. Where the old methods of stone planting, rock clearing, sticking of fragments in reefs, or placement of fragments attached to coral pieces on the bottom are still in use, divers pick the mature plants[5], a practice that is declining.

Only in the advanced nori industry in Japan is mechanized harvesting widely used[95]. Several types of mechanical harvesters are in use, each especially designed for a particular method of cultivation[98]. Basically, they consist of a rotary cylinder with blades fixed at the periphery, such as in old-fashioned lawn mowers. Each harvester is placed on a boat with the long axis parallel to that of the boat. The line or net on which the plants grow is lifted out of the water on one side of the boat and placed a few centimeters above the blades (and kept there by rollers) with the plants hanging downwards within reach of the blades. The turning blades cut the plants a few centimeters from their bases. The boat proceeds sidewise along the line or net, and the harvest accumulates on its bottom. The line or net is lowered back into the water on the opposite side of the boat for further growth until the next harvest. Porphyra may be harvested 3–4 times from a net, usually once a fortnight (a tidal cycle). During this period it grows 10–15(–20) cm in length, and is cut back to about 3–4 cm during each harvest[4,60]. After 3–4 harvests, the nets are replaced. Monstroma, when cultivated *per se*, is harvested in a similar manner three times per net, with the nets then being replaced[4].

For Laminaria a method of harvest by tip-cutting during the growing season was developed in northern China[14]. This serves two additional purposes: it prevents losses due to tearing parts of the thallus, and it enhances the growth of the plant. Consequently, the yield increases by 12–15%[94]. Since the intercalary meristem is situated at the base of the blades, their tips are the oldest parts. Up to a third of the blade is removed with every harvest. The time interval between harvests depends on the local conditions governing growth rates. Thinning the canopy improves light conditions and water movement. It allows more light to penetrate to the lower plants, compensating for the loss of photosynthesizing area taken with the harvest. It also allows the remaining parts of the plants to float at an angle, rather than hang vertically, so that they capture more light[87,94]. The last harvest at the end of the growing season takes place in China in June–July[86,87], when the plants may have reached a length of 3–4 m[87].

Undaria is harvested only at the end of the growing season (in China in March)[87], when it is *ca.* 1 m long[60].

Eucheuma in shallow farms in the Philippines is harvested once a month by manually breaking off portions of the plants, leaving plant masses a few centimeters in diameter to resume growth and produce the next harvest[23]. In some places, where Eucheuma is cultivated on ropes, the ropes are untied from the poles at harvest time, hauled by canoes to shaded, comfortable places to be stripped of the crop, and returned after reloading with fresh seeding material to the cultivation areas[21]. In China, bottom-cultivated Eucheuma is harvested once a year, with divers collecting the entire crop[86,87]. Gracilaria in ponds in Taiwan is harvested either by hand-picking or by nets, every 30–35 days in summer and every 45 days in winter. During the summer it is sometimes possible to harvest every ten days[81]. A third to a half of the plant material harvested is removed, and the remainder is divided into small pieces and returned to the ponds as seeding material[15].

Breeding and stock improvement

As long as natural seeding was the rule in the Porphyra, Laminaria or Undaria industries, the variability of the cultivated plants was similar to that in the natural populations. The development of artificial seeding techniques enabled the improvement of stock by selection and breeding. In Japan Porphyra strains have been selected from among the wild types on the basis of yield, quality, resistance to diseases, *etc.*[98] Many of these selected strains are now cultivated commercially. Hybridization between different types of local and foreign species has also been done in Japan[98] as well as in China[100]. However, Yoshida and Akiyama[98] stated that no commercially important strain has emerged from such hybridization. By contrast, in China hybridization between different types of *Laminaria japonica* and subsequent selection of the hybrids resulted in 1962 in the development of the Haiqing no. 1 strain[87] (Hai Ching no. 1)[14], which proved to produce higher yields but, more important, to be tolerant to higher temperatures than were previously cultivated strains. This enabled the extension of Laminaria cultivation further south, to cover the entire Chinese coast. Later, the same techniques resulted in additional commercial varieties, Haiqing no. 2 and no. 3[87]. X-ray mutagenesis has also been adopted, resulted in two commercial varieties with high yield and high iodine content, which were introduced into large areas[17,87]. This work is being continued, and more and more commercial varieties have been produced, such as the high-yielding Haiza no. 1, which was introduced into wide areas of northern China from 1980 onwards[38].

Among other sea vegetables, breeding through hybridization has not yet reached a commercial level, although Saito[76] performed interspecific hybridization in Undaria and obtained strains that could stand high temperatures better than either parent.

Stock improvement of the vegetatively propagated Eucheuma in the Philippines went along different lines. Here, selection was performed through early removal of the less desirable types by harvesting, and their replacement with vegetative portions of faster growing types[20,22,23]. The Tambalang strain is the result of such selection[21].

Strain selection of sea vegetables that are not yet cultivated on a full commercial scale has also been attempted, and in a few cases preliminary success was achieved. The fast growing, usually infertile, kappa-carrageenan-producing T4 strain of *Chondrus crispus* has been isolated and extensively studied[51]. Selection for infertile lambda-carrageenan-producing strains of Chondrus was also performed[11], as well as for strains capable of growing in warmer water than can most other ones[13]. Strains of the agarophyte *Gracilaria tikvahiae* superior to the best of the wild types were obtained through mutagenesis and selection[20].

Diseases

Diseases, especially those caused by pathogens, are not yet as great a problem among sea vegetables as they are among terrestrial crops. With more and more genetically uniform varieties introduced into cultivation, however, they are bound to become a greater problem. At present, only the more established crops, Porphyra and Laminaria, and to a lesser extent Undaria, are sometimes seriously affected by diseases. Naturally, more diseases have been encountered in crops that have been under cultivation longer. Therefore, the number of known Porphyra diseases is larger than those known for Laminaria. Fewer still are known for Undaria. Diseases affect both seeding material grown indoors and the crops cultivated out-of-doors. Most diseases encountered in sea vegetable farms are ecophysiological in nature. These are physiological disturbances caused by environmental conditions. Only a few are caused by pathogens.

Among diseases of Porphyra caused by pathogens, the most common and most serious is red rot[40,97], or red wasting disease[40,87], which attacks the crop in both Japan and China. It is caused by the fungus *Pythium porphyrae*[39], may spread quickly by zoospores, and may completely wipe out a crop. It has also been reported from natural populations of several Porphyra species in other parts of the world (caused by *P. marinum* on the Pacific and Atlantic coasts of North America[29,40] and in the Mediterranean[3]) and is therefore a threat to Porphyra cultivation everywhere. Other fungi, algae or bacteria sometimes infect Porphyra or Laminaria, causing damage to crops. Among these are Olpidiopsis, Leucothrix, benthic diatoms[98], or Pseudomonas[87] in Porphyra; and Pseudomonas[10], Micrococcus or mycoplasma-like organisms[87] in Laminaria. Some of them (such as Leuchothrix[98]) infect weakened plants and others may pass with seeding material (such as Olpidiopsis, which passes through the carpospores of Porphyra[98]) and affect the next generation. The brown alga *Streblonema* *aecidioides* infects Undaria in Japan, lowering the quality of the product[97]. In other infectious diseases, the pathogen is still unknown[33]. Only a small number of them can be treated by drugs (e.g. Pseudomonas, causing the fall-off disease of Laminaria summer seedlings, which may be treated with erythromycin[10], or the bacteria causing yellow spot disease of the conchocelis phase of Porphyra, where dihydrostreptomycin helps[98]. Both are treated in the indoor seeding tanks). A number of marine algae are infected by viruses[18,50]. No commercial crop has hitherto been reported among them.

Many diseases are caused by physiological disorders resulting from unfavorable environmental conditions, for example, white rot, hole rot, tumor, bud damage[98], or green disease[47] in Porphyra; green rot and white rot[87] in Laminaria; or the 'ice-ice' phenomenon in Eucheuma[23,88]. Causes of such diseases may be the lack of light (green rot of Laminaria[87]) or excess light (white rot of Laminaria[87]); a low supply of nutrients, especially nitrogen or phosphorus[88]; very low temperatures, especially in exposed Porphyra, or too high temperatures; too calm seas, resulting in stagnant water; polluted seawater or air (to exposed Porphyra); quick changes in the environment; mechanical impact of solid particles; too low or too high salinity, *etc.*; or a combination of a number of factors. The causes of other diseases, such as the detachment of sporophytes of Undaria, are unknown[4].

Treatment of the diseases depends on knowledge of their causes. Exposing Porphyra to air for longer periods might help in some cases (exposure period of 4–5 h day^{-1} is recommended as a preventive measure for a number of diseases in Japan, including red rot[98]), whereas lowering the nets or lines for longer immersion may help in others. Nitrogenous fertilization is also used successfully in some cases. Sometimes the only way to reduce damage is an early harvest. Chemical drug treatment seems to be restricted to use in tank culture of seeding material.

Pests

Several herbivores damage sea vegetable crops. The most common are fish and sea urchins. In south China herbivorous fish sometimes graze upon cultured Porphyra to an extent requiring the use of protective nets. A similar approach was taken in the Philippines to protect Eucheuma farms from grazing fish[74]. In the past urchins caused damage to oversummering fronds of *Laminaria japonica* in China. Since summer seeding was introduced, this has no longer been a serious problem[87]. In *Caulerpa racemosa* ponds in Taiwan, Cerithium snails may multiply to levels damaging the crop and should be removed[4].

In Japan, the hydrozoan *Sertularella miurensis* or the bryozoan *Membranipora serrilanella* sometimes settle on Laminaria blades, lowering product quality. The problem is more serious in the second year of Laminaria growth, since the bryozoan settles at the end of the first year. Early harvest of the Laminaria by the end of their first year, possible for plants grown from summer seeding, prevents much of the damage[37].

In tropical waters herbivorous fishes, especially siganids and some sea urchins[20,45] (*e.g.* Diadema, Tripneustes[20]), may sometimes completely destroy the Eucheuma crop in bottom plantations[19,20]. Planting on horizontal nets or lines situated *ca.* 50 cm above the bottom reduces damage by these grazers[19], so that in Eucheuma farms this is usually not a serious problem[67]. Other measures taken against fish and urchins in Euchema farms are: hanging small bags containing paradichlorobenzene around net units to deter fish, or causing heavy clouds of lime to drift among the plants to kill or drive away urchins[20].

Experiments with some commercially important algae indicated that small creatures like isopods, amphipods or small snails, when abundant, can considerably damage crops. In tank cultures of the agarophyte *Gracilaria tikvahiae* (as *G. foliifera*) and of the carrageenophyte *Agardhiella subulata* (as *Neoagardhiella baileyi*), the isopod *Idotea baltica* and the amphipod *Amphithoe valida* consumed considerable portions of the algae when their productivity was very low[63]. Idotea preferred Gracilaria over Agardhiella, whereas Amphithoe preferred Agardhiella[63]. Similarly, *Idotea baltica*, the snail *Lacuna vincta*, and the amphipod *Gammarus oceanicus* caused considerable damage to the carrageenophyte *Chondrus crispus* in flask experiments[79].

In cultures at sea of the carrageenophyte *Iridaea cordata*, the snails *Lacuna variegata* and *Lirularia lirulata* perforated blades of the alga to such an extent that considerable portions were lost to wave action[55]. Such pests are susceptible to a number of insecticides[79]. These may be used with tank cultivation, but in farms in the sea they can harm the environment. Fish readily consumed crustacean pests, but snails had to be crushed prior to feeding them to fish[79]. The latter technique can hardly be considered feasible for control of snails on commercial farms.

Experimental outdoor cultivation

There is very great interest in the cultivation of marine algae in many parts of the world, which is reflected in intensive experimental work. Much of this work was done in North America and was recently reviewed by Mathieson[51] (including studies in the U.S. possessions and Trust Territories in the Pacific). Most of it will therefore not be mentioned here. Much of the experimental work has been carried out indoors. This, as well, will mostly not be referred to here. The experiments have in some cases reached the pilot plant level, with some of the projects being proven successful (*cf.*[51]). Nevertheless, in the West none of them has yet become a fully commercial enterprise.

In addition to North America, investigations are underway also in Central and South America (*e.g.* the West Indies[83], Brazil[96]), Europe (*e.g.* England[39], France[6], Italy[31,82]), Asia (*e.g.* Israel[28], India[9,49,68,69,72], Indonesia[84]), Africa (*e.g.* Djibouti[7], Tanzania[54]), and the Pacific Islands (*e.g.* Hawaii[21,53,74], Micronesia[61]).

A relatively large number of useful algae have been investigated. They include members of at least 25 genera, for a number of which several species are involved. Of these, the majority have not been commercially cultivated before, although natural populations of most have been utilized. These genera are the following: Macrocystis[25,30,62,65,91,93], Gracilaria[21,28,43,61,72,75,82,83,96], Chondrus[6,58], Iridaea[1,55–58,89], Gigartina[58,89,90], Eucheuma[71,84], Hypnea[28,43,53,96], Palmaria[53,58,89], Porphyra[58,89], Laminaria[27,39], Gelidium[91], Alaria[39], Saccorhiza[39], Sargassum[9,91], Gelidiella[49,68,69], Acanthophora[96], Pterocladia[28,96], Cymathere[27], Agardhiella (as Neoagardhiella)[75,89], Plocamium[89], Schizymenia[89], Callophyllis[89], Farlowia[89], and Prionitis[89]. While most of the sea vegetables currently cultivated on a commercial scale are food crops, almost all algae listed above are industrially important. In addition to the conventional purposes for which sea vegetables are cultivated commercially, *i.e.* for food and for the extraction of phycocolloids, investigations aimed at the production of biomass for energy conversion[39,43,61,75] or the purification of waste waters by macroalgae have been carried out[31,43,61,75,82].

The cultivation methods involved in the experimental work include those used in commercial cultivation[1,7,27,39] *cf.*[51,55–58,68,69,72,87,91]. However, a variety of other methods were developed, most of them aimed at a greater control of cultivation conditions. Consequently, large plastic cylinders suspended in the sea were used[68], as well as small to very large and complex constructions located offshore, where water depth is several hundreds of meters[30,93], and a variety of raceways *e.g.*[21,75] and tanks[1,6,43,89,90,96] located on land.

A wide variety of subjects have been studied. Some, like those dealing with fertilization, seeding, or stock improvement, have been referred to above. Others, such as control of the different stages of the life history – induction of reproduction, germination and growth – and questions concerning the storage of 'seed' material[71] or genetic manipulation to obtain 'domesticated' plants[12,62], have not. Most of the experiments have concerned study of the influence of various factors on the growth rates and/or yields of the different sea vegetables studied. The usual growth rates observed were around 3.5–4% daily. However, considerably higher growth rates were shown by some algae under favorable conditions (5.8% day^{-1} by Macrocystis[90], 7.9% day^{-1} by Sargassum[90], 7.6% and 8.3% day^{-1} by two species of Gracilaria[61]). Some of the higher yields obtained were: 12–17 g dw m^{-2} day^{-1} for Gracilaria[43], 16–22 g dw m^{-2} day^{-1} for Iridaea[58], or 17 g dw m^{-2} day^{-1} for Agardhiella[75] (as Neoagardhiella), yearly average values. These values compare well with yields of microalgae or fast-growing terrestrial crops[43]. During the growing season, higher values of more than 40 g dw m^{-2} day^{-1} were obtained[75].

Prospects of sea vegetable thalassonomy

The cultivation of sea vegetable food crops, which markedly developed during the past few decades, seems to have presently closely edged up to its widest potential, with only a limited further expansion to be expected, based on developments in the Far East market. This will be true unless an as yet unforeseen major change takes place in the eating habits of the populations in the developed countries of the world, caused either by a shift of preferences or by necessity. By contrast, a considerable development and expansion of the cultivation of sea vegetable industrial crops is much more likely, as the demand for their products is world-wide rather than being restricted to only a small number of countries.

This future development of thalassonomy will no doubt depend on breeding of truly domesticated varieties of superior yields, quality of product, and success under prescribed cultivation conditions. The best of wild types selected from the natural populations will no longer be satisfactory.

The rapid accumulation of knowledge concerning the environmental requirements of the industrial sea vegetables, the widening understanding of the chemical structures of the industrially important substances produced by them and its bearing on their physical properties, and the experimental effort put into conventional and less conventional genetic research will provide the tools which future breeders of such varieties may use for creation of the appropriate genotypes and for a soundly based selection. This achieved, obtaining the varieties on which to base successful thalassonomy will not be too far off. This alone, however, will not guarantee the success of sea vegetable thalassonomy, as there is still much to be learned about cultivation techniques as well.

Although sea vegetable thalassonomy started on the basis of trial and error, much of its success in the past, especially during the last few decades, is the outcome of achievements of scientific research. So also are the developments mentioned, expected in the future, that will turn it into a modern, sophisticated enterprise. Yet it should be borne in mind that, along with the developments in this field, new problems are bound to arise and thus, intensive scientific research will have to accompany the developing thalassonomy for many years after it becomes such an enterprise.

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