ABSTRACT

There is regional interest in the development of marine industries involving the production and harvest of seaweeds for the extraction of phycocolloids. Two groups of benthic marine algae have received particular attention. These are agarophytes of the genera *Gracilaria* and *Polycavernosa* and carrageenan-bearing species of the genus *Eucheuma*. Although documentation of algal standing stocks and productivity of economic seaweeds within the region is poor, it seems unlikely that there are sufficient natural algal stocks to support processing plants for phycocolloids. An alternative to the harvest of wild crops of seaweeds is to develop seaweed farms to raise economically valuable species. The cultivation of seaweeds for phycocolloid production would seem well-suited for remote areas within the region since the seaweeds can be sun-dried, stored for long periods and shipped by boat. However development should proceed with caution and should be preceded by careful analyses of marketing and economics. This should include the development of strategies for penetrating the existing markets.
INTRODUCTION

The benthic marine macrophytes of Oceania constitute an undeveloped economic resource. The commercial uses of seaweeds are varied, but the major interest within the region lies in the culture and harvest of seaweeds for use in the production of phycocolloids. This interest stems from the growing world-wide demand for phycocolloids, particularly for agar and carrageenan, and from the successful establishment of commercial farms for seaweeds in Taiwan, the Philippines and other tropical areas. This interest has motivated the establishment of several research, development and demonstration projects within the region aimed at the production of phycocolloid-bearing seaweeds.

The purpose of this document is to review the technical literature relevant to the development of regional industries involving the use of seaweeds for the production of phycocolloids, and to identify areas where additional information is needed. The literature survey is not exhaustive, rather the works cited were chosen as regional examples of the issues raised, and to provide a starting place for those wishing additional information.

RESOURCE BIOLOGY

Taxonomy

The benthic algae of interest in regard to development of a phycocolloid industry are in the order Gigartinales of the division Rhodophyta, the red algae. These are the agar-bearing species of the genera Gracilaria and Polycavernosa, within the family Gracilariaceae, and the carrageenan-producing species of the genus Eucheuma, within the family Soleriaceae. Some taxonomic confusion exists within each of these groups, and a phycological workshop was recently convened at the University of Guam in order to address this problem. The results of the workshop include information on the taxonomy of Eucheuma (Doty, 1985; Doty and Norris, 1985), Gracilaria (Tsuda, 1985; Fredericq and Norris, 1985), and Polycavernosa (Xia and Abbott, 1985) relevant to those working in the tropical Pacific. The recent work of Meneses and Abbott (in press) discusses, in detail, the taxonomy of the genera Gracilaria and Polycavernosa within Micronesia.

Geographical distribution

Species of Gracilaria, Polycavernosa, and Eucheuma occur naturally in the shallow waters surrounding volcanic islands; they usually do not occur near atolls (Tsuda, 1982). Phycological works concerning Micronesia are listed in the bibliographies of Tsuda and Wray (1977) and Tsuda (1981). Likewise, phycological bibliographies are available for French Polynesia (Payri and Meinesz, 1985) and New Caledonia (Garrigue and Tsuda, in press). Other distributional accounts of marine algae within the region include those of Womersley and Bailey...

Habitat

Specimens of these genera can be found in a wide variety of habitats including reef-flats, small bays, lagoons, and mangrove areas. Similar habitats usually have characteristic floras, and for particular islands, a given species is usually common in characteristic habitats. On Guam for example, Gracilaria salicornia is common on reef-flats while Polycavernosa tsudae is common in small bays and protected subtidal areas. However, both species occur together in abundance on the reef-flats and in the seagrass beds of Yap proper (Tsuda et al., 1987). However, a species may inhabit several different habitats. For example, a variety of P. tsudae from Saipan is common in Garapan lagoon, a habitat very different from the small bays where another variety of the same species is found around Guam. The abilities of these seaweeds to reproduce vegetatively, in combination with a high degree of phenotypic plasticity, allow populations to become very well adapted to local conditions. Some evidence indicates that there may be distinguishable genetic differences between thalli growing at different depths within particular habitats (Matlock and Romeo, 1981). The work by Womersley and Bailey (1969) provides a summary of the dominant algae found in common habitats of the Solomon Islands and these categorizations may also be applicable to other islands of the tropical Pacific.

Trophic biology

Seaweeds are primary producers and are exploited by a wide variety of herbivores. On Pacific reefs the intense grazing and selective browsing by herbivorous fishes, primarily siganids, acanthurids, scarids, and pomacentrids, are major factors influencing algal standing crops, community structure, and productivity (Birkeland et al., 1985). Although some tropical seaweeds have evolved morphological and chemical defenses against herbivory (Paul, 1987), species of the genera Gracilaria, Polycavernosa, and Eucheuma are not so defended and are readily eaten by a variety of reef herbivores, (Nelson and Tsutsui, 1981) many of which can become pests on seaweed farms (Doty, 1987).

Herbivorous reef fishes, especially siganids, can constitute a major problem in the establishment and maintenance of seaweed farms on reefs and in lagoons (Doty, 1982; 1987). The strategies employed to reduce losses to herbivores include: selection of sites with reduced access to herbivorous fishes, protection of the seaweed by fences, and dilution of the impact of the fishes by increasing the biomass of the initial seaweed stocks so that herbivores become satiated. The latter strategy can be successful since the roaming, mixed-species schools of herbivorous fishes stay within a home range such that migration from distant areas to the farm site is unlikely. In instances
where these strategies are ineffective, they may have to be supplemented by intense fishing pressure.

**Reproductive biology**

Species of the genera *Gracilaria*, *Polycavernosa*, and *Eucheuma* exhibit triphasic patterns of life history. The three phases are: a diploid sporophyte phase, a haploid gametophyte phase, and a diploid carposporophyte phase which is "parasitic" on the female gametophyte. However, most farmed populations are sterile and reproduce vegetatively (Doty, 1987). It is, therefore, relatively simple to propagate those thalli which show superior rates of growth, which have a greater phycocolloid content, or which produce gels of higher quality.

** PHYCOCOLLOID INDUSTRY**

**General description of the industry**

There is a growing international market for phycocolloids. These complex mixtures of polysaccharides extracted from seaweeds form gels at room temperature and are used for a variety of commercial purposes including as emulsifiers and stabilizers in food products, as media for the culture of microbiological organisms, as carriers for pharmaceutical products, and as ingredients in a diverse array of products ranging from ice-cream to shoe polish (Armisen and Galatas, 1987; Stanley, 1987). Markets exist for the dried phycocolloid-bearing seaweeds as well as for the extracts. The production of seaweeds used in the industry comes largely from developing countries in Asia and Latin America, but the production of phycocolloids from these raw materials occurs primarily in the developed nations of Denmark, France, Japan, Norway, Spain, the United Kingdom, and the United States (Food and Agriculture Organization of the United Nations, 1983; Infofish, 1983).

Within the region, possibilities exist for establishing both seaweed farms and small-scale phycocolloid extraction facilities. Since the seaweeds can be dried in the sun, stored for long periods and shipped by boat, seaweed mariculture is well suited for small-scale development in remote locations. However, success in developing a seaweed industry depends upon establishing a distribution and marketing structure which will help to stabilize prices and provide incentive to farmers to produce reliable harvests of consistent quality (Food and Agriculture Organization, 1983). Uwate (1987) surveyed potential seaweed buyers in a study for Yap state and reported that the existing markets may be difficult to penetrate except through joint-ventures with existing firms.

**Harvesting and culture methods**

The successful development of regional phycocolloid industries requires the harvest of large quantities of seaweeds.
It is likely that the wild stocks in most countries within the region will be insufficient to meet such demands. Therefore, regional development will rely primarily on cultivation rather than on the harvest of natural stocks.

The commercial production of phycocolloid-bearing seaweeds is accomplished either by pond culture or by monofilament-line method on reefs and in lagoonal habitats.

Culture of *Eucheuma* is accomplished by tying thalli at intervals along a monofilament nylon line attached within the sublittoral zone to stakes driven into the substratum (Why, 1985; Doty, 1987). Why (1985) reports that a farm consisting of 300 7-m lines can produce 39 tons of raw *Eucheuma* per hectare per year. Species of *Eucheuma* are not cultured in ponds since they generally require areas with considerable water motion.

*Gracilaria* can be cultured either on monofilament lines, as described above for *Eucheuma* culture, or in shallow (<1 m deep) ponds. Chen (1976) provides a general description of the culture of *Gracilaria* in ponds in southern Taiwan. Ponds are stocked with 3,000 to 5,000 kg of healthy stock per hectare. Harvests occur every 10 days from June to December. Other species such as milkfish or shrimp are stocked along with the seaweeds to provide additional income.

**Economics**

Factors affecting the price for dried seaweeds include the content of impurities such as epiphytes, sand, small shells, and encrusting organisms, the moisture content, and the phycocolloid content. A moisture content of 14 to 18 percent is desirable (Moss and Doty, 1987) and can be achieved by drying the algae under bright sunlight. The price paid to the farmer for suitable dried *Eucheuma* in the Philippines is $275 to $325 per ton (Moss and Doty, 1987).

The quality of the extracts is largely determined by the strength of the gel, determined as grams per square centimeter. Extracts from seaweeds collected within Micronesia have been shown to exhibit gel strengths in the range which render them suitable for use in food-grade agar production (Nelson et al., 1983). Attempts to develop post-harvest treatments to increase the gel strength have met with limited success (Wilkins, 1986).

Prices for phycocolloids vary with season, quality, and form of the product. For example, Armisen and Galatas (1987) reported that from 1984 to 1986 the price for food-grade agar imported to Japan in strips or squares ranged from $10 to $21 per kg, while the average value of these products which were exported ranged from $16 to $45 per kg. Moss and Doty (1987) estimate that the world-average prices will stabilize at $5 to $6 per pound for food-grade agar and at $10 to $12 per pound for bacteriological-grade agar. The price for carrageenan, which depends on the degree of refinement of the product and sales volume, ranges from $2.50 to $8.00 per pound (Moss and Doty, 1987). In 1983 the estimated world-average price was $3.50 per pound for carrageenan (Moss and Doty, 1987).
Processing and marketing

The techniques for producing agar and carrageenan differ, but, commercial plants for either require large volumes of heated water to extract the gels (Armisen and Galatas, 1987; Stanley, 1987). Moss and Doty (1987) provide detailed descriptions of the extraction procedures for both agar and carrageenan in their feasibility analysis of establishing phycocolloid plants in Hawaii. Plants also must dispose of waste water and solid wastes.

In considering the possibility of developing regional facilities for the production of either agar or carrageenan, a number of general considerations come to mind. Production of agar is technologically less complex and requires less of a capital investment, than the production of carrageenan. Also, agar production can be carried out on a small scale, and numerous production facilities have been established. On the other hand, few companies, only 18 world-wide in 1980, are involved with the production of carrageenan (Food and Agriculture Organization of the United Nations, 1983), and approximately 75% of the world production comes from only three companies (Moss and Doty, 1987). Although the opportunities for regional involvement in phycocolloid production seem to be better for agar than for carrageenan, detailed cost-analyses are needed. Among the major considerations for agar production in tropical areas are the costs of cooling and freezing the extracts and the associated economies of scale (Food and Agriculture Organization, 1983).

ASSESSMENT OF STOCKS

Survey techniques

A number of techniques can be successfully employed to survey natural seaweed stocks. Birkeland (1984) recommends guarding against over-standardization and suggests the use of several independent methods for exploratory surveys. Most such assessments begin with qualitative surveys to document the presence or absence of particular seaweeds at selected locations. Qualitative observations can be effectively accomplished by divers working from small boats by free-swimming observation, towed observation, or spot-check surveys (Kenchington, 1978). Preliminary aerial, photographic surveys can also be useful for broad-scale mapping of zones such as seagrass beds or coral habitats (Hopley, 1978). More detail concerning distributions and abundances of algal resources can be obtained with the use of replicate transects or quadrats, or a combination of both as discussed by Loya (1978). A recent example of a tropical marine algal survey is provided in the work of Mshigeni (1987) for the Seychelles.

Standing stocks of marine algae are usually expressed as percent cover and/or biomass per unit area. For example, Ramirez et al. (1981) studied beds of *Gracilaria verrucosa* in Chile and found that percent cover ranged from 35 to 76% at densities...
ranging from 272 to 540 grams dry weight per square meter. Tsuda et al. (1987) found up to 80% percent cover by Gracilaria in natural beds of Yap lagoon. Doty (1973) noted that Eucheuma densities of 50 to 1500 grams per square meter characterize beds which are attractive for wild-crop harvesting, and Dawes (1974) reported that, in Florida, densities of Eucheuma isiforme can reach 2000 grams per square meter.

**Estimating production**

Several methods have been used to estimate algal productivity in the field. Thalli can be weighed, marked, allowed to grow and reweighed to determine the percent growth per day (Hoyle, 1978; Nelson and Tsutsui, 1982; Nelson et al., 1982). This method is particularly effective for farmed algae. Also, laboratory measurements of production, usually in terms of the rates of O₂ production (James, 1982; Morrissey, 1985; Nelson, 1985; Nelson and Siegrist, 1987), can be used in conjunction with data on standing stocks and environmental factors (photon flux density, temperature, etc.) to estimate rates of production in the natural environment (Pendleton, 1983; Carpenter, 1985; Garrigue, 1985).

**Yield per unit area**

Growth rates of *Eucheuma* thalli generally are between 1 and 5% per day (Parker, 1974; Doty, 1987), and successful *Eucheuma* farms produce 15 to 30 dry tons per hectare per year (Moss and Doty, 1987). Trials at Kirabati have demonstrated production within the range of 26 to 39 dry kg per hectare per year (Why, 1985).

Growth rates of *Gracilaria* and *Polycavernosa* thalli range between 2 and 7 percent per day in shallow tropical waters (Nelson et al., 1980; Nelson et al., 1982; Nelson and Tsutsui, 1982). In Taiwan, production of *Gracilaria* in ponds generally ranges from 10,000 to 20,000 dry kg per hectare per year (Chen, 1976; Chueh and Chen, 1982) with a drying ratio of 1:7 (Chen, 1976).

**Habitat degradation/destruction**

Natural beds of seaweeds in accessible areas can be easily overharvested as has been documented in the Philippines for *Eucheuma* (Parker, 1974) resulting in declining annual yields. Also, Santelices (1987) points out that careless harvesting of wild stocks can have serious long-term effects and that cutting the thalli rather than scraping the substratum will result in more rapid regrowth in harvested areas. Removal of the creeping portions of the thalli from the substratum during harvest allows the competitive invasion of other algal species.

Economic seaweeds have been shown to grow well in areas where they do not occur naturally. However, the introduction of exotic marine macrophytes for culture may be of consequence to the indigenous flora and fauna, and consideration of the
potential environmental impacts of exotic species should be considered prior to introduction. Eldredge (1987) provides a general discussion of the introductions of marine organisms to coral reef habitats and includes a section on introduced seaweeds. The introduction of *Eucheuma* to Hawaii and Fanning Atoll have also resulted in the inadvertent introduction of epiphytic algae. Also, the intentionally introduced *Eucheuma* began to spread in Kanehoe Bay, Hawaii (Russell; 1983) with associated decline of fishes and invertebrates in the areas of heavy infestation. However, efforts to control the introduced alga were successful, and the spread of *Eucheuma* from farm sites has not been a problem in other areas where it has been introduced.

**REGULATION, MANAGEMENT AND CONSERVATION**

Economic seaweeds are renewable resources and, as such, need to be conserved for future generations. The development of regional seaweed industries will require regulation by local governments or traditional policy-formulating bodies in regard to issues such as reef ownership and the introduction of exotic species. Parker (1974) points out that, for numerous reasons, conservation measures for *Eucheuma* were difficult to establish in the Philippines, but that the development of seaweed cultivation itself serves as a conservation measure. Santileces (1987) reports that there are regulations established regarding the harvest of *Gracilaria* in Chile, but the nature of the regulations was not specified. Among the first steps toward management of these resources for many islands of the region is to identify the local species of economic potential and to obtain estimates of their abundance. Once potentially economic species have been identified, steps can be taken to develop and manage these resources.
LITERATURE


