# *Assessment of Macrocystis Biomass, Quality, and Harvesting Effects in Relation to Herring Roe-on-Kelp Fisheries in Alaska*

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# ASSESSMENT OF *MACROCYSTIS* BIOMASS, QUALITY, AND HARVESTING EFFECTS IN RELATION TO HERRING ROE-ON-KELP FISHERIES IN ALASKA

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# ABSTRACT

Interest in harvesting *Macrocystis* kelp for use in herring roe-on-kelp (ROK) fisheries is increasing, but information on the biology and ecology of kelp is limited for southeast Alaska. This is a report of a four month pilot study to evaluate the amount of kelp available for harvest and the recovery rates of kelp from harvest. Estimating the amount of kelp available consisted of first estimating the total abundance of kelp in a survey area and second estimating the biomass of available and desirable kelp. The total biomass was estimated by surveying the surface area of kelp beds in selected regions on the west coast of Prince of Wales Island. Randomly selected index beds were surveyed to determine kelp density, and samples were measured and weighed to estimate the average weight of kelp. An estimated 225,225 tons of *Macrocystis* kelp were found in the survey area. The harvest of kelp for ROK is highly selective. By comparing harvested to available kelp, it was found that blades at least 14 cm in width and fronds with a high proportion of desirable blades were selected. The proportion of blades and fronds meeting these selection criteria was estimated for the index beds, and the biomass of desirable kelp was estimated to be 32,663 tons or about 14% of the total kelp biomass in April. The growth in kelp canopy was rapid from March to April, with March canopies about 45% smaller than April canopies. Therefore, the biomass of desirable kelp in March was about 18,000 tons. Even if kelp harvests increase 10 times over present levels, the harvest will only represent about 3% of the lowest estimate of the biomass of desirable kelp.

There were few significant effects of experimentally harvesting kelp canopies in March and/or April. Kelp beds that were experimentally harvested at both times or only in April had shorter fronds and possibly fewer large fronds and fronds per plant. This experiment was monitored only one month after the last harvest, so there may not have been sufficient time for the cut kelp to fully recover. This preliminary experiment indicates that kelp recovers rapidly from harvesting in the spring.

# INTRODUCTION

Kelp beds are a conspicuous element of the outer northeast Pacific Coast (Foster and Schiel 1985). All kelp belongs to the order *Laminariales* (*Phaeophyta*), and are made up of holdfasts, stipes, and blades. Some of the kelps produce floats that buoy them to the surface, these are known as the canopy forming kelps. The giant kelp, *Macrocystis* sp., is a well known canopy forming genus that occurs in much of the coastal Pacific Ocean. The terminology associated with *Macrocystis* is fairly complex as is the morphology (Figure 1), consisting of an attached holdfast with numerous fronds supporting numerous blades. *Macrocystis* often grows in thick beds that form a unique and important habitat.

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 provide as much as 15 $m^2$ 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 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).

The morphology of kelp 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).

There has been interest in harvesting kelp for various purposes on the Pacific Coast of North America since at least 1911 (Foster and Schiel 1985). In California, about 100,000 tons of kelp are harvested annually for various products. Harvesting north of California has been sporadic, with few large scale commercial harvests. In British Columbia and Alaska *Macrocystis* kelp is harvested to support the herring roe-on-kelp (ROK) fishery. Since the price paid for the end product is dependent upon the quality of the kelp blade, harvesting kelp for ROK is highly selective. In particular, fronds with many wide blades are desirable.

The research described here was initiated due to interest in harvesting kelp for a roe-on-kelp (ROK) fishery near Sitka, Alaska. A proposal was made by commercial harvesters to the Alaska Board of Fisheries in 1996 to allow Sitka Sound herring sac roe purse seine permit holders the option of using open pound racks to harvest herring roe on kelp. This would be in lieu of, or in addition to, using purse seines. The board took no action on the proposal at their 1997 meeting, but requested that the department conduct an experimental gear test fishery. The department conducted the test fishery in 1998 focusing on management issues related to the pound fishery and the gear. A second test fishery was conducted in 1999 primarily to fund the kelp research described here, as well as to revisit some issues related to fishery management. A second proposal to allow for a roe-on-kelp fishery in the Sitka area will go before the board at their 2000 meeting.

An understanding of the abundance and dynamics of giant kelp, *Macrocystis* spp., is essential to manage the use of this alga for existing and emerging herring ROK fisheries. Kelp harvests in Alaska are currently being managed with limited knowledge of kelp abundance, growth, or recruitment. In conjunction with other roe-on-kelp fisheries, the Sitka Sound open harvest platform herring roe-on-kelp test fishery presents the possibility of greatly increasing the harvest pressure on *Macrocystis* kelp resources. At least two pieces of information are needed to properly manage kelp harvests in Alaska, 1) the amount of kelp that is available and desirable for harvest, and 2) the effects of harvesting on kelp beds and associated communities. This report provides a preliminary assessment of the abundance of *Macrocystis* kelp resources in Alaska. Also, the results of an experiment assessing the short term effects of harvesting on kelp beds and the ability of kelp beds to recover from harvests are reported.

## METHODS

### *Standing Crop Estimates*

#### Aerial Surveys

Aerial surveys of kelp beds on the west coast of Prince of Wales Island were conducted between March 23-29, 1999 (Figure 2). The coastline was surveyed by Scott Walker, an experienced ADF&G herring spawn recorder. During the flight all significant *Macrocystis* kelp beds were marked in red pen on black and white charts by the surveyor, recording the approximate outline of each bed. The area around Duke Island and Tree Point was surveyed on 11 June 1999.

The resulting maps with marked kelp beds were analyzed to ascertain the surface area of kelp beds. The original maps were scanned into digital format (Figure 3), and an image that included only the red "kelp beds" was produced from the original scanned image (Figure 4). These two images were produced with Adobe PhotoShop. Using an image analysis program (Optimus), the original image was used to scale the red only image, using landmarks of known length. An averaging procedure (5x5 pixels) was applied to the red-only image to eliminate small lines, numbers, and letters within the red patches. The red patches were then automatically outlined, and any remaining unwanted "holes" or other images were removed by hand. The image analysis program then determined the total area of mapped kelp beds and the data were downloaded to Excel for analysis. The Duke Island and Tree Point survey was not analyzed due to relatively low *Macrocystis* abundance and limited time.

## Index Beds

One index bed was randomly selected from each subdistrict surveyed, resulting in a total of 11 index beds. To select a bed, a randomly placed point was located in each subdistrict. The bed that was closest to the point and was at least 20 $m^2$ in surface area was selected. To estimate the growth of beds during the spring, these index beds were photographed during the March aerial survey and on April 28, 1999. Photographic methods were consistent between dates and the altitude was recorded for each photograph. For each index bed, a pair of photographs, one each from March and April, were selected based upon similarity of photograph angle, direction, and altitude. The photographs were scanned into digital format and analyzed using Optimus image analysis program. All canopy forming kelp was outlined by hand using the image analysis program and the total area of kelp plant canopy (excluding water area between fronds) was obtained. This is not the same measure of the surface area of beds obtained from the hand-drawn bed maps in March which includes water area between fronds.

The April photographs were calibrated using a photograph of an object of known dimensions taken from the same altitude. The March photographs were calibrated by measuring a distinctive object in the April photograph and using the same object as a scale in the March photograph. This procedure insured that each pair of photographs were calibrated similarly. If the calibrations were off, they were off by the same amount for each date so between date comparisons could still be made.

To estimate the length of fronds and the density of plants and fronds, four index beds were visited between April 19-24. The density of kelp in each bed was estimated by scuba divers. Six transects were oriented perpendicular to the long axis of the bed and placed at even intervals along the length of the bed. If transects were longer than 20 m, then 20 m long sections were sampled at the inside edge, outside edge, and approximate center of the transect. The total length of the transect was recorded as well as the distance between transects. The start and end depths of each transect were also recorded. Divers swam along transect lines and counted the number of large (>1.5m) and small (<1.5m) *Macrocystis* fronds for each holdfast encountered within one meter of the transect line. Every tenth frond was measured for length starting with the tenth frond.

## Commercially Harvested Bed

Kelp was harvested for the Sitka Sound open harvest platform test fishery from a bed on the northeast side of Port Alice in Sea Otter Sound (Figure 2). This bed was surveyed by scuba in March just after the harvest and again in April as part of the index bed survey. The methods of survey were similar to the methods used for the index beds. The total harvest taken from this bed was recorded.

## Frond Biomass

To estimate the average weight of fronds, 22 fronds of varying length were weighed and measured. The fronds were cut into 1 meter sections starting from the tip and working towards the base. The weight and section number were recorded for each section. At the base, the length of the final piece was also recorded. Thus, the total weight and length of each frond could be determined.

## Total Biomass Estimates

The total biomass was estimated by multiplying the total surface area of kelp beds (March) by the average density of large fronds (April) and the average weight per frond (April). The average weight per frond was estimated by multiplying the ratio estimator of average frond weight/average frond length from the weighed fronds by the average length of fronds in the index beds. The relationship between frond length and weight was linear and had a zero intercept, so using a ratio estimator was appropriate. The surface area of the beds drawn in March was assumed to remain constant through April for purposes of this calculation.

An estimate of the variance associated with the total biomass estimate was generated by combining variance estimates for both frond density and average frond biomass. Frond density averages and variances were weighted by bed size (Cochran 1977). The variance associated with the average frond biomass was calculated using the methods of Barnett (1991).

## Estimated Versus Harvested Biomass

Two small beds were surveyed by scuba divers to assess the accuracy of the biomass estimates. The beds were small ($<150m^2$) enough that an entire frond count census was completed for each bed in one day by two scuba divers. Every tenth frond was measured for length. After surveying, the canopy was harvested from both beds and the total frond biomass was harvested from one bed. All harvested material was weighed. Thus, the estimated biomass from scuba sampling could be compared to the actual biomass obtained by harvesting.

*Desirable Biomass*

## Blade Morphology

The morphology of individual kelp blades was examined to assess the desirability of kelp. Three fronds from each of ten systematically located points in the Port Alice bed were collected before any commercial harvest occurred. The tenth, fifteenth, and twentieth blades from the apex were detached and measured. The youngest free blade was counted as blade number one. The total length and maximum width of each blade were measured. In addition, the number of holes in the blade, the general condition of the blade, and the presence or absence of epiphytes and silt were recorded. The harvested kelp was also sampled. Forty haphazardly selected fronds were collected from the harvested kelp and three randomly chosen blades were sampled. The morphology of blades sampled before harvest was compared to commercially harvested blades to determine the criteria used to select blades sampled.

Fronds were collected from the four visited index beds to determine the proportion of desirable blades over the entire region. Fronds were collected over dive transects. The initial goal was to collect a frond at three locations (inside edge of bed, outside edge of bed, and in the center of the bed) along each transect, but time constraints often reduced the sample size. Blades were then sampled in the same manner as the blades in the harvested bed.

Frond quality was assessed by comparing the number of desirable blades out of the three sampled blades between fronds from various locations. As with blade morphology, frond selectivity was determined by comparing the fronds available in the harvested bed before harvest to the fronds actually harvested. The proportion of fronds desirable over the entire region was then determined by using the sampled fronds from the index beds.

**Biomass Estimates**

The biomass of desirable kelp was estimated by multiplying the total area of kelp beds by the density of desirable fronds by the average weight of fronds harvested. The density of desirable fronds was estimated by multiplying the total frond density by the proportion of fronds that were available and the proportion of fronds desirable obtained from the index bed surveys. Available fronds were defined as those that were at least 5.3 m in length. This definition was needed to eliminate those fronds that did not reach the surface (average depth of about 3 m) and have enough additional length to harvest (2.3 m, obtained from the average length of harvested fronds).

The variance component of the biomass estimate was obtained by combining variance estimates from the average weight of harvested fronds and the average density of available and desirable fronds.

*Effects of Harvesting*

**Experimental Design**

The goal of this experiment was to assess the impact of harvesting on kelp beds. Three kelp beds in the Craig area were used (Figure 2), and four 20 m transects were permanently established in each bed perpendicular to the depth contours. Kelp density was estimated using the techniques described above for index beds for each study plot before any treatments were assigned.

All transects were marked, numbered, and surveyed between 24-25 March 1999. After the initial survey, the experimental treatments were assigned to the transects. There were four experimental treatments, 1) March harvest (early), 2) April harvest (late), 3) March and April harvest (early+late), and 4) an unmanipulated control. Each of the four treatments were randomly assigned to the four plots in each bed. After treatments were assigned, the plots receiving the early and early+late treatments were harvested by cutting all fronds around the mean low water mark. An 8-meter wide swath centered on the transect line was harvested. The late and early+late plots were similarly harvested after sampling in April. All plots were resurveyed using the standard dive measurements on 24-26 April and 15-16 June 1999.

# RESULTS

## *Standing Crop*

### Aerial Surveys

The aerial survey identified 751 distinct beds from eight regions on the west coast of Prince of Wales Island (Table 1). The average bed size over the surveyed area was 46,936 $m^2$ ranging from 415 to 886,774 $m^2$. More than 35 million square meters or 3,524 hectares of kelp beds were surveyed (Table 1). It should be emphasized that this is only a partial survey of *Macrocystis* kelp on the west coast of Prince of Wales Island. It is estimated that this survey represents about 60% of the kelp in this area. In addition there are kelp resources around Baranof Island, Sumner Strait, Kuiu Island, and Duke Island but the area of these resources is unlikely to exceed the kelp beds on the west coast of Prince of Wales Island. In 1913, Cameron (1915) estimated there are about 45,300 acres (18,332 hectares) of kelp in southeast Alaska, but only a small portion of this was *Macrocystis*.

### Density Estimates

Many characteristics of kelp populations at the index beds were evaluated using the information from scuba surveys (Table 2). The selection of Port Alice was heavily biased and the scuba surveys reflect this bias. The density of plants, large fronds, and frond length were all greater at Port Alice compared to the index beds (Table 2). The density of small fronds and the number of fronds per plant at Port Alice were both within the range observed at index beds. The overall density of individual plants was about 0.34/$m^2$ (excluding Port Alice data). There were more large fronds (mean of 2.44/$m^2$) than small fronds (0.46/$m^2$) at all index beds. The number of fronds per plant ranged between 3.8 and 12.5 with an average of 9.3. Excluding Port Alice, frond length was relatively constant between sites and averaged 6.1 meters.

The average depth of the 4 index and 3 experimental harvest beds was 3.28 m below mean low water (MLW), ranging from 1.25 to 6.13 m below MLW. The depths at Port Alice were greater than at the index beds ranging form 4.27 to 9.45 m below MLW and averaging 7.08 m below MLW.

### Frond Biomass Estimates

There was a linear relationship between the length of a frond and its weight (Figure 5). Length was a good predictor of weight, explaining 88% of the variation in frond weight. Since a plant of zero length cannot have any mass, the intercept must be zero. In this case a ratio estimate (average weight:average length) is a simple method to estimate average frond biomass from a sample of lengths. The ratio generated from the data in Figure 5 is 0.39 kg/m. The average length of fronds at the surveyed index beds was 6.11

meters, so the average weight per frond was 2.37 kg. (0.39 kg/m* 6.11 m). The variance about this estimate was 0.065, calculated using Barnett's (1991) method.

## Total Biomass

The estimated biomass of kelp in the areas surveyed was 204,319,652 kg (225,225 tons) with an 80% confidence interval of $\pm$43,802,512 kg (48,284 tons). Based upon the weight per unit area, this estimate corresponds to "very thin" beds reported by Cameron (1915) and the June harvest yields of Coon (1982).

## Estimated Biomass Versus Harvested Biomass

The estimated biomass at both beds was greater than the actual harvested biomass (Table 3). At Pt. Ildefonso, only the canopy was harvested, so the biomass below the harvest level was left. This site, however, was only 2-3 m deep, so the amount that was left was minimal. Not all of the harvested material was weighed as some fragments drifted away before weighing.

### *Desirable Biomass*

## Blade and Frond Quality

The harvest of kelp for the roe-on-kelp fishery was highly selective with both blades and fronds being chosen for high quality. According to Richard Walsh (personal communication) of Home Port Seafoods in Bellingham, Washington, the two most important factors in grading kelp blades is the overall health and the blade width. For the 1999 SOK fishery, kelp blades in the 14-16 cm size range or higher were selected relative to the blade widths available in the bed (Figure 6). At Port Alice, blade widths in the bed did not change between March and April (Figure 7), but blade areas increased from March to April, indicating that blades grew in length but not width (Figure 7). The width of blades varied between the index beds (Figure 8). Eagle Island had narrow blades with few blades wider than 16 cm. Those blades that were wider than 16 cm were often torn and broken. There was a higher percentage of both narrow (<14 cm) and wide (>20 cm) blades at Harmony Island relative to Port Alice. The few samples taken at Balena Island indicate that most blades were in the 14-18 cm range. At Port Real Marina, blades were very wide with almost all blades more than 16 cm wide, but most blades at this site were covered with fine silt or damaged by grazers.

To evaluate the quality of fronds, the three blades sampled on each frond were rated as desirable or undesirable. A desirable blade had to be at least 14 cm wide, have few small holes, no large holes, free of silt, and not torn. Virtually all of the harvested fronds from Port Alice used in the test fishery had 2 or 3 desirable blades of the 3 sampled (Figure 9), and the percentages used in these two categories were greater than the available fronds in the Port Alice bed. In the index beds, 38.7% of blades had 2-3 desirable fronds. Most of these desirable fronds were found at one index bed.

### Available and Desirable Biomass

To determine the biomass of kelp available and desirable for kelp harvest, both the density of large fronds and the weight per frond needed to be adjusted for the selection of fronds. The density of fronds available for harvest was calculated by multiplying the total large frond density by 51.25%, which is the proportion of fronds that were longer than 5.3 m. The threshold length of 5.3 m was deduced as follows: The average depth of beds surveyed by scuba in this study was rounded down to 3 m below MLS, and this length was added to the average length (2.3 m) of the cut segments of fronds harvested for the Sitka ROK fishery. That is, a frond must be at least 3 m to get to the water surface and then be an additional 2.3 m to make the frond worth harvesting. Thus, the estimated density of available fronds was the average frond density, (2.45 fronds/$m^2$) (Table 2), times the proportion of fronds longer than 5.3 m (0.5125) with a result of 1.26 available fronds/$m^2$. The proportion of desirable fronds in the index beds was 38.7%. Therefore the density of available and desirable fronds is 1.26 available frond/$m^2$ times 0.387, equal to 0.486 available and desirable fronds/$m^2$. The average weight of harvested fronds was 1.73 kg/frond. Thus, the biomass of available and desirable fronds in the surveyed area in April 1999 was 29,631,711 kg with an 80% confidence interval of $\pm$20,161,522.8 kg, or about 14% of the total kelp biomass.

### Growth of Beds - March to April

The canopy cover within all index beds increased from March to April (Table 4, Figure 10). The percent increase in cover ranged from 12% to 311% with a mean increase of 82%. Thus, beds in March will average about 45% less canopy than beds in April. If there is a linear relationship between canopy cover and biomass, then the April biomass estimate can be appropriately reduced to obtain a March biomass estimate. Decreasing the April biomass estimate by 45% results in a total biomass in March of 112,375,808.4 kg and a desirable biomass in March of 16,297,441.3 kg.

## *Effects of Harvesting*

Over three months there were few detectable effects of harvesting upon *Macrocystis* plants or beds (Figure 11). To account for variation in the starting densities or lengths, differences between the June sampling date and the pre-harvest March sampling date were statistically analyzed (Table 5). Average frond length was significantly lower on plots harvested later in the season compared to the early harvest or control plots (Figure 11F, Table 5). There were also marginally significant decreases in the density of large fronds and the number of fronds per plant in the plots harvested in both March and April (Figure 11C, E, Table 5). There were no detectable effects of harvesting on the densities of plants, small fronds, or juveniles (Figure 11A, B, D, Table 5).

## DISCUSSION

The total biomass estimate is made up of aerial surveys of the extent of kelp beds, estimates of frond densities, and estimates of frond weight. Each of these three components can contribute to errors in the biomass estimation. Any error inherent in the aerial survey methods was not quantifiable, so the estimate of total kelp bed area was treated as a census with no error in the analysis. There may have been errors in recording the extent of individual beds during the surveys with some beds being overestimated in size and others underestimated. Also, there may have been errors in identifying *Macrocystis* beds. Some *Nereocystis* beds may have been included in the survey, resulting in an overestimate of *Macrocystis* area. Conversely, some *Macrocystis* beds may have been identified as *Nereocystis* beds, resulting in underestimation of *Macrocystis* bed area. Without performing multiple surveys over a single area, it is impossible to estimate these sources of error. A more accurate and efficient method of estimating the area covered by *Macrocystis* needs to be developed. Aerial photography from belly or wing mounted cameras using infrared film would eliminate errors in canopy area estimation and has been used in British Columbia (Foremen 1975) and in Alaska (M. Ridgway, Oceanus Alaska, personal communication).

The error estimates for total biomass were obtained from a combination of the estimates for frond density and frond weight. Frond density estimates made up about one third of the error estimate for total biomass while the frond weight estimates accounted for the remaining error. The disparity between the error contributions of frond density and frond weight indicate that relatively more effort should be devoted to sampling frond weight. A more efficient approach would be to have fewer transects per bed (about 5), sample more beds, and sample about 30 more fronds for weight and length. However, the precision of the sampling was within 22% of the mean with 80% confidence intervals, indicating a reasonable estimate of the total kelp biomass in the surveyed area.

For the two small beds examined, the biomass estimated by scuba surveys was higher than the harvested biomass. Part of this difference was due to handling the fronds in the process of weighing, resulting in the loss of an unknown amount of material. Only the canopy at Point Ildefonso was harvested, so some of the estimated biomass was left on the sea bottom. With these sources of error, the harvested biomass may have been within the range of variation of the estimated biomass. More beds need to be surveyed and harvested to determine if the scuba surveys consistently overestimate the available biomass.

Estimating the amount of kelp desirable by the ROK fishery proved difficult. The quality of kelp blades is mainly dependent upon blade width and blade health, defined by the absence of holes, tears, and debris. In addition, fronds with a high proportion of desirable kelp blades are selected over other fronds. Since blade and frond quality can only be assessed by field sampling and the estimates for the proportion of desirable kelp reflects sampling from only four beds, the precision of the biomass of desirable kelp was quite low ($\pm$68%). More beds need to be surveyed to make more accurate estimates of desirable biomass.

Blade morphology is dependent upon wave exposure and currents (Druehl 1978, Hurd et al. 1997), so it may be possible to predict the quality of blades in kelp beds if the exposure of the bed is known. The water flow regime for any particular area depends upon many factors including the fetch, bottom topography, local land masses, and the wind regime. It may be possible to sample blades and fronds in a variety of kelp beds varying in exposure and relating the blade morphology to a derived exposure index. The health of kelp blades also seems to be indirectly dependent upon water flow. Both grazing and fouling seems to be greater in protected areas. Waves may limit the activities of herbivores (Menge and Sutherland 1976) and prevent fouling organisms from colonizing. Thus, in very protected waters, as at Port Real Marina, kelp blades may be wide but their quality may be low due to severe grazing and fouling. At the exposed Eagle Island site, few grazers or epiphytes were observed on the sampled kelp blades.

The canopy area of kelp beds declines in winter and reaches a maximum in late summer (Harrold and Reed 1985, Foster and Schiel 1985, Dayton 1985, Watanabe and Harrold 1991). Thus, kelp canopies increase in area during the spring months. The extent of kelp canopies increased by an average of about 82% from March to April. The canopy available for harvest in March is about 55% of that available in April. Since the Sitka Sound herring typically spawn in March, the kelp available for herring ROK is much less than that available for later herring fisheries.

The estimate of bed surface area, obtained in March, is surely a conservative estimate of bed area in April. Because the March estimate was used in the calculation of total biomass in April (using April estimates of average frond density and mass) the total biomass estimate must be regarded as conservative.

## Effects of Harvesting

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. For example, harvesting kelp has shown increases, decreases, or no change in kelp growth, holdfast growth, frond production, and plant survivorship. Hence, the results must be interpreted with extreme caution.

Of the studies that examined recruitment, all found that recruitment increased when kelp was harvested. The only significant effect observed in this study was a decrease in the average length of fronds in harvested areas. The lack of significant results in this study does not necessarily indicate that there was no effect of harvesting, but may be a result of low replication of treatments. Also, the experiment has only been monitored once, two months after harvest, so any long-term effects have not been determined. This experiment implemented the maximum harvest possible under current regulations, and the lack of detectable effects indicates that the more limited harvest done by the ROK industry may have little effect on kelp beds. These experiments need continued monitoring and expansion to estimate potential long-term effects of harvesting on kelp bed and associated communities.

## CONCLUSIONS

This study has provided some preliminary answers to the questions of 1) how much kelp is available and desirable for harvest, and 2) what are the effects of harvesting on kelp beds and associated communities? There appears to be enough kelp available in the surveyed area to support all Sitka Sound herring purse seine permit holders harvesting ROK with the following assumptions. There were more than 225,225 tons of kelp identified in this study. There are 51 permit holders in the Sitka Sound purse seine herring fishery. If each were permitted to conduct an ROK operation and if each harvested 5 tons of kelp (hypothetical amount based upon the test fishery), then the total kelp harvested would be 255 tons. Total *Macrocystis* harvests to support other ROK fisheries in Alaska (Craig, Hoonah Sound, Prince William Sound, and Nome) were 25 tons in 1998, and as high as 44 tons in 1992. If harvests for all of these fisheries, plus the Sitka fishery, were to occur in one season, the total harvest would still be less than 300 tons. This represents about 0.1% of the biomass of *Macrocystis* in the surveyed area. If the kelp harvests are not concentrated in any one bed or area, there is a low probability of depleting the kelp resource. In addition, the effects of the most severe harvesting allowed are apparently minimal. A more complete survey should be performed to survey all of the *Macrocystis* resources in Alaska. If a good photographic system is developed, a thorough survey should be practical. In addition, kelp density should be monitored yearly on a few representative kelp beds to ascertain yearly fluctuations in kelp density. Kelp beds often have dramatic yearly changes in abundance that are related to El Nino events (Dayton et al. 1984, 1992, Dayton and Tegner 1984, Tegner and Dayton 1987, 1991).

Increasing the demand for high quality kelp may result in conflicts among users for more desirable kelp. Of the 225,225 tons of kelp surveyed only about 14% of this kelp was deemed desirable to the ROK industry. A total harvest of 300 tons would represent about 1% of the estimated amount of desirable kelp available; however, the estimate for the amount of desirable kelp is very uncertain. The low estimate of desirable kelp is about 10,000 tons, and the maximum potential harvest is 300 tons, resulting in a potential harvest of 3% of the desirable kelp. If this harvest is concentrated in a small number of areas, as it has been in the past, users may find desirable kelp hard to locate and conflicts may occur among users. The estimate for the amount of desirable kelp needs to be improved. This can be accomplished by visiting more beds to sample more blades. It appears that the width of kelp blades does not vary at a site over the season, so a kelp bed can be evaluated at any time during the spring and early summer.

We observed few lasting effects of harvesting on kelp beds. This experiment was limited in scope and duration and should be monitored, continued, and expanded in spring of 2000. The effects of harvesting the same bed every year as well as harvesting only once need to be assessed. In addition, the effect of harvesting on the kelp bed community needs to be evaluated. Given the high growth and production rates of *Macrocystis* elsewhere (Lobban 1978a, 1978b, Coon 1982, Wheeler and Druehl 1986, Jackson 1987), it is anticipated that kelp recovery from harvesting should be completed by the end of summer for harvests in March or April.

Based upon the preliminary results of this study, there was sufficient kelp in March 1999 to support the currently proposed Sitka Sound ROK fishery assuming total harvests would be in the neighborhood of several hundred tons. Conflicts between users may occur over access to high quality kelp, but these conflicts may encourage harvesters to locate currently unused high quality beds. The effects of harvesting on kelp and associated communities appears minimal or negligible, but this needs to be verified by further research.

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Table 1. The number of beds, average area of bed, and total area of all beds in primary areas of *Macrocystis* concentrations on the west coast of Prince of Wales Island.

| AREA | #Beds | Area/Bed ($m^2$) | St. Dev. | Total Area ($m^2$) |
|---|---|---|---|---|
| Sea Otter Sound | 112 | 86,750.6 | 115,590.5 | 9,716,063.8 |
| Maurelle Islands | 166 | 66,557.2 | 90,087.6 | 11,048,501.3 |
| Gulf of Esquibel | 57 | 29,030.1 | 37,064.7 | 1,654,714.0 |
| Portillo Channel | 60 | 60,058.4 | 105,187.2 | 3,603,501.0 |
| Port Estrella | 17 | 25,228.5 | 32,495.8 | 428,884.9 |
| Goat Island | 18 | 34,984.8 | 34,977.1 | 629,726.5 |
| Grand Islands | 90 | 21,651.9 | 23,425.5 | 1,948,669.0 |
| Barrier Islands | 231 | 26,921.1 | 36,272.3 | 6,218,782.3 |
| Average | | 46,935.9 | 76,628.6 | |
| Total | 751 | | | 35,248,842.9 |

Table 2. Summary of kelp data collected at scuba survey sites. Data include the mean and standard deviation of the density of plants, small fronds, large fronds, the number of fronds per plant, and frond length. The total bed area is given for each bed and weighted averages are given with and without the Port Alice site.

| SITE | Area of Bed ($m^2$) | Plants (#/$m^2$) | | Small Fronds (#/m2) | | Large Fronds (#/m2) | | Juveniles (#/m2) | | Fronds/Plant | | Small:Large Fronds | | Frond Length (m) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Mean | St. Dev. | Mean | St. Dev. | Mean | St. Dev. | Mean | St. Dev. | Mean | St. Dev. | Mean | St. Dev. | Mean | St. Dev. |
| Port Alice | 89516.0 | 0.5042 | 0.2527 | 0.5167 | 0.2084 | 3.7083 | 1.7086 | 0.7042 | 0.8737 | 8.5655 | 2.0514 | 0.1474 | 0.0396 | 9.4889 | 2.0188 |
| Balena | 660.0 | 0.3125 | 0.2298 | 0.2000 | 0.0354 | 0.9500 | 0.7425 | 0.0250 | 0.0354 | 3.7895 | 0.2977 | 0.2822 | 0.1834 | 5.4000 | 1.5556 |
| Eagle | 1180.0 | 0.4495 | 0.1716 | 0.6467 | 0.2251 | 3.5457 | 1.2874 | 0.2302 | 0.2836 | 12.4970 | 12.3657 | 0.2013 | 0.0880 | 5.9412 | 0.6344 |
| Harmony | 750.0 | 0.3085 | 0.1514 | 0.3483 | 0.3248 | 2.2587 | 1.5607 | 0.0612 | 0.0668 | 8.3140 | 4.3223 | 0.1403 | 0.0907 | 6.4832 | 2.0744 |
| Port RM | 2670.0 | 0.3125 | 0.2005 | 0.4750 | 0.2679 | 2.3833 | 1.1175 | 0.0375 | 0.0586 | 9.5157 | 2.6829 | 0.1924 | 0.0456 | 6.2551 | 1.6863 |
| Averages (weighted) | | | | | | | | | | | | | | | |
| With Port Alice | | 0.4952 | 0.0051 | 0.5136 | 0.0022 | 3.6383 | 0.0390 | 0.6697 | 0.0191 | 8.6060 | 0.0374 | 0.1502 | 0.0016 | 9.3013 | 0.1021 |
| Without Port Alice | | 0.3427 | 0.0168 | 0.4609 | 0.0322 | 2.4465 | 0.1806 | 0.0825 | 0.0237 | 9.2947 | 0.5846 | 0.1983 | 0.0079 | 6.1099 | 0.0767 |

Table 3. The estimated biomass and harvested biomass of *Macrocystis* at two sites near Craig, Alaska. The data used to estimate biomass is also given for each site.

| Site | # Large Fronds | Frond Length (m) | Frond Weight (kg) | Estimated Biomass (kg) | Harvested Biomass (kg) |
|---|---|---|---|---|---|
| Point Ildefonso | 678 | 7.43 | 2.88 | 1954.27 | 738.50 |
| Portillo Channel | 402 | 7.93 | 3.08 | 1236.63 | 1087.00 |

Table 4. The estimated size of the *Macrocystis* canopy in March and April at the index beds. The percent change from March to April is also given.

| SITE | March | April | %change |
|---|---|---|---|
| Balena Island | 50395 | 68160 | 35 |
| Cape Pole | 12980 | 21466 | 65 |
| Eagle Island | 10727 | 13043 | 22 |
| Gooseneck Harbor | 3518 | 14484 | 312 |
| Grace Harbor | 3182 | 3827 | 20 |
| Harmony Island | 5049 | 8443 | 67 |
| Kassa Inlet | 16349 | 28447 | 74 |
| Natoma | 1576 | 4983 | 216 |
| Noyes Island | 32694 | 45720 | 40 |
| Point Ildefonso | 2790 | 3305 | 18 |
| Port Real Marina | 20119 | 22667 | 13 |
| Sentinals | 2172 | 4365 | 101 |
| | | | |
| Mean Deviation | | | 81.9 |
| Standard Deviation | | | 91.4 |

Table 5. Statistical results of experimental harvest. The F/MSE columns are composed of the F-ratios for site and harvest treatment and the mean square error. Full ANOVA tables can be reconstructed from the supplied information.

| | | Plants (#/m2) | | Small Fronds (#/m2) | | Large Fronds (#/m2) | | Juveniles(#/m2) | | Fronds per Plant | | Frond Length (m) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Source | df | F/MSE | p-value | F/MSE | p-value | F/MSE | p-value | F/MSE | p-value | F/MSE | p-value | F/MSE | p-value |
| Site | 2 | 3.110 | 0.118 | 3.780 | 0.087 | 2.690 | 0.147 | 0.170 | 0.848 | 1.090 | 0.393 | 1.240 | 0.353 |
| Harvest | 3 | 0.670 | 0.600 | 0.670 | 0.600 | 3.840 | 0.076 | 0.920 | 0.485 | 3.510 | 0.089 | 7.270 | 0.020 |
| Error | 11 | 0.403 | | 1.000 | | 0.808 | | 0.127 | | 2.150 | | 1.040 | |

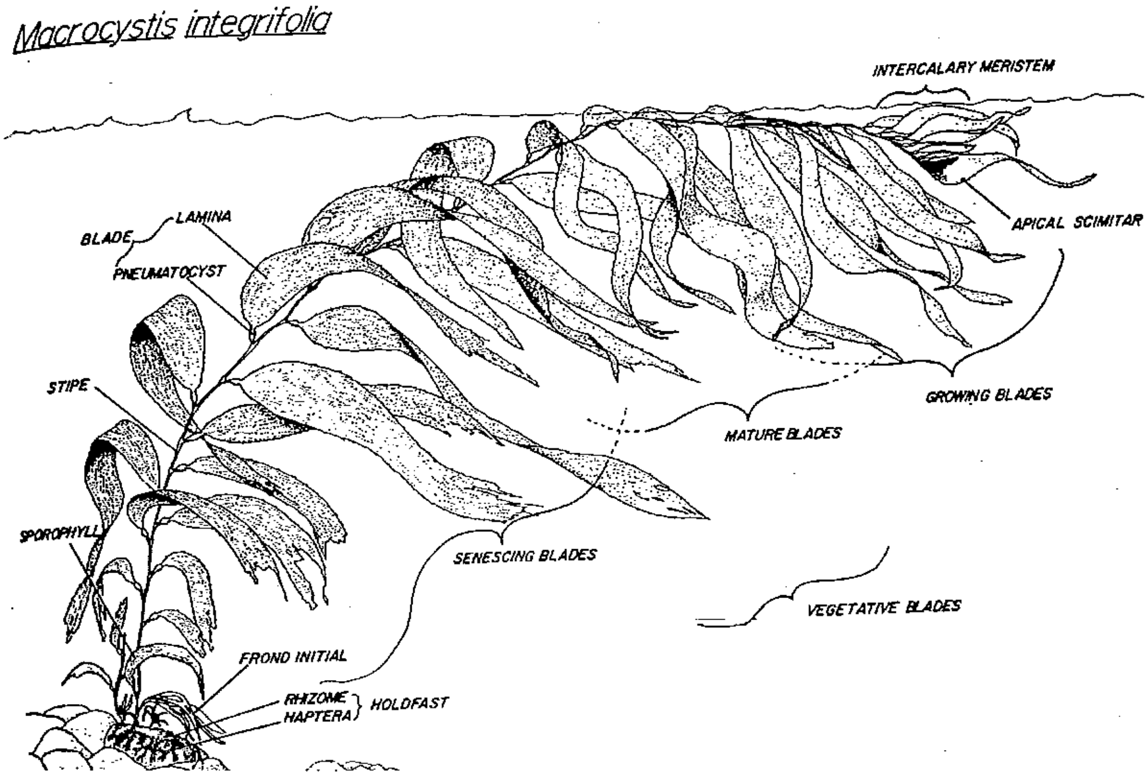


Figure 1. The morphology of a *Macrocystis* individual (taken from Druehl 1984).

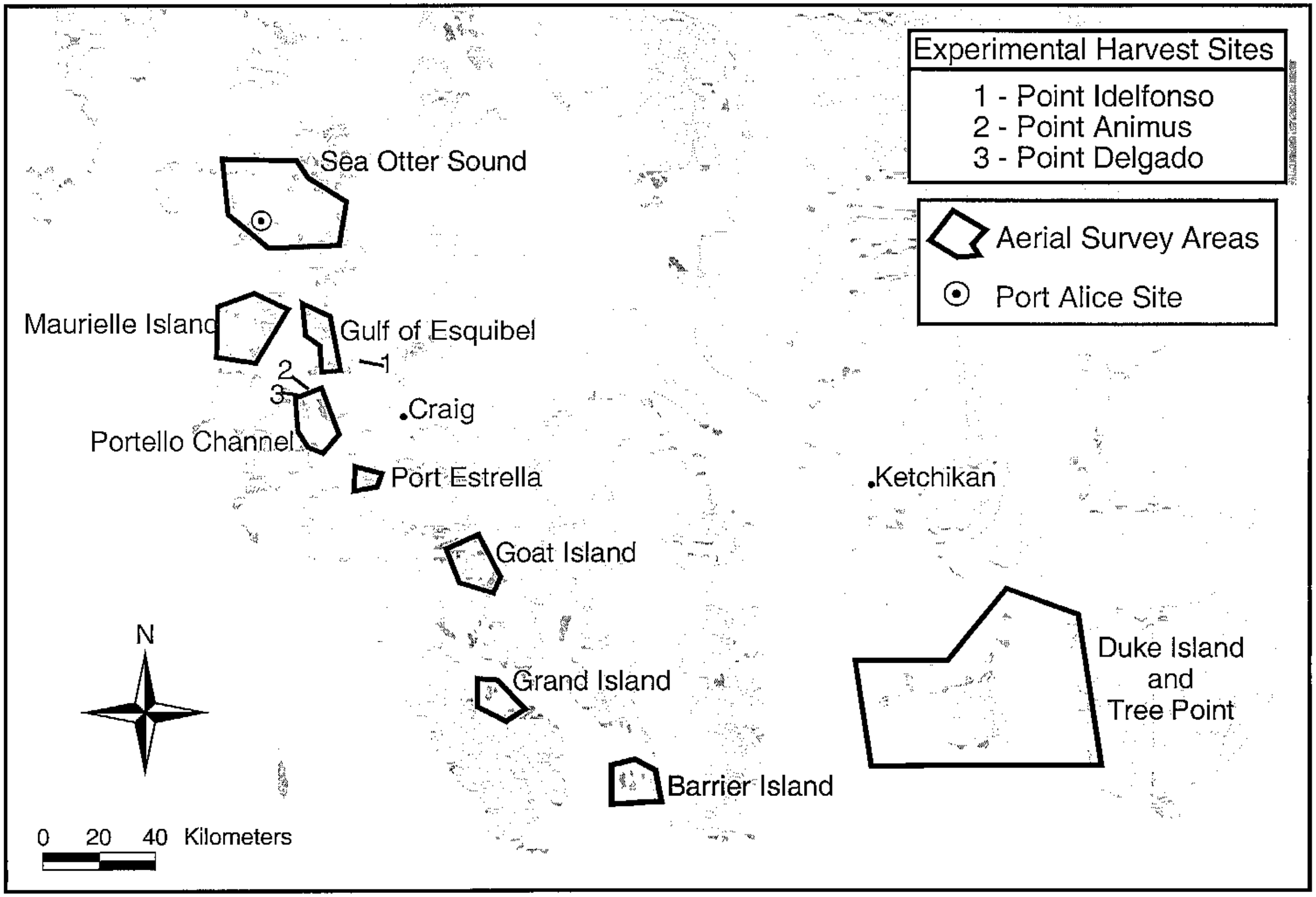


Figure 2. Map of the study area showing the location of aerial survey regions, experimental harvest beds, and the commercially harvested bed. The locations of index beds are shown in Figure 10.

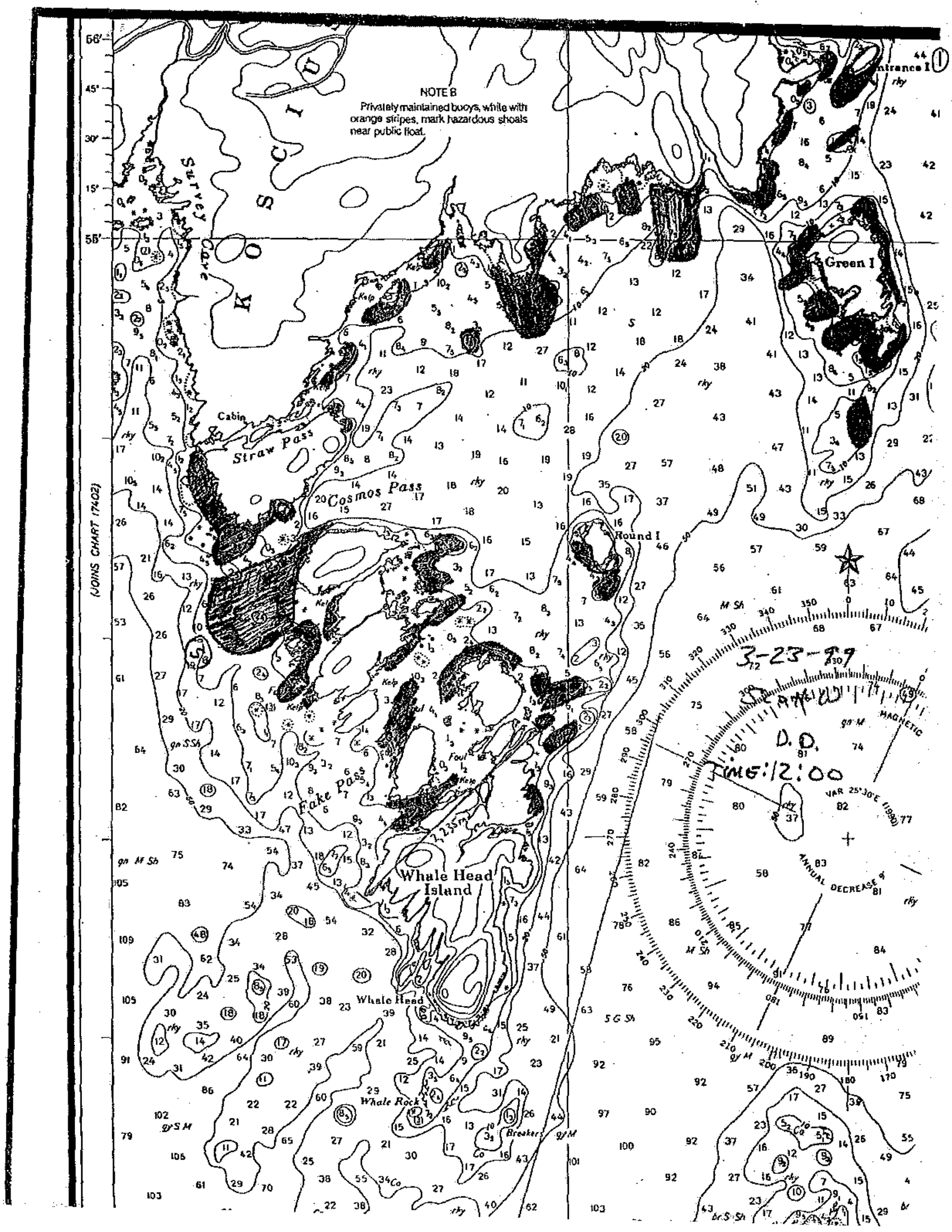


Figure 3. An example of the aerial survey outlining *Macrocystis* beds.


Figure 4. The same area as in Figure 3 showing "red only" beds after the black lines of the chart had been removed.

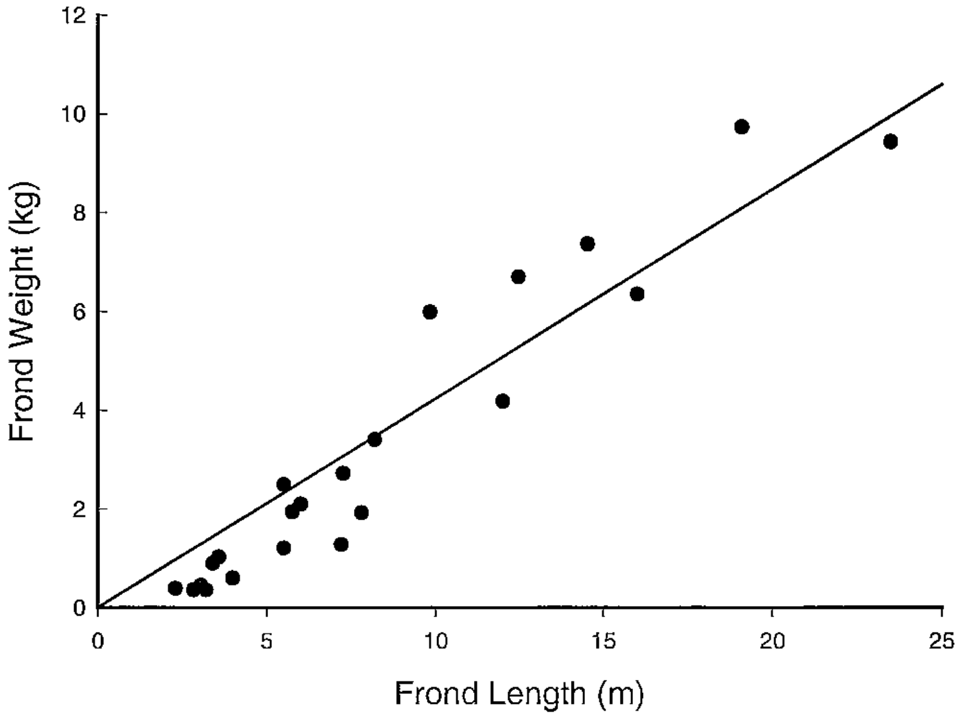


Figure 5. The relationship between frond length and weight.

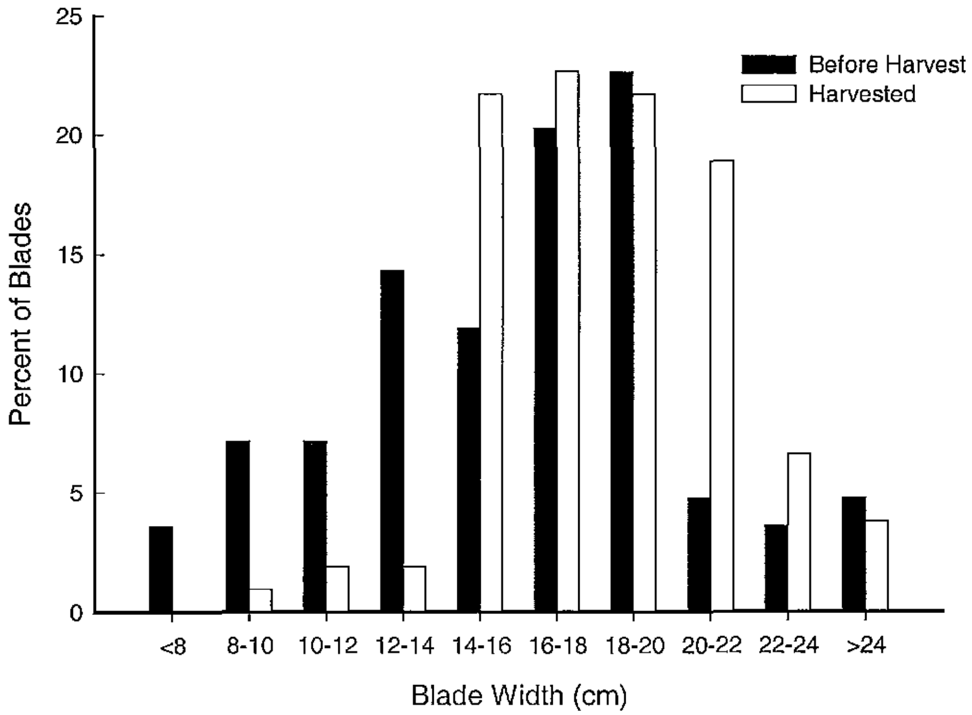


Figure 6. The proportion of *Macrocystis* blades of various widths in the Port Alice bed. Data are for kelp sampled before harvest and for the harvested kelp.

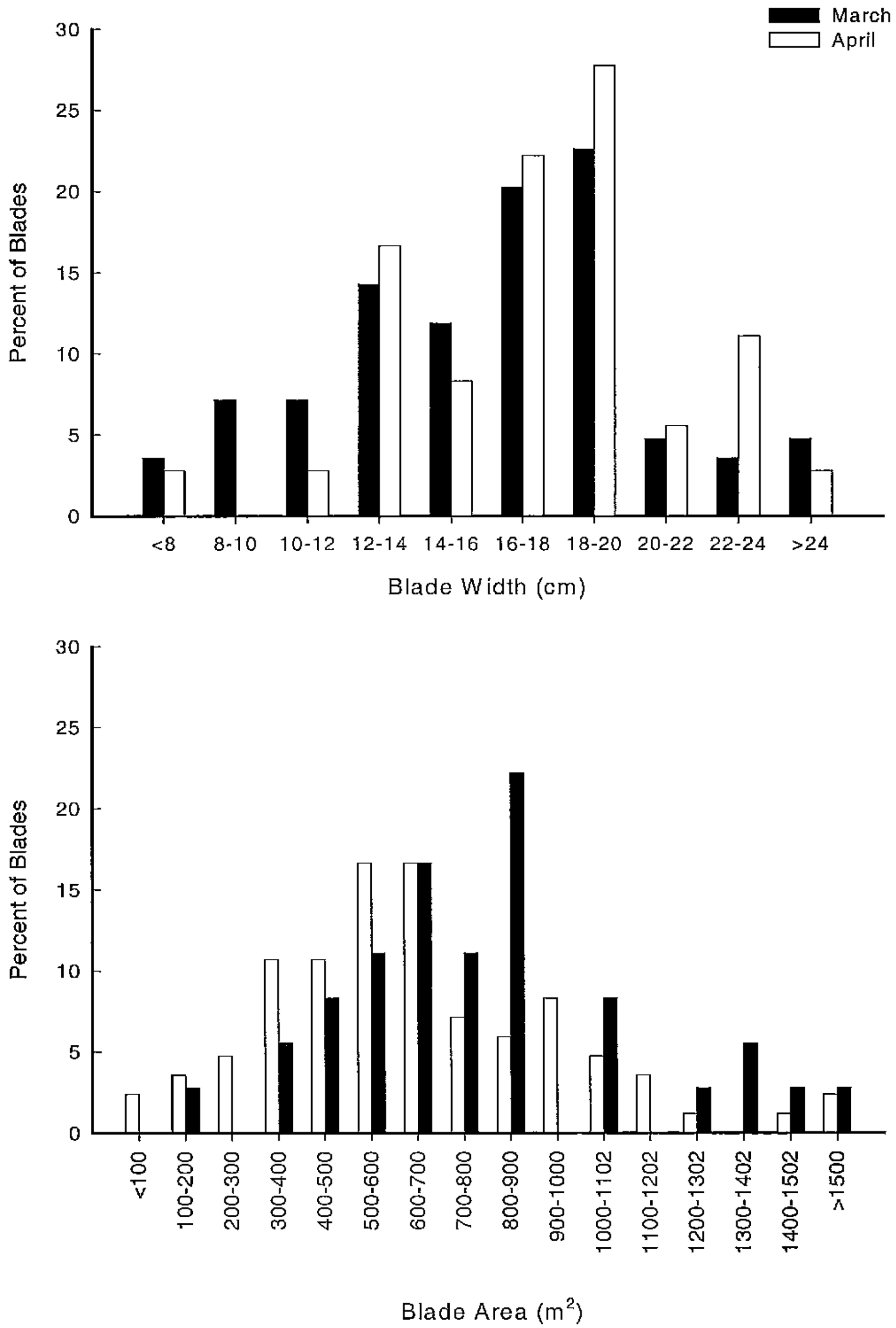


Figure 7. The proportion of *Macrocystis* blades of various widths or sizes at the Port Alice site in March and April.

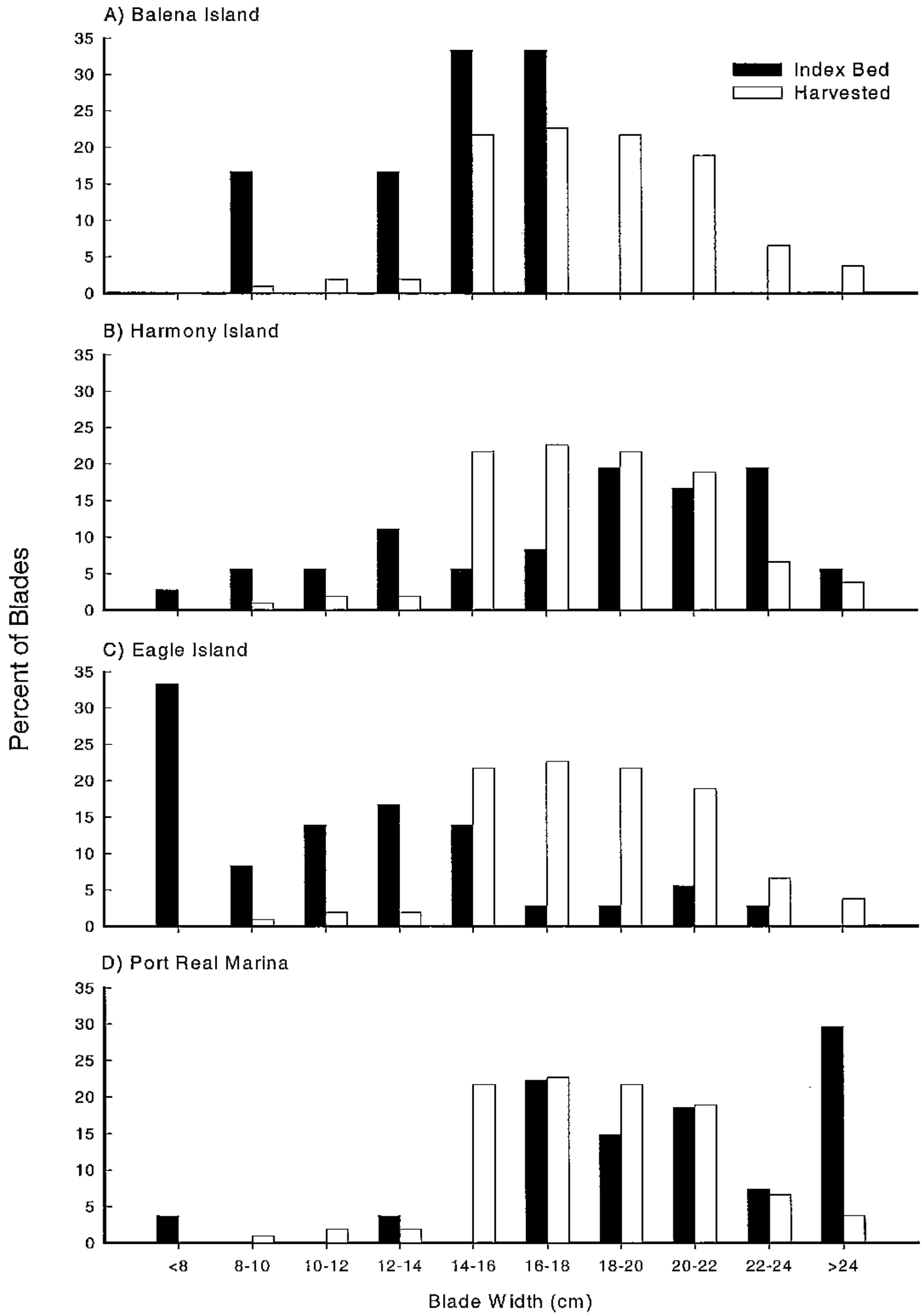


Figure 8. The proportion of *Macrocystis* blades of various widths at the index beds compared to the harvested kelp from Port Alice.

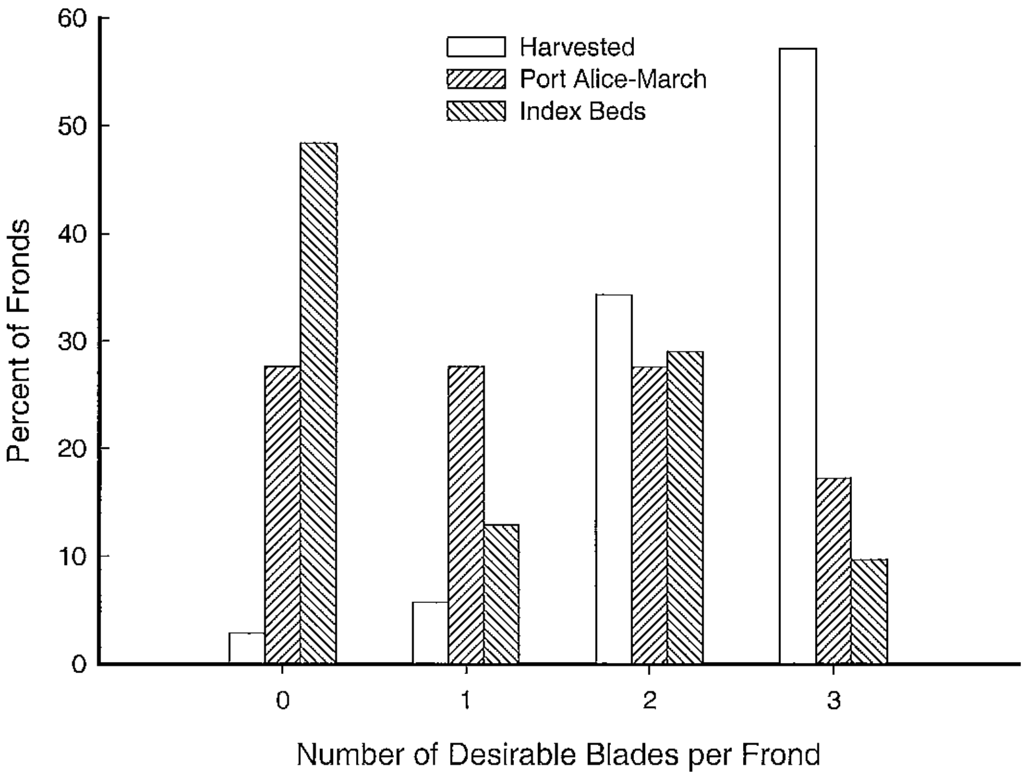


Figure 9. The proportion of *Macrocystis* fronds with 0, 1, 2, or 3 desirable blades at the Port Alice site before harvest, at the index beds, and that were harvested.

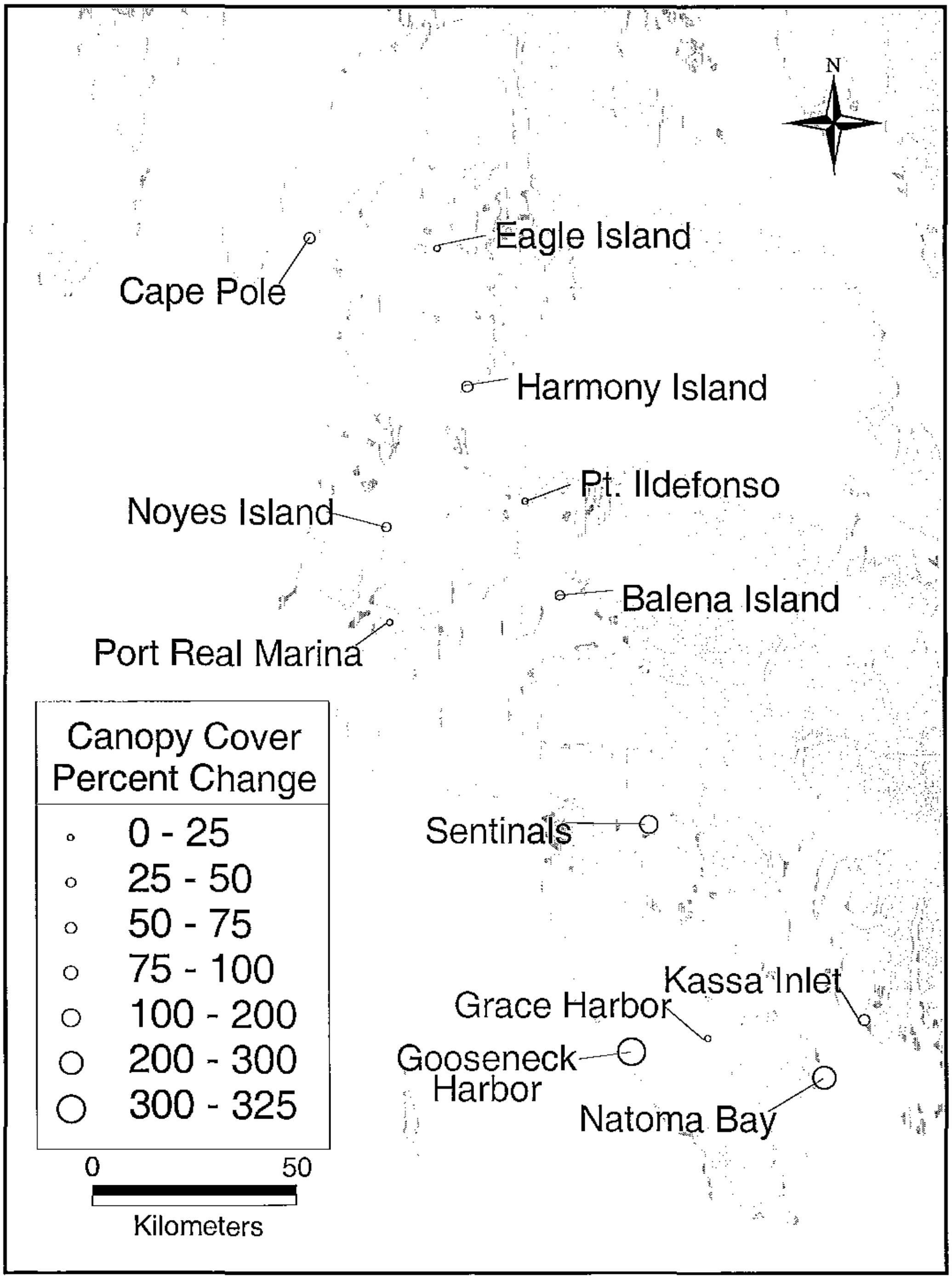


Figure 10. The location and growth of index beds on the west coast of Prince of Wales Island. The size of the circle indicates the relative growth rate of the canopy from March to April.

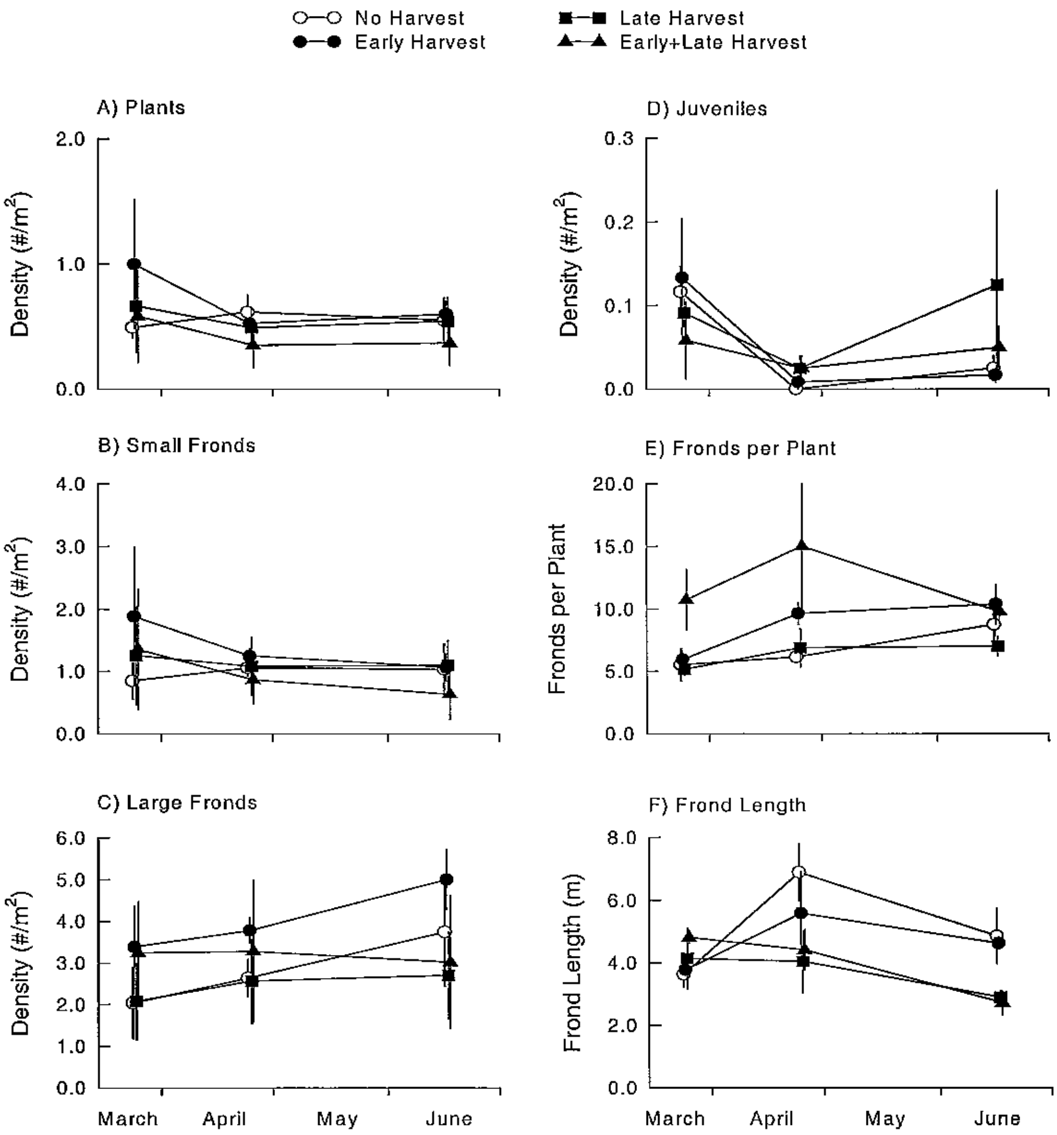


Figure 11. Results of the experimental harvest on the density of plants, small fronds, large fronds, juveniles, the number of fronds per plant, and the frond length. Error bars represent one standard error of the mean.

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