1999 Nearshore Rocky Reef Assessment

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1. Introduction

Oregon is facing increasing pressure to utilize living marine resources of nearshore subtidal rocky reef areas. Much of the increase has resulted from a shift toward nearshore reef fisheries due, initially, to the dramatic decrease in traditional salmon harvest, and now to a reduction of traditional groundfish fishing opportunities. Emerging or proposed marine resource uses include the live-fish fishery, expansion of open access hook and line fisheries, kelp (*Nereocystis luetkeana*) harvest, propagation or enhancement of sea urchins, abalone, and other species, and increased and diversified recreational uses.

Because nearshore reefs are in state waters, Oregon is responsible for managing these living resources and habitats to sustain their long-term use and productivity. Resource managers lack scientific information about the organisms and habitats on Oregon's nearshore (<50 m deep) rocky reefs, and need to develop this information for making sound resource management decisions.

We initiated a nearshore rocky reef research project in 1995 to begin gathering information necessary for managing nearshore reefs. This report summarizes work completed during 1999. One major work area during the last four years has been to examine methods to characterize reef bottom habitat. We successfully used side-scan sonar in 1995 and an acoustic ground discrimination system in 1998 to map seafloor habitat, but found the methods to be either too subjective or inconsistent. In 1999, we completed a high-resolution multibeam bathymetry survey of Orford Reef and developed methods to quantitatively classify reef bottom habitat. Section 2, below, presents the results of this work. In 1999, we also continued our kelp biomass study on the southern Oregon coast. Section 3 of this report includes the 1999 estimates of bull kelp (*Nereocystis luetkeana*) biomass at Orford, Blanco, Redfish, Humbug, and Rogue Reefs, and compares the results to previous years. Section 4 of the report discusses how the results of the 1999 work might affect nearshore reef management.

2. Bottom Habitat Survey and Classification

Orford Reef, on the southern Oregon coast, has been studied by ODFW's Marine Habitat Project over the past several years (Fox, et al. 1996; Miller, et al. 1997; Fox, et al. 1998). This reef is an outstanding site for understanding the relationships between marine resources and their physical habitat. In addition to a diversity of nearshore rockfish species, the reef contains extensive bull kelp beds, a rich and diverse invertebrate community, numerous seabird colonies, and is a Steller sea lion rookery. The reef complex consists of two areas, Orford and McKenzie's Reefs, that span an approximate 50 square kilometer region just southwest of Cape Blanco. The rocky reefs and islands comprise a highly productive marine ecosystem that is a valuable resource to the community of Port Orford and to the state's ocean users.

Our studies over the past few years have relied heavily on SCUBA techniques combined with video footage to describe the fish populations that inhabit the area. In 1999, we used multibeam sonar bathymetric mapping to produce a highly detailed bathymetric map that could be used to describe rocky reef habitat. We desired coverage at the scale of the reef, as well as a scale that is ecologically meaningful to rockfish, approximately a 1-2 meter wide rock structure. Section 2.1, below, describes the multibeam bathymetry survey. Section 2.2 describes methods used to characterize rockfish habitat using the multibeam bathymetry data.

2.1 Multibeam Bathymetry Survey

2.1.1 Methods

Survey Area and Survey Planning

The objective of the Orford Reef multibeam sonar survey was to develop a detailed bathymetric data set for evaluating and characterizing nearshore reef habitat. To accomplish this objective, we contracted with Seavisual Consulting, Inc. (SCI) to conduct the survey. SCI collected nearly 100 million soundings with state-of-the-art multibeam sonar technology from June 9-18, 1999, covering approximately 42 square kilometers of Orford Reef (Figure 2.1.1).

The survey area was divided into two categories, high resolution and low resolution (Figure 2.1.1). The survey was designed to resolve features at the following horizontal scales:

- high resolution survey area
    1 m horizontal dimension at depths less than 30 m
    horizontal dimension of 0.03 times the water depth at depths greater than 30 m
- low resolution survey area
    2 m horizontal dimension at depths less than 30 m
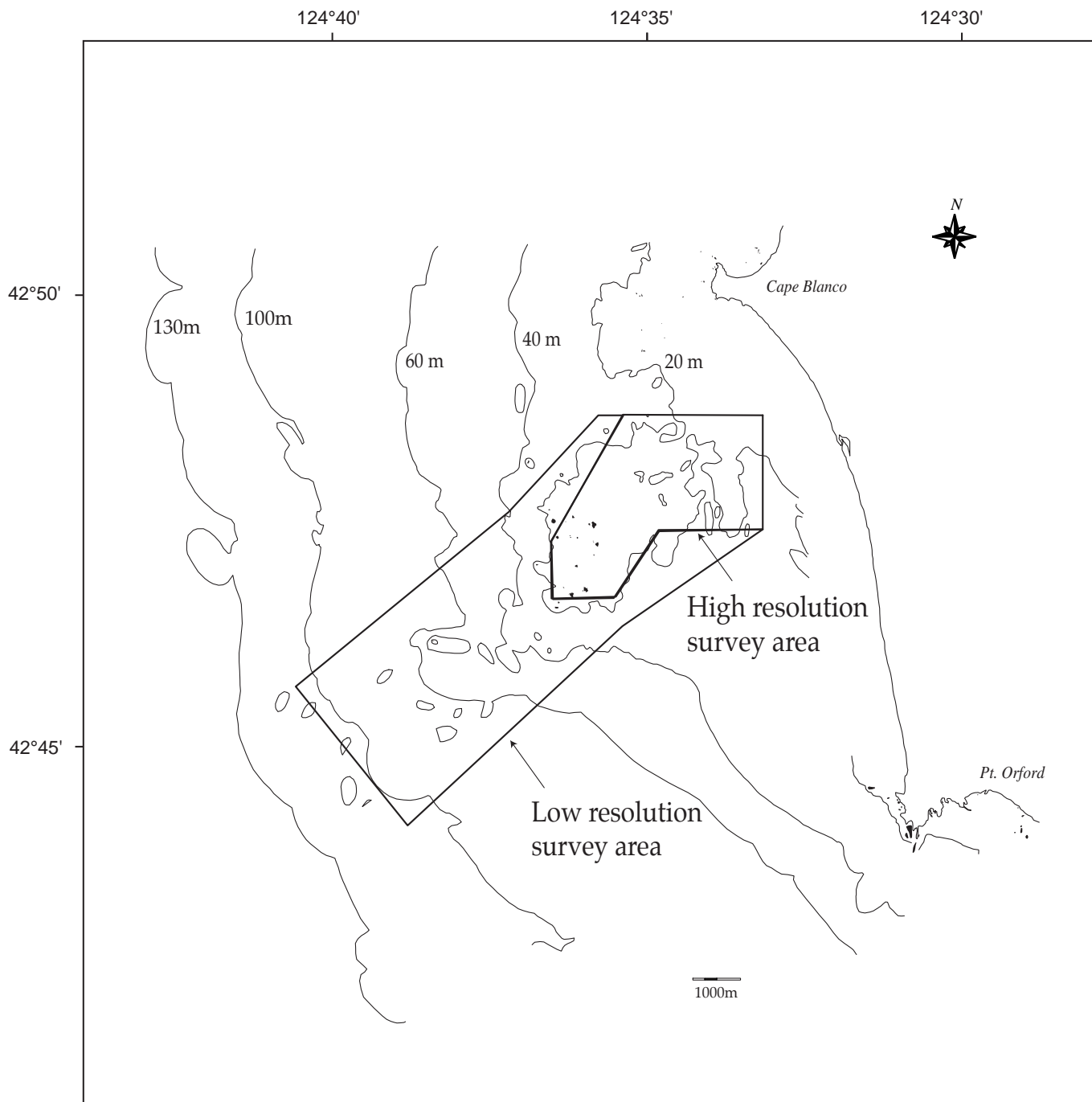   horizontal dimension of 0.07 times the water depth at depths greater than 30 m

Figure 2.1.1. Orford Reef multibeam sonar survey area. The high resolution area was intensively surveyed to achieve a 1m x 1m horizontal resolution. The low resolution area was surveyed with wider tracklines and achieved a lower degree of horizontal resolution.

We chartered a local fishing vessel, the F/V MADDOG, for the data collection effort. This vessel proved ideal for the project, both in seaworthiness and in the ability to accommodate all data acquisition sensors. In particular, the stout nature of the aluminum hull and gunwale, and willingness of the owner to make modifications, were critical factors in obtaining high resolution bathymetric data in this challenging environment. The experience of the vessel captain, Mr. Frank Barnes, in navigating the intricate structure of Orford Reef was pivotal to the successful completion of the project.

The survey employed the following equipment:

- Sonar: Reson Seabat 8101 multibeam sonar,
- Heave, pitch, roll sensor: TSS DMS05 motion sensor,
- Heading sensor: SG Brown 1000S GyroCompass,
- Horizontal positioning sensor: SATLOC Differential Global Positioning System (DGPS),
- Vertical control: NOAA tide gage at the Port Orford dock,
- Speed of sound measurements: Seabird SBE-19 CTD, and
- Hydrographic data acquisition system: Coastal Oceanographics Hypack for Windows version 8.9 software running on a Pentium 300 MHz laptop PC.

Appendix A describes the system components, field survey methods, and data processing procedures.

Orford Reef is known as an area exposed to strong winds and rough seas. During the project, however, weather and seas remained relatively calm. Combined swells and waves during survey days did not typically exceed 6-7 feet and the expected afternoon winds only appeared on one of the survey days (June 10th). In these conditions, the position sensors accurately measured and compensated all vessel heave, pitch, roll, and yaw motions experienced by the sonar.

2.1.3 Results and Discussion

The high-resolution survey area map clearly shows the fractured rock, rock ridges, and rock pinnacles that characterize the area (Figure 2.1.2). The fractured rock on the east side of the survey area is known as McKenzie's Reef (Figure 2.1.2). The fractures are directional and vary in size from a few meters to a kilometer. To the west of McKenzie's Reef are a series of north-south trending ridges. The area known as Orford Reef to the west and southwest is mainly a metamorphic-type rock that manifests itself as outcrops, pinnacles, and islands (Figure 2.1.2). Figure 2.1.3, which includes both high and low resolution survey areas, shows the expansive and continuous rock structure that dominates the region. To the southwest, the dynamic nature of the shallow Orford and McKenzie's Reef region is accented by submerged seastacks in the deeper part of the survey area. These relatively large formations appear as vague rocky shoals on the nautical chart for the Cape Blanco region (Chart No. 18589, Region 14, National Ocean Service, NOAA). The multibeam data presents these formations with a more defined structure. Finally, small wavy ridge-like artifacts appear along survey tracklines in the

middle of the survey region. These artifacts illustrate the resolution limits of the SeaBat 8101 in depths greater than 30 meters.

In comparison to the towed side-scan sonar survey performed several years ago, the vessel-mounted multibeam data are striking in their continuity and depiction of relief. The side-scan sonar provides a view of the bottom similar to a photograph, using acoustic backscatter to show bottom texture (mud, cobble, boulders, rock). The sonar transducer is towed behind a boat and can undergo motions independent of the motions of the boat due to cable tension and water currents. The resulting data can thus be distorted and shifted, even with standard corrections applied. There are ways around problems caused by towfish movement, but in general they are expensive (e.g. motion and positioning sensors on the towfish, digital processors on board the towfish, etc.). In contrast, a multibeam sonar is generally mounted on the survey vessel and the positioning and motion sensors can be mounted directly above the sonar transducer head, resulting in more accurate data georeferencing. Multibeam sonar does have the capability to provide georeferenced backscatter data of bottom texture, similar to side-scan. However, for both cost and practicality, we chose not to collect backscatter data during this survey. Side-scan sonar data we previously collected provided adequate texture information (Fox, et al. 1998).

While the limits of resolution were reached by this survey, the final map of the reef is clearly a large step forward in mapping marine habitat. The fine-resolution bathymetric data provided by multibeam sonar has a high potential for use in all fields of marine science. Section 2.2, below, discusses how multibeam bathymetry can be used at the level of fish ecology and fishery management.
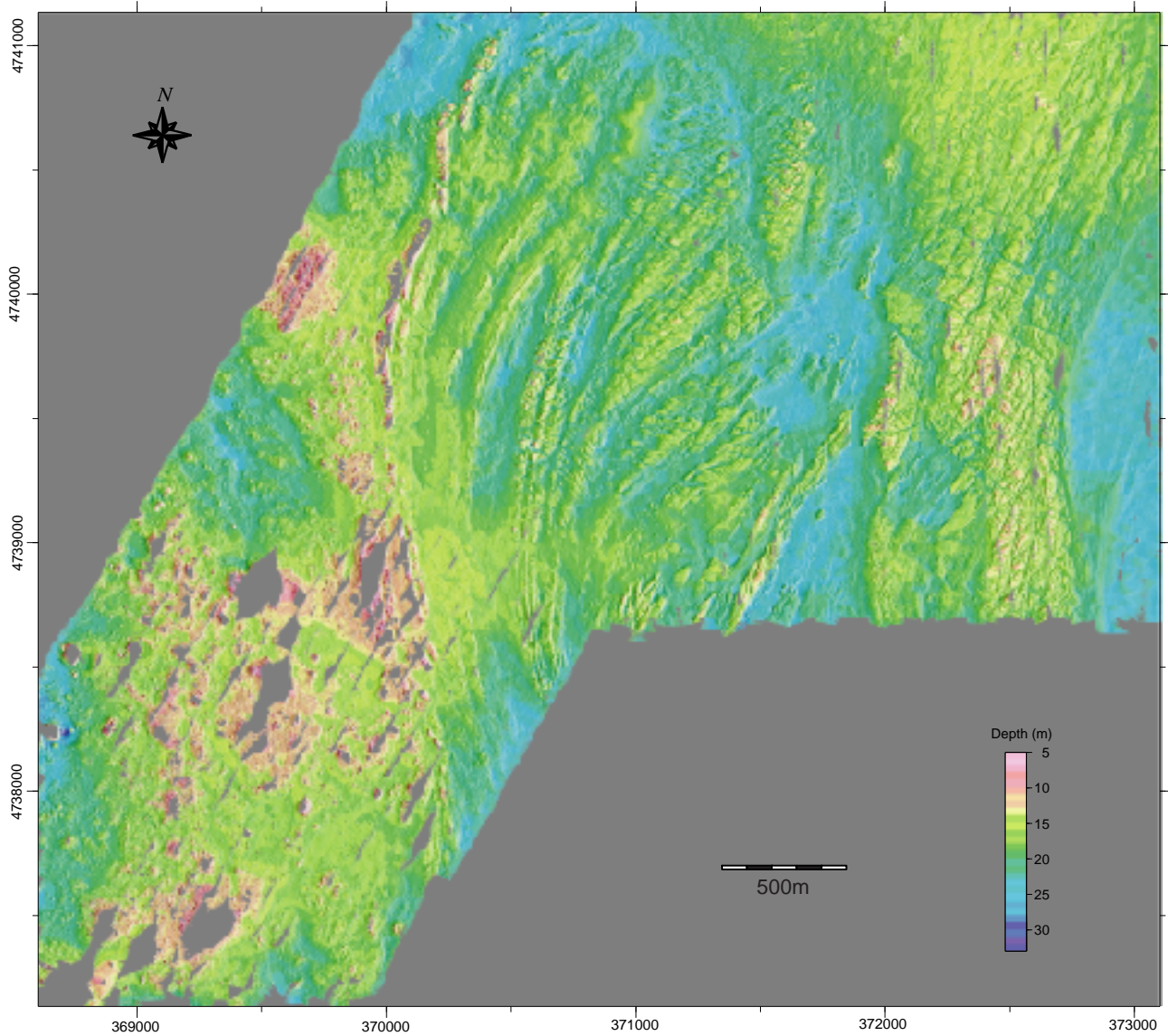
Figure 2.1.2 Shaded relief bathymetric map of the high resolution survey area. Coordinates
 and projection are Universal Transverse Mercator, Zone 10, NAD-83 (meters). Gray areas
represent unsurveyed locations. NOT FOR NAVIGATION

Figure 2.1.3. Shaded relief bathymetric map of the Orford Reef multibeam surveyarea. High resolution and Low resolution areas were mosaick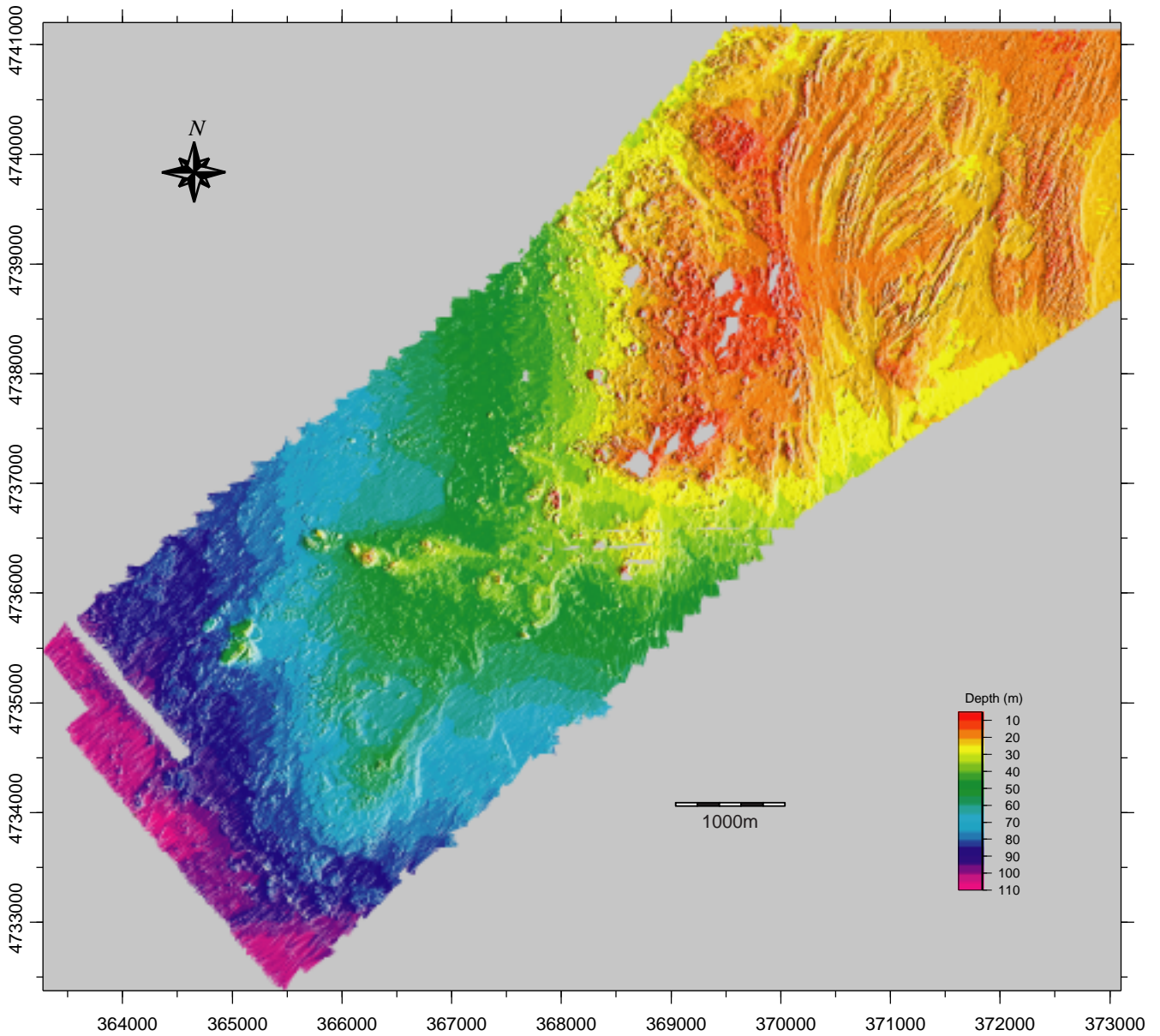ed and resampled to produce this map. Coordinates and projection are Universal Transverse Mercator, Zone 10, NAD-83 (meters). Gray areas represent unsurveyed locations. NOT FOR NAVIGATION

2.2 Fish Habitat Characterization

Our objective was to develop methods of describing bottom habitat in a biologically-meaningful fashion using multibeam bathymetry data. The habitat descriptions need to be useful for predicting fish abundance and distribution. Both fishers and researchers have long known that rockfish abundance patterns within a reef are strongly related to physical habitat structure (Hixon, et al. 1991; Stein, et al. 1992; O'Connell and Carlile 1993; Richards 1986; Matthews 1990a; Matthews 1990b; Krieger 1992a; Krieger 1992b; Murie, et al. 1994). Structure within a reef can be described in terms of the size, shape, and arrangement of rocks or rock outcrops, and surface roughness of the rocky substrate. Many of the rockfish species on nearshore reefs aggregate around rocky outcrops or crevices for a number of reasons including cover from predators, shelter from currents, and presence of prey. In general, areas of high topographic relief have more fish. Our analysis explores how patterns of topographic relief within a reef can be indexed and mapped to represent patterns of rockfish abundance and distribution.

To characterize fish habitat, we classified bottom surface topography and examined the relationships of rockfish abundance to different bottom types. Numerous methods have been developed to describe topographic relief using elevational data (DeMers 1997). In our analyses, we selected two approaches that could prove useful in characterizing topographic relief as a component of fish habitat. The first involved direct measure of changes in depth over defined portions of a reef. We expressed this variation in depth as the slope of bottom surfaces. Average slopes of small segments of the bottom within a defined area provided an index of topographic relief. The second approach drew on principles of landscape ecology by examining the size, abundance, and distribution of habitat patches. In this approach, we first defined what constitutes a habitat patch of high topographic relief. Then, computation of the area coverage and density of patches provided a framework for characterizing an area as either high relief or low relief.

Methods for characterizing topographic relief must account for the spatial scale used to describe bottom features. In bathymetric surveys, the density of depth soundings limits the scale at which bottom features can be detected and described. For example data with a sounding every 100 m can only be used to resolve features that are 100 m or more in extent. In contrast, data with a sounding every meter can be used to resolve features that are 1 m in extent or larger. Although it is possible to examine relationships between fish and topographic relief at any scale, it is essential to focus first on physical scales that the fish are likely to respond to. Within a reef, rockfish most likely individually respond to local scales from a meter to a few tens of meters. Detailed multibeam bathymetry data can provide the high density of depth soundings necessary to describe surface topography at a scale of a few meters. Our analysis explores how patterns of topographic relief within a reef can be classified, mapped and compared to the abundance and distribution of fish observed in an earlier SCUBA survey.

2.2.1. Methods

A 1996 SCUBA fish survey conducted at Orford Reef provided the fish density data for this analysis (Fox, et al. 1996). The fish survey consisted of 2 m x 80 m visual belt transects between the depths of 10 and 25 m. Twenty-three of the transects completed during the summer of 1996 fell within the high resolution multibeam survey area (Figure 2.2.1). The analyses described below use total adult rockfish density as the dependent variable. The density values were log-normally distributed, and were transformed with $\ln(x+1)$ to approximate normality (Fox, et al. 1996).

Procedures for georeferencing the fish transects to the multibeam data accounted for potential positioning errors in the transects. The 1996 survey documented geographic position of fish transects by fixing the transect starting points with a non-differential GPS, and recording the compass direction swam by the divers. Tests of the GPS accuracy against surveyed benchmarks in 1996 showed an average position error of plus or minus 30 m. The divers swam precise compass courses; however, due to currents and avoidance of obstacles, they sometimes deviated up to 10° or 15° from the desired course. This deviation would lead to a maximum locational error of approximately plus or minus 20 m at the end of an 80 m transect. Applying an average potential error of 40 m (±30 m at the start of transect; ±50 m at the end of transect), we used a GIS to generate a 40 m buffer area around each plotted dive transect. The resulting transect buffers (Figure 2.2.1) represented the sampling area of each transect in the analyses described below. Each transect buffer covered an area of approximately 1.1 ha.

Multibeam bathymetry data used in this analysis are from the high resolution survey area (Figure 2.1.2) gridded to a scale of one depth measurement per 2 x 2 m pixel. Section 2.1 and Appendix A describe how the data were collected and processed. We used 2 x 2 m gridded data rather than 1 x 1 m data because small areas of missing data in the finer resolution grid precluded full characterization of the transect buffer areas. Based on previous side-scan sonar surveys, all of the high resolution survey area consists of rocky bottom habitat (Fox, et al., 1998). Therefore, the analyses presented below are restricted to rockfish abundance patterns within rocky bottom habitat types.

Measures of bottom slope within 3 x 3 pixel windows (6 m x 6 m) provided an index of topographic relief. The software ENVI (Research Systems, Inc.) computed the slope of a best-fit plane on the nine depth data points that occur within each 3 x 3 pixel window and assigned the slope value to the central pixel of each window. We then calculated the mean of assigned pixel slopes within each transect buffer area to represent the transects' topographic roughness in our analyses. To compare the effects of bathymetric data resolution on slope data, we generated mean slopes for transect buffers using pixel sizes of 2 x 2 m, 5 x 5 m, and 10 x 10 m. We used simple linear regression to examine the relationship between adult rockfish density and mean slope within transect buffers for each of the pixel resolution scales.

We developed maps displaying mean slope of the reef bottom to provide a whole-reef context for the transect buffer data. ENVI generated these data by computing the mean of the slope values within 53 x 53 pixel windows (106 m x 106 m)
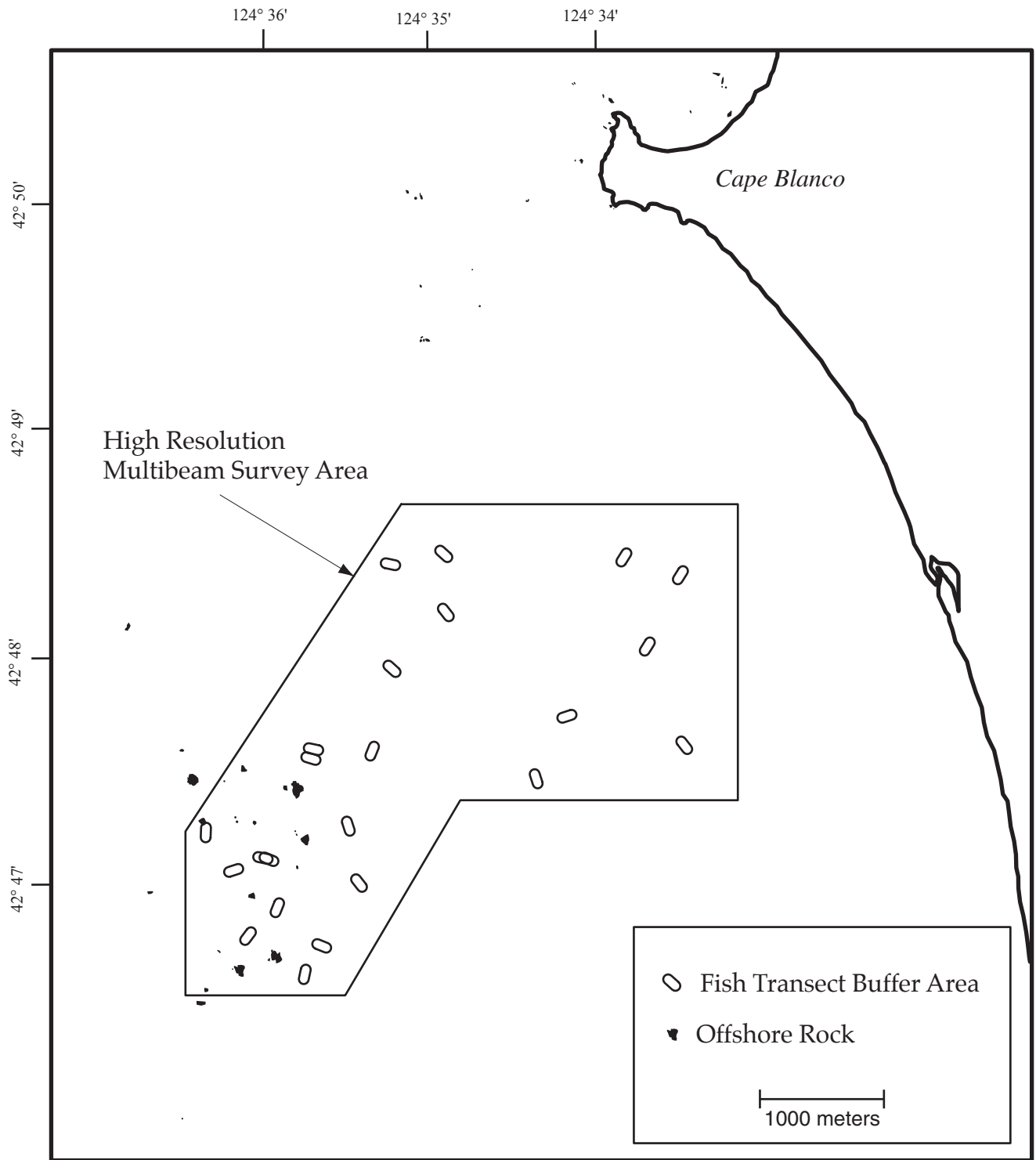
Figure 2.2.1. Location of fish transect buffer areas within the high resolution multibeam survey area.

and assigning those mean values to the central pixel of each window. A 53 x 53 pixel window covers an area equal in size to the transect buffers (1.1 ha), thus the mean slopes computed from these windows were comparable to those derived from within the transect buffers. We separated the mean slopes of transect buffer areas into high and low slope habitat categories using a k-mean cluster algorithm (Verbela 1995; Wilkie and Finn 1996). We tested for differences in mean adult rockfish density between high and low slope categories using a two-sample t test.

As an alternate method of characterizing topographic relief, we analyzed the spatial structure of high relief habitat patches within the study area. The analysis defined high relief areas using depth differences within 3 x 3 pixel windows (using 2 x 2 m pixel resolution multibeam bathymetry data). The central pixel of each 3 x 3 pixel window was characterized as high-relief if there was more than 1.5 m difference in depth between any of the pixels within the window. Any contiguous group of pixels that met this criterion was then called a "patch" of high-relief habitat. All other areas were considered low-relief. We estimated the area coverage and density of high-relief habitat patches within transect buffer areas using the program FRAGSTATS (McGarigal and Marks 1994). The area coverage was expressed as percent cover of total high relief patches in a defined area and the density was expressed as number of patches per hectare. We used linear regression to examine the relationship between total adult rockfish density and percent cover of high-relief habitat patches.

We categorized the study area into high and low relief habitats based on a combination of percent cover and density of patches using mapping and cluster analysis. Mapping followed a procedure similar to the slope data where values were summarized within 53 x 53 pixel windows to emulate the spatial scale of the transect buffers. Similarly, counts of patches within 53 x 53 pixel windows, converted to patches/ha, provided patch density values comparable to the transect buffer values. K-means clustering of the percent patch cover data and patch density data grouped transects into categories of high and low relief habitat. We used a two-sample t test to test for differences in mean adult rockfish density between the two habitat categories.

Stratifying sampling by habitat type may increase precision of mean fish density estimates. We post-stratified the fish transects into high and low relief strata based on habitat patch cover and density, and used bootstrapping methods to compare mean fish density and 95% confidence intervals between stratified random sampling to simple random sampling schemes. The bootstrapping technique randomly resampled the fish density data to generate sets of 10,000 means for sample sizes of 2, 4, 8, 16, 32, 64, and 128, and computed 95% confidence intervals. The technique allowed for both comparison of 95% confidence intervals among these data sets and examination of how sample size effects 95% confidence intervals within each data set. For the simple random sampling data scenario, we used all 23 transects to provide the rockfish density data for bootstrapping. For the stratified data scenario, we divided the transects into high and low relief strata and weighted mean density by the proportional areal coverage of each stratum. The resampled means for the high and low relief categories were then recombined randomly to generate a set of stratified sampling means. The bootstrapping was performed on log-transformed data, and the results were back transformed. The 95% confidence intervals from simple random and stratified

sampling data were then compared to examine changes in sampling precision that might result from sample stratification.

2.2.2 Results

The spatial distribution of slope data clearly depicts relative topographic relief (Figure 2.2.2). Steep slopes generally occur on the sides of large topographic features such as ridges, pinnacles, and crevices (Figure 2.2.2). Habitats with mean slopes higher than 7.6° were categorized into high slope areas based on a k-means cluster analysis. High slope areas covered 32.4% of the high-resolution study area and low slope areas covered 67.6% (Figure 2.2.3).

The linear relationship between adult rockfish density and mean slope was statistically significant (P = 0.020), but weak (r^2 = 0.23) (Figure 2.2.4a). Fish densities in the higher slope areas were consistently high (right hand half of Figure 2.2.4a), whereas fish densities in the lower slope areas varied over a broad range (left hand half of Figure 2.2.4a). The regression is even weaker when using mean slope data based on 5 m x 5 m pixels and 10 m x 10 m pixels (Figure 2.2.4b and c). Aggregating the slope data into larger pixels tends to average the data and reduce variation among the transect buffers (Wong 1996). This accounts for the narrower range mean slopes in Figure 2.2.4b and c compared with Figure 2.2.4a, and the corresponding weaker relationships. There was no significant difference in mean adult rockfish density between transects in high versus low slope habitat areas as depicted in Figure 2.2.3 (*t* test, P= .055).

The spatial distribution of high relief habitat patches depicts relative topographic relief in a similar manner as slope (Figure 2.2.5). The percent cover of high relief patches within transect buffers is similar to the mean slope data (linear correlation r = 0.95, P < .001). This is an expected result as both values use variation in depth of adjacent pixels to depict the vertical extent of rocky structures within an area.

Patch density, however, does not show a constant relationship with percent patch cover (Figure 2.2.6). On transect buffers with low percent cover, patch density increases rapidly as percent cover increases (Figure 2.2.6, left hand half of the graph). Then, as percent cover increases further, patch density levels off and shows no distinct relationship with percent cover (Figure 2.2.6, right hand half of the graph). This is an expected result; as percent cover increases, patches increase in size and begin to join together, resulting in fewer patches, thus a lower patch density. The number of patches would continue to decline until, at 100% cover, there would be one large patch (patch density = 1).

The transects were separated into three categories using k-means cluster analysis of percent cover and patch density (Figure 2.2.6). Cluster 1 includes transects with high percent cover of patches and various levels of patch density. We categorize these areas as high relief habitat due to the relatively high cover of high-relief habitat. Clusters 2 and 3 include transects with low percent cover of habitat patches. Transects in cluster 2 have relatively high patch densities and are classified as high relief. These have many small-scale bottom structures that are too small in total to register a high coverage
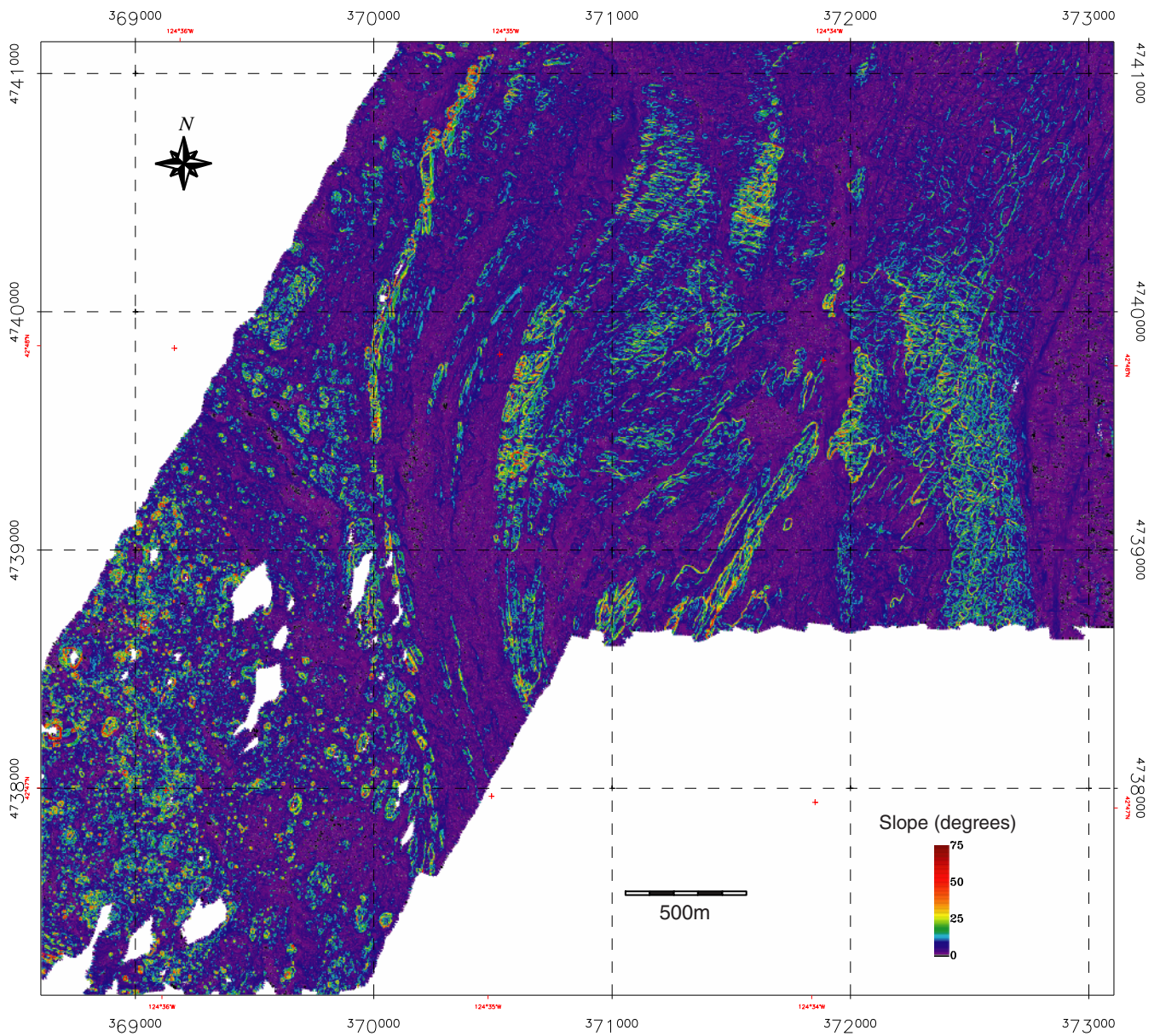
Figure 2.2.2. Slope map of high resolution survey area. Slope was determined by fitting a 3x3 pixel plane at each data location and assigning the value to the central pixel. Pixel size was 2 x 2m.
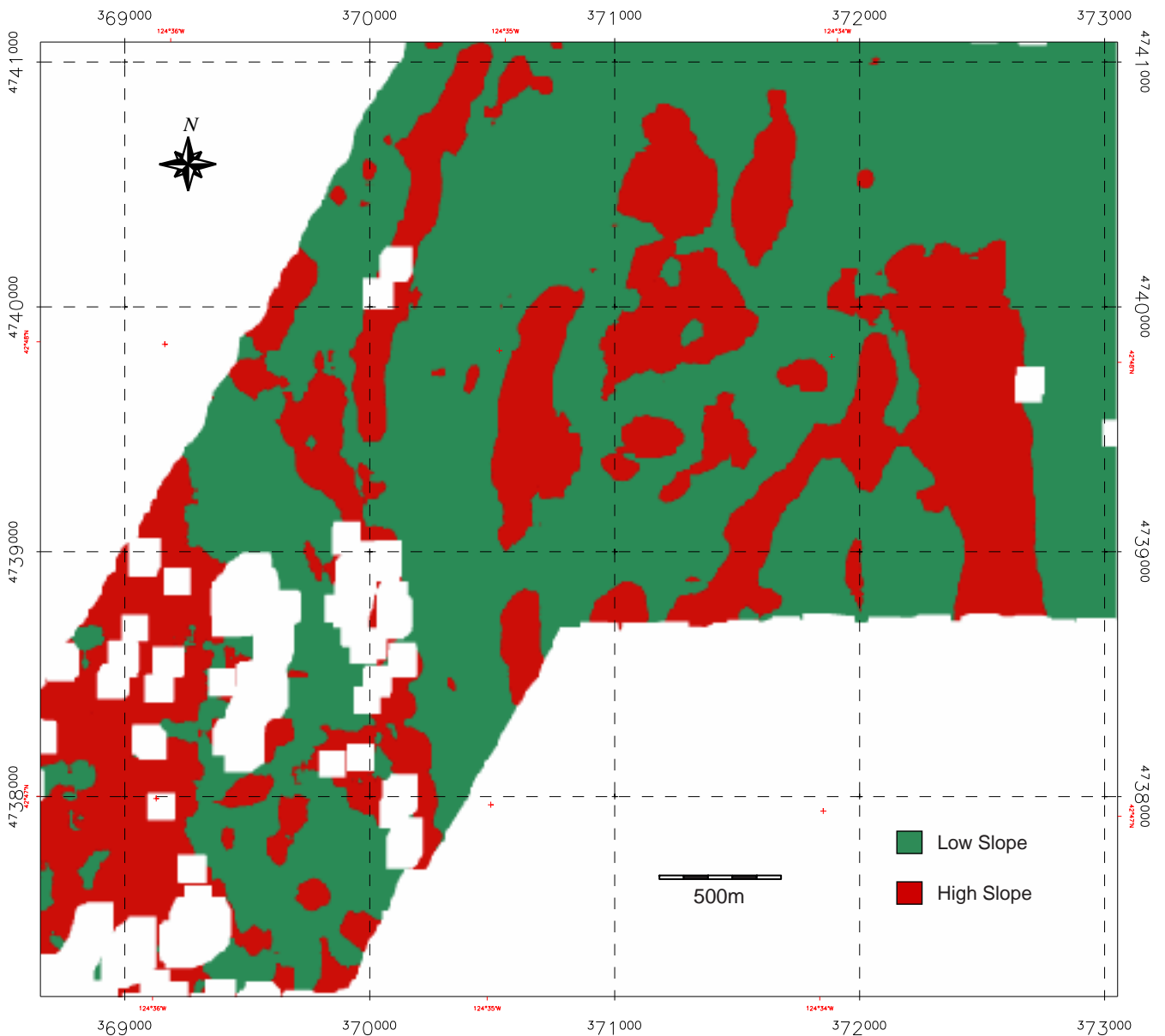
Figure 2.2.3. Mean slope classified into two categories by a k-means algorithm. The mean values were calculated by running a 53x53 pixel moving window over the data (thus approximating the area of the fish transect buffers). Pixel size was 2 x 2m.
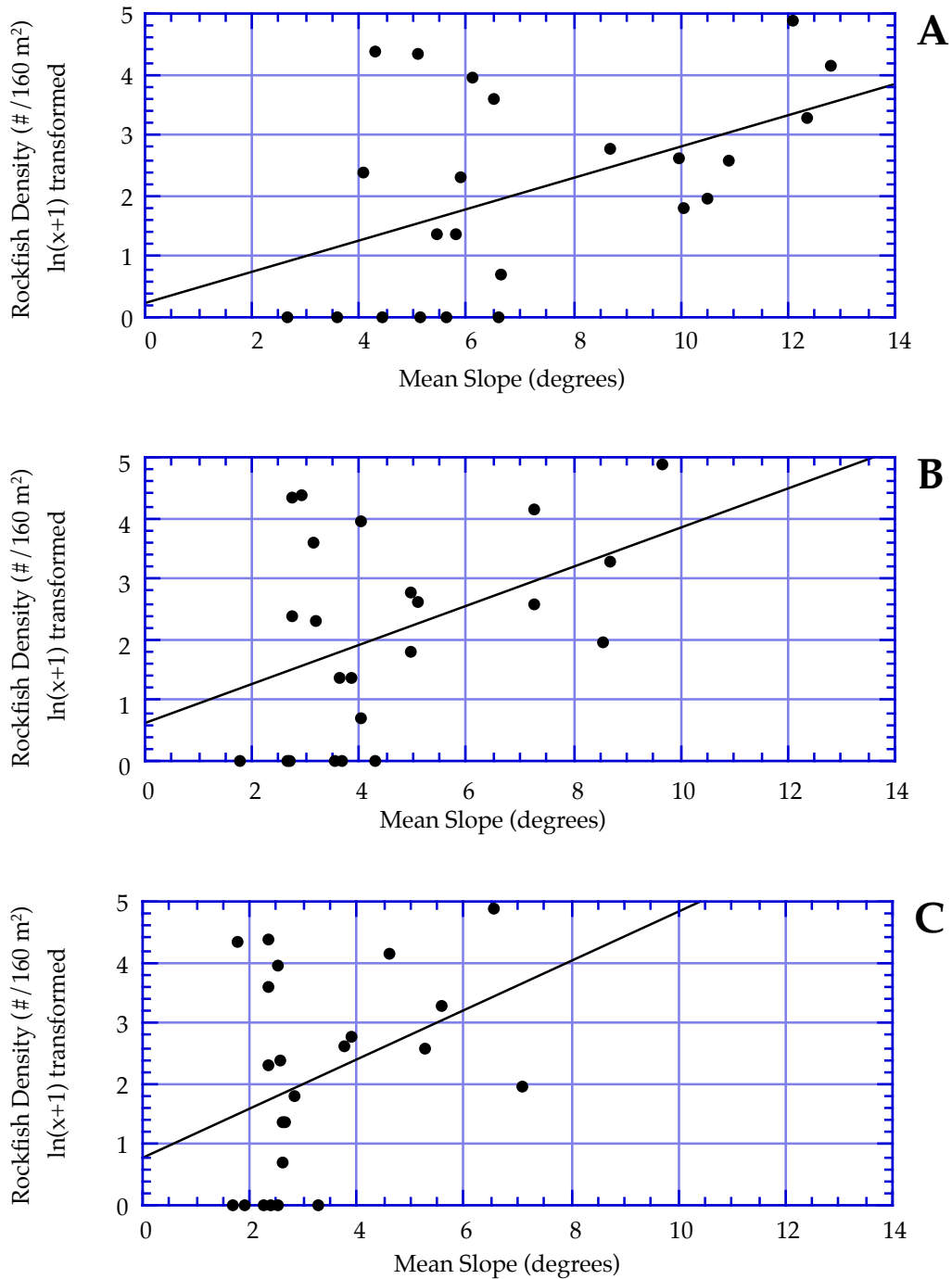
Figure 2.2.4. Linear regression of log-transformed rockfish density and mean slope within transect buffers. The three graphs compare regression results using (A) mean slope data generated with a 2 x 2 m pixel size ($r^2 = 0.23$, P = .020), (B) mean slope data generated with a 5 x 5 m pixel size ($r^2 = 0.18$, P = 0.042), (C) mean slope data generated with a 10 x 10 m pixel size ($r^2 = 0.14$, P = 0.079).

Patch %Cover= 29.1 %
Patch Density= 34.5/ha

Patch %Cover= 12.3 %
Patch Density= 21.3/ha

Patch %Cover= 23.1 %
Patch Density= 28.4 /ha
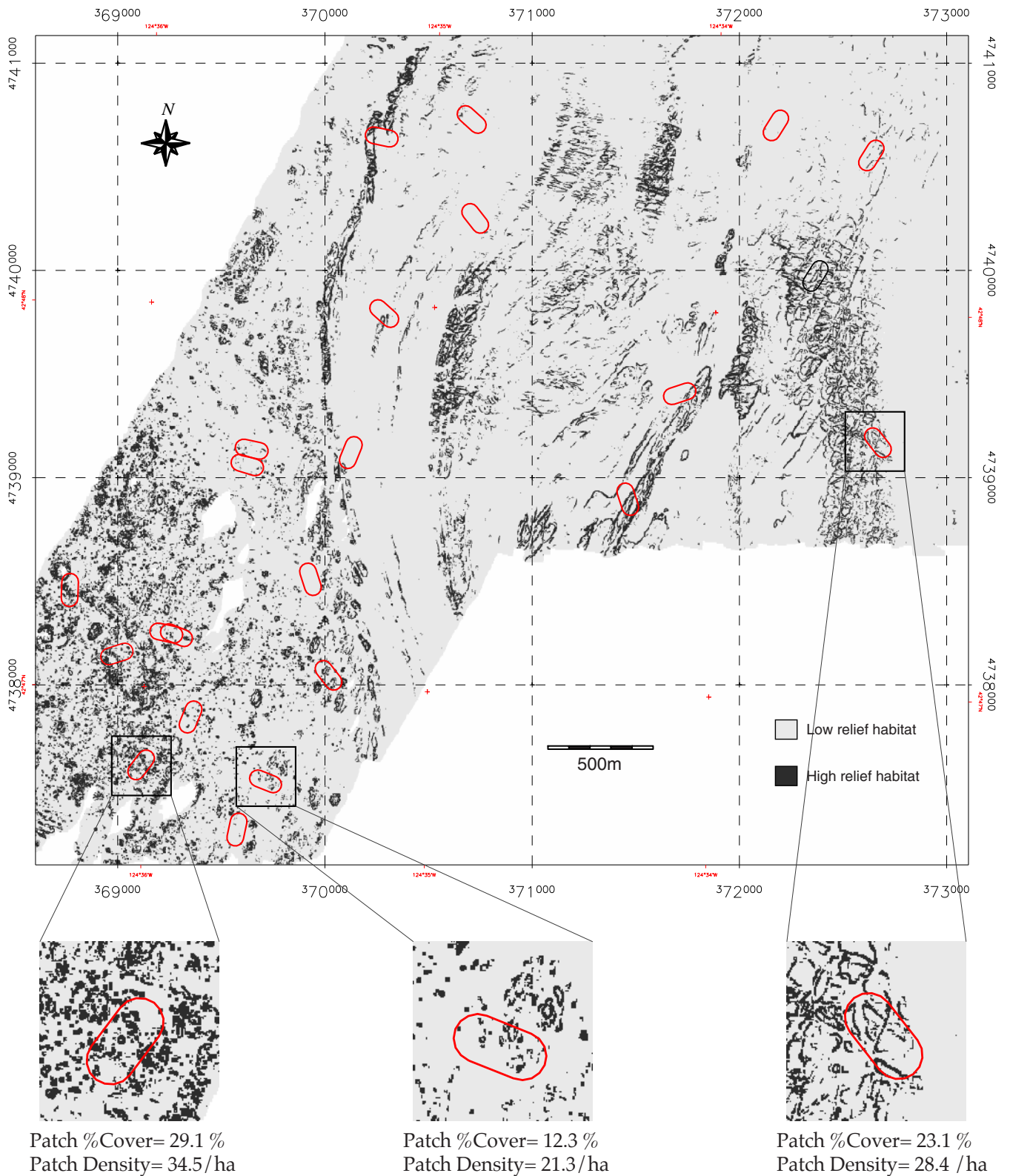
Figure 2.2.5. Map of high-relief habitat patches as determined by local differences in depth.
Examples of 40m fish transect buffer overlays and patch statistics are shown.
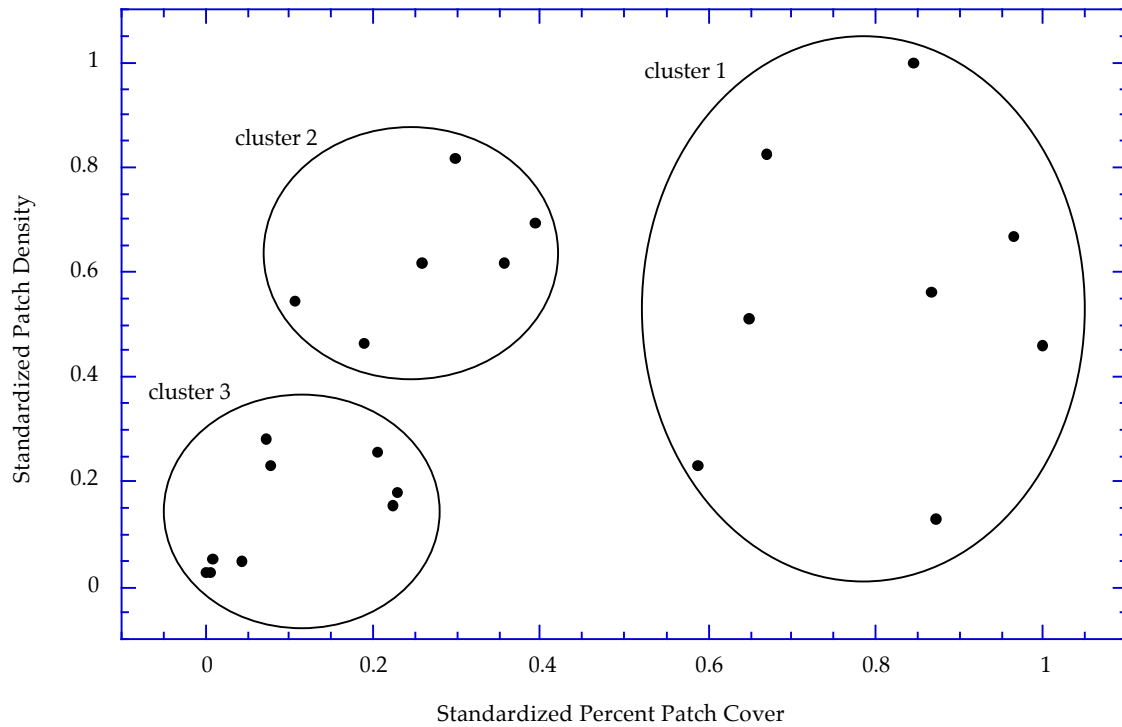
Figure 2.2.6. Results of cluster analysis of patch cover and density in the transect buffers. Percent patch cover and patch density are standardized proportionally to values ranging from 0 to 1. Cluster 1 represents high-relief transects with high patch cover and variable patch density. Cluster 2 represents high-relief transects with low patch cover and high patch density. Cluster 3 represents low-relief transects with low patch cover and density.

value, but are still of adequate scale to attract fish. Transects in cluster 3 have relatively low patch densities and percent cover, and are classified as low relief.

More of the reef was categorized as high relief using the method based on percent cover and patch density when compared to the slope method (Figure 2.2.7). On the map (Figure 2.2.7), areas of low patch density and percent cover correspond to cluster 3 on Figure 2.2.6 and were classified as low relief. Areas of high percent cover and either high or low patch density correspond to cluster 1 in Figure 2.2.6 and were classified as high relief. Areas of high patch density and low percent cover correspond to cluster 2 on Figure 2.2.6 and were also classified as high relief. The percent cover and patch density method resulted in 43.7% high relief habitat and 56.3% low relief habitat. This is due primarily to addition of areas where patch density is high enough to be classified as high relief, even though percent patch cover is low. When categorizing transects based on this analysis, rockfish densities showed a significant differences between high and low relief habitat (t test, P = .011).

Bootstrapped 95% confidence intervals showed only a modest gain in statistical precision between stratified random and simple random sampling (Figure 2.2.8). When sampling high relief habitat alone, the predicted gain in statistical precision was about 30% over simple random sampling across the entire reef (Figure 2.2.9). This large gain in statistical precision suggests that focusing sampling on high relief habitat only might be advantageous when designing, for example, a study of changes to nearshore rockfish relative abundance over time. The accuracy of predicting the mean can vary widely between stratified and simple random sampling. In the example based on our data set, the simple random sampling mean density is 40% higher than the stratified random mean density, primarily because the simple random design, by chance, sampled high relief habitat disproportionately to its surface area.

2.2.3 Discussion

Multibeam bathymetric surveys provide for consistent and quantitative characterization of bottom habitat attributes. Until the application of fine resolution multibeam sonar, obtaining detailed bottom description depended on methods such as visual observation or side-scan sonar. Visual methods are limited in their ability to cover large areas, and, in most cases, side-scan sonar data interpretation is qualitative and requires extensive groundtruthing. High resolution multibeam sonar can cover areas comparable to side-scan sonar, while allowing for quantification of bottom attributes with reduced groundtruthing requirements. Multibeam sonar has been used extensively to map and classify large-scale ocean bottom features (e.g., Fox and Hayes 1984; Shaw and Smith 1990; Mitchell and Hughes Clarke 1994; Hughes Clarke, et al. 1996). We used only the bathymetric capability of multibeam sonar because we were interested in the topographic characteristics (flat vs. convoluted) of the bottom, more than textural (mud vs. sand vs. rock). There has been some question regarding the ability of multibeam bathymetry data to describe features at scales small enough to reflect fish habitat features. This study has demonstrate the promise of multibeam data in examining habitat characteristics at the scale of meters.
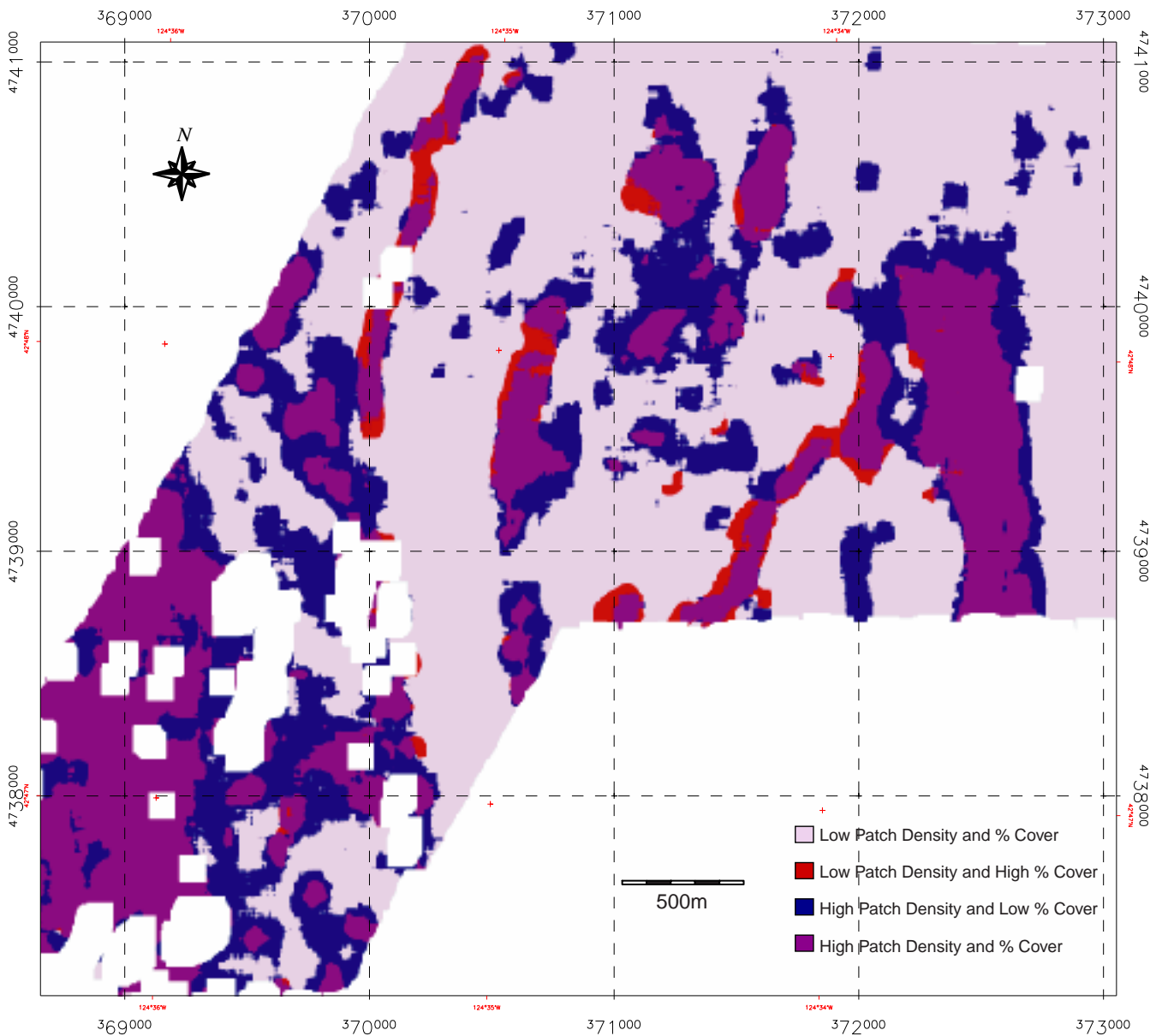
Figure 2.2.7. High relief fish habitat patch map as determined by k-means clustering of patch density and percent cover. High relief patch density, percent cover, and areas of overlap are shown. The patch density and percent cover values were calculated by running a 53x53 pixel moving window over the data (approximating the area of the fish transect buffers). Pixel size was 2 x 2m.
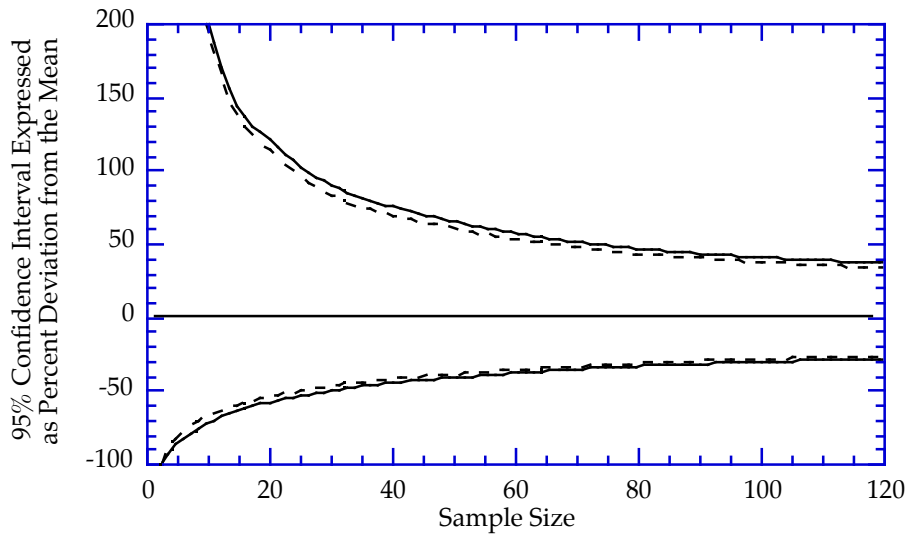
Figure 2.2.8. Comparison of bootstrapped 95% confidence intervals between simple random sampled fish transect data (solid line) and fish transect data stratified by habitat type(dashed line).
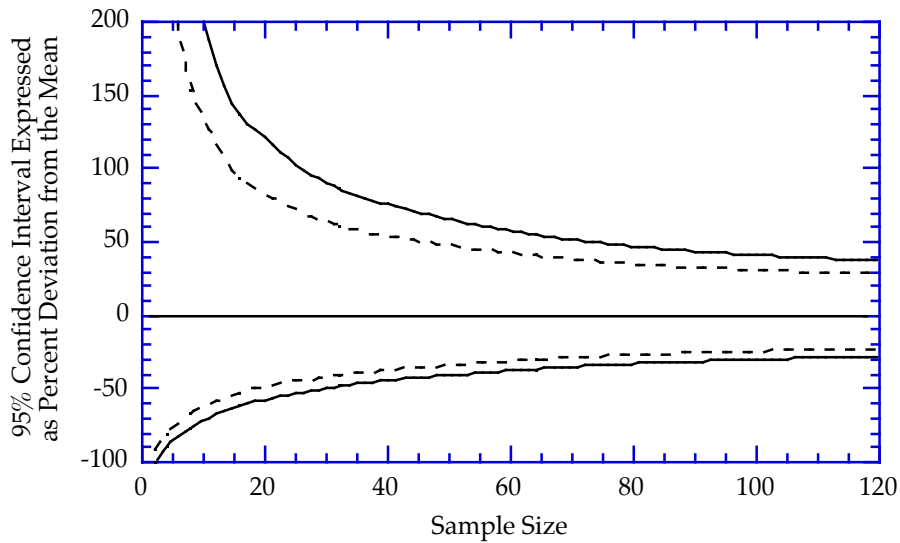
Figure 2.2.9. Comparison of bootstrapped 95% confidence intervals between simple random sampled fish transect data (solid line) and fish transect data in high relief habitat only (dashed line).

A single descriptive measure of topography such as mean slope can characterize bathymetric features but does not capture all the attributes of bottom topography that may affect fish. The mean slope data successfully characterized areas with prominent rocky features such as ridges, large crevices or large pinnacles. We generally observed high rockfish use at these areas. However, on transects characterized by uniformly lower mean slopes, visual observations revealed a broad range of bottom roughness characteristics. Some transects had numerous smaller rocky structures, often with associated fish, while others were relatively flat. Mean slope of an area reflects both the steepness and size (horizontal extent) of topographic structures. Transects with a few large structures produce high mean slopes, while transects with many small structures produce low mean slopes. However, based on qualitative visual assessment, both large and small topographic structures appear to be important to nearshore rockfish species. These observations suggest that mean slope does not adequately describe all scales of bottom roughness that might be important to fish. Because rockfish appear to associate with many small patches (2 – 20 m) of rough bottom, as well as with large patches (20 – 100's of m), bottom roughness measures need to incorporate the small habitat patches as well as the large ones.

An analysis of the size, distribution, and abundance of habitat patches can account for different scales of patches and improve habitat characterization. Incorporating density of small-scale habitat patches into habitat characterization separated areas containing many small topographic features from relatively flat areas and expanded our definition of high-relief habitat. One important objective of habitat classification is to develop habitat categories that match direct observations of fish. The decision to incorporate small habitat patches in the definition of high-relief habitat resulted from our direct observations of small-scale rockfish distribution patterns on rocky reefs. Analysis of habitat patches is a common method used in terrestrial landscape ecological studies and shows promise for describing marine habitats (Garrabou, et al. 1998).

The analysis of bottom topography and patch spatial characteristics provided a method for scaling up habitat characterization from the scale of individual fish to the scale of the whole reef. Definition of high relief areas began with assigning values to 2 m x 2 m pixels based on the change in depth within a 3 x 3 pixel area. Grouping these pixels into high-relief patches expanded the definition to the scale of 10's to 100's of meters. Finally, combining habitat patch cover and density using cluster analysis allowed for classifying the reef into two habitat classes at a scale of 1000's of meters.

Consideration of within-reef habitat differences can influence the precision and accuracy of reef fish population estimates. Statistical precision of rockfish population estimates or related variables can be improved (i.e., variance reduced) by stratifying samples by habitat type. In our analysis the gains in precision were modest because the reduction in estimated variance due to stratification only slightly outweighed the effect of reducing sample size within each stratum. However, in our example, the estimate of the mean habitat-weighted fish density differed markedly between stratified and unstratified scenarios. Although a thorough random sampling of an entire reef should account for inaccuracies in estimating means without considering habitat differences, large enough sample sizes to ensure complete representation of different habitats are often impractical. Thus, stratifying by habitat increases the likelihood of estimating a

mean that more closely approximates the true mean value. This has important ramifications in fisheries management as grossly underestimating or overestimating fish abundance can result in either over-restrictive or over-exploited fisheries.

3. Kelp Biomass Survey

3.1 Methods

Kelp Biomass was estimated using the same methods employed in the previous three years (Fox, et al. 1996; Miller, et al. 1997; Fox, et al. 1998). The biomass estimate was derived from the multiplication of mean plant weight, mean percent cover (density), and total kelp canopy surface area. For further explanation of the biomass estimate calculation, refer to Fox, et al. (1996).

Plant weights were obtained from all five reefs in the study area: Blanco, Orford, Redfish Rocks, Humbug, and Rogue. The project team collected and weighed plants from Orford, Redfish and Humbug reefs at sea on Sept. 2, 1999. Plants from Blanco and Rogue reefs were collected under contract by commercial fishermen on Sept. 20, 1999, then subsequently weighed at the dock by project staff. All aspects of collecting, cutting and weighing the plants followed methods used in previous years. The number of plants obtained from each reef was similar to 1998 (Fox, et al. 1998).

The method of converting percent cover to density was similar to previous years using the KIM-1 method developed by Foreman (1975) and Foreman and Cabot (1979). However, we altered the sampling rate of the point intercept component. In 1998 we used a sampling rate of one grid per hectare. Given the enormous increase in kelp canopy surface area for this year's crop, the number of samples required would have been extremely high and unnecessary. We confirmed this by performing a power analysis on last years' percent cover data and determined that a 0.4 grid per hectare sampling rate was sufficient to maintain roughly a 30% variance of the mean.

Aerial photographs were used for mapping kelp beds and determining kelp canopy surface area. The photography was obtained on October 2 and 11, 1999 by Bergman Photographic, Inc. Due to the extensive kelp canopy this year, flight lines were extended to cover the southern end of Orford reef. The number of photographs used to map kelp increased from 19 photographs in 1998 to 33 in 1999. The photographs were geo-referenced using control points obtained from previous year's projects.

3.2 Results and Discussion

3.2.1 Kelp Plant Weight

Kelp plant weights were not pooled as in previous years since pooling the weights did not significantly reduce variance. Individual plant weights ranged from 0.16 to 18.43 kg. Mean plant weights by reef ranged from 1.58 to 3.36 kg. (Table 3.2.1).

Table 3.2.1 Mean weights and statistics for 1999 kelp plants.

Reef	Mean weight (kg)	Sample Size	Variance	Standard Error
Blanco	2.063	70	1.261	0.134
Orford	3.115	71	5.939	0.289
Redfish	1.577	70	0.918	0.115
Humbug	3.357	71	4.635	0.256
Rogue	2.936	70	10.036	0.379

3.2.2 Percent Cover

Overall, kelp plants appeared very dense throughout most of the beds. However, some beds had large areas of low plant density. This resulted in a wide range of percent cover values within the beds. Mean percent cover between reefs ranged from about 15 to 32% (Table 3.2.2). Orford reef had the highest percent cover at 32%, followed by Blanco and Redfish reefs at 25%. Humbug and Rogue had 15% cover (Table 3.2.2).

Table 3.2.2. Kelp canopy percent cover and surface area for 1999.

Reef	Mean Percent Cover	Sample Size	Standard Error	Canopy Surface Area (ha)
Blanco	25.386	130	1.738	283
Orford	31.196	333	0.979	670
Redfish	25.041	47	2.420	93
Humbug	15.287	27	1.906	50
Rogue	15.632	150	1.093	304

3.2.3 Mapping and Surface Area Estimation

Kelp canopy surface area was both visibly and quantitatively extensive on all reefs. The total kelp canopy delineated from the photographs was 1400 ha. Orford Reef had the largest total canopy at 670 ha (Table 3.2.2). The 1999 kelp canopy was the largest seen in the 4 years of the biomass analysis, and for a number of years prior, according to previous studies and local fishermen.

As in past years, defining a kelp beds was subjective. This years' beds were additionally challenging to delineate because plants were numerous and widely spread across the reefs in varying densities. Figures 3.3.1, 3.3.2, and 3.3.3 show the extent of kelp beds for the reefs as they were delineated from the photographs. Density within the beds is not shown in the figures.
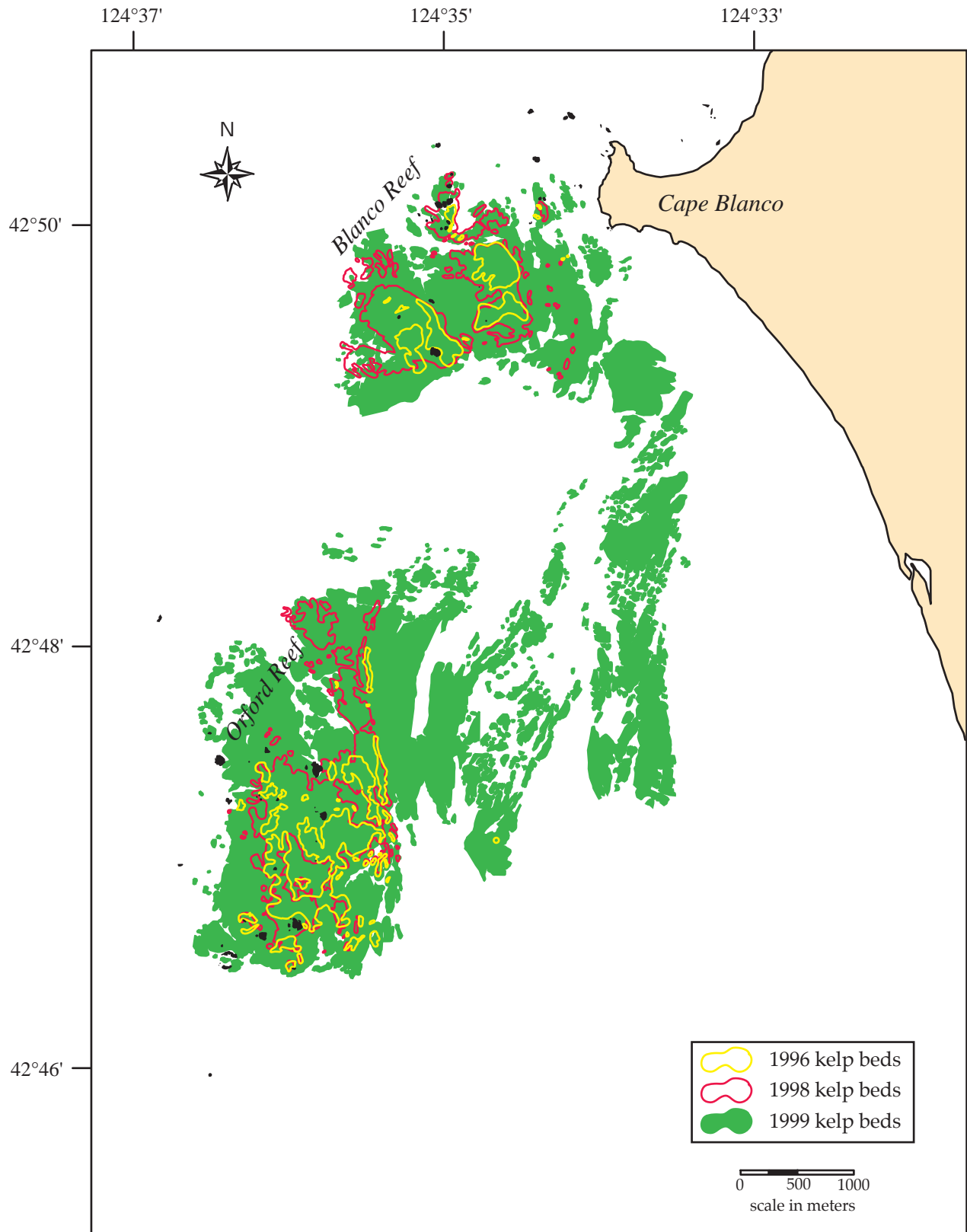
Figure 3.2.1. Kelp beds on Orford and Blanco Reefs in 1996, 1998, and 1999.
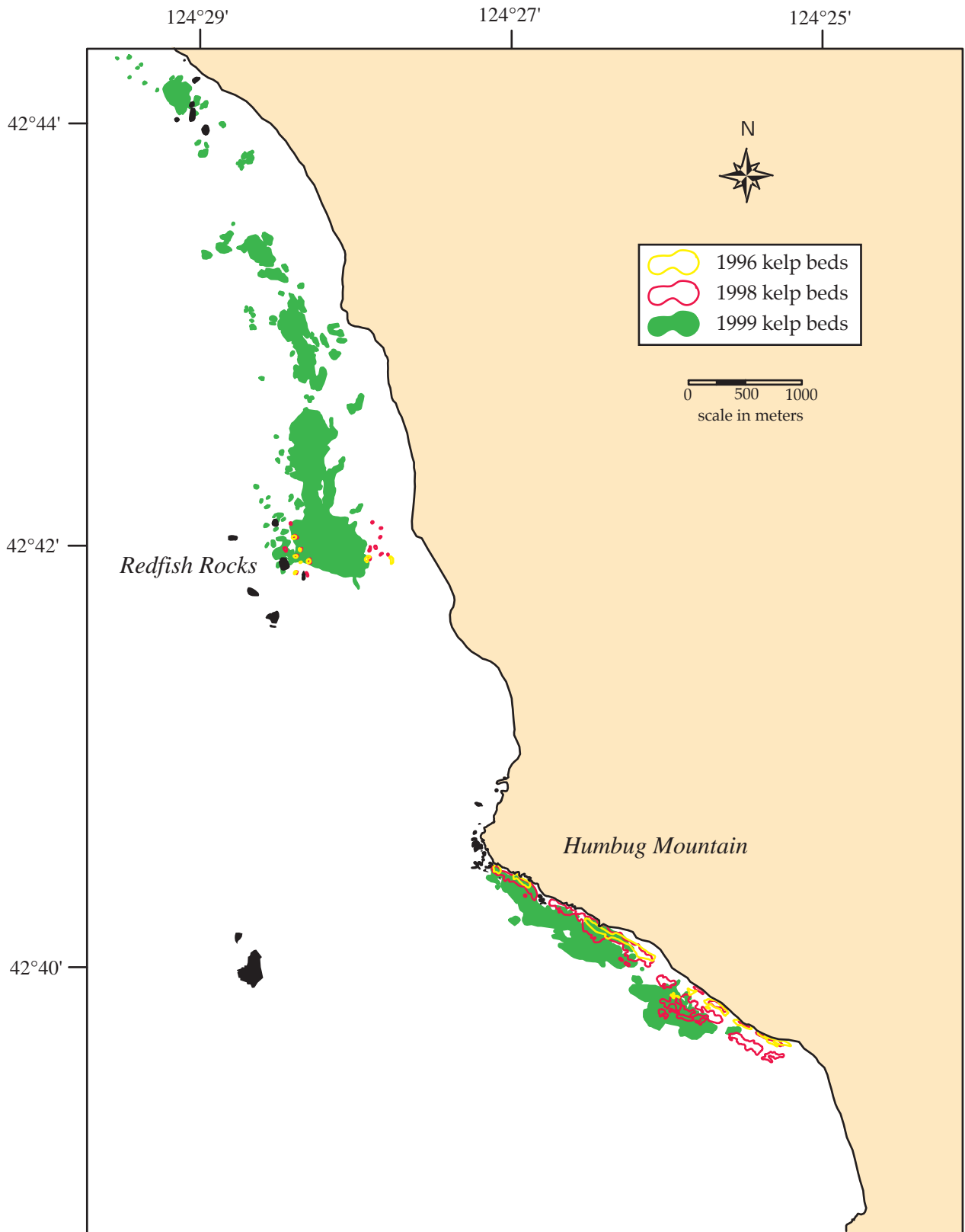
Figure 3.2.2. Kelp beds on Redfish Rocks and Humbug Mountain Reefs in 1996, 1998, and 1999.
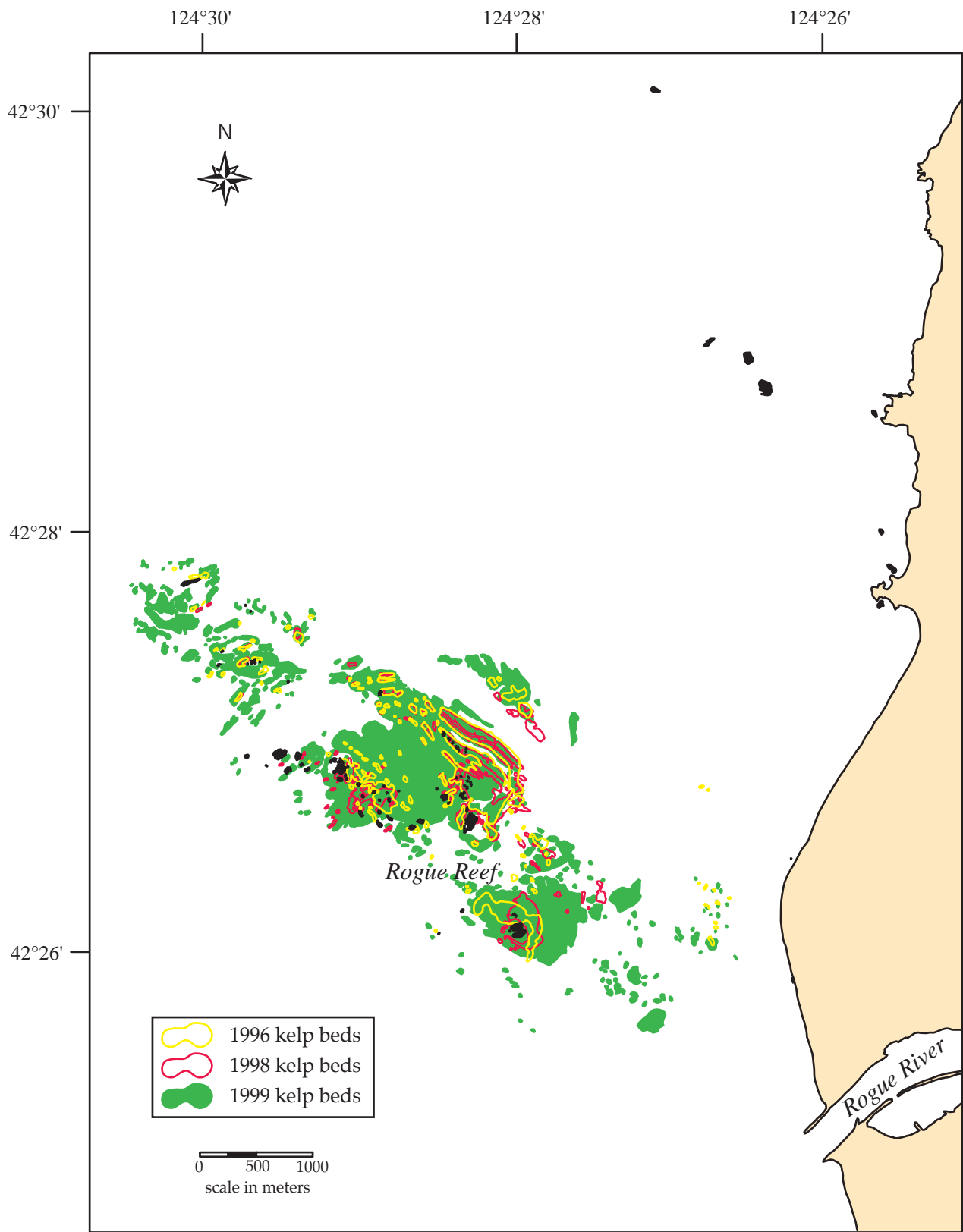
Figure 3.2.3. Kelp beds on Rogue Reef in 1996, 1998, and 1999.

3.2.4 Kelp Canopy Biomass

The total kelp canopy biomass for all reefs was 81,165 tons $\pm$ 11,539 (95% confidence intervals), or 58 tons/ha. (Table 3.2.5). The total biomass within Oregon Division of State Lands experimental harvest lease area was 78,804 tons $\pm$ 11,520 (95% confidence intervals). The DSL lease area includes Blanco, Orford, Redfish and Rogue Reefs.

Table 3.2.3 1999 Kelp bed biomass.

Reef	Total Biomass (tons)	Standard Error	95% Confidence Interval	90% Confidence Interval	Biomass (tons /ha)
Blanco	12058	1161	2276	1916	43
Orford	50991	5365	10516	8853	76
Redfish	2985	334	656	552	32
Humbug	2362	332	652	548	47
Rogue	12770	2074	4064	3422	42
All Reefs	81165	5887	11539	9714	58
DSL Lease Area	78804	5878	11520	9698	58

3.2.5 Annual Variation

Annual Variation by Total Study Area

Total kelp biomass for the study area was remarkably higher in 1999 than in years past (Table 3.2.4). The biomass estimate for 1999 indicates almost a 500% increase from 1998, and a 1,000% increase from 1998. Kelp canopy surface area also increased dramatically from previous years and is the principal component of the increase in biomass for 1999. Surface area increased 400% from 1998. It is interesting to note that the increase in biomass from 1997 to 1998 was attributed to an increase in plant density, and surface area had no relevant effect on the biomass increase. Even though surface area was higher in 1997 than 1996, the 1997 biomass was lower than 1996. This can be attributed to both reduced plant weights and reduced density in 1997. It appears that density was the main contributor to variation in total biomass for two of the four years sampled thus far, and surface area was the main contributor for one year.

Plant weight and kelp bed density for the study area differed only slightly from 1998. Plant weight has been relatively constant for the past consecutive 3 out of the 4 years sampled, with differences of less than 7%. Density increased 22% from 1998, but increased 270% from 1997.

Biomass expressed as tons per hectare (t/ha) exhibits less annual variation than total biomass. Three of the four years had biomass (t/ha) ranging from only 52 to 58, despite the dramatic difference in total biomass for the same three years, which ranged from 10,000 to 81,000 tons. The primary reason for differences between the two estimates is that in the biomass (t/ha) estimate, surface area is factored out of the equation, thus biomass (t/ha) represents the combined effect of plant weight and density, which for these 3 years, appears to even out the other's contribution to biomass (t/ha). The ability to predict a year's total biomass from surface area alone may be possible if biomass (t/ha) were relatively constant through time. This trend is apparent for the total study area but is less consistent for some of the individual reefs. More data sets should produce higher confidence and predictability in mean plant weight and plant density, thus facilitating predictions about biomass.

Annual Variation by Reef

Annual variation within individual reefs is not as easily summarized since each reef displays different anomalies from year to year. Surface area and total biomass were substantially higher at all reefs in 1999 than in previous years. Biomass (tons / ha) decreased from 1998 and 1996 at Blanco, Redfish and Rogue reefs. Orford reef had the highest biomass (tons / ha) at 76, well above the average of 58 for the study area. This is attributed to very high density in 1999 at Orford Reef.

Plant density for 1999 was markedly higher than in 1998 at Blanco and Orford reefs, but lower at Redfish and Rogue reefs. In 1998, kelp beds at Redfish reef were few and small, and plants were tightly clustered, resulting in much higher density than at the other reefs where beds were larger and plants were more loosely associated. Beds at Redfish Reef in 1999 resembled a distribution typical of other reefs in the study area, with patches of tightly clustered plants among patches of loosely clustered plants. Rogue Reef exhibited a similar pattern. Plant densities in 1999 were notably higher than in 1997 at all reefs.

Mean plant weights have fluctuated little in the past 3 years with weights between 2.1 and 3.8 kg, with the exception of Humbug reef. Humbug plant weights were notably lower in 1997 and 1998 than at other reefs, and notably higher in 1999. Plant weight seems to have the least influence on overall biomass totals since plant weight varied little between most years and within and between most reefs.

We suspect a correlation may exist between plant weight and density, though the data are not sufficient for statistical analysis. Data for Blanco and Orford reefs, though limited, suggest a possible inverse relationship. An inverse relationship has been shown to occur in *Nereocystis* kelp beds off British Columbia (Foreman 1984). If the relationship between plant weight and density can be determined for beds off Oregon, this would facilitate the process of estimating kelp biomass, as discussed in the previous section.

Table 3.2.4 Annual biomass data for 1996, 1997, 1998 and 1999.

Reef * Year	Mean Plant Wt. (kg) unpooled	Mean Percent Cover	Mean Density Plants/ha	Surface Area (hectares)	Total Biomass Estimate (tons)	Biomass (tons / ha)
Blanco * 96	5.04	8.99	8324	33.2	1717	52
Blanco * 97	2.51	6.92	7270	112.5	2259	20
Blanco * 98	3.12	19.02	14977	101.6	5239	52
Blanco * 99	**2.06**	**25.39**	**18736**	**283.0**	**12058**	**43**
Orford * 96	5.61	9.23	8446	65.6	3442	52
Orford * 97	3.82	4.39	5984	154.9	3900	25
Orford * 98	3.16	17.45	14052	144.5	6454	55
Orford *99	**3.11**	**31.20**	**22166**	**669.9**	**50991**	**76**
Redfish * 96	2.19	25.17	16569	0.3	13	40
Redfish * 97	2.03	12.34	10032	36.6	743	20
Redfish * 98	2.10	34.62	24189	0.9	46	53
Redfish * 99	**1.58**	**25.04**	**18532**	**92.7**	**2985**	**32**
Humbug * 96	not sampled	6.05	6828	13.5	574	42
Humbug * 97	1.60	9.34	8504	32.9	566	17
Humbug * 98	1.84	13.60	11776	22.0	564	26
Humbug* 99	**3.36**	**15.29**	**12772**	**50.0**	**2362**	**47**
Rogue * 96	not sampled	14.13	10945	66.5	4522	68
Rogue * 97	not sampled	3.36	5455	29.1	669	23
Rogue * 98	2.60	37.92	26140	51.5	4279	83
Rogue * 99	**2.94**	**15.63**	**12976**	**304.0**	**12770**	**42**

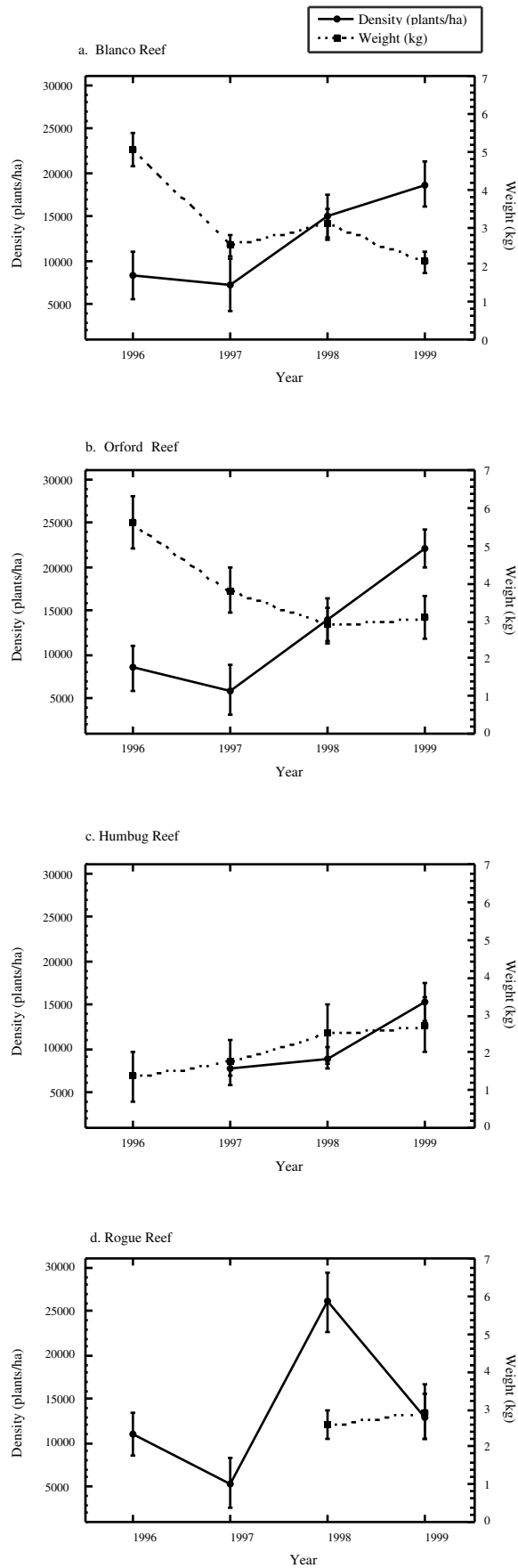| Year	Average	Average	Average	Total	Total	Average
1999	**2.77**	**25.67**	**18900**	**1399.6**	**81166.00**	**58**
1998	2.96	21.02	16158	320.5	16582.85	52
1997	2.97	6.33	6968	366.0	8137.00	22
1996	5.41	10.79	9243	179.2	10267.18	57

Figure 3.2.4. a-d. Plant density and weight for Blanco, Orford, Humbug
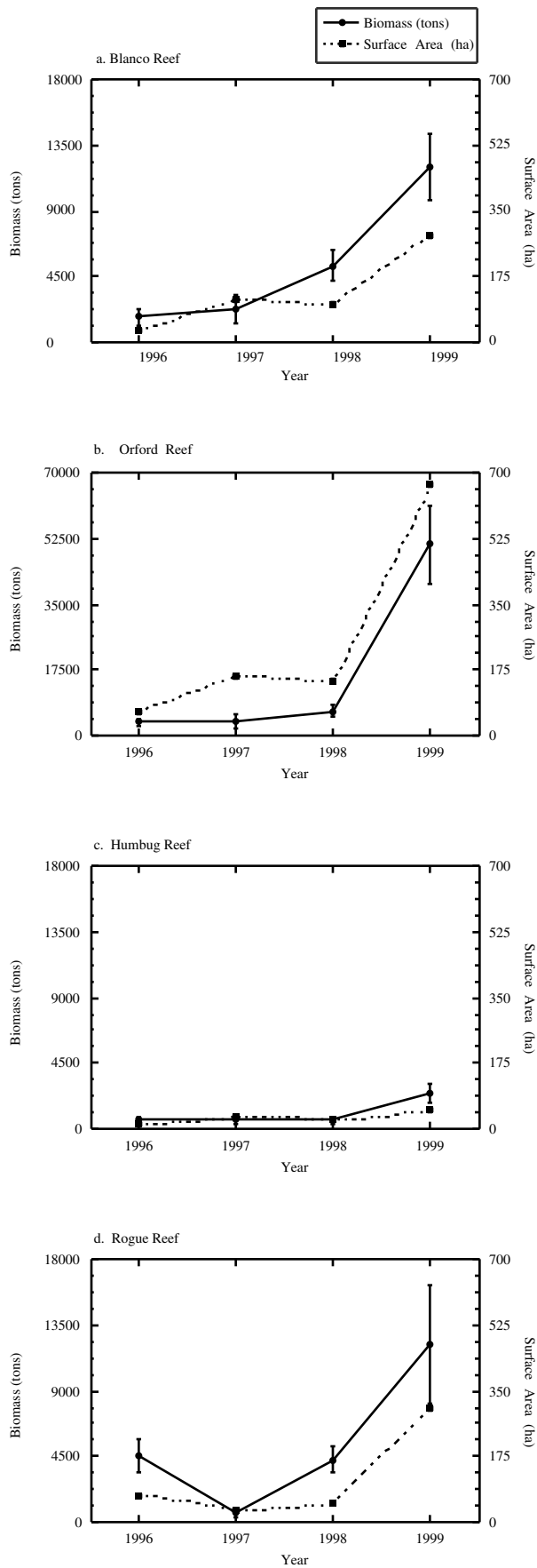and Rogue Reefs. Error bars denote 95% confidence intervals.

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Figure 3.2.5. a-d. Kelp Biomass and surface area for Blanco, Orford, Humbug and Rogue Reefs. Error bars denote 95% confidence intervals. Note scale difference for Orford Reef biomass axis.

4. Management Analysis

4.1 Habitat Characterization and Mapping

Characterizing and mapping marine habitat provides resource agencies with a tool to increase the effectiveness of fisheries management. A habitat is the place where a population, species, or community of organisms lives. Identifying and mapping habitats allows resource managers to predict and track organism abundance, and geographically subdivide human uses in an ecologically meaningful way. Knowledge of fish habitat serves a variety of purposes, including:

1) improving stock assessments,
2) allowing for partitioning or zoning of human uses according to habitat location,
3) designing and locating special management areas and marine protected areas,
4) monitoring and protecting important habitat, and
5) improving research design.

Recognizing the importance of habitat in fisheries management, the 1996 reauthorization of the Magnuson-Stevens Fishery Conservation and Management Act requires identification and consideration of essential fish habitat in fisheries and other ocean use decisions.

There are numerous types of rocky, soft sediment, and water column habitats across the continental shelf and slope that affect fisheries. Our work has focused on nearshore (0 – 50 m water depth) rocky reefs and their associated kelp beds. In particular, we have concentrated on the benthic portion of the reefs, which provide habitat for several rockfish species, and other groundfish such as lingcod, cabezon, and kelp greenling. Characterizing and mapping reefs requires two phases of information gathering: 1) developing an understanding of how habitats within reefs affect fish abundance, and 2) surveying all reefs along the coast and develop an understanding of between reef differences. Our 1999 work provided information on within-reef habitats by developing methods to describe and map habitat types based on bottom roughness. This effort has provided insight on both habitat survey and characterization techniques that can be applied to the second phase of mapping reefs coastwide.

Over the past four years, we have surveyed reefs with three instruments: side-scan sonar, acoustic ground discrimination system, and multibeam bathymetry. Selecting an appropriate survey instrument depends on the objective of the survey and the desired scale of data resolution. For fine-scale description of within-reef habitats, we have concluded that multibeam bathymetry provides the most quantitative and useful information of the three survey tools. However, a high-resolution survey (2 m pixel size) is needed to gain full utility from the multibeam data. This level of survey may be prohibitively expensive for mapping large areas, and may not be appropriate if the survey objective was coastwide reef mapping. A more cost-effective means of mapping reefs coastwide could include a coarser scale multibeam bathymetric survey (10 m pixel size) combined with simultaneous collection of acoustic backscatter data. The multibeam data would allow resolution of the principal structural elements of the

reef, while the acoustic backscatter data would allow identification of fine-scale bottom features such as boulder or cobble fields.

We recommend proceeding to the second phase of work and mapping reefs coastwide. This should begin with an analysis of existing bathymetric data to map the major reef features. Interviews with nearshore reef fishers would provide information on reef areas that do not show up in the mostly coarse-resolution existing bathymetry data. From this initial work, reef areas should be prioritized and cooperative projects developed to survey reef areas using methods and resolution scales that optimize cost-effectiveness and usefulness.

4.2   Kelp Management

During the past four years of kelp biomass surveys on the south Oregon coast, we have observed three low kelp years (1996 – 1998), and one year (1999) that could be considered a high kelp year. The 1999 kelp biomass in the study area was 5 to 10 times greater than in the previous three years. The variation seems to be correlated to changes in ocean conditions. Upwelling conditions were excellent in 1999, and both fishers and scientists observed increases in ocean productivity. The cold water and high nutrients during upwelling provide excellent conditions for kelp growth.

The large annual variation in kelp would pose a major obstacle in developing an economically viable kelp industry. Harvest rates would fluctuate from year to year in proportion to kelp biomass, making it difficult to provide predictable supplies to the market. However, the fishing industry in Oregon and elsewhere has been able to adapt and develop markets in the face of widely-fluctuating product availability. Harvest fluctuation alone would not preclude a commercial kelp industry.

The Essential Fish Habitat provisions of the Magnuson-Stevens Fishery Conservation and Management Act may add a regulatory impediment to kelp harvest. National Marine Fisheries Service is currently developing designations of "habitat areas of particular concern", a subset of essential fish habitat that requires elevated levels of protection due to its particular importance and vulnerability. Kelp bed habitat will likely be one of the first "habitat areas of particular concern" designated due to the role kelp beds play in the nearshore reef ecosystem. That designation process will affect prospects for future of kelp harvest in Oregon.

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Appendix A: Orford Reef Multibeam Bathymetric Survey System Components, Field Survey Methods, and Data Processing Procedures

Survey System Components

Sonar

The Reson Seabat 8101 multibeam sonar was used to obtain bathymetric soundings of Orford Reef. The Seabat, operating at 240 kHz, transmits a 150° x 1.5° acoustic beam. On return, the acoustic beam is divided into 101, 1.5°x 1.5° acoustic soundings. The 150° beam casts a bottom footprint of 7.4 times the water depth in depths of less than 70 meters. Typical hydrographic surveys make use of the wide swath of the Seabat 8101 to efficiently survey large areas. The Orford Reef project however, required not only full coverage of the survey area, but also required the detection and resolution of relatively small bottom features. These requirements restricted use of the sonar swath to the central 45° – 65°. The larger acoustic beam footprints produced from the outer beams, although capable of detecting, could not fully resolve such small features.

The Seabat 8101 Sonar system consists of the transducer head, an onboard processor, and a video monitor. The transducer was deployed on a fixed mount over the starboard side of the vessel. The mount was firmly fixed in position during data collection such that all motion sensors, located at different points on the vessel, reflected the true motion of the sonar.

Seabat data rates vary depending on the depth of measurement and baud rate of the serial line to the data acquisition computer. During this survey, the system was producing between 6 and 7 swaths/second providing 600 to 700 soundings/second.

Heave, Pitch, and Roll Sensor

A TSS DMS05 motion sensor was used to monitor and measure sonar roll (rotation port and starboard), pitch (rotation fore and aft), and heave (vertical displacement) during data collection. The DMS05 was interfaced to both the Differential Global Positioning System (DGPS) and the SG Brown 1000S gyrocompass to reduce heave error during vessel turns and speed changes. The sensor provided data at a rate of up to 32 Hz at 9600 baud transmit. Manufacture specifications of accuracy are as follows:

        Roll , Pitch;
                Range: +/- 50 degrees
                Accuracy: +/- .03 to .05 degrees
        Heave:
                Range: +/- 99m
                Accuracy: 5 cm or 5%, whichever is greater

Heading Sensor

The SG Brown 1000S gyro compass was used to monitor vessel and sonar yaw (rotation about the Z-axis) during sonar data collection. A gyrocompass is utilized

during high resolution acoustic surveys due to its accuracy (0.5 degree) and its immunity to varying magnetic fields. The SG Brown 1000S updates at a rate of 2 Hz.

Horizontal Positioning Sensor

Sonar positioning was determined with a SATLOC Differential Global Positioning System (DGPS). SATLOC is a Wide Area Differential Network (WADN) that incorporates differential reference stations situated at 14 locations across the continental United States. The WADN utilizes corrections determined at each of these locations, along with ionosphere models, and clock corrections to determine a unique set of corrections for the DGPS rover's position. The corrections are computed at one of two locations in the US and broadcast to the rover via a geo-synchronous satellite.

Speed of Sound Measurements

Sound velocity profiles of the water column were recording with a Seabird SBE-19 CTD (Conductivity, Temperature, Depth). The SBE-19 is a self contained measurement device with on-board memory that calculates sound velocity (SV) from the measured values of C, T, and D. The profiler was lowered at a rate of approximately 1 meter/sec. The resulting data set represented sound velocities recorded approximately every 0.5 meters of water column.

Hydrographic Data Acquisition System (DAS)

Coastal Oceanographics Hypack for Windows version 8.9 software running on a Pentium 300 MHz laptop PC, was used to collect all sensor data and provide vessel guidance during field operations. The DAS computer acquired all multibeam system data (Seabat and motion sensors) through a multiport PCMCIA card.

<u>Field Survey Methods</u>

Horizontal and Vertical Control

Tide level data were acquired from a NOAA tide gage at Port Orford. The vertical datum for the survey is Mean-Lower-Low-Water (MLLW), with depths expressed in meters. Tide level, recorded every 6 minutes, was downloaded each night of field operations and visually inspected for data gaps and/or spikes.

The Horizontal Datum for the project is Universal Transverse Mercator (UTM), North American Datum 1983(NAD83), Zone 10, Meters. The two closest SATLOC base station sites to Orford Reef are Oroville, CA, and Olympia, WA. A local known position monument, LEAD NJ 3+16.34, (42° 44' 20.18545"N, 124° 29' 57.28720"W WGS84) at the northern end of Port Orford breakwater was used as a position check point at the beginning of the survey. From that point, the position of the DGPS antenna was recorded at the vessel's berthing site. Subsequent daily position checks utilized this temporary horizontal control point.

Sound Velocity Profiles

Water properties such a temperature, salinity, and presence of fronts affect the speed that sound (from the sonar) travels through the water. Periodic CTD casts

provided sound velocity profiles at various times and locations during survey. At a minimum, profiles were obtained at sites encompassing the area chosen for each day's survey. When, in the course of a day, surveying extended beyond the area defined by previous profiles, additional casts were obtained. In addition, tides and currents changed the seawater properties over the course of a survey day. Additional profiles obtained at various times of the day accounted for these changes.

Each profile was repeated as a check on instrument operations. The data were downloaded at the end of each day for use in sound velocity and ray path bending corrections of the Seabat sonar data.

Sonar and Sensor Alignment Verification (Patch Test)

The patch test is a critical element to reliable and accurate multibeam sonar surveys. The vessel motion and position instrumentation must reflect the motions of the sonar head; therefore, their associated positions, orientations, and timing, in relation to the sonar must be precisely known. The key elements measured with the patch test were:

- Roll offset of the sonar to the motion sensor
    Reciprocal survey lines were run over a flat bottom and roll offset was adjusted until the resulting soundings match. These lines were run in the relatively calm environment of Nellie's Cove. The roll offset is the most critical of the alignments and was repeated each survey day. Offsets ranged from 2.3 to 0.4 degrees.
- Pitch offset of the sonar to the motion sensor
    Pitch offset is measured by running reciprocal lines up and down a slope. These lines were run in to and out of Port Orford Marina. No measurable pitch offset was determined.
- Yaw offset of the Sonar to the SG Brown Gyrocompass
    Yaw offset is measured by running lines up and down a slope at the same speed. The lines are meant to overlap by approximately half a swath width. As with the pitch calibration, two lines were run in the inshore and offshore directions at Port Orford Marina. No measurable yaw offset was determined.
- Navigation latency
    The time offset between the positioning system and the sonar is determined by running two lines up a slope, one fast and one slow. These lines were run up the shallow slope as described in (2) and (3) above. A latency of 0.5 seconds was determined.

Data Processing Procedures

Initial processing of data from the Orford Reef multibeam survey followed standard multibeam procedures described in steps 1-7 below.

1. Sensor alignment and calibration adjustments
    - An initial patch test was conducted on June 6, 1999. Critical roll offset calibration was repeated daily to account for slight variations in the re-placement of the sonar mount and motion sensor. Results from each calibration were applied to that survey day's results.

2. Inspection and editing of vessel motion and position data
   - Satellite coverage and position qualities were dependable throughout the survey. Either seven or eight satellites were typically visible.
   - Inspection of heave records indicated only one occurrence of turn-induced heave at the beginning of a line. This small section of data, prior to actual start-of-line, was eliminated from the data set.
3. Developing tide and sound velocity profile data files
   - Vertical profiles of sound velocity showed a strong gradient in the upper 10 meters, thereafter remaining constant with depth. Horizontal variations were more significant as tide and current fronts were predominant in the survey area. Repeated and numerous CTD casts were conducted to accurately record the horizontal variations.
   - Tides monitored at the NOAA station at Port Orford proved accurate predictors of water level at the survey site.
4. Motion, position, and tide data were merged with Seabat sounding data along a common time base.
5. Editing sounding data manually and/or automatically
   - Fully resolved soundings were edited both manually and automatically to eliminate spikes and bad returns. The predominant causes of bad data were;
     1. Kelp interference – Kelp was not as much of a problem as expected; there was no major loss of data.
     2. Hull flow noise – Hull noise primarily interfered with the outer beams on the port side of the sonar, and was only significant when sea state increased.
     3. Water column aeration due to breaking waves near rocks – This problem caused the greatest loss of data. This problem only occurred near rocky outcrops and wash rocks.
   - Automatic spike filters eliminated 2m or greater jumps in point-to-point soundings. Maximum and minimum depth filters were varied depending on area covered but were typically set to –5 m (minimum) to eliminate problems (1), (2), and (3) mentioned above.
6. Thinning edited data to desired density
   - Data collected in the high resolution area was thinned to one sounding per 1m x 1m grid. The average value of soundings in the grid square was retained along with the grid square's center point geographic location.
   - Data collected in the low resolution area was thinned to one sounding per 2m x 2m grid. The average value of soundings in the grid square was retained along with the center point geographic location.
7. Data set handling and presentation
   - The large data set was handled in sections, which were combined into a single map for presentation and analysis.
   - The HR area data at 1m grid cell size consisted of 10,887,452 points, with a x,y,z (Easting, Northing, and depth) file size of 318 megabytes (text column format). We further thinned the dataset to a 2m cell size to provide more coverage in some no-data areas (through cubic convolution interpolation), and to reduce the unwieldy size of the dataset. The 2m data were then used for analysis in Section 2.2.
   - The LR area data was initially gridded at 2m as well, but the limits of resolution were being reached at this cell size. The LR data was not used in the analysis of Section 2.2, as it falls in a different part of the reef.