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A remote sensing approach to estimating harvestable kelp biomass

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Abstract

Regulations of the Alaska Department of Fish and Game require that all fisheries in the state have a harvest management plan. In southeast Alaska two species of floating kelps, *Nereocystis luetkeana* and *Alaria fistulosa*, have been commercially harvested since 1992 for use as agrochemicals by the Alaska Kelp Company. However, there is currently no harvest management plan for this fishery. The lack of a formalized management plan is one factor that has kept the kelp industry from expanding in the state. We have employed an aerial digital multispectral imaging system (DMSC) calibrated with ground truthing for performing such an assessment. The system can be flown at varying altitudes to achieve spatial resolutions ranging from 0.5 to 2 m. Rapid ground truthing techniques were developed using morphometric measurements to predict biomass. Analysis of the DMSC imagery showed that good correlations could be developed between the multispectral imagery and kelp biomass estimates collected at the ground-truth sites. Repeatable estimates of kelp bed area derived from the multispectral imagery could be made at varying tidal levels. However, broad scale maps of kelp biomass suitable for estimating harvest rates could not be made at different tide levels. Multispectral imagery suitable for this purpose must be collected at a standard tidal level.

Introduction

Kelp beds with floating canopies cover much of the near shore ocean surface along the West Coast of North America (Foster & Schiel, 1985). There are major beds of these kelps in the Alexander Archipelago of southeast Alaska. A survey of floating kelps in southeast Alaska in the early 1900's found over 100 separate beds containing an estimated seven million metric tons of plant biomass. The majority of the plants were *Nereocystis luetkeana* (Mertens) Postels *et* Ruprecht with *Alaria fistulosa* Postels *et* Ruprecht and *Macrocystis* sp. making up the remainder (Frye, 1915). Subsequent surveys have confirmed the locations and area extent of these beds, but have noted that the dominant species making up the beds has changed since 1915 (van Tamelen & Woodby, 2001). Current accurate estimates of kelp biomass are lacking at this time. Although selected areas of *Macrocystis* have been surveyed in southeast Alaska (van Tamelen & Woodby, 2001) there has been no survey done for *Nereocystis* since 1915.

There are currently two commercial uses for floating kelps in Alaska. The giant kelp, *Macrocystis*, is harvested in southeast, south-central and western Alaska, mainly for the commercial herring roe-on-kelp harvest (Stekoll, 1998). In addition, in southeast Alaska the two other species of floating kelps, *N. luetkeana* and *A. fistulosa*, have been commercially harvested since 1992 for use as agrochemicals. The major harvester of this resource is the Alaska Kelp Company (formerly Pacific Mariculture Company, Inc.) which processes the seaweeds for use as a plant fertilizer supplement. The product (formerly sold as OptiCrop and now as Alaska Kelp or Garden Grog) is used in various agricultural and horticultural applications and has enjoyed moderate commercial success.

In order to ensure the sustainability of *Nereocystis* harvesting, it is necessary to develop a stock assessment method for management of the kelps. Because resource managers normally use estimated biomass to regulate harvests, the key to the harvest management plan is the ability to determine the biomass of the kelp beds. However, estimation of the biomass of floating kelps is problematic with respect to time and expense needed for accurate estimates. The Alaska Department of Fish & Game is currently considering management of these beds using the area covered by the kelp canopy (van Tamelen & Woodby, 2001).

Mapping of kelp beds by remote sensing has primarily used near-infrared aerial photography for delineating surface canopy area. Aerial photography has been used in Canada (Foreman, 1975) and for over 30 years to map the *Macrocystis pyrifera* canopies in California (North et al., 1993). This method is used for determining kelp bed lease data by the California Department of Fish and Game. SPOT satellite imagery was found to be useful for estimating the biomass of floating canopies of *M. pyrifera* (Belsher & Mouchot, 1992). However, work on *Macrocystis* beds in California has shown that only the largest beds in this region can be effectively mapped due to the 20-meter spatial resolution currently available with the SPOT multispectral sensor (Deysher, 1993). The kelp beds in Alaska are comparable to the small and medium sized beds in California. A spatial resolution finer than 20 m is required to quantify the biomass of these beds. In addition, kelp beds in Alaska can be composed of three different kelp species. Kelp monitoring surveys in Washington State using a multispectral imaging system found that a 4 m spatial resolution was not sufficient to distinguish *Macrocystis* from *Nereocystis*.

The research described here addresses the biomass and area assessment aspect of a kelp harvest management plan. The objective of our research was to develop a reliable and cost effective method for estimating the area and biomass of the two species of kelps (*Nereocystis luetkeana*, and *Alaria fistulosa*) in southeast Alaska that have potential for a viable fishery

Methods

Site selection

The study area was a harvest area used by the Alaska Kelp Company. The site lies north of Pt Baker at the south end of Keku Strait along the southwest coast of Kupreanof Island (Figure 1) at approximately 133°24′W and 56°29′N. The study area consisted of approximately 20 distinct kelp bed areas that ranged in size from 0.2 to 12 hectares. Many of the beds fringe the small islands and shallower reefs in the area and comprise mainly *A. fistulosa. Nereocystis* was found on the outside of the *Alaria* beds and on reefs with more wave exposure and current flow.

Ground truthing

In 2002 seven separate kelp beds in the permitted harvest area north of Pt Baker were selected and classified by their estimated kelp densities. A surface buoy was anchored in the middle of the each of the selected sites. Scuba divers swam transects of 20 to 40 m parallel with the outer edge of the kelp canopy, starting at the buoy anchor. Density counts were taken with 1 m square quadrats placed every 4 m along the transect. All *Nereocystis* and *Alaria* were counted. Several *Nereocystis* plants (thalli) to represent all sizes of plants were haphazardly selected near each transect and taken back to Pt Baker for morphometric measurements. In order to determine the consistency of the morphometric correlations from more distant sites, we also collected about 90 *Nereocystis* plants near Juneau, Alaska. Fresh weight was determined for each plant along with the same suite of measurements made on the plants near Pt Baker.

The following measurements were taken on individual plants collected from sites near Pt Baker and in Juneau in the summer of 2002.

Stipe length: measured from the holdfast to the top of the bulb (pneumatocyst).
Blade length: measured from the top of bulb to the end of longest blade.
Bulb diameter: the outside diameter of the bulb.
Sub-bulb diameter: the diameter of the stipe 15 cm below the bottom of the bulb.
Blade weight: the fresh weight of all of the blades.
Total weight: the fresh weight of the blades, stipe and bulb.

Based on correlation results from 2002, in 2003 only the bulb and sub-bulb diameter and the total fresh weight were measured.

In 2003 the density counts were performed by preselecting eight sites of varying density from beds in the study site. The center of each of the selected density sites was marked with a buoy. At the surface four sets of two floating quadrats (0.5 × 2.0 m) were placed orthogonal to each other (“+” shape), centered on the

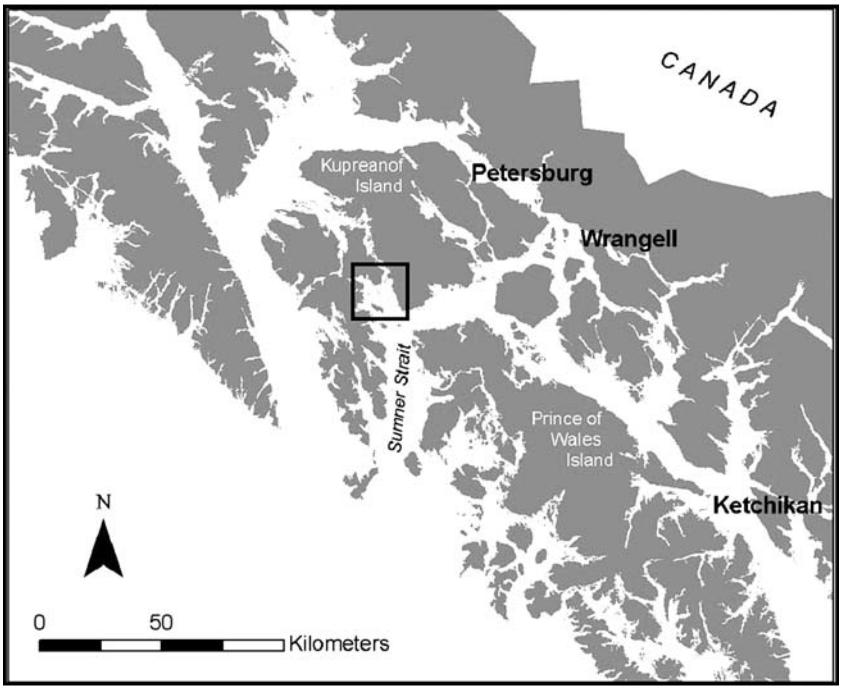

Figure 1. Study area in Keku Strait at the south end of Kupreanof Island.

buoy. In essence we sampled a 4+ m diameter circle along two diameters that were at right angles to each other. The number of *Nereocystis* bulbs in each quadrat was counted and the diameters of the bulb and sub-bulb sections of the thallus were measured using calibrated plastic forceps. Kelp densities on the bottom were estimated by scuba divers counting plants within quadrats (2×0.5 m) radiating away from the buoy anchor weight. In addition about 100 *Nereocystis* plants were harvested by scuba and used for additional data for morphometric measurements and biomass.

At a separate bed that was to be commercially harvested, we arbitrarily selected ten locations inside the southeast facing edge of the bed. At each sampling location we measured the diameters of the bulb and the sub-bulb of all *Nereocystis* plants lying within two 2.0×0.5 m quadrats. An estimated plant density and biomass per area in the area to be harvested were calculated from these data.

In 2002 the estimated plant biomass in the density sites was determined by multiplying the densities as determined from the scuba transects by the mean plant biomass as determined from the plants harvested near the transects. These estimated biomasses and plant densities were used in the calibration of the digital multispectral camera (DMSC) imagery. In 2003 the biomasses in the density plots were estimated from the morphometric data. Each individual plant weight was estimated using the regression equation for the relationship between the weight of a plant and its sub-bulb diameter. Final biomass estimates for the sampled quadrats were calculated from the sum of the individual plant weights within the quadrats.

Alaria biomass was estimated in 2003 by determining the mean fresh weight per meter length of the blade region and multiplying by the total length of *Alaria* in each quadrat. This number was adjusted by a factor (1.33) to account for the subsurface *Alaria* biomass determined from scuba surveys.

DMSC flights

The initial DMSC image set was collected on July 14, 2002, 9:11–10:27 ADT (17:11–18:27 GMT). The area covered by the DMSC imagery was a 4.8 km^2 rectangle on the east side of the AKC harvest area extending approximately 4 km north from Trouble Island (Figure 2). The flight lines were set up in a north-south direction over seven kelp bed ground-truth stations. The tide levels during the flight were between -0.21 m and the day's low of -0.66 m. Skies were partly cloudy with a ceiling of approximately 823 m. The aircraft altitude

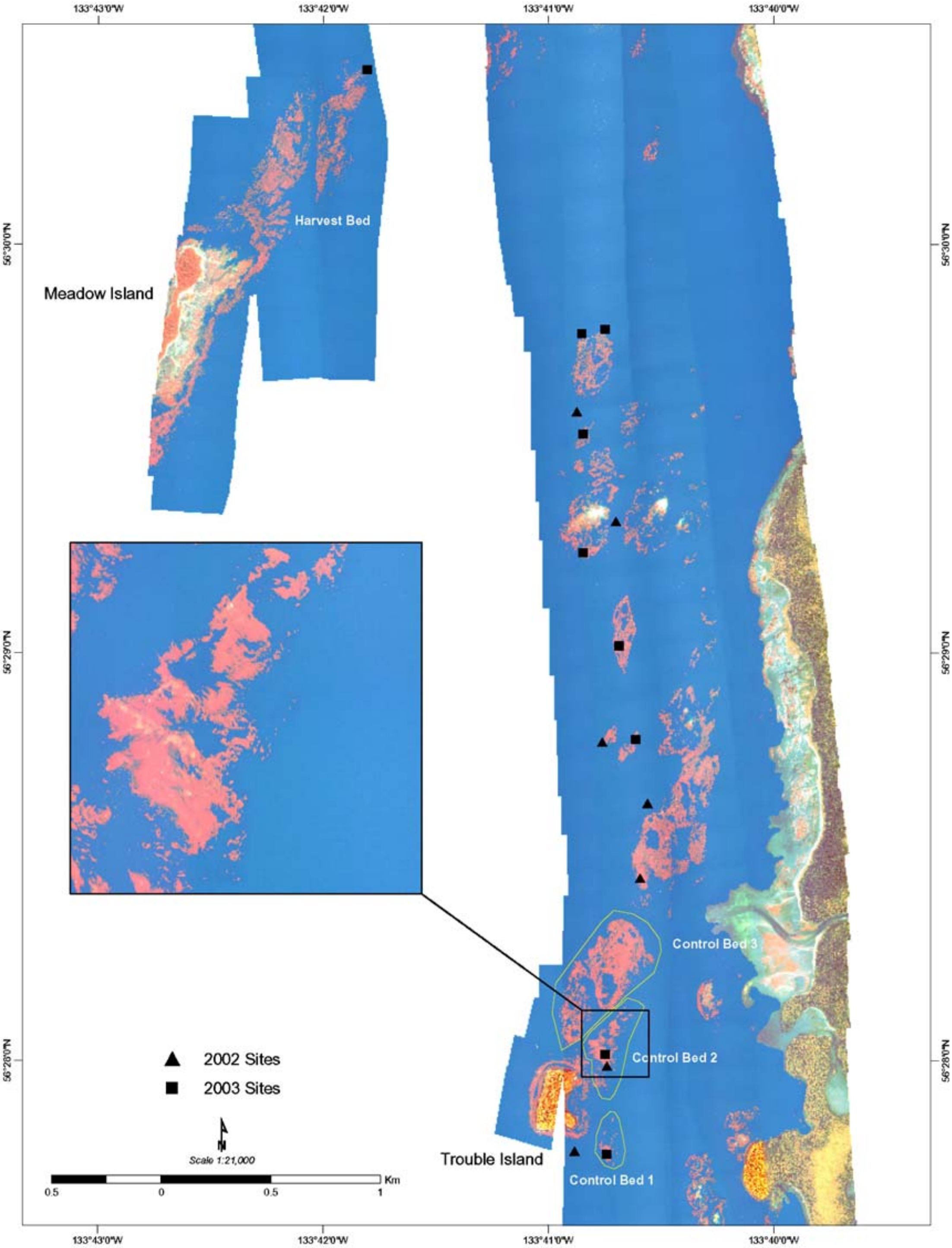

Figure 2. Mosaic of DMSC imagery acquired on the pre-harvest flight on 26 July 2003 showing locations of the ground control sites used for determining kelp biomass in 2002 and 2003 and the control beds used to compare area and biomass estimates between the pre- and post-harvest flights in 2003.

Table 1. Spectral characteristics of the DMSC color filters used for the kelp monitoring flights

	2002		2003	
	Peak (nm)	Bandwidth (nm)	Peak (nm)	Bandwidth (nm)
Band 1	451	20	451	20
Band 2	601	10	551	20
Band 3	643	10	710	10
Band 4	782	20	782	20

was 731 m, which produced a resolution of approximately 0.3 m. The DMSC was fitted with filters to acquire data in four wavelengths (Table 1) that had been used to differentiate three maturity stages of *Macrocystis* in a previous study in Monterey Bay (R. Zimmerman, personal communication).

During the 2003 field season, DMSC imagery was collected before and after a harvest of approximately 6800 Kg of *Nereocystis* by AKC. The kelp was harvested from a single bed located just north of Meadow Island and approximately 1 km northwest of the beds used for collecting the ground truth data in both (Figure 2). The DMSC was set up with a spectral filter combination (Table 1) optimized to differentiate *Nereocystis* from *A. fistulosa*. The bands were selected based on field spectrometry of *Nereocystis* and *A. fistulosa* populations in the Juneau area. The pre-harvest DMSC data were collected on July 26, 2003 between 9:03 and 10:06 AM ADT (17:03–18:03 GMT). Weather conditions were calm with light winds of approximately 2.5–5 m s^{-1}. Tide levels during the time of collection were between +2.11 and +2.64 m. The skies were partly cloudy with a ceiling of approximately 3915 m. Ground sampling distance was 0.39 m.

The post-harvest DMSC data were collected on July 31, 2003 between 2:41 and 3:05 PM ADT (23:41–00:05 GMT). Weather conditions were calm with light winds of approximately 2.5–5 m s^{-1}. Tide levels during the time of image acquisition were between +3.65 and +3.75 m. The skies contained scattered clouds with a ceiling of approximately 850 m. Light levels were sufficient and comparable to those of July 26. Collected data scenes had a ground sampling distance of 0.36 m.

Image processing

Five multi-scene image mosaics were created from the DMSC scenes acquired in 2002 and 2003. Each 4-banded mosaic was created by selecting the best scenes from each of the flight lines and georeferencing them to US Forest Service DOQQs (Digital Ortho Quarter Quads)with a pixel resolution of 1.8 m.

In order to improve water depth penetration and adjust for the different environmental conditions that existed at the time of each acquisition, processing steps were taken to help normalize the data. Natural log transformations of the five 4-banded mosaics were created in order to increase water penetration and decrease the reflectance variance created by the inconsistent flight height and depth of the target plants. Taking the natural log of each band also helped to minimize background noise in the data. Band ratios and "normalized difference" (ND) images were tested to identify band combinations that best separated the kelp from water and other vegetation.

The "normalized difference" raster images were created using an algorithm very similar to the Normalized Difference Vegetation Index (NDVI) commonly used to create indices of vegetation health or vigor for agricultural and terrestrial applications. For example, the normalized difference between DMSC Band 1 (451 nm) and Band 4 (782 nm) was calculated using Equation (1) below:

$$(B4 - B1)/(B4 + B1) \tag{1}$$

For both the 2002 and 2003 data, an unsupervised classification method, ISODATA (Iterative Self-Organizing Data Analysis Technique) (Tou & Gonzalez, 1974), was used to generate thematic maps that segregated kelp canopy from the surrounding water pixels. The unsupervised classification was also used to identify the mats of *Fucus* that collected in the kelp canopy and to try to distinguish between the *Nereocystis* and *A. fistulosa* canopy areas. The bands that showed the best separation when used as input to the ISODATA algorithm were a combination of the natural log transformations of Bands 1 through 4; the normalized difference of Bands 2 and 4, and Bands 1 and 4; and the ratio of the natural log of Band 4 to the natural log of Band 1.

The classification rasters for each area mosaic were used for two purposes. A 20-class raster was merged down to a three-class raster showing *Nereocystis/Alaria, Fucus* and all other classes. This image was then used to compute the area covered by *Nereocystis* and *Alaria* for select kelp beds. The classification was also merged down to generate two-class raster that isolated F*ucus*. The F*ucus*-only raster image was later applied as a mask to the biomass index image in order to exclude F*ucus* dominated pixels in the final products.

The relationships between the DMSC imagery and kelp biomass were determined by calculating the average pixel values of various band combinations for a 4 × 4 m area in the imagery centered on the buoy marking each ground-truth station. This area covered the area sampled by the surface quadrats. The ratio of the log (ln) of band 4 and log (ln) of band 1 yielded the highest correlation coefficient of a number of different band combinations that were regressed with the biomass values. The biomass images were generated by applying the biomass regression equation developed for each year to each pixel of the raster images generated from the band ratios.

Results

Morphometrics and biomass correlations

The best predictor for whole plant wet weights of *Nereocystis* was the weight of the blades from the plant (Table 2). The next best predictor was the diameter of the stipe just below the bulb or the sub-bulb diameter (Table 2). The exponential regression line calculated for the 2002 data had an R^2 of 0.88. Other measurements had poorer correlations with plant weight (Table 2).

The relationship of the sub-bulb diameter to the total plant weight varied among the three separate data sets (Figure 3). In 2003 the best correlation for the regression line was found using a power curve rather than an exponential curve. This regression was strongly influenced by one very large plant measured in 2003.

Nereocystis maximum density in the beds was 9–10 plants per square meter with the biomass per square meter of bottom area as high as 16 kg (Table 3).

Table 2. Regression equations for the different morphometric measurements for *Nereocystis* wet weight estimation. Data for these regressions are from 2002 sampling.

Meristic	Best fit regression equation	R^2
Weight of blade (Kg)	Plant weight = 1.3212 × + 0.1052	0.98
Diameter of 'sub-bulb' (cm)	Plant weight = $0.038e^{0.125\times}$	0.88
Length of blade (m)	Plant weight = $0.0455e^{0.124\times}$	0.85
Diameter of bulb (cm)	Plant weight = $0.0006e^{1.435\times}$	0.78
Length of stipe (m)	Plant weight = $0.0346e^{0.501\times}$	0.65
Total length (m)	Plant weight = $0.0664e^{0.295\times}$	0.33

Table 3. Summary of density and biomass data for *Nereocystis luetkeana* (*Nl*) and *Alaria fistulosa* (*Af*) from the study site north of Pt Baker, Alaska

Site	Species	plants m^{-2}	SE	kg m^{-2}	SE	N*
2002						
1	*Nl*	7.2	1.6	5.62		
2	*Nl*	7.2	2.5	9.92		
3	*Nl*	8.2	1.9	13.64		
4	*Nl*	7.2	2.3	14.10		
5	*Nl*	1.0	0.4	0.62		
6	*Nl*	7.2	1.1	3.65		
7	*Nl*	10.3	1.6	14.18		
2003						
Harvest	*Nl*	3.2	0.70	8.51	2.13	20
1	*Nl*	8.4	1.16	10.95	1.57	8
1'	*Nl*	9.0	2.00	15.95	5.07	2
2	*Nl*	3.5	0.87	5.05	2.02	4
3	*Nl*	0.0	0.00	0.00	0.00	8
4	*Nl*	1.0	0.38	1.75	0.56	8
5	*Nl*	0.6	0.38	2.66	1.98	8
6	*Nl*	0.0	0.00	0.00	0.00	8
7	*Nl*	5.3	0.92	12.56	1.35	8
8	*Nl*	0.9	0.44	0.46	0.32	8
1	*Af*	0.3	0.25	0.03	0.03	8
1'	*Af*	0.0	0.00	0.00	0.00	2
2	*Af*	15.0	1.47	1.81	0.18	4
3	*Af*	0.0	0.00	0.00	0.00	8
4	*Af*	4.3	1.85	0.51	0.22	8
5	*Af*	2.9	1.25	0.35	0.15	8
6	*Af*	6.9	2.17	0.83	0.26	8
7	*Af*	4.4	1.15	0.53	0.14	8
8	*Af*	6.6	2.43	0.80	0.29	8

Data were collected as described in Methods. Site 1' is a revisit to site 1. N* = number of quadrat sampled.
SE = standard error of the mean.

Alaria fistulosa data were obtained in 2003 from 19 samples. The mean weight of a one meter long section of *Alaria* was 182 ± 16 (SE) g. The mean was adjusted by multiplying by a factor of 1.33 which is a rough estimate to correct for the proportion of the frond that was submerged. Mean densities varied from 0 to 15 plants per square meter. Estimated biomass in the kelp canopy was up to 1.8 kg m^{-2} (Table 3).

Kelp bed area

The mosaic of the DMSC imagery for the pre-harvest flight on 26 July 2003 (Figure 2) shows the harvest bed and the kelp beds used for generating the biomass

Table 4. Kelp bed area comparisons for the harvest and control beds including percent changes in the estimates between surveys

	Harvest bed		Control bed 1		Control Bed 2		Control bed 3	
	Area	% Chg	Area	% Chg	Area	% Chg	Area	% Chg
7/14/02	No Data	–	4,465	–	22,537	–	88,210	–
7/26/03	47,742	–	4,588	+2.8	22,913	+1.7	91,902	+4.2
7/31/03	51,150	+7.1	4,991	+8.8	22,850	−0.3	89,667	−2.4

All areas are in m^2.

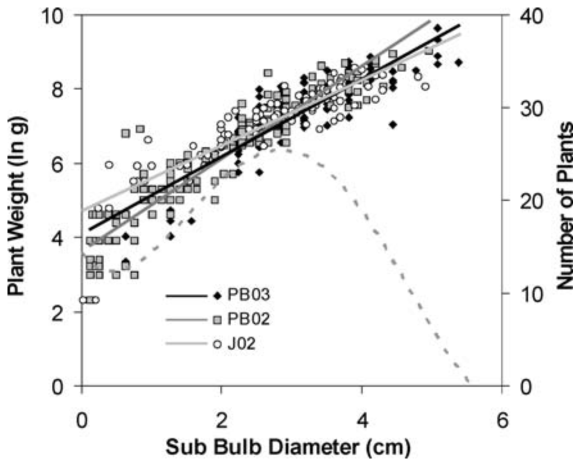

Figure 3. Nereocystis luetkeana wet weight per plant as a function of the diameter of the stipe below the pneumatocyst (sub bulb). Points represent individual plants from beds north of Pt Baker (PB), Alaska in 2002 and 2003 plus plants from Juneau (J), Alaska in 2002. Straight lines are best fit regression lines from the corresponding data sets. The dotted curve is the size-frequency distribution of the *Nereocystis* plants measured for the three data sets.

relationships. The three kelp beds imaged on both the pre-harvest and post-harvest flights, which serve as controls for quantifying errors in areal cover and biomass estimates, are delineated at the south end of the study area. The total kelp bed areas derived from the classification images for the harvest and three control beds are summarized in Table 4. The classification images showing the extent of the harvest bed for the pre- and post-harvest flights are shown in Figure 4. The kelp bed area included both surface canopy and subsurface *Nereocystis* and *Alaria* plants, but excluded areas with *Fucus* cover. The error ranges in the coverage estimates at the control sites between the two flights in 2003 were all within 10%.

The kelp canopy areas were also estimated from a LandSat 7 Enhanced Thematic Mapper (ETM+) satellite image acquired on 4 August 2002. The ETM+

Table 5. Kelp bed area estimates derived from ETM+ (Landsat 7) satellite imagery acquired on 4 August 2002

	Pixel Count	Area (m^2)
Harvest bed	396	80,412.75
Control bed 1	42	8,528.63
Control bed 2	167	33,911.44
Control bed 3	546	110,872.13

panchromatic band has 15 m spatial resolution and the spectral bandwidth extends into the near-IR. The estimates of kelp canopy area obtained from this image are presented in Table 5. The canopy estimates from the ETM+ imagery are approximately 50% greater than the areas derived from the high resolution DMSC imagery.

Biomass relationships with DMSC data

The ratio of the natural log of band 4 to the natural log of band 4 (ln band 4/ln band 1) showed the best correlation of the various band combinations that were compared (Figure 5). Because *Nereocystis* was not distinguishable from *Alaria fistulosa* under all of the imaging conditions, the image data were regressed against the combined estimated biomasses of *Nereocystis* and *Alaria*.

A biomass map was generated for the pre-harvest flight on 26 July 2003 (Figure 6). The beds were largely composed of low and medium biomass classes with patches of high biomass just north of Trouble Island, small patches in the harvest bed, and some larger patches just north of Meadow Island. The biomass estimates for the 2003 flights ranged from 38% to 66% lower than the estimates from the 2002 flight, and estimates for the post-harvest flight in 2003 averaged 8% lower than the pre-harvest flight (Table 6).

Various unsupervised classification algorithms were used to separate *Nereocystis* and *Alaria fistulosa*, the

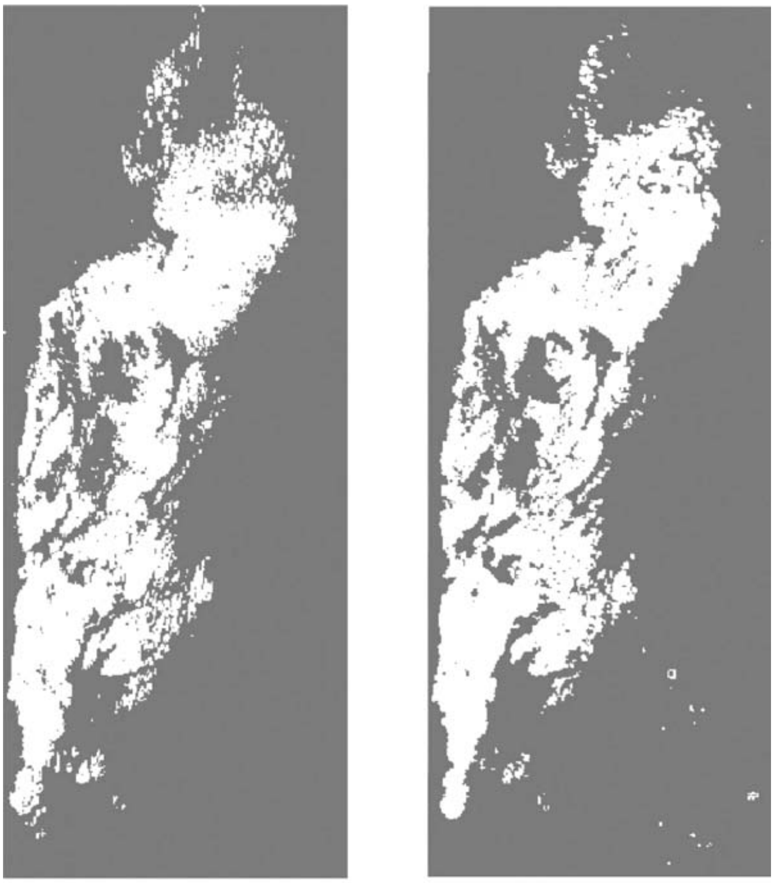

Figure 4. Classified kelp bed areas of the harvest bed on the pre- and post-harvest flights.

two main kelp species that form a surface canopy in this area from masses of drift *Fucus.* The masses of drift *Fucus* were easily separable from the kelp canopy. We produced a *Fucus* mask to exclude these plants from the biomass calculations. The masking procedure most likely led to an underestimation of kelp biomass because in many instances there were kelp plants directly below the *Fucus*.

The unsupervised classification algorithms could not consistently differentiate areas of *Nereocystis* and *A. fistulosa* canopy. Regions of very uniform *Alaria* canopy, such as the canopy adjacent to the shoreline on the north side of Trouble Island were distinguished as a distinct class. However, other areas that we knew were predominantly *Alaria* were classified as *Nereocystis*. Regions of mixed *Nereocystis* and *Alaria* were uniformly classified the same as areas that were predominately *Nereocystis*.

Discussion

Ground truthing biomass for floating kelps is a very time consuming and expensive enterprise. Scuba divers are usually necessary in order to retrieve the whole thallus. In addition the size and morphology of floating kelps make it very difficult to keep plants from becoming entangled and tearing during retrieval for weighing. The size of the plants requires a fairly large vessel for obtaining fresh weights. For these and other reasons we attempted to find a morphometric measurement that would be relatively easy to measure in the field and yet be a reasonable predictor of biomass.

Of the measurements we made, the best predictor of whole plant biomass was the weight of the blade (Table 2). Although it is possible to cut and weigh the blades while in the field without the use of scuba, this process requires too much time and effort. In contrast

Table 6. Kelp bed biomass (kg m^{-2}) comparisons for the harvest and control beds including percent changes in the estimates between surveys

	Harvest Bed		Control bed 1		Control bed 2		Control bed 3	
Date	Biomass	% Chg	Biomass	% Chg	Biomass	% Chg	Biomass	% Chg
7/14/02	No Data	–	658,103	–	2,567,142	–	9,919,719	–
7/26/03	2,843,044	–	222,911	−66	1,266,062	−51	6,141,369	−38
7/31/03	2,708,261	−5	229,675	+3	1,311,964	+4	3,981,751	−35

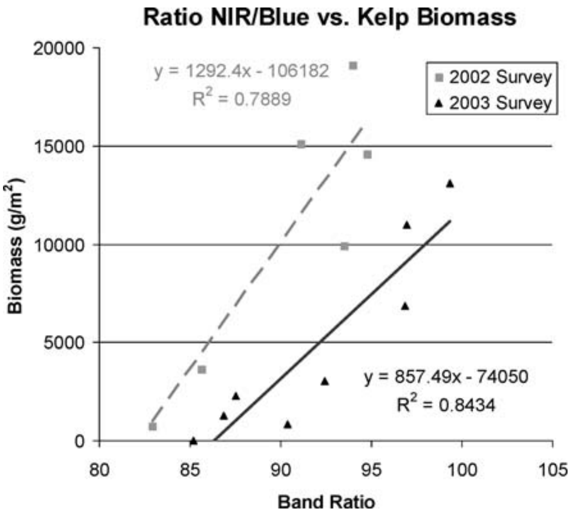

Figure 5. Relationship between kelp wet biomass and the ratio of Bands 1 and 4 from the DMSC imagery. The DN values from the two bands were log (ln) transformed before forming the ratio. The regression lines were significantly different between years (ANCOVA F=21.224, p=0.001).

the diameter of the sub-bulb is relatively easy and quick to measure and has a reasonable correlation to the total fresh weight of the plant.

A drawback of the sub-bulb method is that there are significant variations among different locations and/or different times of the growing season. An analysis of covariance of the $\log_e$ of the plant weight versus the sub-bulb diameter revealed that regression lines are not similar. For the best accuracy in estimating *Nereocystis* biomass, separate ground truthing should be performed in each area to be assessed. On the other hand, the regression equations are in closest agreement in the middle of the size range which includes the majority of the plants (Figure 3). For management purposes a regression equation combining several data sets may be the best compromise.

Other researchers have used various methods to estimate biomass of floating kelps. During investigations on the subtidal effects of the *Exxon Valdez* oil spill the biomass of *Nereocystis* was estimated by measuring the diameter of the stipes one meter above the bottom (Dean et al., 1996). In southeast Alaska van Tamelen and Woodby (2001) found a significant linear correlation between biomass of *Macrocystis* and individual frond lengths. Stekoll and Else (1992) used a similar approach to estimate the biomass of artificially cultured *Macrocystis* near Sitka, Alaska. In Chile *Macrocystis* biomass has been estimated from the diameter of the holdfast (Vasquez & Vega, 2004). In Canada from 1975 to 1996 biomass of the floating kelp beds was assessed using an inventory method (KIM-1) developed by Foreman (1975). The KIM-1 method used near-IR aerial photographs to determine the density and the area of beds containing *Macrocystis* and/or *Nereocystis*. These data were combined with field sampling for plant densities and mean plant weight to obtain species specific biomass estimates for large areas of kelp beds.

The biomass of *Alaria* was estimated assuming that most of the plant can be considered to be a two dimensional plane with a constant weight per meter of plant. This process is similar to that used in the KIM-1 method on other floating kelps (Foreman, 1975). In contrast, the *Nereocystis* estimates we performed were based on individual plant measurements. Although it would not be too difficult to cut and weigh the *Alaria* fronds within each quadrat, the precision gained from on site weighing of all of the fronds of *Alaria* does not justify the extra cost in time and effort.

Comparisons of the areas of the harvest bed and three control beds (Table 4) show that the DMSC multispectral imagery provides very reliable estimates of kelp bed size even when the imagery is acquired at very different tidal levels. The DMSC provides a distinct advantage over traditional near-IR aerial photography that can detect only the portions of the kelp plant directly on the surface. The area of the surface canopy is strongly influenced by tide and current conditions and this will be reflected in kelp bed area estimates made with near-IR aerial photography. The DMSC provides additional

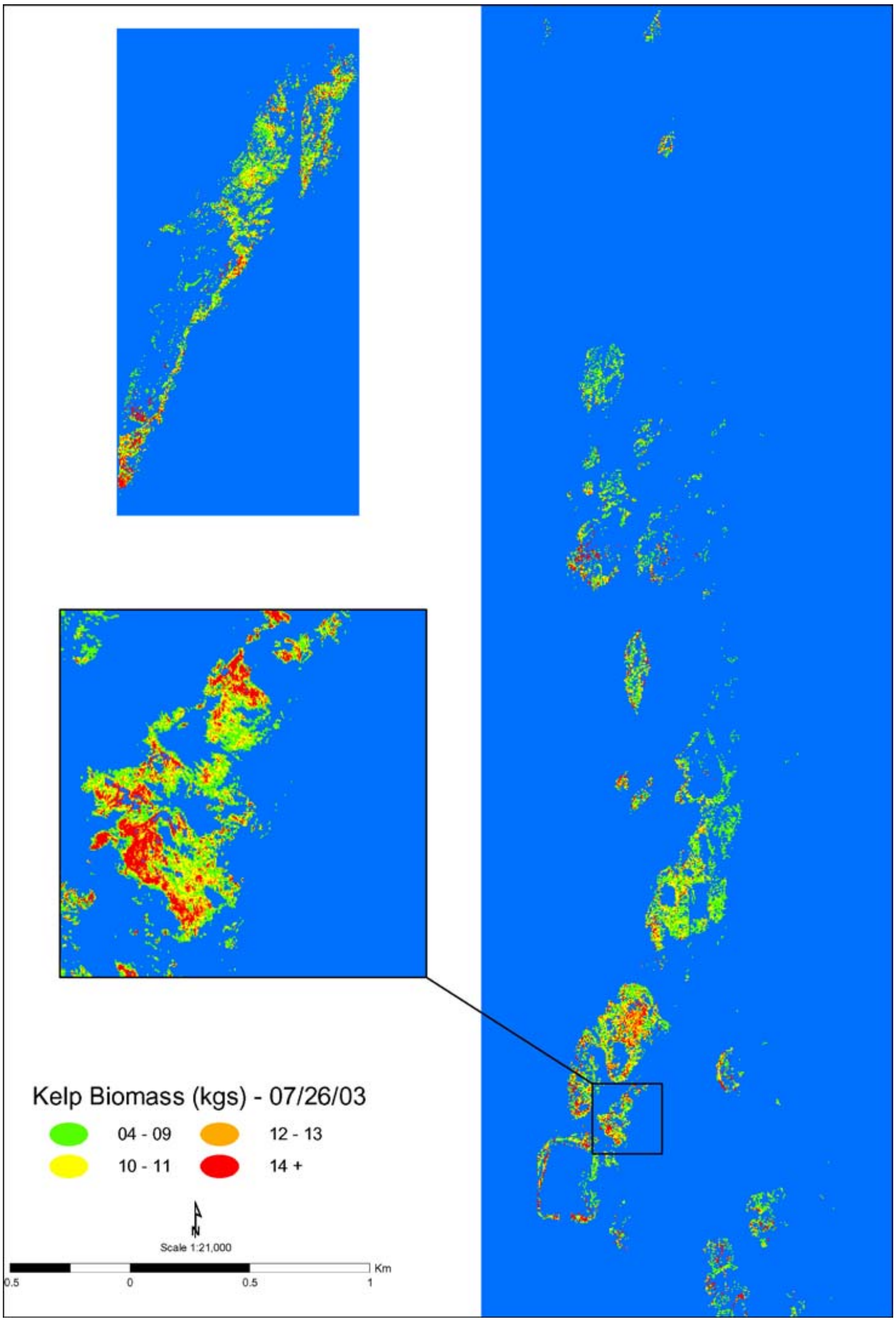

Figure 6. Map of kelp biomass (Kg m^{-2}) for the harvest and control beds calculated from the pre-harvest DMSC imagery collected on 26 July 2003.

spectral bands (451 and 551 nm) that can detect subsurface kelp plants down to 3 m. Secchi disk measurements in this region made during the sampling in 2003 ranged from 4 to 5 m. Classification algorithms using the 4 spectral bands of the DMSC imagery can distinguish both canopy and subsurface kelp plants and thereby provide a very accurate estimate of kelp bed size that is fairly independent of tidal or current conditions.

The sizes of the three control beds used for the 2003 studies were nearly identical to their sizes in 2002. The beds in this area grow on distinct reef structures and it appears that reef size defines the upper limits for the size of the kelp beds. Other beds in the region, however, decreased in size from 2002 to 2003. For reasons not clear at this time, a *Nereocystis* bed on the south side of Trouble Island that we used for a ground truth site in 2002 had only a few plants in 2003.

The radiometric characteristics of the DMSC imagery provided good correlations with the kelp biomass estimates made at the ground truth sites. However, the comparisons of the biomass images between 2002 and 2003 showed much higher biomass values for 2002. The beds did not change in size between the two years and it appears that the higher biomass estimates for 2002 are related to the lower tidal levels at the time the imagery was collected in 2002. Lower tidal levels allow more frond material to float on the surface thereby increasing the overall brightness in the near-IR band, which is the dominant spectral band that we found useful for estimating biomass. Currents can also affect the amount of kelp canopy on the surface and our experience at the AKC harvest site showed that the currents are spatially variable even at the same time in the tidal cycle. The optimum method for estimating biomass over a large harvest site with the multispectral imagery would be to collect the data at a standard tidal level with low currents.

Field spectroscopy studies in Juneau showed small differences between the reflectance spectra of *Nereocystis* and *Alaria fistulosa*. We tried to capitalize on these differences by selecting filters for the DMSC in the spectral areas where the two species showed the most difference. However, we could not differentiate the two species based on the 4 spectral bands of the DMSC imagery. We noted that there was significant variability in the canopy color of the two species in different areas of the study site. *Nereocystis* plants in more protected areas appeared to have a lighter color than plants in more exposed areas. A study in Washington State using a CASI (Compact Airborne Spectrographic Imager) sensor with 11 bands of spectral data could not distinguish *Macrocystis* from *Nereocystis* at 4-m resolution (Pers. Comm. T. Mumford).

We were also not able to differentiate the two species based on any morphological differences of the surface fronds. Even though the general morphology of the two species is quite different, the fronds in the surface canopy for both species are long linear objects with smooth edges. The 0.3 m resolution of the DMSC imagery was not sufficient to show differences in the two canopies. High resolution aerial photography has been shown to differentiate *Macrocystis* and *Nereocystis* canopy in California (Berry et al., 2001), but the surface fronds of these two species are very different.

Weather was the main problem encountered in both years of the study. It was difficult to get even minimum flying conditions (915 m ceiling) during low tide periods and during the optimal windows for sun angle. The lack of a dedicated aircraft for the project also contributed to the logistical constraints because aircraft time could not be scheduled more than 24 h in advance. In addition, the charter pilots who flew these surveys were not accustomed to flying the straight and closely spaced flight lines that are required for this type of survey.

There have been numerous studies using different multispectral sensors to map kelp canopies. The primary problems with the visual satellite sensors are spatial resolution, cloud cover, and cost. Studies in California (Augenstein et al., 1991; Deysher, 1993) have shown that SPOT satellite imagery with a spatial resolution of 20 m is sufficient to map the larger kelp beds in southern California, but is marginal for the smaller beds in this region. The panchromatic band of ETM+ imagery from Landsat 7 has 15 m spatial resolution, which is sufficient to resolve most of the kelp beds in southeast Alaska. However, the overestimation of canopy area (Table 5) as compared to higher resolution imagery must be resolved before this imagery can become a regular tool in harvest management. Multispectral images with spatial resolutions as high as 4 m can be obtained from the Ikonos (Space Imaging), QuickBird (DigitalGlobe), and OrbView-3 (Orbimage) satellites. However, the cost of acquiring imagery over large areas of a region such as southeast Alaska would be prohibitive for only kelp mapping activities. The costs could be reduced if the imagery can be acquired for multiple uses within the same region and a multiagency license can be developed.

There is an inverse relationship between the spatial resolution of satellite images and the time that elapses between repeat passes over an area. Satellites with image resolution sufficient to map kelp canopy generally have a revisit time of between 16 and 25 days. In areas such as southeast Alaska, long periods of cloud cover may preclude the collection of imagery for months at a time. The revisit frequency becomes a problem even in areas of moderate cloud cover if image acquisition during a specific tide period is required.

Since radar frequencies are not blocked by clouds, radar satellite imagery has the advantage of being able to be acquired even during periods of complete cloud cover. However, to be able to discriminate kelp canopy there must be a significant difference in surface roughness between the water and the kelp. There are differences in the surface roughness requirements in the different types of radar imagery (X-band, L-band, and C-band), but it appears that there are many false positives due to areas of increased sea roughness due to wind squalls (X-band) or slicks due to oil or other naturally occurring surfactants (L-band and C-band) (Jensen et al., 1980).

The KIM kelp inventory method developed in Canada (Foreman, 1975) is very similar to the methods used for the present study. The main difference, however, is that the KIM method is dependent on diver surveys for every inventory. The methodology developed by this project is planned to be independent of ongoing field biomass surveys.

Kelp beds in California are inventoried primarily by area determined by aerial near-IR photography and, more recently, digital multispectral imagery. Visual estimates of biomass made by Dale Glantz of ISP Alginates, the largest kelp harvester in California, are also being integrated into the state's kelp bed inventory data. The visual estimates have been calibrated by years of experience comparing visual observations with harvest records.

At this time, we believe that the DMSC imagery combined with the relatively quick method for ground truthing is the best tool for mapping kelp beds for both area and biomass estimates in SE Alaska.

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