CULTURING AND UTILIZATION OF LARGE BROWN SEAWEEDS (KELPS)

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Abstract

Kelp species, the larger members of brown-colored marine plants, are widely cultivated and have been utilized by many peoples as food, fertilizer, a source of chemicals, and as fodder for domestic animals. Interest has recently developed in usage as alternative energy sources (kelp tissue would be converted to methane via bacterial fermentation). Kelp life cycles involve an alternation of generations from an entirely microscopic phase to a phase that includes the large macroscopic plant utilized by humans. The complex life history imposes culturing requirements beyond the usual degree of care needed for propagating terrestrial plants. These difficulties notwithstanding, kelp cultivation is successfully practiced, particularly in the Orient. Culturing techniques range from artificially "seeding" an artificial substrate which may eventually be outplanted to the sea, to transplanting large mature individuals to desired locations, allowing them to "seed" naturally and establish their populations. Giant kelp, Macrocystis, is the principal brown alga utilized commercially in the United States. Culturing techniques have been developed for growing Macrocystis. Depleted kelp beds in southern California have been successfully restored utilizing these methods.

Introduction

Large brown seaweeds--the kelps--have been utilized in various places in the world as food, fertilizer, a source of chemicals, and as fodder for domestic animals. Recent studies have investigated uses of kelps and other seaweeds as fuels through bacterial degradation of the biomass to methane. Kelps may be collected as wild crops, cultivated by various methodologies, or the total harvest may be a combination of both wild and cultured material. A number of genera are currently exploited (e.g., Laminaria, Undaria, Ascophyllum, Sargassum, Lessonia, Macrocystis), the particular species utilized depending on local distributions. Many other potentially useful genera are probably underexploited or not utilized (Ecklonia, Eisenia, Egregia, Pterygophora, Durvillea, Nereocystis, Pelagophycus, to name a few). Kelps have been used for centuries as food, fodder, and fertilizer[1] and as raw material for production of chemicals during the past century or so. Initially, plants were collected from natural stands or as drift material stranded on beaches after storms. As needs increased and technology developed, kelp culturing has been successfully practiced in some countries to enhance supplies.[2,3,4]

The People's Republic of China is the world's largest producer of cultured kelp (primarily Laminaria japonica), followed by Japan and the Republic of Korea. Natural stands of kelp are harvested in North and South America, Northern Europe, and South Africa. Most kelp species prefer temperate or colder waters, hence are missing from the tropics. Exceptions are Sargassum and Padina. Michanek[5] provided detailed estimates of world seaweed resources while Moss[6] described commercial seaweed supplies according to nation of origin.

Kelp beds or populations may also possess ecological values that benefit associated fauna and flora.[7] Herbivores may consume kelp directly, encrusting organisms utilize kelp surfaces as settling substrate, and many fishes associate closely with the foliose fronds, presumably seeking shelter. Kelp beds in southern California are often favored fishing areas.[8,9]

Biology of Kelps with Reference to Culturing and Propagation

Life Histories

Complexities of the life cycles of kelp species figure importantly in most culturing methodologies. Kelp farmers cannot take advantage of easily manipulated reproductive units such as seeds, as used extensively in terrestrial agriculture. Kelp aquaculturists cope with microscopic swimming spores only slightly larger than bacteria (Figure 1).

After liberation from the diploid parent plant, haploid kelp spores swim or drift in the ocean until they encounter solid substrate. After attachment to favorable bottom, they develop into microscopic-sized sexual gametophytes. Mature male gametophytes produce another motile phase, the sperm or antherozooid. Antherozooids are attracted to ova on mature female gametophytes by chemoorientation. Fertilization ensues, reconstituting the diploid phase or sporophyte. The embryonic zygote develops into the large macroscopic plant which is the desired end product of culturing. We depict the life cycle of Macrocystis in Figure 1, but the alternation of generations pattern shown is typical of all kelps. Gametophytes or young sporophytes of different kelp species are often indistinguishable. Species identification usually requires an intermediate-sized sporophyte or larger plant. Mature sporophytes develop specialized tissues for spore production. The reproductive tissues may be localized at one place on the sporophyte or in some species they may be distributed more generally. Spore production in Macrocystis occurs in specialized blades, the sporophylls, usually clustered just above the holdfast (Figure 1). Spore production may be seasonal or can occur more or less continually, depending on the species.[10]

The gametophytic phase of the life cycle can be completed in about 2 weeks under favorable laboratory conditions but probably requires much longer in nature, particularly if illumination is low. Development to fully mature sporophytes requires several months or longer, again depending on environmental circumstances and also on the species involved. Many kelps are potentially perennials but actually exist in nature largely as annuals because winter storms regularly destroy practically the entire crop of mature sporophytes.

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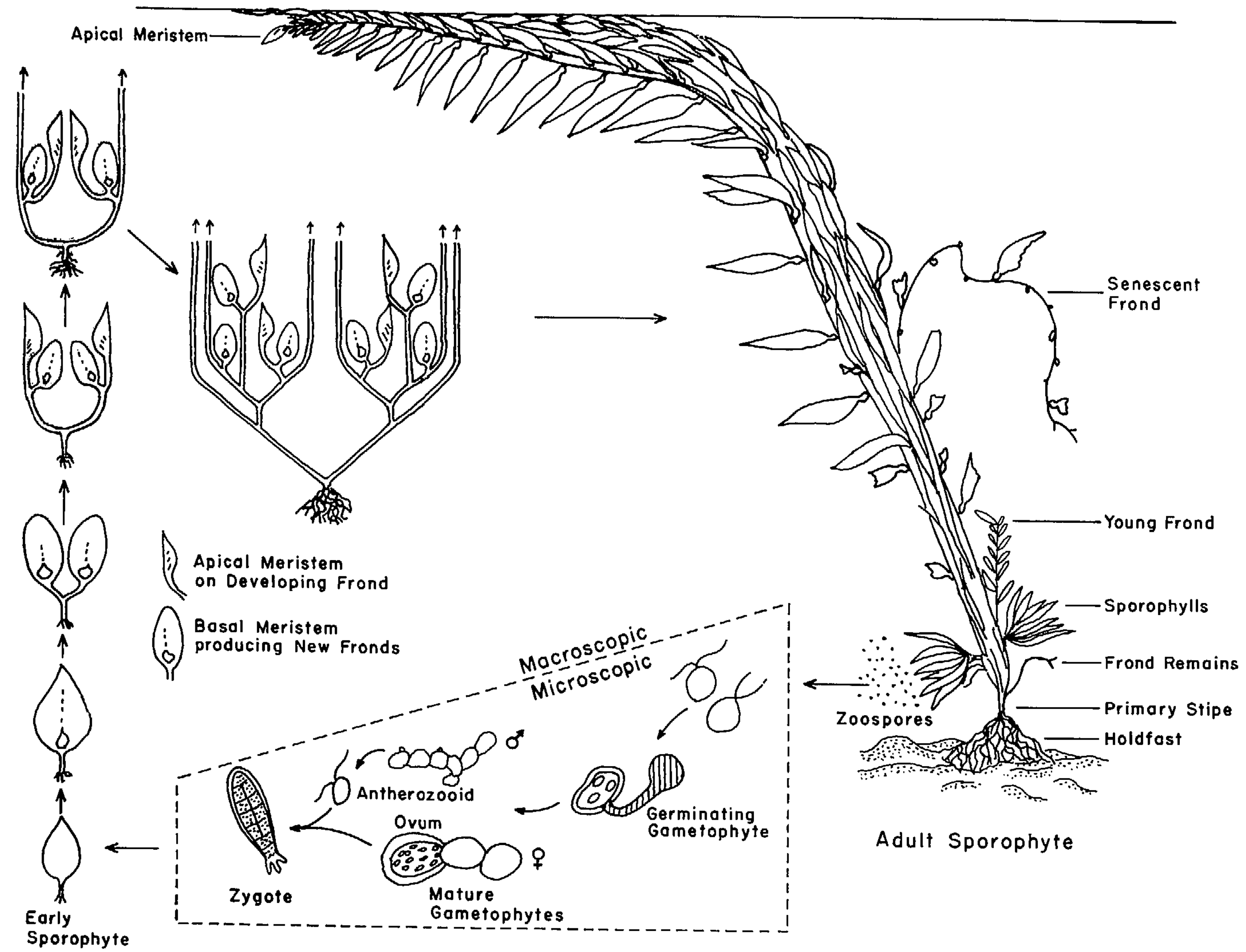

Figure 1. Life cycle of a representative kelp, Macrocystis. The microscopic stages in the life cycles of most kelp species are very similar. Morphology and details of the macroscopic phases may differ.

Physiology

Like other plants, kelps require adequate light and nutrition for proper growth. Nearly all kelps are attached to the sea floor during their normal existence, but many are able to survive when adrift. Two Sargassum species exist entirely in the drifting state. Nutrients are absorbed by kelps directly from seawater in the dissolved state, across all exposed tissue surfaces. Kelps do not depend on roots that are specialized organs for nutrient absorption. Attachment to the bottom is solely for anchoring purposes, explaining survival in the drifting state. Because of the simplicity of the basal attachment, kelps are easily transplanted compared to many terrestrial plants.

Kelp nutrition is relatively simple. For example, Macrocystis requires only nitrogen, phosphorus, and trace elements in addition to inorganics common in seawater and never growth-limiting.[11] Nitrogen is thought to be the primary critical element that at times may limit growth by kelp and other plant life in the sea.

Temperature and salinity tolerances vary with species. As noted above, most kelps prefer temperate or colder waters. This becomes a serious problem in areas where summer temperatures become elevated to lethal levels. Temperature sensitivity may be partially alleviated by fertilizing.[12] Some kelp species can tolerate salinity below that of seawater and can colonize semienclosed bays and outer portions of estuaries. None apparently survive in fresh water.

Environmental requirements may differ somewhat for gametophytes and sporophytes of the same species, possibly complicating any culturing system. In particular, most young sporophytes require fairly vigorous water motion across blade surfaces to sustain rapid growth, whereas gametophytes and embryonic sporophytes are frequently cultured under stagnant conditions in tanks and aquaria.

Many kelps possess microtubules that conduct or translocate dissolved substances between widely separated tissues within a single plant. Translocation capabilities permit movement of photosynthate from well-illuminated kelp canopies downwards to sustain growth in shaded underlying tissues. This allows dense packing of individuals growing either in culture or in nature. At least some kelps can accumulate reserves of critical elements such as nitrogen and phosphorus during periods when external supplies are high, to sustain growth when external sources are low.[13,14,15]

Distribution of meristematic tissues within plants and modes of growth vary among kelp species. Productivities are often good and in some species may be excellent.[16,17] Yields for productive species may attain excellent levels (e.g., 10 or more dry tons/acre yr).[18,19,20]

Some kelps such as Macrocystis can be coppiced successfully (i.e., a portion is harvested leaving the remainder to grow and reconstitute the crop). Parker[21] showed that the conducting elements within a severed Macrocystis stipe seal their cut ends rapidly, limiting losses of the internal fluids.

Composition

Although kelps all have similar general compositional characteristics, substantial variability occurs between species, while lesser variability usually exists within a species, resulting from seasonal, geographical, and possibly other influences. Dry weights of the commercially utilized kelps range from about 10 to 30 percent of the fresh weights. Ash weights may be as low as 10 to as high as 45 percent of the dry weight.[22] Organic fractions are typically low in protein, fat, and fiber, but carbohydrate contents are high. Principal carbohydrates are alginate (10 to more than 30 percent), laminarin (0 to more than 35 percent), and mannitol (5 to 30 percent). Terrestrial animals probably lack the digestive enzymes required to break down complex alginates, and their abilities to utilize the soluble carbohydrates remain uncertain.[1] It is believed that the food value of kelps lies primarily as roughage in the diet, with some added value from vitamins and trace elements from the plant tissues. The iodine in kelp, for example, prevents goiter in areas where soils are deficient in this element.

Morphology

Kelps exist in a variety of shapes and sizes. The simplest form of the adult sporophyte, displayed by several Laminaria species, consists of a short basal stipe subtending a large sprawling blade. The stipe may be thickened and lengthened up to one to two m in slightly more complex forms, so that one to several blades may be borne as a crown of foliage supported a short distance above the bottom. These plants resemble miniature palm trees, and dense populations may create a canopy that eliminates competing vegetation by shading the bottom. The largest kelps range up to 20 to 60 m long with widely differing morphology. Many of these large species produce gas-filled floats or pneumatocysts that provide buoyancy to the foliage (an example is adult Macrocystis, Figure 1). Surface canopies may be formed which also shade the bottom and affect short-statured vegetation. Morphology of the adult sporophyte usually profoundly influences the culturing and harvesting methodologies utilized for a particular species.

All kelps except for the drifting species of Sargassum attach to solid substrates by anchoring structures known as holdfasts. Holdfasts may be pried free during transplantation and will usually reattach to new substrate in a few days to weeks. Reattachment is not mandatory, however, so that transplants may simply be moored at a desired location by ropes or net bags entwined around holdfasts. If wave surge is present, it is important that contact between any loosely moored holdfast and rocky bottom be avoided. Holdfasts can be destroyed in a few days by abrading back and forth across an uneven bottom. The problem can be avoided by buoying holdfasts up a meter or so above the bottom.[23]

Culturing Methodologies

Kelp culturing has been widely undertaken on scales ranging from laboratory experimentation to fully developed and highly successful farming operations. Most culturing systems consist of two phases. The first phase involves intensive care under controlled conditions during the gametophytic and early sporophytic stages of a culture. This is usually followed by transfer of the culture into natural waters where sporophytes mature and are eventually harvested. The first phase may last a few weeks or months; the second, many months to several years. Basic aspects of first phase methodologies tend to be similar because requirements for culturing gametophytes do not vary greatly from one kelp species to the next. Second phase methodologies differ widely reflecting requirements imposed by physiology and morphology of the species under cultivation, harvesting techniques employed, environmental circumstances, as well as economic and other considerations.

Culturing Microscopic Stages of Kelp

Kelp spores usually attach and develop without difficulty on any nontoxic solid substrate such as wood, fiber, glass, plastic, stone, paper, iron, lead, etc. Cultures are typically initiated by exposing the desired substrate to a spore suspension for a few hours to allow settling and attachment under quiet conditions (stirring or other water movement tends to inhibit spore settling[24]). Spore suspensions may be obtained by placing the fertile or spore-producing tissues from several fully mature sporophytes into a container with clean filtered seawater for an hour or more. Spore liberation may occur freely or may require induction. Inducement methods have included holding the fertile tissues out of water overnight in dark, cool, moist air, or chilling the seawater prior to introduction of the fertile tissues (chilling is believed to cause tissue contraction, forcibly ejecting the spores). It is advisable to examine a few drops of spore suspension microscopically (25 to 50 magnification) to verify that spores are healthy and swimming vigorously. Spore suspensions are usually visibly turbid from high concentrations of spores. Many culturists prefer to dilute their suspensions to avoid overcrowding among the gametophytes and sporophytes that develop on the settling substrate.

The settling substrate may or may not be the material transferred to the ultimate culturing grounds used during the second phase of a complete cultivation system. Considerable labor is saved, however, if the initial settling substrate and the ultimate substrate are the same.

After settling, substrates are transferred to large holding tanks or aquaria under suitable conditions of temperature, illumination, and nutrition. Many culturists use a PES (Provasoli Enriched Seawater) medium for raising kelp gametophytes. We have, however, successfully and reliably raised *Macrocystis* gametophytes simply in running filtered seawater or in batch cultures with clean stirred seawater supplemented with 15 μM nitrate and 1 μM phosphate. Diseases and competing organisms can affect cultures adversely, as attested by an extensive and growing literature. Such difficulties can be prevented to some extent by strict attention to cleanliness, particularly during initial stages of culturing.

Transition to the second phase of cultivation may range from the time that embryonic sporophytes first appear, to appearance of small sporophytes easily visible to the naked eye. In many cases, sporophytes are crowded so densely on the settling substrate that future development is inhibited. In such cases, a "thinning" procedure artifically removes and discards most of the plantlets. Some problems posed to the second phases of culturing by unfavorable seasonal factors can be ameliorated or avoided by suitably timing completion of the first phase.[25,4] The Japanese authors described techniques for enhancing growth of young sporophytes in culture ("forced cultivation") to coincide with more favorable environmental conditions during subsequent cultivation in the field.

Transfer to Natural Waters

Transfer processes range from simply dispersing cultured material in the sea, to carefully fastening settling substrates to preexisting structures in the field. Probably the most complex operations are conducted in the Oriental farming of *Laminaria* and *Undaria*. First phase cultivation produces 1-2 cm sporophytes on cord or rope. These settling substrates are hung in the sea until plants are 10-15 cm long. At this stage, plants are fastened to large rope by laying their bases into the crevices formed between strands as a result of untwisting the large rope slightly. The large or "cultivation" rope plus its plants is then fastened to a "hanging" rope which supports the growing plants at depths from the surface down to 5-6 m. Hanging ropes in turn are fastened at their upper ends to surface moorings and weighted with stones at their lower ends. A common surface mooring consists simply of a 30 to 60 m stout line with buoys distributed along its length and held at both ends by cables passing down to anchors 10-30 m deep on the sea floor. Plant densities average 150,000 to 300,000 individuals per hectare on Chinese farms.[4]

Some cultivation methodologies avoid husbanding the crop beyond the early sporophytic stages. Japanese have attempted to enhance *Laminaria* stands by introducing stones to the sea floor.[3] Chinese farmers have dispersed stones with *Laminaria* zoospores attached.[26] North[27] experimentally attempted to restore depleted *Macrocystis* beds by dispersing cultures of gametophytes and embryonic sporophytes close to the bottom. McPeak[28] and colleagues devised methods for transplanting small *Macrocystis* sporophytes 20 to 300 cm long into depleted kelp beds to enhance natural populations. He sometimes used sporophytes obtained from culturing, but he also eliminated the culturing operation entirely by using small plants collected in areas where "blooms" were occasionally occurring. Young *Macrocystis* plants appear on ropes hung in kelp beds for several months (Harger, personal communication).

Amounts of kelp produced by farming operations are impressive. China's kelp production in 1979 was estimated at 1,000,000 wet tons (this includes some other seaweeds besides kelp) while kelp production for the Republic of Korea in 1978 was 195,000 tons.[4,29] The 1975 production of cultivated kelp in Japan was 130,000 tons while almost 160,000 tons were additionally gathered from harvesting natural stands.[30] *Macrocystis* is harvested as a wild crop in California, the annual yield from 1960 to 1976 ranging from 109,000 to 156,000 tons.[31]

Wu *et al.*[32] reported that yield from *Laminaria* cultivation could be increased by harvesting the outer 1/3 of the blade about 3/4 through the growing season. Tip-cutting did not affect growth of the remaining portion, but it reduced crowding in the cultures and enabled blades to tend at a greater angle to the vertical for a given current velocity, so that plants received more sunlight.

Breeding and selection experiments in China succeeded in developing a temperature tolerant strain of *Laminaria japonica* that extended the geographical range of farming operations substantially and adding to the country's total kelp production by one-third.[33,34] Similar work led to further varieties displaying enhanced productivity and iodine content.[35] The Chinese have also fertilized crops during periods when background nutrient levels are low. Experimental fertilizing of *Macrocystis* beds was attempted by North and colleagues.[36]

Several novel cultivation methodologies are under investigation that may find application to kelp production. These include systems where the growth medium is sprayed on the crop, instead of total immersion.[37,38] Possibilities of growing kelp on structures moored near the surface in deep sea settings have also been studied.[39,40,41]

Use of exotic species to boost kelp production has been considered and in some cases implemented. Laminaria japonica, the mainstay of the Chinese kelp industry, was itself believed to be an introduced species. It was first observed in Dalien Harbor in 1927 by Yoshiro Otsuki. The world's largest kelp cultivation system arose from this humble beginning. Interest in introduction of Macrocystis to northern European waters has been expressed by French scientists. The proposal, however, engendered considerable controversy. Macrocystis cultures were initiated in China in 1978.[42] Experimentation involving survival and growth in the Yellow and Bohai Seas is currently in progress.

Protection of Macrocystis plants from grazing by sea urchins is routinely undertaken in California by the Department of Fish and Game and staff of Kelco Company, a San Diego-based harvesting and processing concern.[23] Substantial restoration of depleted Macrocystis beds was accomplished by a combination of predator control measures and cultivation techniques.[43, 44]

Harvesting and Utilization

Like cultivation, harvesting techniques differ from one type of crop to another. Simple methods merely involve hauling mature sporophytes aboard small craft by hand and transporting them to the shore for processing. A variety of hooks, rakes, knives, and dredges are used in Japan to sever and recover naturally attached kelp from the sea floor.[2] Mechanical harvesting of Macrocystis canopies occurs in California. Considerable human labor is required for hand harvesting of kelps. The potential for reduction in labor costs by substituting mechanized harvesting has created considerable interest in importation of Macrocystis as an exotic species.

The two principal uses of harvested kelp tissues currently are as food and as raw material for alginic acid production. Food usages occur primarily in the Orient. Harvested Laminaria is sun dried, packed into bales, and shipped to processing plants where they receive a variety of treatments before sale to the ultimate consumer in many different forms.[1] Undaria is sold after only drying and chopping. Kelp foodstuffs are known as kombu in Japan and haidai in China.

The complex colloidal polymer, alginic acid, was first isolated by a British chemist, Stanford, in 1883. It is a mixture of D mannuronic and L guluronic acids joined through 1-4 glycoside linkages. Salts of alginic acid (the alginates) have useful emulsifying, thickening, and stabilizing properties. These serve widespread usages in foods, beverages, pharmaceuticals, textile manufacturing, and other industries. A portion of all kelp harvested or collected throughout the world is processed for algin, even in China and Japan where good demand for food usage exists. Japanese alginate production in 1970 was about 1400 tons,[2] while Tseng[45] reported Chinese production of similar magnitude. About half of China's kelp production is used as food and half is processed for alginate.[18] Okazaki[2] outlined the Japanese alginate manufacturing process.

A potentially large demand for kelp might develop as world energy needs become more critical. Seaweed biomass as feedstocks for fuel production has been under scrutiny in the United States[46] and interest is appearing in other countries. Primary attention has been directed toward producing methane from Macrocystis tissues by means of bacterial digestion systems.[47]

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Acknowledgements

Financial support from the Gas Research Institute, the U.S. Department of Energy, and Office of Sea Grants for a portion of the work reported herein is gratefully acknowledged.