

INTERIM MANAGEMENT PLAN
FOR COMMERCIAL HARVEST OF *MACROCYSTIS* SP. IN ALASKA



By

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APPENDIX A: LIFE HISTORY OF *MACROCYSTIS* SPP.

This review of giant kelp biology and ecology focuses on issues important to developing a sustainable harvest strategy for use in the herring spawn-on-kelp fishery. Key issues include standing crop measurements, blade quality and morphology, general biology and ecology, and associated organisms.

Classification

Giant kelps belong to the division Phaeophyta (brown algae) and order Laminariales (kelps). On the west coast of North America there are two species of giant kelp recognized, *Macrocystis pyrifera* and *M. integrifolia*. South of Dixon Entrance, *M. pyrifera* occurs mostly south of Santa Cruz, California (Foster and Schiel 1985) while *M. integrifolia* occurs north of Point Conception (Abbott and Hollenberg 1976). It appears, however, that both species occur in southeast Alaska and that they may hybridize (Lindstrom, personal communication). The distinguishing characteristic is the morphology of the holdfast, with *M. pyrifera* having a conical holdfast and *M. integrifolia* having a flattened, rhizome-like holdfast (Figure 1). Since the species can not be reliably distinguished as juveniles or from the surface, no attempt will be made to treat the two species separately and will be referred to here as *Macrocystis*. Although algae are not technically plants, kelp individuals will be referred to as "plants" in this document.

Reproduction

Macrocystis has a heteromorphic life cycle in which a large, diploid sporophyte alternates with a haploid, microscopic gametophyte (Figure 2). Mature sporophytes release haploid meiospores from specialized blades near the base of the plant called sporophylls. The motile meiospores settle and develop into male and female gametophytes. The gametophytes then produce eggs that remain attached or near the female, and sperm that are released by the male. Fertilized eggs then develop into macroscopic sporophytes. Relatively little is known about the gametophyte stages of kelps (Dayton 1985, Foster and Schiel 1985). Sporophytes, on the other hand, are well studied. Sporophytes can release meiospores year round in British Columbia (Druehl and Wheeler 1986), but in Alaska mature sporophylls were observed almost entirely from May to August (Stekoll and Else 1990, 1992). Dispersal of *M. pyrifera* is limited to about 3 m from a source plant in California (Reed et al. 1988). Drifting plants torn up by storms can also release spores resulting in longer-range dispersal (Dayton et al. 1984).

Reproduction may also occur vegetatively through division of the holdfasts, and this may be the dominant method for reproduction for plants in British Columbia in the winter (Lobban 1978b). The elongated holdfast of *M. integrifolia* essentially deteriorates in the middle and breaks into two separate plants.

Reproductive events of *Macrocystis* are highly dependent upon environmental conditions. Dean and Deysher (1983) showed that lower temperatures, low sedimentation rates, and higher light levels increased the production of sporophytes from gametophytes. Increased recruitment in high light levels

may be an adaptation to take advantage of gaps formed in the canopy by disturbance. In Alaska, seawater temperatures of 6-12°C are generally much lower than the temperatures that have been found to inhibit sporophyte production (about 16°C, Dean and Deysher 1983). Therefore, low light levels, especially in the winter, and high sedimentation rates, especially near areas of high runoff, may limit reproduction and recruitment in Alaska. Field studies in California have shown that recruitment events are episodic and generally coincide with low abundances of *Macrocystis* and other kelps (Dayton et al. 1974, 1984, 1992, Reed et al. 1988). When the *Macrocystis* canopy is decreased, more light reaches the substrate and stimulates recruitment (Dean and Deysher 1983).

Growth

The growth form and associated terminology of *Macrocystis* is complex and potentially confusing (Lobban 1978b). The terminology laid out by Druehl (1984) will be used in this document (Figure 3). Sporophytes adhere to the substrate with a holdfast, consisting of a rhizome and numerous haptera. Haptera grow downwards or sideways from the holdfast and increase adhesion to the substrate. Fronds initiate from the holdfast and consist of a ropelike stipe with numerous blades attached at more or less regular intervals. Each blade consists of a gas filled pneumatocyst attached to the stipe and supporting a large blade or lamina. Blades can be up to 40 cm wide and 200 cm long. New blades are produced at the growing tip of the frond, called the apical scimitar. As the frond grows, new pneumatocysts are formed sequentially and unilaterally and the blades of the newly formed pneumatocysts are initially united. As the blades develop, they split into individual blades. Growing blades are found near the frond tip while mature blades are found farther down the fronds. Near the frond bases are senescent blades. A single holdfast can produce up to 100 fronds with an average of about 5 to 10. Growth occurs at both the apical meristem at the frond tip and at a basal meristem in each blade.

Once established, sporophytes can grow rapidly (Lobban 1978a, 1978b, Coon 1982, Foster and Schiel 1985, Wheeler and Druehl 1986, Jackson 1987). In British Columbia, *M. integrifolia* grows most of the year with the exception of December and January, and maximum growth and biomass occurs in July (Lobban 1978a, 1978b, Coon 1982, Wheeler and Druehl 1986). Stekoll and Else (1990, 1992) observed slower and inconsistent growth in Sitka with many fronds decreasing in length. Frond elongation rates in California can reach as high as 30 cm/day and growth continues year around (Foster and Schiel 1985). In BC, growth is not as rapid with elongation rates of about 2-6 cm/day (Lobban 1978a, 1978b, Coon 1982, Wheeler and Druehl 1986). Individual blades also grow after they are formed, but blade growth rates have not yet been recorded. Kelp plants apparently allocate growth to different tissues throughout the spring and summer. Blades grow first followed by sporophylls, haptera, and finally stipes (Stekoll and Else 1990).

There are numerous factors that may limit the growth of *Macrocystis*. Light has been shown to be limiting under certain conditions (North et al. 1986). Jackson (1987) inferred from mathematical models that light may limit growth in northern latitudes and that *Macrocystis* plants would not survive at latitudes higher than 53° at depths greater than 12 meters. In Alaska, the lower depth limit of about 4-m below mean low water (MLW) (Druehl 1978) may be set by light levels. Lack of nutrients, particularly nitrogen, may also limit growth of both juveniles and adults (North et al. 1986). In the summer, low nitrogen levels correspond with high water temperatures (Druehl 1978), but kelp is more sensitive to low nutrient levels than to high water temperatures (North et al. 1986). In addition to light and nutrients, Druehl (1978) noticed that *Macrocystis* was not found where salinities were low in the summer.

Water motion, either from waves or currents, is essential for the growth of *Macrocystis* (Druehl 1978, Wheeler 1982). One effect of water motion is to effectively increase nutrients available to the plants by decreasing the boundary layer around the plant and increasing convective transport (Hurd et al. 1997). Water motion may also decrease temperatures by transporting water heated by the sun away from the kelp bed. Water motion effectively reduces the limiting effects of low nutrients and high water temperatures.

All tissues in a *Macrocystis* plant can be photosynthetically active, and *Macrocystis* has the ability to translocate photosynthate within a plant (Lobban 1978a, 1978b, Druehl 1984). Even though all parts of a plant are potentially able to photosynthesize, there are photosynthate sinks and sources (Lobban 1978c, 1978d, Druehl 1984). The photosynthate sinks are the apical scimitar, new blades, holdfast, and stipe. The mature blades and senescent blades are the major producers of photosynthate. Generally, a plant will translocate photosynthate from the mature blades up to the apical scimitar and growing blades. Photosynthate produced by the lower senescent blades is translocated to the holdfast. The holdfast uses the photosynthate for storage of reserves and to initiate new fronds. When a frond is cut near the water surface, the mature and senescent blades will continue to photosynthesize, translocating their products to the holdfast that is then able to produce more new fronds. It has been suggested that spring growth and production of new fronds can be predicted from the growing conditions of the previous fall and winter (Stekoll, personal communication). Under good fall and winter growing conditions, photosynthate may be stored or maintained in the holdfast. In spring, when daylength increases the stored photosynthate may be used to produce new fronds.

The morphology of blades has been shown to be dependent upon water movement in many kelps (Norton 1969, Druehl 1978, Norton et al. 1982, Koehl and Alberte 1988). In low flow areas, blades generally have more undulations, are larger, wider, and are not split. *M. integrifolia* shows similar plasticity in growth form (Druehl 1978, Hurd et al. 1997). This plasticity in growth form is highly functional. Undulations dramatically increase drag forces, resulting in higher blade mortality in high flow regimes, but in low flow areas the undulations serve to increase nutrient uptake by initiating turbulent flow around the blade (Hurd et al. 1997). Also, larger blades are better able to gather light but cannot withstand the drag and accelerational forces exerted by wave action (Denny et al. 1985).

Kelp beds can be highly productive. In British Columbia, annual production rates of canopy forming kelps range from 1.3 kg of carbon/m²/year for *M. integrifolia* (Wheeler and Druehl 1986) to 2.8 kg of carbon/m²/year for *Nereocystis* if exudates and detritus are included (Foreman 1984, Watson 1992). If understory algae is also included, then production may be as high as 40 kg of carbon/m²/year (Watson 1992). Much of this carbon becomes available to the kelp bed community and surrounding areas in various forms (Albright et al. 1982, Foster and Schiel 1985). Some of the kelp is consumed while it still attached. Unattached, drifting kelp plants are consumed by abalone, sea urchins, and other grazers (Gerard 1976, Foster and Schiel 1985). Some of the drift kelp may find its way to deeper waters where it is utilized by benthic fauna (Harrold 1990, Harrold et al. 1991). In California, about 40% of the drift kelp is used within the kelp forest and the rest is transported to other areas by water motion (Gerard 1976). Also, kelp exudes dissolved organic matter that is available for consumption by filter and suspension feeders. Kelp derived carbon may constitute more than half of the carbon in consumers in kelp forest communities (Duggins et al. 1989).

Mortality

Mortality of recruits is as high as 90% for a summer (Rosenthal et al. 1974, Druehl and Wheeler 1986, Stekoll and Else 1990, 1992). Larger plants, defined as those with more than one frond, have a mortality of about 30% per year (Stekoll, personal communication). The life span of individual plants is not well known, but it can be as long as four or five years (Lobban 1978b, Druehl and Wheeler 1986, Watson 1992). Mortality of plants is usually caused by loss of attachment due to wave action or by herbivory (Lobban 1978b, Foster and Schiel 1985, Druehl and Wheeler 1986). Also drift plants can entangle attached plants, dislodging the attached plants (Rosenthal et al. 1971, Dayton et al. 1984). Older holdfasts with a large number of fronds may be more susceptible to being dislodged by waves since many of their fronds are both larger and entangled with themselves, increasing drag and accelerational forces exerted upon the holdfast. Also, older holdfasts may be degraded by herbivory and disease (Dayton 1985, Dayton et al. 1992). Mortality in thick beds may be lower since kelp beds reduce water motion (Jackson and Winant 1983) and thus reduce mechanical stress on plants within the beds. Potentially, if beds are thinned enough to result in increased water motion, mortality of remaining plants may increase due to higher mechanical stresses. This could result in the loss of most plants within a bed.

Individual fronds are not as long-lived as holdfasts. Most fronds will be productive from four to eight months (Lobban 1978a, 1978b, Druehl 1984), but some fronds that are at least one-year old and in their second growing season have been observed (Lobban 1978b, P. van Tamelen, personal observation)

Distribution and Abundance in Alaska

In Alaska, *Macrocystis* occurs from Dixon entrance in the south to near Cross Sound in the north (Stekoll, personal communication, van Tamelen, personal observation). All *Macrocystis* beds occur in areas with some exposure to wave action or strong currents (Druehl 1978). For reasons discussed above, water motion is necessary for the growth and reproduction of *Macrocystis*. However, too much wave action results in dislodgment of *Macrocystis* holdfasts, and the more wave tolerant kelp, *Nereocystis*, is found on exposed outer coasts (Foreman 1975, Harrold et al. 1988, Watson 1992).

The majority of *Macrocystis* beds occur along the shore in fringing beds that are about 5 to 30 m wide (Watson 1992). In British Columbia, *M. integrifolia* does not grow naturally at depths greater than about 4 m below mean low tide (Druehl 1978). The lower depth limit appears to be set either by urchin grazing since individuals can grow at deeper depth (Druehl 1978) or by light levels (Jackson 1987). Given this depth limitation, large beds of *Macrocystis* are limited to shallow water over gently sloping shorelines.

Cameron (1915) performed a survey of all kelps in Alaska and on the west coast of the United States in 1913. This early study was conducted to assess the potential of kelp as an American source of potash. This survey consisted of bed size estimates and maps, general density estimates, wet weight estimates, species identification, and some limited chemical analyses. The study also rated the "availability" of kelp beds to harvesters according to the degree of exposure to swells and the abundance of rocks in and near the bed. The beds with the highest availability were protected from swells and had few dangerous rocks. Cameron (1915) estimated that there were almost 8 million tons of kelp in southeast Alaska. The abundance of *Macrocystis* was much lower in 1913 compared to extent of present day beds. Interestingly,

many of the current *Macrocystis* beds were *Nereocystis* beds in 1913. Harrold et al. (1988 and references therein) observed similar switches in species composition of kelp beds. The switch was attributed to the reintroduction of sea otters, causing a reduction in sea urchin abundance. *Nereocystis* is more resistant to the grazing pressures of sea urchins than *Macrocystis* and became more abundant when sea otters were removed and sea urchins were abundant. When sea otters were reintroduced, *Macrocystis* replaced *Nereocystis* at the more protected sites (Dayton et al. 1984, Harrold et al. 1988).

There are currently about six major areas of *Macrocystis* abundance in Alaska: Sitka Sound and the west coast of Baranof Island, Sea Otter Sound, Sumner Strait, Maurelle Islands, the Barrier Islands, and Duke Island. There are other areas, mostly on the west coast of Prince of Wales Island, that have significant *Macrocystis* populations. In a survey of the areas where kelp harvest has been concentrated in the past, van Tamelen and Woodby (1999) found that there was about 3,525 hectares of *Macrocystis* kelp beds with a total biomass of 225,225 tons (20,432 tonnes). Of this amount, however, only about 14%, or 32,663 tons (29,632 tonnes), was useful for herring SOK fishing. Since the survey was mostly done in April and the canopy coverage was about 45% less in March relative to April, the total amount of kelp available for SOK in April was estimated to be about 14,698 tons (13,334 tonnes) in the area surveyed.

Ecology and Associated Communities

Kelp beds play an important role in nearshore ecosystems in at least three ways (Duggins 1988). Kelp beds greatly increase the habitat complexity, increase sedimentation rates, and contribute large amounts of fixed carbon to the ecosystem (Duggins 1988, Duggins et al. 1989). Kelp beds may provide 15 m² of surface area for every square meter of substrate (Wing and Clendenning 1971), providing habitat for infaunal and epifaunal organisms (Duggins 1988). In addition, several pelagic species such as fish, mysids, and shrimp utilize kelp beds extensively (Coyer 1984). Juvenile and young-of-the-year fish may exhibit particularly strong, positive relationships with kelp beds (Carr 1991, Ebeling and Laur 1985). Kelp beds can also be significant sources of production, contributing large amounts of carbon in the form of attached plants, drift plants, particulate organic matter (POM), and dissolved organic matter (DOM) (Duggins et al. 1989). This carbon production is not limited to kelp beds as some of the unattached plants drift outside of the bed with some pieces drifting miles from the source bed. In areas with lush kelp beds, about 50% of the total carbon in some fishes and birds is derived from kelp primary production (Duggins et al. 1989). Finally, kelp beds alter the flow of water in and around the bed (Jackson and Winant 1983). This altered flow results in higher sedimentation rates that may increase suspension feeding and recruitment of planktonic larvae. Altered flow caused by kelp beds may also increase the availability of planktonic food sources, such as barnacle cyprids, to resident kelp bed fish (Gaines and Roughgarden 1987).

Many species of fish and invertebrates utilize kelp bed habitats. In California, many species of fish, including some commercially important species, are strongly associated with kelp beds (Ebeling and Laur 1985, Foster and Schiel 1985, Bodkin 1986, Carr 1991). In more northern latitudes, however, the association between fish and kelp is less clear (Watson 1992). Many fish species are more abundant in kelp beds than out of kelp beds in British Columbia (Leaman 1980), but few commercially important species are found frequently in kelp beds. Some unpublished work by Edward Black indicates that some commercially important species are more abundant in kelp beds than out of kelp beds, but there were no obligate relationships (Watson 1992).

Numerous invertebrates are strongly associated with kelp beds (Foster and Schiel 1985, Watson 1992). Detritivores and herbivores may obtain a large portion of their nutrition from kelp-derived sources and many of these, such as amphipods and isopods, may also be food sources for fishes. There are also encrusting organisms that live on kelp blades and stipes as well as infaunal invertebrates living in kelp holdfasts. Three commercially important invertebrates, abalone, sea urchins, and sea cucumbers are often associated with kelp beds and may benefit from high kelp productivity. Abalone prefer to eat kelp and are more abundant in and around kelp beds. Sea cucumbers have been found in kelp beds and may ingest some kelp-derived detritus (Watson 1992). Sea urchins, being a major consumer of kelp are found in and near kelp beds (Foster and Schiel 1985, Dayton 1985, Watson 1992). When conditions are favorable to kelp recruitment, growth, and survivorship, sea urchins remain in cracks and crevices and feed upon drift algae that they capture and hold with their tube feet (Dean et al. 1984, Harrold and Reed 1985, Tegner and Dayton 1991). When drift algae become scarce, however, sea urchins actively forage and can rapidly decimate kelp beds during these urchin "stampedes" (Dean et al. 1984, Harrold and Reed 1985, Tegner and Dayton 1991, Watanabe and Harrold 1991). Urchins not near kelp beds grow more slowly, have lower gonadal indices, and are more susceptible to disease relative to urchins near kelp beds (Harrold and Reed 1985, Watanabe and Harrold 1991).

It is generally accepted that sea otters, when present, can control the population of sea urchins so that kelps become abundant (Simenstad et al. 1978, Duggins 1980), but otters are not necessary to control urchin abundances (Tegner and Dayton 1991, Watanabe and Harrold 1991). The sea urchin fishery in southern California apparently is enough to control urchin populations to allow high kelp abundances (Tegner and Dayton 1991). Watanabe and Harrold (1991) observed a kelp bed recover from sea urchin devastation due to lack of urchin recruitment and an ample supply of drift algae. The presence or absence of sea otters and kelp can affect higher predators as well. Aboriginal Aleuts had very different diets when otters were present, and they were able to control sea otter populations (Simenstad et al. 1978). Also, fish and birds had higher proportions of kelp derived carbon when otters were present. Urchin die-offs in urchin barrens have been observed without the presence of otters, resulting in the establishment of lush kelp beds (Watanabe and Harrold 1991). In British Columbia urchins appear to set the lower growth limit of kelp at about 4 m below MLW (Druehl 1978, 1979). It is unclear why urchins do not forage higher than this level but it may be due to the effects of wave action (Watson 1992).

Macrocystis is generally a superior competitor to other kelps (Dayton et al. 1984, Dayton 1985, Foster and Schiel 1985). By intercepting much of the solar radiation at the water surface, *Macrocystis* prevents the recruitment and growth of other kelps on the seafloor. Conversely, if there is a thick stand of any kind of kelp, recruitment of *Macrocystis* will be inhibited (Dayton et al. 1992). *Macrocystis* will readily colonize available space when there are *Macrocystis* propagules available. Once established, *Macrocystis* overgrows most other algae since it is a floating kelp. *Macrocystis* is the competitive dominant to *Nereocystis* due to its perennial life history, but *Nereocystis* is better able to withstand wave forces (Koehl and Wainwright 1977) and herbivory (Harrold et al. 1992). When space is made available through a disturbance event, there is "scramble" competition between seaweed species to colonize the new resource (Dayton et al. 1992), with the species colonizing first becoming dominant.

Kelp beds can also affect the structure of intertidal habitats inside of the bed. Gaines and Roughgarden (1987) showed that barnacle recruitment was reduced by kelp beds. Fish in the kelp bed ate large numbers of barnacle cyprids as they passed through the kelp bed. Also, intertidal community structure is highly dependent upon wave action. Since wave action is reduced by kelp beds (Jackson and Winant 1983), the structure and productivity of intertidal communities will be altered by the kelp bed.

Kelp beds are very persistent and can last for decades in one area. Large portions of the kelp bed can be wiped out by storms and severe weather conditions (Dayton et al. 1984, 1992, Dayton and Tegner 1984, Tegner and Dayton 1987). After large disturbances, however, recruitment of young sporophytes can be

rapid even when the substrate was scoured clean (Dayton et al. 1992, Dayton and Tegner 1984). Although kelp beds appear uniform from the surface, there are numerous patches of various types of algae within the bed. For example, Dayton et al. (1992) have identified discrete, dense patches of *Pterygophera*, *Eisenia*, *Laminaria*, *Desmarestia*, and *Cystoseira*. These patches can also be quite persistent over time.

APPENDIX B: THE HISTORY OF COMMERCIAL EXPLOITATION OF *MACROCYSTIS* ON THE PACIFIC COAST OF NORTH AMERICA

History of Kelp Harvest

There have been three main uses of floating kelps in the last century. In 1916, *Macrocystis* was harvested as a source of potash for military purposes (Foster and Schiel 1985). Starting in the 1950s both *Macrocystis* and *Nereocystis* were harvested in large quantities and used for a variety of purposes, including kelp meal, fertilizer, mulch, fodder, and alginate production (Watson 1992). Finally, *Macrocystis* is currently the preferred substrate for herring roe-on-kelp.

The interest in potash generated a comprehensive survey of kelp beds from southern California to western Alaska (Cameron 1915). Although the survey covered almost all of the kelp resources on the west coast, harvests were restricted to California from 1916 to 1920 (Foster and Schiel 1985, CDFG 1996). The average harvest was about 400,000 tons per year in 1917 and 1918, and this was the highest harvest rate ever in California. The harvest techniques were severe resulting in the loss of the kelp bed (Foster and Schiel 1985). One method involved dragging a large chain over the sea floor tearing up all available kelp plants.

Alginates used for food and pharmaceutical processing are obtained from kelp. In California the alginate industry is large (about \$35 million/year) and dominated by one company, KELCO (Foster and Schiel 1985). Excluding the early harvests of 1916-1920, the amount of kelp harvested has varied over time, starting out at about 10,000 tons per year in 1932 and reaching a high of about 170,000 tons per year in the 1970s (CDFG 1996). The current harvest level is around 100,000 tons per year. Harvest occurs by means of commercial kelp cutters. These machines resemble large lawn mowers and cut all kelp fronds near the surface in an 8-meter wide swath. Interest in harvesting kelp for alginates is not limited to California. Around 1995, Oregon issued a permit to harvest *Nereocystis*, but no harvest occurred (Fox, personal communication). Several large-scale kelp harvesting operations have been initiated in British Columbia starting in 1946, but these have met with limited success (Watson 1992). In 1966, six companies had received licenses to harvest kelp. By 1974, all but one had ceased operations and only three ever harvested any kelp (Watson 1992). Currently, only a few companies harvest kelp in BC, and the harvest amounts to about 20 tonnes per year (Black, personal communication). Most of the commercial operations were willing to harvest both *Nereocystis* and *Macrocystis*.

The herring roe-on-kelp (ROK) industry is relatively new and still developing. The main difference between harvesting kelp for herring ROK and for either potash or other uses is that the ROK harvest is very selective. Kelp for ROK is hand picked, selecting only those fronds with many wide blades. Typically, ROK kelp harvesting results in little or no obvious reduction of kelp canopy in a bed.

California has a small ROK fleet in San Francisco Bay, consisting of about 10 permit holders. British Columbia has about 45 ROK permit holders, resulting in an annual harvest of about 45 tons of kelp per year. Alaska currently has four established ROK fisheries (Craig, Hoonah Sound, Prince William Sound, and Nome) and one new fishery being considered in Sitka Sound. All kelp for these Alaskan fisheries comes from the west coast of Prince of Wales Island. About 60% of harvested kelp comes from Sea Otter Sound. The kelp harvest for ROK in Alaska has ranged between 2.6 to 44.4 tons per year (Figure 4). In addition, from 1992-1998, permits have been issued to harvest relatively small quantities (1-5 tons) of *Nereocystis* to produce fertilizer. The 1999 harvest of *Nereocystis* is estimated to be about 100 tons.

There have been other potential uses of kelp suggested and attempted. During the energy crisis of the 1970s, the possibility of using kelp as a source of energy was investigated. To make this endeavor viable required an inordinate use of fertilizers to increase the growth of kelp and maintain steady production.

Management of Kelp Harvest

California

Since the vast majority of kelp harvest in California is for the alginate industry, management strategies have been implemented to regulate these large-scale harvests. The state leases the right to harvest kelp in particular kelp beds. When the initial bid is placed, the interested company is required to give the state a non-refundable deposit for the right to harvest that bed. If the bed is not harvested that year, the state keeps the deposit. If the bed is harvested, the state obtains a royalty from all proceeds. The initial deposit is applied to the royalties. If a bed is being over harvested and is deteriorating, then harvesting can be suspended from that bed by removing the bed from possible lease. The harvesters are limited to cutting kelp no more than 4 feet below the surface of the water. Monitoring is done by harvest and landing logs. The harvester is required to maintain a harvest log that can be inspected by CDFG personnel and to submit landing logs to CDFG.

The ROK fishery in California is small (10 permit) and regulated in its growth, so there is little incentive to actively manage kelp harvests.

Oregon

There has been sporadic interest in harvesting kelp in Oregon for the past 10 years. In the mid 1990s a kelp harvesting policy was developed and kelp biomass estimations were conducted. Around 1995 a permit to harvest kelp on an experimental basis was issued, but no harvest has occurred to date (Fox, personal communication).

Washington

No commercial harvest of kelp is allowed in the state of Washington, and there is no management plan in place. Although Washington supports a limited ROK fishery, the amount of kelp taken is so small that there is no management plan. No ROK fishery has occurred for the last five years (Mumford, personal communication).

British Columbia

The proposals to harvest kelp for alginates generated much research into the biology and ecology of kelp beds in British Columbia. The results of the research were sufficient to write a management plan, but a management plan was never finalized since the commercial endeavors withdrew their permit requests before a management plan was needed. The research did indicate that it was more appropriate to regulate kelp-cutting height above the sea floor as opposed to depth below the water surface. It was recommended that kelp harvest occur no lower than 4.5 m above the sea floor. The frequency of harvest was also investigated, and it was found that it was impractical to harvest more than three-times per year. Harvesting earlier in spring or early summer was less likely to have long lasting negative effects on a kelp bed since there was enough growing season left to produce fronds for the fall and winter.

British Columbia considers the ROK harvest of kelp to be essentially self regulating. Since only the most desirable fronds are harvested from kelp beds, there is little concern about over harvesting a bed. However, ROK kelp harvesters may not take more than 20% of any bed at any one time. Some marine reserves have been opened for native users of kelp.

APPENDIX C: PLAN FOR DETERMINING THE PRODUCTIVITY OF *MACROCYSTIS* AND IMPACTS OF HARVESTING

Despite the large amount of research concerning *Macrocystis*, there is little practical information regarding the regulation of *Macrocystis* harvest. In British Columbia kelp is managed with the view that the resource and harvest methods are "self regulating" by means of the kelp growth form and life history, and the highly selective nature of the fishery. This approach is sufficient for the small scale harvesting in BC. In California, kelp is managed by leasing beds to essentially one responsible company. Being on the northern end of the *Macrocystis* range, southeast Alaska kelp may be more prone to over harvesting than kelp in other areas.

If kelp harvesting for roe-on-kelp (ROK) or other purposes increases dramatically in southeast Alaska, then a comprehensive research and monitoring program should be established. The emphasis of this research plan will be on monitoring the size, productivity, and health of *Macrocystis* beds in southeast Alaska with work contingent upon the availability of funds. The quality of kelp blades will also be assessed to more accurately determine the biomass of kelp that is useful for SOK. Also, the effects of harvesting on kelp beds and associated communities will be addressed through manipulative experiments.

Growth and Density

The density of kelp plants and fronds can vary dramatically over years (Rosenthal et al. 1973, Dayton 1985, Dayton et al. 1984, 1992). The year to year variation in kelp density will be assessed at three to five kelp beds representing the major harvest kelp harvest areas. Randomly located, permanent transects (50 x 2 m) will be marked at each site and kelp density will be assessed every spring. The number of plants, large fronds (>1.5 m), small fronds (<1.5 m), and juvenile plants will be recorded. Additionally, the average length of 10% of the fronds will be determined.

The year to year variation in growth of *Macrocystis* is poorly understood. Stekoll (personal communication) thinks that spring growth can generally be predicted based upon fall and winter conditions. To test this idea, kelp growth will be estimated for multiple years and correlated to environmental conditions, including light levels and sea temperatures. Kelp growth will be measured by the change in length of tagged fronds. At each of the permanent sites used for density estimates, 40 fronds will be tagged at each site in March. The sites will be revisited in April and the fronds remeasured. Tagging fronds for growth will also allow the assessment of plant and frond mortality.

Effects of Harvesting

The effect of the most severe harvesting methods allowed for *Macrocystis* will be assessed by small scale harvesting experiments. The effects of kelp harvesting in different seasons, harvesting multiple times per year, and harvesting the same bed every year will be assessed. This experiment was initiated in 1999 and should be expanded and monitored in subsequent years. The effect of harvesting on the associated kelp bed community will also be determined, and the abundance of drift algae will be assessed. The percent cover of understory algae will be estimated by placing three quadrats (0.50 x 0.50 m) along the permanent transect line and visually estimating the coverage of each species. All drift algae found within each quadrat will be collected. Similar experiments have been done in California and British Columbia, but they have been plagued by serious flaws in experimental design, rendering the results ambiguous. This research is needed to ascertain the effects of harvesting *Macrocystis*.

Aerial Extent of Beds

The most efficient method for estimating the abundance of kelp over large areas is to use aerial photography. To keep costs minimal, only those areas from which kelp is harvested will be surveyed. The most efficient methods for these photographic surveys have not yet been determined. Dr. Michael Stekoll (University of Alaska Fairbanks) has applied for Sea Grant funds to assess the effectiveness of various remote sensing technologies to estimate kelp biomass. Based upon his results, a remote sensing technique will be chosen and implemented. One goal of this project is to input the surface areas of kelp beds into a GIS database, so that changes in kelp abundance can be easily followed over years.

Blade Quality

The quality of kelp blades is vitally important to the SOK industry. It is desirable for management purposes to determine the proportion of high quality blades (at least 14 cm wide and free of debris and holes) or fronds (fronds with a high proportion of high quality blades) in each kelp bed. So far, the only method to do this is to visit each bed and measure a random sample of blades at that bed. The quality of blades in any particular bed may remain relatively constant from year to year, so that once a bed is surveyed it need not be surveyed again. Another method to estimate blade quality would be to relate blade quality to exposure and currents and then derive an exposure index for each bed. Since blade morphology is dependent upon water motion, this may be a fruitful avenue of research. Either method requires visits to a large number of beds. Initially, beds of varying wave exposures will be examined. If a consistent relationship between kelp blade morphology and exposure can be determined, the quality of kelp blades at the remaining beds will be estimated from the exposure index. The number of beds visited will be determined by the availability of funds.

APPENDIX D: CONSERVATION IMPACTS OF THE PREFERRED MANAGEMENT APPROACH ON NON-TARGET SPECIES AND ON INDIVIDUALS OF THE SAME SPECIES.

Effect of the Fishery on Macrocystis

From a manager's viewpoint, *Macrocystis* presents a unique situation in that only part of individuals are harvested. Therefore it is appropriate to consider the impacts of harvesting on targeted individuals of *Macrocystis*. The unit of harvest for *Macrocystis* is the frond and there are many fronds per plant. Since fronds grow from an apical meristem, removal of the meristem by cutting the frond results in cessation of growth or very limited growth due to elongation of the stipe (Coon and Roland 1980). The remaining blades, being either mature or senescing, continue to photosynthesize, supplying the holdfast with photosynthate to store or to initiate new fronds (Lobban 1978b). The cut frond will eventually die.

The effects of harvesting kelp have been examined in numerous studies. Of the studies surveyed here, five were done in *M. pyrifera* beds in California (Miller and Geibel 1973, Kimura and Foster 1984, Barilotti et al. 1985, Barilotti and Zertach-Gonzalez 1990) and Chile (Santelices and Ojeda 1984), and two were done in British Columbia in *M. integrifolia* beds (Druehl and Breen 1986, Coon and Roland 1980, Coon 1982). Of these seven studies, all but one (Coon and Roland 1980, Coon 1982) suffer serious flaws in experimental design. None of the remaining six studies were replicated and each harvest treatment was represented by a single area or bed and compared to a single control area. All but one of these unreplicated studies were guilty of pseudoreplication (Hurlburt 1984) by applying inferential statistics to replicate samples within one experimental unit. The remaining study (Druehl and Breen 1986) did not use statistics in their study and differences were judged by intuition and experience. The results of these studies are frequently contradictory, so the results must be interpreted with extreme caution.

The growth of uncut fronds in harvested areas is either decreased or increased compared to fronds in unharvested areas (Coon and Roland 1980, Coon 1982). Fronds in beds harvested early in the season (early June) grew about 1 cm/day slower than fronds in control beds. The opposite result was obtained for beds harvested later in the season (July). Miller and Geibel (1973) found no differences in frond growth between cut and uncut areas. The growth response of uncut fronds to harvesting seems to be dependent upon many factors other than harvesting, including light levels, nutrients, temperature, and season.

Plants with cut fronds may increase the production of new fronds since more energy is diverted down to the holdfast instead of to growth of the cut frond (Coon and Roland 1980). Thus, cut fronds may be replaced by new fronds rapidly. Harvesting early in the summer may not reduce the fall canopy but later harvests may reduce the fall canopy (Coon and Roland 1980, Coon 1982). By harvesting early in the growing season (March-July), new fronds are likely to contribute to the canopy by the end of summer, resulting in no net loss of photosynthate production and storage for the winter. If the fronds are cut later in the season, however, the fall canopy will be reduced and the amount of photosynthate stored for winter and early spring will be reduced, resulting in poor spring growth. The timing of kelp harvest is important to the health of individual plants and the kelp bed.

The effect of harvesting on holdfast condition is unclear. Miller and Geibel (1973) found that cutting fronds of individual plants resulted in reduced production of holdfast haptera. They speculated that the smaller number of haptera would result in increased dislodgment rates during winter storms due to poorer attachment. Barilotti et al. (1985) found either decreased, increased, or similar haptera elongation and branching in harvested areas compared to unharvested areas. The plants studied by Barilotti et al. (1985) may not have had any fronds cut even though they were located in harvested areas. A varying number of cut fronds per plant may have contributed to the varying results reported by Barilotti et al. (1985). It is likely that harvesting fronds from a plant, especially if all fronds are cut and they are cut near the substrate may result in weaker holdfasts.

Similarly, the effect of harvesting on plant survivorship has received conflicting reports. Rosenthal et al. (1974) observed about 20%-increased mortality following commercial harvest of a bed. Some of this mortality occurred as a result of entanglement with dislodged plants. On the other hand, Barilotti and Zertuch-Gonzalez (1990) found no change in survivorship in harvested areas compared to control areas. Survivorship is probably not increased by cutting fronds *per se*, but increased tugging on the fronds by the kelp cutting blades may dislodge individuals, which may then entangle other plants and dislodge them.

Reproductive structures (sporophylls) are located near the base of *Macrocystis* fronds and are thus not removed in the process of harvesting kelp. It is likely, that harvesting the growing end of fronds may increase reproductive effort by diverting resources to the base of the plant instead of to the growing tips. The effect of harvesting on sporophylls has not been investigated.

Recruitment of *Macrocystis* juveniles is consistently enhanced in harvested areas (Kimura and Foster 1984, Santelices and Ojeda 1984). Many other studies have indicated that *Macrocystis* recruitment is increased following canopy removal (Dayton et al. 1984, 1992, Dayton 1985, Foster and Schiel 1986, Watson 1992).

Large scale harvesting of *Macrocystis* has occurred in California since 1916 with little or no long lasting detrimental effects. This is due in large part to growth and reproductive strategies of *Macrocystis*. Although cutting fronds stops the growth of the cut frond, resources may be diverted to producing more fronds. Since fronds have a life span of only about six months, the loss of several frond tips may not have a long lasting impact on the plant or bed. When the kelp canopy is removed, light levels are increased and recruitment is enhanced. As long as the fronds are not cut too low and are cut early in the growing season,

harvesting should have little effect on individual plants or entire beds. There may also be a danger of harvesting too frequently and slowly depleting the resources of the kelp bed and component plants (Miller and Geibel 1973, Kimura and Foster 1984).

Effect of The Fishery on Non-Targeted Species

Other Algae

Removal of floating kelp canopies can have dramatic effects on understory algae. Druehl and Breen (1986) observed increased abundance of Ulvoid algae and *Desmarestia* sp. following the removal of either the *Macrocystis* canopy or all *Macrocystis* plants. Their data also indicate a decrease in the abundance of *Laminaria groenlandica*, a large stipitate kelp. Similarly, Santelices and Ojeda (1984) saw a decrease in the stipitate kelp, *Lessonia flavicans*, following the removal of *M. pyrifera* canopy. On the other hand, Kimura and Foster (1984) saw no change in the total abundance of algae following kelp harvest, but they did not present data on individual algal species. Dayton and co-workers (Dayton and Tegner 1984a, Dayton et al. 1984, 1992, Tegner and Dayton 1987) have seen increases in *Pterygophera californica* (a large stipitate kelp), *Desmarestia*, and other species of brown algae following the removal of large portions of the kelp bed during severe storms.

If whole beds of *Macrocystis* are eliminated, *Nereocystis* may become abundant where *Macrocystis* is removed. Many of the *Macrocystis* beds in southeast Alaska were *Nereocystis* beds in 1913 during the "Potash From Kelp" survey (Cameron 1915), demonstrating that *Nereocystis* was able to live and reproduce where *Macrocystis* is now found. It is generally believed that *Macrocystis* is the superior competitor and excludes *Nereocystis* in the absence of disturbance by storms or herbivores (Foster 1982, Harrold et al. 1988, Foster and Schiel 1985).

Urchins

Sea urchins, *Strongylocentrotus fransicanus*, *S. pupuratus*, and *S. droebachiensis* benefit from the presence of kelp beds. Drift kelp is an important part of the diet of sea urchins, and if drift kelp is not available, sea urchins may begin actively foraging (Harrold and Reed 1985). In British Columbia (Druehl and Breen 1986) and California (Harrold and Reed 1985), the absence of kelp canopy resulted in lower abundances of drift kelp and lower gonad indices of urchins. Watanabe and Harrold (1991) also observed lower urchin gonad indices in urchin barren areas relative to nearby kelp forests.

Sea urchins have the potential to decimate kelp beds (Tegner and Dayton 1991, Watanabe and Harrold 1991). If drift kelp becomes limiting, sea urchins will begin actively foraging and eating attached kelp (Harrold and Reed 1985). Decreased abundances of drift kelp associated with kelp canopy removal (Druehl and Breen 1986, Tegner and Dayton 1991) may trigger active sea urchin foraging, further reducing the abundance of kelp. When harvesting kelp, it may be important to leave enough kelp to continue to provide enough drift algae to keep urchins satiated.

Fish

Many species of fish utilize kelp bed habitats. In California, many species of fish, including some commercially important species, are strongly associated with kelp beds (Miller and Geibel 1973, Ebeling and Laur 1985, Foster and Schiel 1985, Bodkin 1986, Carr 1991). In more northern latitudes, however, the association between fish and kelp is less clear (Watson 1992). Many fish species, including some commercially important species, are more abundant in kelp beds than out of kelp beds in British Columbia (Leaman 1980). Some unpublished work by Edward Black indicates that some commercially important species are more abundant in kelp beds than out of kelp beds, but there were no obligate relationships (Watson 1992). There is anecdotal evidence that kelp beds are important to migrating adult salmon (Tom Mumford, personal communication). When there was a proposal to harvest large quantities of kelp in Washington state, the fishers were strongly against the proposal because they felt salmon use the edge of kelp beds during migration. The fishers often set their gear next to kelp beds to catch these migrating fish. Also, the natives used kelp beds to gather salmon by cutting a hole in a long fringing kelp bed and setting their nets in the hole. The salmon would follow the edge of the kelp bed into the hole.

Ecosystem Impacts

Kelp beds are important to the ecosystem in at least three ways (Duggins 1988): First, kelp beds provide structural habitat that may be utilized by fish and invertebrates to avoid predation, to forage, and to spawn. Second, kelp beds are very productive, providing the ecosystem with drift algae, particulate organic matter, and dissolved organic matter. Many invertebrates use these sources of energy, including abalone, sea urchins, crabs, sea cucumbers, and shrimp (Watson 1992). In addition, numerous small crustaceans (amphipods, mysids, and shrimp) and other small invertebrates are more abundant in kelp beds and are a food source for various fish and other predators (Coyer 1984). About half of the carbon utilized by fish and birds near kelp beds is derived from the kelp (Duggins et al. 1989). Finally, kelp beds alter the hydrographic conditions in and around the beds (Jackson and Winant 1983). This altered flow can increase larval or gamete retention times, making kelp beds more attractive to organisms that have short lived larvae or are free spawners. Long-lived larvae may also recruit more abundantly in kelp beds since lower water flows result in increased sedimentation rates. Also, lower flows in kelp beds may increase the availability of planktonic food sources for filter feeders and predators.

Destruction of kelp beds can therefore have numerous deleterious effects on the surrounding ecosystem. The abundance, health, and recruitment of many commercially important invertebrates (abalone, sea urchins, crabs, sea cucumbers, and shrimp) may be reduced as a result of kelp bed destruction. Abalone and sea urchins feed, in part, upon drift algae produced in kelp beds. Crabs and sea cucumbers may benefit from detrital food webs associated with kelp beds. Some shrimp also use kelp beds as nursery habitat (Marliave and Roth 1995). In addition, commercially important and forage fish species may suffer from the loss of kelp beds by reduced food sources (small crustaceans and other invertebrates) and habitat.

As long as kelp beds remain healthy, there appears to be little impact of harvesting kelp on the ecosystem. On the other hand, if a kelp bed is destroyed by harvesting, there can be severe and dramatic changes in the ecosystem. Loss of the entire kelp canopy can occur given severe harvesting regimes (Miller and Geibel 1973), the removal of sea otters (Duggins 1980), or natural factors such as increased urchin recruitment (Watanabe and Harrold 1991) or storms (Dayton et al. 1992). When kelp beds are removed,

the amount of drift algae decreases, urchins begin to actively forage, further reducing algal abundance, and the community shifts to an urchin dominated system (Harrold and Reed 1985). Actively foraging urchins maintain the urchin barrens by removing any new algal recruits (Harrold and Reed 1985, Watanabe and Harrold 1991). Compared to kelp bed communities, urchin communities are characterized by low abundances of drift seaweed, low productivity, low fish abundances, low invertebrate (other than urchins) abundance, and urchins have lower gonadal indices (Harrold and Reed 1985).

In light of the potential effects of the loss of kelp beds, it is recommended that all reasonable precautions be taken to protect this valuable resource. Fortunately, *Macrocystis* is an ideal species to harvest. Cutting fronds does not kill the individual and may actually stimulate the production of new fronds. It is possible to remove enough kelp to cause drastic changes in the community resulting in dramatically lower kelp abundances. Reductions in kelp canopy, from harvesting or natural means, results in decreased drift algae (Harrold and Reed 1985, Druehl and Breen 1986, Tegner and Dayton 1991). When drift algae becomes limiting, urchins will begin to actively forage (Dean et al. 1984, Ebeling et al. 1985, Harrold and Reed 1985, Tegner and Dayton 1991). Actively foraging urchins can completely deforest a kelp bed in less than 4 months (Watanabe and Harrold 1991). Thus, even partial removal of kelp canopy can ultimately result in deforestation of the kelp bed.

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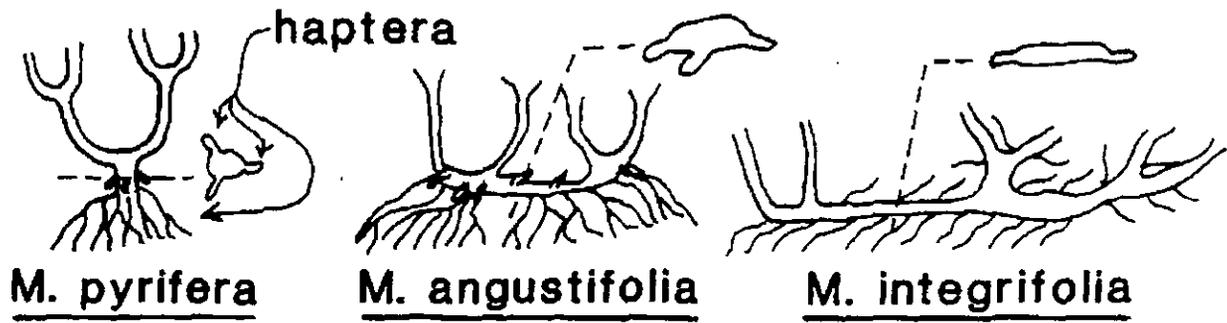


Figure 1. Diagram of the holdfasts of *M. pyrifera* and *M. integrifolia* (taken from Foster and Schiel 1985).

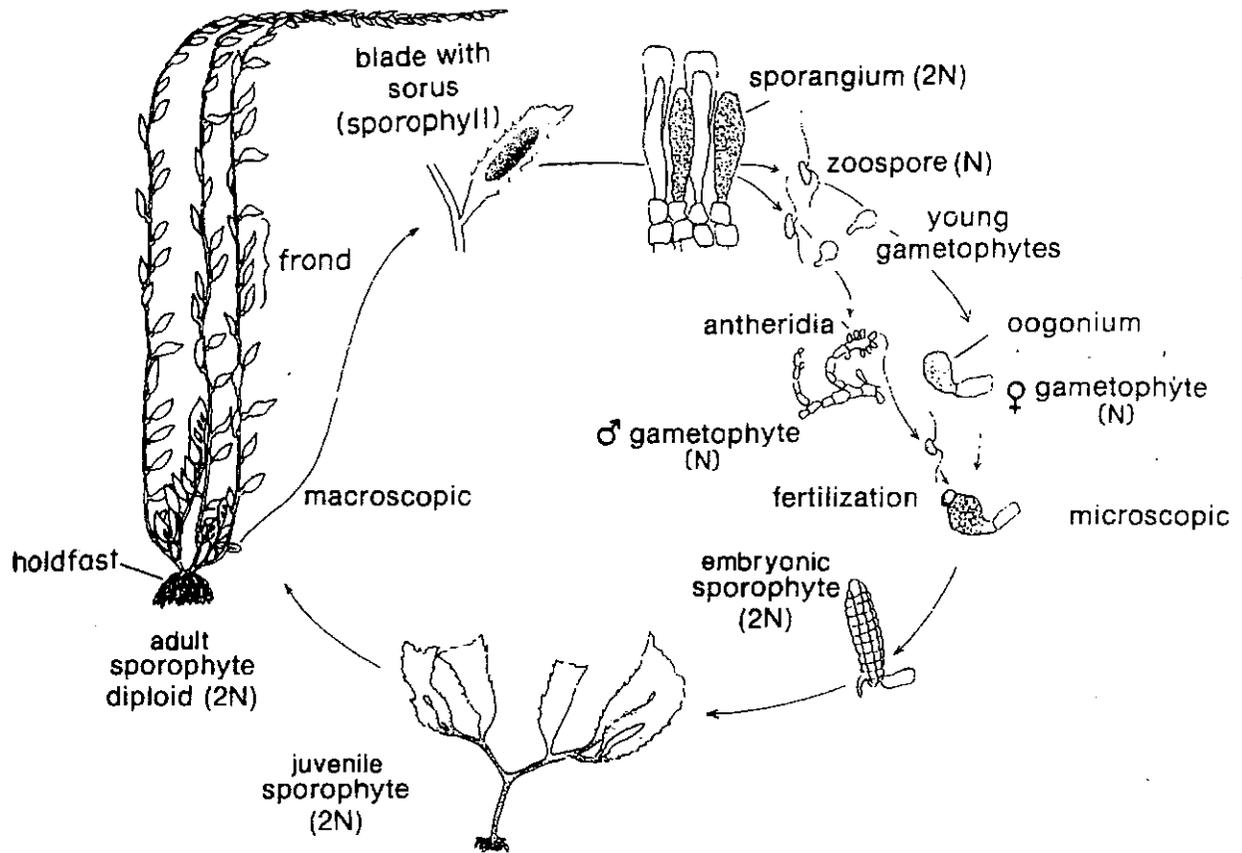


Figure 2. Diagram of the life history of *Macrocyctis* (taken from foster and Schiel 1985).

Macrocystis integrifolia

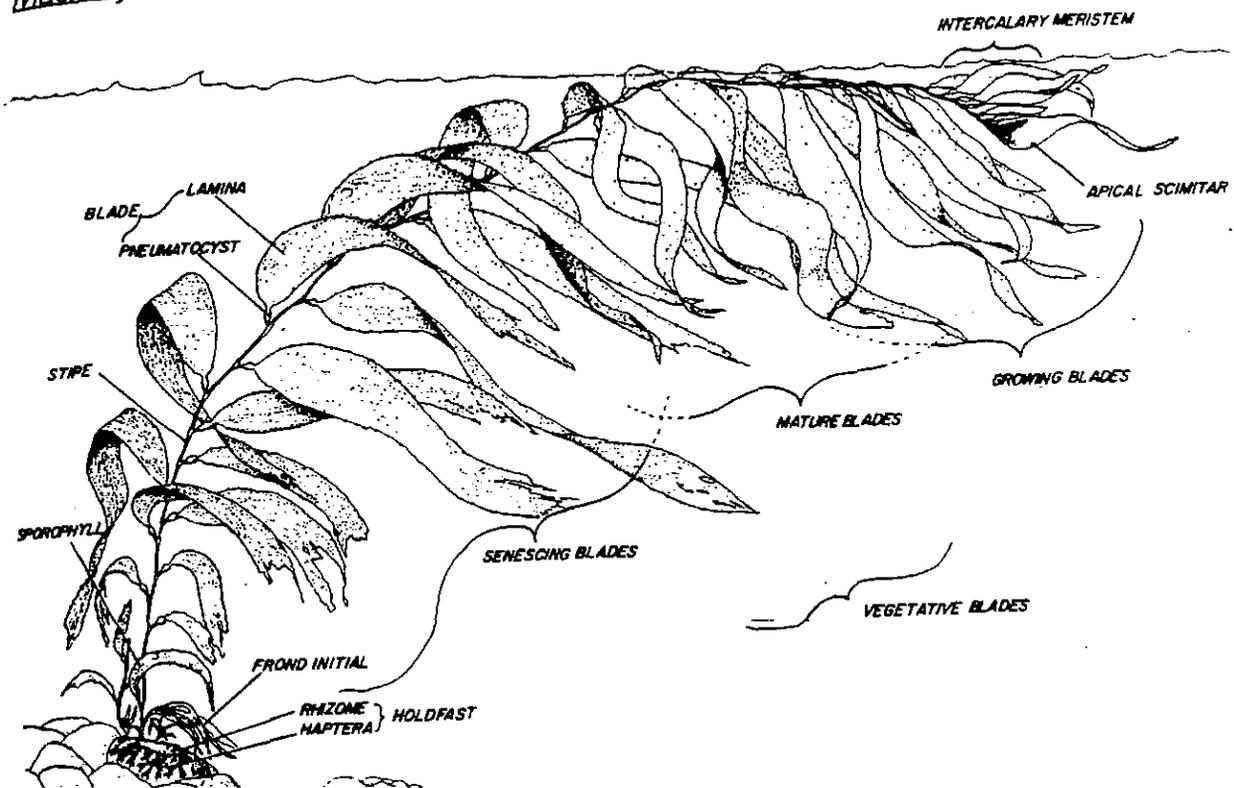


Figure 3. The morphology of a *Macrocytis* individual showing the terminology used in this report. Only one of many fronds is depicted in the drawing (taken from Druehl 1984).

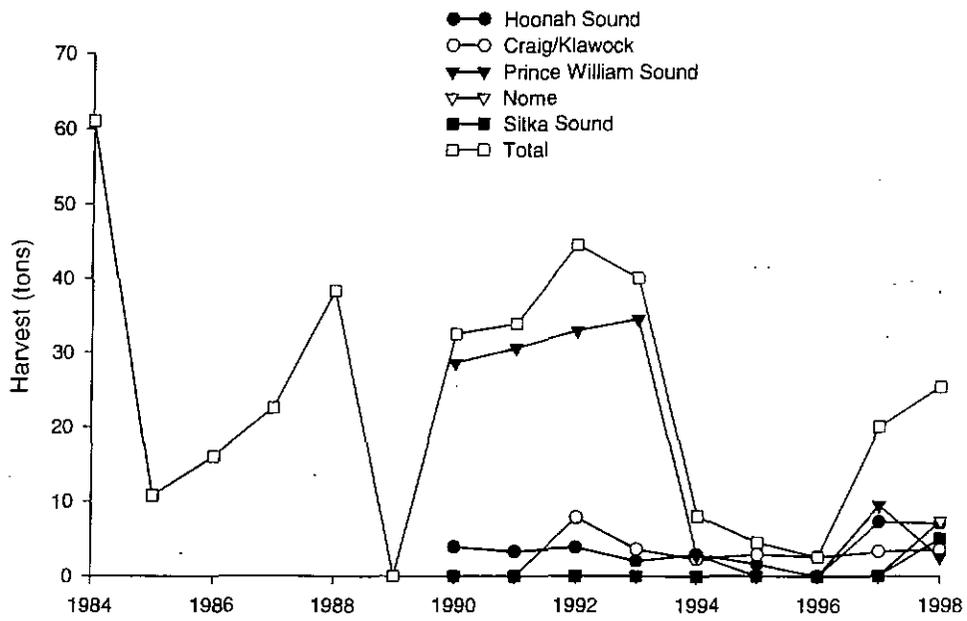


Figure 4. The total harvest of *Macrocystis* kelp in Alaska from 1984 through 1998. The amount of kelp taken for each herring roe-on-kelp fishery is shown.

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