Potential Yields from a Waste-Recycling Algal Mariculture System

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For centuries seaweeds have been an integral part of the Oriental diet, but only since World War I have they become an important commodity in the Western World. In recent years they have been used in the United States primarily for their phycocolloids (alginates, agar, and carrageenan). Agar and carrageenan, cell wall polysaccharides produced by various red algal species, are widely used in food, pharmaceutical, textile, cosmetic, and other industries as suspending, thickening, stabilizing, and emulsifying agents (13, 26, and Moss, this volume). The principal source of agar has been *Gelidium* spp., which is harvested in Japan where the agar is extracted and exported to the rest of the world. Carrageenophytes have been harvested from natural populations throughout the world, dried, and shipped to factories in North America or Western Europe, where the phycocolloid is extracted and refined for sale. Most of the world's supply of carrageenan comes from *Chondrus crispus* (Irish moss) populations in Eastern Canada and to a lesser extent New England and Northern Europe.

These seaweed resources are limited in area and are now heavily exploited. At the same time, the demand for phycocolloids is steadily increasing. The discovery that different algal species or blends of phycocolloids from different algal species have dissimilar gelling or emulsifying properties has led to a large number of new applications of these products. These factors together have led to screening of various species and world-wide surveys of seaweed resources by the industry over the past two decades, in an attempt to expand

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[1]This research was supported in part by NOAA Office of Sea Grant, Department of Commerce, under Grant No. 04-6-158-44016, Contract E(11-1)-2948 from the U. S. Energy Research and Development Administration, and the Jessie Smith Noyes Foundation, Inc. Contribution No. 4027 from the Woods Hole Oceanographic Institution.

the base of its operation. One example of such expansion is the relatively new exploitation of the red alga *Eucheuma* in the Philippines and other parts of Southeast Asia. These resources, old and new, are decreasing due to overharvesting (2, 27, and Doty, this volume), pollution (17, 27, 29), and storm damage (18) to the extent that the industry is resource limited. Attention has become focused on cultivation as the only long-term solution.

Most studies with seaweeds have been concerned with their taxonomy, anatomy, life history, or distribution. Unfortunately, there is very little known about the physiology and autecology of most of these algae and even less concerning their cultivation.

CULTIVATION OF AGAROPHYTES AND CARRAGEENOPHYTES

To supplement insufficient natural supplies of agarophytes, the Japanese initiated a seaweed cultivation program several decades ago. One method involved scattering small fragments of *Gelidium* or *Gracilaria* (11) in bays where the plants are allowed to regenerate vegetatively. More recently the Japanese have propagated *Gracilaria* and *Gelidium* (12) on ropes in shallow bays. *Gracilaria* culture in Taiwan (25) has undergone a rapid expansion since its initiation in 1962. The unattached *Gracilaria* plants are grown in shallow ponds of approximately 1 hectare, which formerly were used for milkfish culture. *Eucheuma* farming, developed in the Philippines (7, 8, 18, and Doty, this volume), utilizes a net-culture technique that is similar to the cultivation of edible seaweeds in Japan. No commercial seaweed cultivation farms exist in North America[2], but several research projects involving the cultivation of red algae have evolved in the past decade.

Beginning in the late 1960s, a group headed by A. C. Neish at the Canadian National Research Council Atlantic Regional Laboratory near Halifax initiated studies on the culture of unattached *Chondrus crispus* in tanks containing flowing seawater. One of their early observations was that plants of different origin grew at considerably different rates in the same tank. One clone (T-4) grew much faster than others and attracted fewer undesired algal species as epiphytes (14). Another important finding was that the chemical composition of the plants could be altered by manipulation of the culture environment. Neish and his co-workers discovered that plants grown in unenriched seawater have a higher carrageenan content than those grown in nitrogen-enriched seawater. If *Chondrus* grown in nitrogen-enriched seawater was transferred to unenriched seawater, its carrageenan content increased. The effects of several other operating parameters were also investigated (14, 15, 23, 24).

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[2]Atlantic Mariculture Ltd. of Grand Manan Island, New Brunswick, Canada, uses V-shaped, air-agitated ponds as part of a commercial *Rhodymenia* operation (16). Their primary objective is not cultivation, but rather to keep the plants alive until they can be processed.

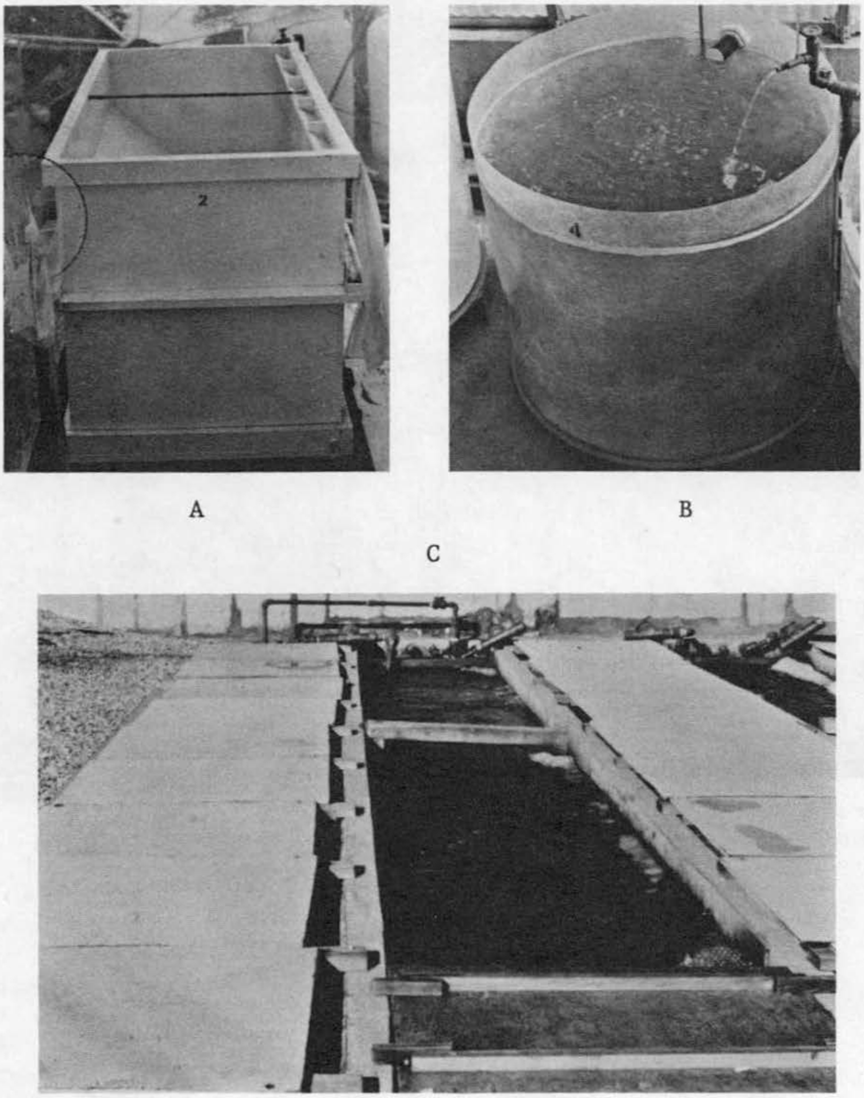

Figure 1. *Enclosures used in the cultivation of seaweeds at the Woods Hole Oceanographic Institution. A - Rectangular plywood tanks. B - Circular fiberglass tanks. C - Concrete raceways.*

Following Neish's lead, several research groups in the U. S. have experimented with growing unattached seaweeds in suspended culture. For example, Ryther's group (3, 4, 5, 10, 19, 20, 22) in Woods Hole and in Florida has grown *Gracilaria* sp., *Neoagardhiella baileyi, Chondrus crispus, Gracilariopsis sjoestedtii, Hypnea musciformis,* and other species in tanks (Figs. 1A-B), raceways (Figs. 1C and 2), and ponds (Fig. 2). Other research teams in the U.S. have used similar tank culture methods to grow *Hypnea* (9), *Iridaea* (28), and *Gigartina* (28 and Waaland, this volume).

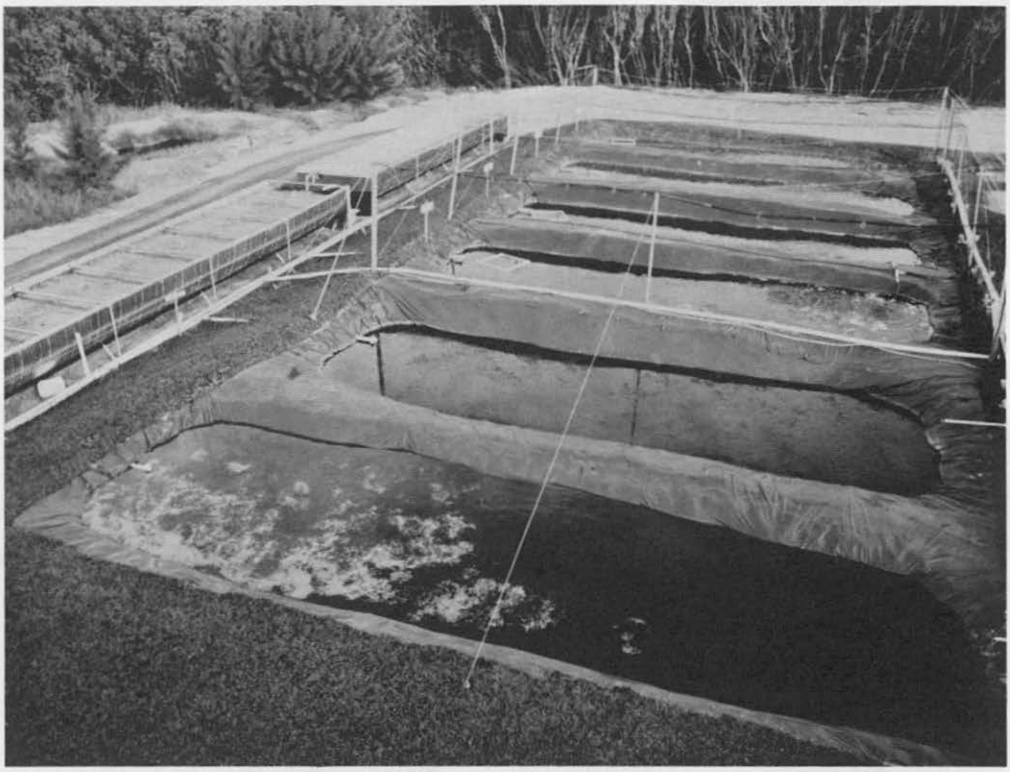

Figure 2. *Aluminum raceways (upper left) and PVC-lined ponds (right) used to cultivate seaweeds at the Harbor Branch Foundation in Ft. Pierce, Florida.*

Two commercial seaweed companies, Marine Colloids, Ltd., and GENU Products, Ltd., have started pilot *Chondrus* projects in Nova Scotia, with partial support from the Canadian Government, using modifications of Neish's technique. Full-scale production in both projects was delayed by the slow growth of *Chondrus* and the difficulties in control of algal contaminants (e.g., *Ulva, Enteromorpha,* and *Ectocarpus*) in the culture system.

A WASTE-RECYCLING MARINE-POLYCULTURE SYSTEM

Beginning about 1970, a project at the Woods Hole Oceanographic Institution developed a waste-recycling marine-aquaculture system. This system has the capacity of removing the inorganic nutrients from treated sewage effluent, prior to its discharge to the environment, and recycling these nutrients into commercially valuable crops of marine organisms.

The concept of this system is to grow unicellular marine algae in ponds in continuous flow cultures on mixtures of seawater and secondarily treated sewage effluent (Fig. 3). The algae are fed to bivalve molluscs, maintained in Nestier® trays in raceways. The

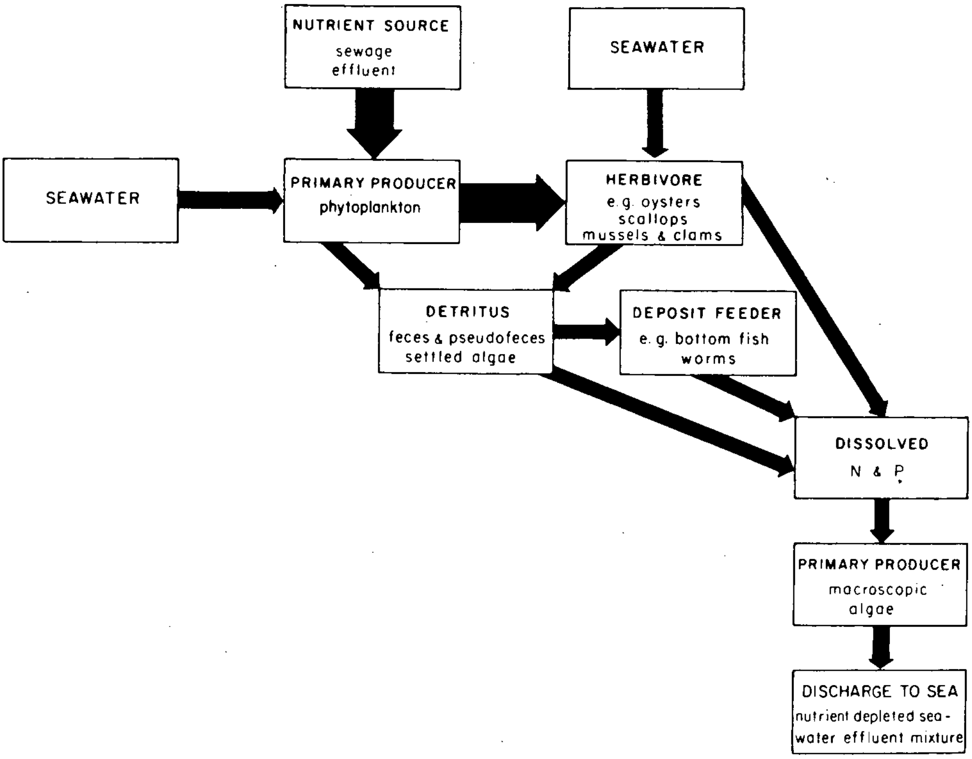

Figure 3. *Model of the Woods Hole waste recycling-polyculture system.*

algae remove the nutrients from the wastewater and the shellfish remove the algae from suspension. Finally, the effluent from the shellfish culture passes through tanks containing macroscopic algae (seaweeds). The seaweeds remove the dissolved nutrients regenerated by the animal culture before final effluent is discharged. The objective of this polyculture system is to achieve a low nutrient final effluent that will meet the standards for tertiary treatment while producing commercially valuable marine organism crops.

Two species of macroscopic red algae, *Gracilaria* sp. and *Neoagardhiella baileyi,* were grown in the Woods Hole waste-recycling seaweed-mariculture projects. Several species of *Gracilaria* harvested from natural populations serve as a major source of agar. *Neoagardhiella,* which contains iota-carrageenan (4), is not yet harvested but has potential commercial value. Species of a closely related genus, *Eucheuma,* which contain the same phycocolloid, are cultivated and harvested commercially in the Philippines (Doty, this volume). Unattached, free-floating plants were grown in concrete raceways 12.2 m (long) x 1.2 m (wide). Sloping plywood bottoms provided depths ranging from 0.6 m to 1.5 m. The seaweeds were kept in suspension by aeration from an airline at the bottom of the raceway which extended its entire length. The aeration provided for mixing,

Table I. *Culture conditions for Neoagardhiella and Gracilaria in raceways at the Woods Hole Oceanographic Institution during 1975-1976.*

	Nutrients (μM)		Water Flow	Density (kg wet wt/m^2)	
Dates	ΣiN	PO_4^{-3}	1/min*	*Neoagardhiella*	*Gracilaria*
Mar 20-Apr 15	37	12	48	3.9	2.8
Apr 15-May 6	14	8	48	9.5	3.9
May 6-May 20	21	7	72	8.9	5.5
May 20-May 28	11	2	72	12.3	6.4
May 28-Jun 5	27	7	72	10.1	8.1
Jun 5-Jun 12	16	7	72	11.5	8.4
Jun 12-Jun 27	34	9	96	8.2	10.2
Jun 27-Jul 16	75	13	138	5.5	5.9
Jul 16-Aug 14	58	10	96	6.6	6.3
Aug 14-Aug 27	81	14	48-144	5.9	6.5
Aug 27-Sep 18	-	-	48-144	4.2	4.0
Sep 18-Oct 6	-	-	48-144	3.1	2.6
Oct 6-Nov 7	-	-	70	2.6	1.7
Nov 7-Nov 21	44	8	72	3.1	2.8
Nov 21-Dec 19	37	5	60-80	2.0	2.2
Dec 19-Feb 20	40	6	60-80	3.0	-
Feb 20-Mar 19	-	-	60-80	2.9	-

*48 1/min = 3 exchanges/day

gas exchange, and uniform exposure of the plants to sunlight. The seaweed cultures received the effluent from similar raceways containing various species of bivalve molluscs.

Because of major problems with the molluscan cultures during the first year of operation, considerable research was devoted to experimentation with flow rates, temperatures, shellfish stocking densities, and other factors. Therefore, the chemical and physical characteristics (Table I) of the effluent from the shellfish raceways

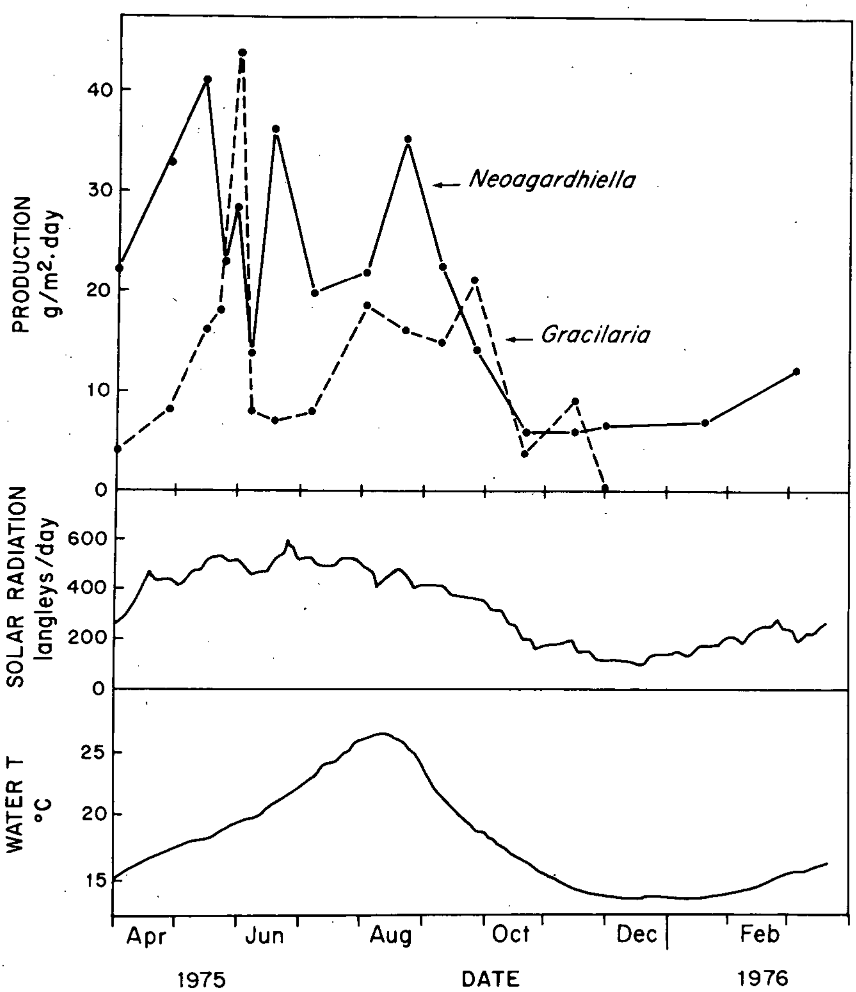

Figure 4. *Production rates of Neoagardhiella and Gracilaria grown in raceways at Woods Hole Oceanographic Institution during 1975-76.*

varied throughout the year. In spite of variations, the flow of water and the supply of nutrients were not believed to have been limiting to seaweed growth. The stocking density was varied experimentally during the year because the optimum density for the maximum rate of production in the raceways had not been previously determined. *Gracilaria* and *Neoagardhiella* were monitored from March 20, 1975, to March 19, 1976.

Production was measured by dip-netting the algae from the raceways, draining the plants in nylon mesh bags, and weighing. After weighing, the biomass was reduced to its initial weight or allowed to accumulate. Populations were weighed at intervals of about 1 week during the period of most rapid growth in spring and early summer and at longer intervals during the remainder of the year. Samples of the algae were oven dried at 60° C to determine the relation between fresh and dry weight. Production rates or yields were expressed in terms of dry weight which ranged between 10 and 15% of the fresh weight.

The seaweed production rates are shown in Fig. 4. *Neoagardhiella* had surprisingly high rates of production in the spring (22-41 g dry weight/m^2·day) and summer (20-36 g/m^2·day). *Gracilaria* production rates were variable, increasing from 4 g/m^2·day in April to 43 g/m^2·day in early June and decreasing again during the latter part of the summer to 7-18 g/m^2·day. Production rates of both species declined during the fall and early winter. By mid-December the *Gracilaria* production rate had fallen to zero, and the plants had deteriorated. *Neoagardhiella* remained viable (although stunted) with a production rate of 6 g/m^2·day.

Gross seasonal changes in production appear to be correlated with both water temperature and incident solar radiation. The seawater entering the bivalve mollusc cultures was heated in winter to enable the shellfish to feed and grow, but it had cooled to as low as 13° C by the time it entered the seaweed cultures and as low as 8° C when it left during midwinter. From June 1 to October 1, however, when the water temperatures and solar radiation were presumably optimal for the seaweeds (3), production showed little correlation with those variables. Low production rates then were probably due to the high densities of seaweeds maintained in the raceways (as high as 12.3 and 10.2 kg fresh weight/m^2 for *Neoagardhiella* and *Gracilaria*, respectively).

SEAWEED MARICULTURE--OPERATIONAL CONSIDERATIONS

In addition to using seaweeds as a final step in a waste recycling-polyculture system, they may also be grown in a one-step waste recycling system to remove the nutrients directly from mixtures of seawater and secondary sewage effluent. This one-step system has been more successful than polyculture because of its simplicity. Even so, there are several operational parameters which need examination to ensure success and to optimize yields.

One important operational consideration in the polyculture experiment was the biomass of seaweeds to be maintained to provide maximum yield per unit of area. Two experiments were conducted to determine the relationship of seaweed density to the growth rates and production of *Gracilaria* sp. One experiment was conducted June 2-28, 1976, and the other, November 3-30. Each of six plywood tanks (Fig. 1A) was stocked with 180-4000 g fresh weight/m^2. These tanks, 2.4 m long x 1.0 m wide x 1.2 m deep at maximum, were designed with sloping bottoms. An airline on the bottom along the deep side of each tank enabled the plants to be maintained in suspension and circulated by aeration. The tanks were in a geodesic dome fitted with a vinyl cover to retain heat during the winter. Filtered seawater heated to 18.5-21.5° C was enriched with ammonium chloride and sodium phosphate to give a concentration of 50 μM NH_4^+ and 10 μM PO_4^{-3}. This seawater was circulated through the tanks continuously at a rate of 2 tank volumes (3650 liters) per day. Three times per week the plants

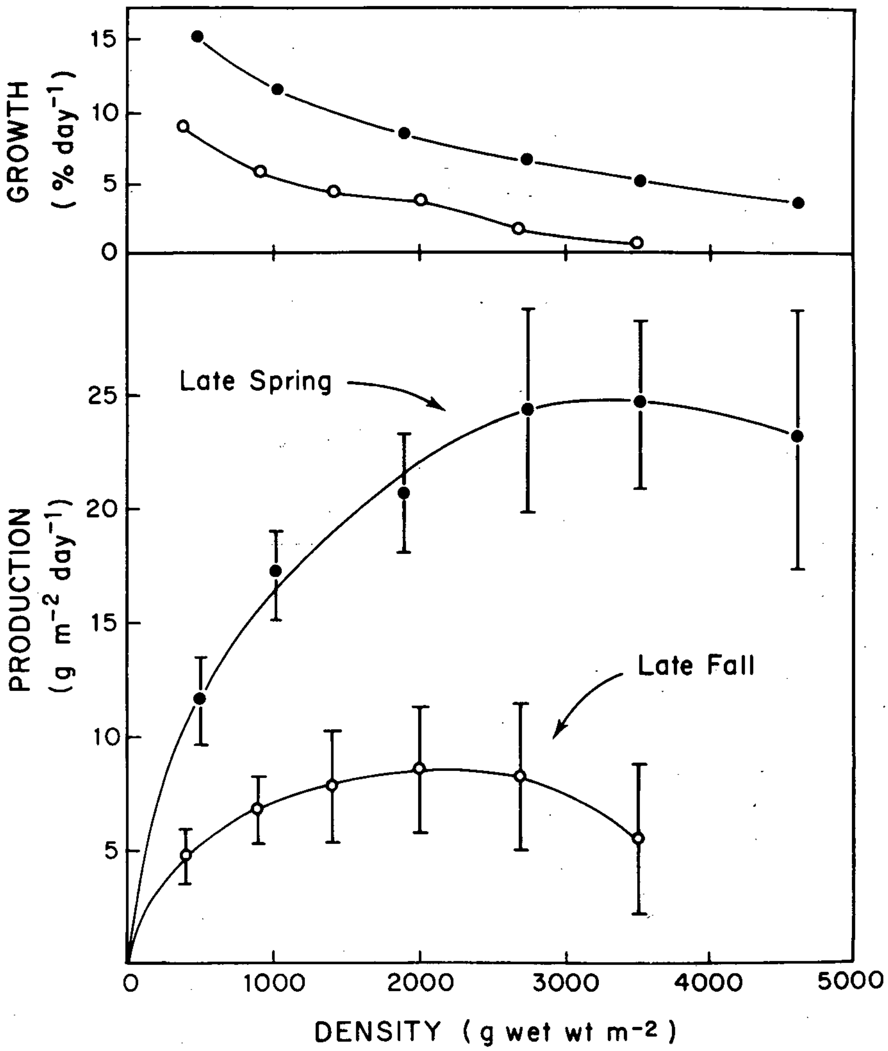

Figure 5. *Specific growth rates and production rates of Gracilaria as a function of culture density in the tanks at the Woods Hole Oceanographic Institution during 1976.*

were weighed and the density in each tank adjusted to the initial stocking density by harvesting the incremental growth. The specific growth rate (μ), equivalent to the percent increase per day, was calculated by the equation:

$$\mu = \frac{100(\ln^{N/}No)}{t}$$

where No is the initial biomass and N is the biomass on day t.

The mean specific growth rates and production rates at the

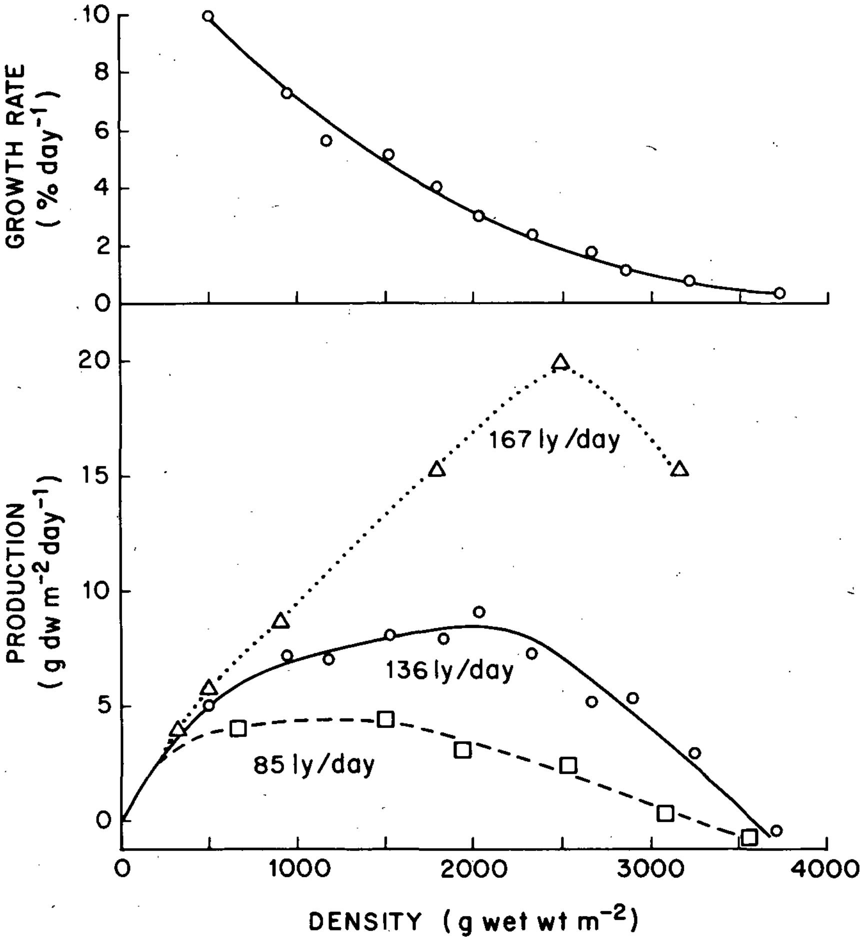

Figure 6. *Specific growth rates and production rates of Neoagardhiella baileyi as a function of culture density in tanks at the Woods Hole Oceanographic Institution during 1975.*

different mean densities are shown in Fig. 5. The average solar radiation was 549 langleys/day (ly/day) during the late spring experiment and 152 ly/day during the late fall experiment. The growth rate decreased exponentially with increasing culture density from 14%/day to 4%/day during the spring and from 9%/day to 1%/day in the fall. Production, or yield, which is a function of both specific growth rate and density, was highest at an intermediate density of 3000-4000 g fresh weight/m^2 in spring. In the fall, maximum production was achieved at densities of 2000-2500 g fresh weight/m^2.

Another experiment using similar methods (3) investigated the relationships among growth rate, production rate, and density in *Neoagardhiella baileyi*. The results, shown in Fig. 6, are averages over the entire 40-day experiment (Nov.-Dec., 1975), when the mean incident solar radiation was 136 ly/day. Maximum production occurred

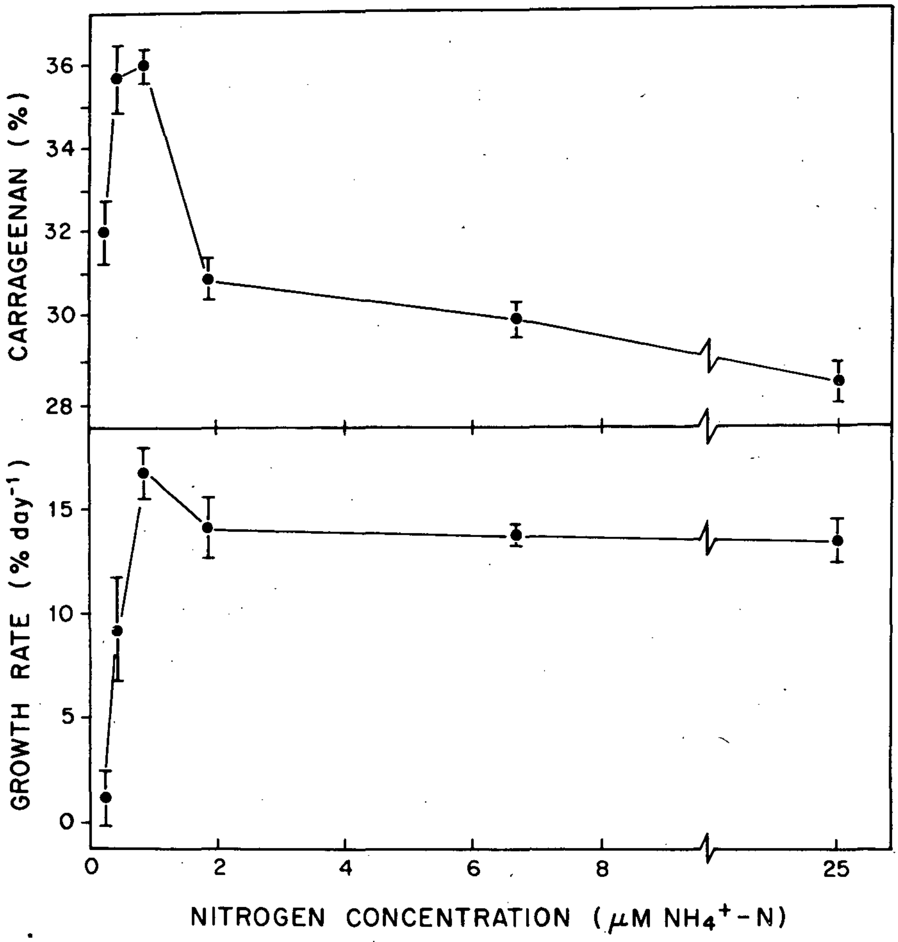

Figure 7. *Effects of nitrogen enrichment on the growth rate and carrageenan content of Neoagardhiella grown in tanks at the Woods Hole Oceanographic Institution during 1976.*

at densities of 2000-2500 g fresh weight/m^2. During brief periods (ca 1 week) of sunny weather when the solar radiation averaged 160 ly/day, productivity increased markedly to a peak of 22 g dry wt/m^2/day at a density of 2900 g fresh wt/m^2. During cloudy periods (85 ly/day) production decreased to less than 5 g dw/m^2/day at densities of 500-1500 g fresh wt/m^2.

These experiments indicate that to obtain maximum yields of *Gracilaria* and *Neoagardhiella*, the density should be maintained in the range of 1800-2800 g/m^2 during the winter, 2800-4500 g/m^2 during late spring and summer, and at intermediate densities during the remainder of the year. These relations between production and seaweed density for *Gracilaria* and *Neoagardhiella* are similar to those reported for other red algae. For example, the maximum rate of production for *Chondrus* during the summer was obtained at a population density of 5800 g fresh weight/m^2 (15). The optimum density for

Iridaea in April was approximately 2100 g fresh weight/m^2 (28).

The optimum depth of the culture system is another variable that is best determined empirically. Shacklock *et al.* (24) found that the growth of *Chondrus* was greater at a depth of 91 cm than it was at either 46 or 1800 cm. Experience with various types of culture enclosures and modes of circulation of the plants and water has shown that the optimum depth for the suspended cultures of *Gracilaria* and *Neoagardhiella* is 60-110 cm.

Another critical operating parameter in seaweed cultivation is the concentration of nutrients necessary to sustain a maximum growth rate. Ryther and Dunstan (21) found that nitrogen is the chemical nutrient most likely to limit algal growth in marine waters. Seaweed studies have also indicated nitrogen to be the critical limiting factor in the Woods Hole seaweed mariculture system. As a result, an investigation (4) was undertaken (Mar. 21-Apr. 8, 1976) to determine the concentration of ammonia at which maximum growth rate occurs in *Neoagardhiella baileyi*. Each of the six tanks described in the density experiments was stocked with 1500 g of the algae. Influent nutrient concentrations of the enriched seawater ranged from 4 to 70 μM NH_4^+ and from 1 to 14 μM PO_4^{-3}, respectively, in five of the experimental tanks, with an unenriched seawater control in the sixth tank. The continuous flow rates were equivalent to three tank volumes per day. Every 3 days the algae were weighed and the biomass in each tank adjusted to the initial stocking density. Growth rate (Fig. 7) increased with increasing nitrogen concentration up to approximately 0.8 μM NH_4^+ but remained constant at higher concentrations.

At the conclusion of the experiment described above, the carrageenan content was determined. Details of the methods and results have been previously reported (4). Carrageenan (Fig. 7) was highest at a residual nitrogen concentration of 0.8 μM NH_4^+ and was less at both higher and lower nitrogen levels. These results are similar to those of Neish and Shacklock (15) who found that *Chondrus* grown in unenriched seawater has more carrageenan than when grown in nitrogen-enriched seawater. Our results show, however, that even higher levels of carrageenan can be produced at low (0.5-1.2 μM) NH_4^+ concentrations than in unenriched seawater.

In another study[3] it was determined that the half-saturation constants for growth in *Gracilaria* and *Neoagardhiella* are approximately 0.5 μM NH_4^+ or NO_3^-. These constants are very low, demonstrating that seaweeds can utilize very low concentrations of inorganic nitrogen.

Half-saturation constants for growth in phytoplankton are

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[3]DeBoer, J. A., H. J. Guigli, T. L. Israel, and C. F. D'Elia. Studies on the cultivation of the macroscopic red algae. I. Growth rates in cultures supplied with nitrate, ammonium, urea, or sewage effluent. (In prep.)

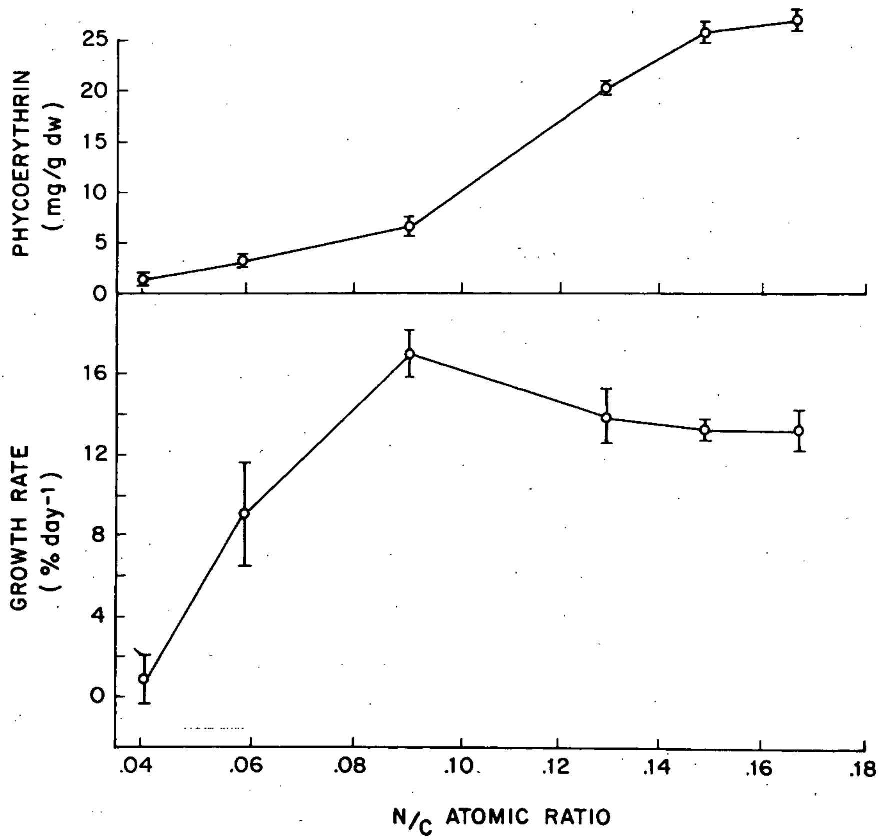

Figure 8. *Phycoerythrin content and growth rate of Neoagardhiella as a function of their analytical nitrogen:carbon ratio.*

usually in the 0.1-5 M range for inorganic nitrogen. As far as we are aware, no other studies describe the half-saturation constants for growth or uptake of inorganic nitrogen by seaweeds. This study also showed that ammonia-grown *Gracilaria* and *Neoagardhiella* exhibit higher growth rates than nitrate-grown plants, that both species show a decided preference for ammonia over nitrate in mixtures of the two, and that growth of both species is essentially equivalent whether the nitrogen source is secondary sewage effluent or chemical fertilizer.

These results indicate that for maximum biomass and carrageenan production, the inorganic nitrogen concentration should be maintained at 0.5-1.5 μM NH_4^+. Because of diurnal and other changes in the rate of nitrogen uptake by the seaweeds, maintaining optimum nutrient concentration constantly is difficult. Some simple indicator of the nutrient condition or status of the plants would facilitate large-scale culture operations. The nitrogen:carbon ratio (N:C) of the plants may serve as that indicator. Growth rate (Fig. 8) increases with increasing N:C atomic ratio up to approximately 0.85 with no increase in growth rate at higher N:C ratios. This and other studies (4) indicate that plants having an N:C ratio above 0.85 are probably not nitrogen limited but lower ratios suggest nitrogen limitation. Additional studies under a variety of environmental conditions are necessary to substantiate these findings, but initial results indicate that large deviations in the N:C ratio can be used to predict a nitrogen deficiency or surplus. Such an indicator would be extremely useful in seaweed mariculture to show when and how much to fertilize for maximum biomass and phycocolloid production.

A simple color index may be used as an indicator of nutrient status and phycocolloid content (4). Plant color in *Neoagardhiella* is due primarily to the relative proportions of chlorophyll and the red accessory pigment, phycoerythrin. Fig. 8 shows the phycoerythrin concentration as a function of the N:C ratio. Phycoerythrin concentration increased rather consistently with increasing N:C ratio. Plants with high concentrations of the red pigment appear dark reddish-brown while those with very low levels are yellow to straw colored. However, before such a simple color index of phycocolloid content and nitrogen status is considered reliable, it must be verified that other nutritional deficiencies that may not affect carrageenan levels do not influence the development of the accessory pigment. At very high light intensities, for instance, photo-oxidation of pigments occurs, so that in those circumstances pigmentation may not be a valid indicator of nutritional status and carrageenan content.

One common observation is that if the seaweed density varies greatly from the optimum or if the nitrogen concentration is higher than is necessary to support the maximum growth rate, algal contaminants often proliferate, significantly decreasing both the growth and the economic value of the cultured species. We have found that if the plants are grown near the optimum density and at optimum nutrient concentrations (1-2 μM NH_4^+ or NO_3^-), the algal contamination does not become serious. We have shown that the carrageenan content is also higher in plants grown at low nitrogen concentrations. The agar content in *Gracilaria* sp. is also higher at low nitrogen concentrations[4]. A nitrogen level to maximize both growth rate and polysaccharide content is a crucial parameter.

SEAWEED MARICULTURE--PRODUCTIVITY

The polyculture experiment described previously was conducted before the density and nutrient experiments. The densities in the raceways were at times far above those optimum for the maximum rate of production. The production rates were, therefore, probably lower than might have been obtained if optimum densities had been maintained throughout the year. Nevertheless, the mean annual dry weight production was 17 g/m^2·day or 63 metric tons/hectare·year for *Neoagardhiella* and 9 g/m^2·day or 33 t/ha·year for *Gracilaria*. These rates may

[4]DeBoer, J. A. Effects of nitrogen enrichment on growth rate and phycocolloid content in *Gracilaria foliifera* and *Neoagardhiella baileyi*. Submitted to Proceedings of the Ninth International Seaweed Symposium.

be higher than would be realized in a commercial enterprise because the raceways were maintained at elevated temperatures for approximately 6 months of the year. Annual production rates based on a 5 1/2-month growing season when the raceways were not heated (May 8 - Oct. 20, 1975) were 46 t/ha·year and 28 t/ha·year for *Neoagardhiella* and *Gracilaria*, respectively (Table II).

Table II. *Comparative productivity values for cultivated seaweed crops.*

Species	Location	Annual Production tons/hectare dry weight	Culture Method	Reference
Neoagardhiella	Massachusetts, USA	46.0	Raceway	This study
Gracilaria	Massachusetts, USA	28.0	Raceway	This study
Gracilaria	Florida, USA	46.0	Tank	10
Hypnea	Florida, USA	39.0	Tank	10
Iridaea	Washington, USA	20.0	Tank	28
Gracilaria	Taiwan	7-12.0	Pond	25
Gracilaria	Taiwan	2.0	Net	18
Gracilaria	Japan	0.4-1.3	Bay	11
Eucheuma	The Philippines	13.0	Net	18
Gelidium	Japan	1.5	Stones	18
Gelidium	Korea	1.4	Stones?	6
Porphyra	Japan	0.3-3.0	Net	18,29

The yields obtained in this study were similar to those recently reported for *Gracilaria* sp. and *Hypnea musciformis* grown in essentially the same way but for shorter periods at the Harbor Branch Foundation in Florida. In other small-scale, short-duration experiments, production rates of cultured seaweeds exceed these values 2-3 fold (3, 9, 16, 28, and Waaland, this volume), but these yields have not been substantiated by large-scale, long-term production studies. However, given favorable growing conditions it seems realistic to expect production rates to exceed 50 t/ha/yr based on a 5- to 6-month growing season in temperate latitudes. The yields obtained in both the Woods Hole and Florida studies are considerably greater than values reported in the literature for other highly profitable seaweed crops (Table II) and are as high or higher than many agricultural crops (5, 10).

SUMMARY AND CONCLUSIONS

Most agarophytes and carrageenophytes currently cultivated are grown attached to ropes or nets (1, 13, and Doty and Mumford, this volume). These methods, although profitable in some areas, are labor intensive and are, therefore, best suited to countries with low labor costs. The method used in the present study, growing unattached plants in raceways or ponds, is a more versatile means of culture and one that could easily be mechanized.

We have used domestic sewage effluent as a nutrient source in the waste-recycling polyculture systems in Woods Hole and in Florida, but other nutrient sources could also be used. Alternative nutrient sources include agricultural wastes from cattle feed lots or swine farms, wastes from seafood processing plants or other food processing wastes, and wastes from open animal mariculture systems such as penaeid shrimp farms. In all of these applications seaweeds can be used to lower the nutrient and heavy metals content of the wastes, enabling the discharge to meet state and federal regulations. Algae may also be incorporated into a closed animal mariculture system, serving as biological filters to remove the animals' toxic metabolic wastes. Upwelled, nutrient-rich waters may also be used as a nutrient source in seaweed mariculture systems (9), and conventional commercial fertilizers will serve as adequate (though perhaps more costly) nutrient sources in seaweed monoculture operations.

In summary, cultivated seaweeds are apparently among the most productive primary producers and prospects for seaweed cultivation look optimistic. However, there is still a need for considerable basic and applied research on the biology of the macroscopic marine algae. Both biomass and phycocolloid production are undoubtedly functions of many interrelated variables: availability of chemical nutrients, light intensity, light quality, photoperiod, turbidity, CO_2 availability, mixing, rate of water exchange, temperature, population density, culture depth, water quality (toxins, growth enhancement factors, pH), and the seaweeds themselves (differences among species and physiological races, seasonality of growth, etc.). Results of our studies on some of these variables suggest that, if properly managed, the yields of seaweed mariculture can be substantially increased.

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