Kelp Canopy and Biomass Survey

Oregon State Wildlife Grant Program
T-22 N-03
Final *Companion* Report

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August 29, 2011

1. Introduction

Canopy-forming kelp forests in Oregon are comprised primarily of bull kelp (*Nereocystis luetkeana*), and to a much lesser extent, giant kelp (*Macrocystis* sp.). Both of these species are very important biologically and ecologically because of their high level of primary production and the habitat and food they provide to the nearshore ecosystem. As stated in former Governor Kitzhaber's *State of the Environment Report* (2000), bull kelp and giant kelp can also be used as primary "indicator species" for monitoring the health and status of nearshore rocky reef habitats and biological communities in less than 20 meters depth. The spatial extent and abundance of kelp forests is known to be highly variable both seasonally (due to the solar and weather cycle) and annually for reasons that are not well understood. Fortunately, bull kelp and giant kelp form floating surface canopies that can be surveyed efficiently and effectively in a cost-effective manner using remote-sensing imaging methodologies. The last (and only) state-wide aerial kelp survey was conducted in 1990, which produced kelp canopy imagery, but no estimate of biomass. Biomass surveys were conducted on south coast reefs from 1996 – 2000 but there has never been a state-wide kelp biomass assessment. It has now been 20 years since the last statewide mapping survey and 10 years since the last regional survey, therefore it would be informative to management to know if and how the geographic distribution and abundance of kelp forests has changed over time

The objectives of this study are to map the spatial extent of kelp canopy off Oregon, calculate total kelp biomass and compare kelp extent and biomass to historical data.

1.1 Remote sensing methodology compared

ODFW's kelp surveys of the early 1990's used Color-infrared (CIR) aerial photographs to map kelp canopy and for extracting biomass parameters for calculating kelp biomass. Methods for calculating biomass were based on those developed for large-scale kelp harvest management in Washington and British Columbia (Foreman 1975). CIR aerial photographs of kelp beds were hand-delineated to measure the spatial extent and density of kelp beds on the ocean surface.

In more recent years, remote sensing techniques have been developed using a digital multi-spectral imaging system to obtain digital, rather than film-based imagery of kelp beds. The potential benefits were intriguing. During post-processing of the multispectral imagery spectral bands are combined to systematically detect and automatically classify kelp canopies based on their spectral signatures. The resulting classification of kelp canopy is at a finer spatial resolution than is possible using traditional photographic interpretation methods. Most intriguing was that spectral bands can be classified such that subsurface kelp can be detected up to 1 meter below the water surface (compared with only a few centimeters with CIR imagery). This is a significant advancement in the science of kelp resource assessment surveys from both an ecological and a management perspective. This technology has now become cost-efficient for even small projects such as ours and was the method of choice for this project.

2. Methods

2.1. Aerial Survey Planning

Ocean Imaging (OI) was contracted for this project for their innovation and expertise in digital multi-spectral imaging of kelp beds, and for their development of customized algorithms to estimate kelp biomass. OI has provided this service to California Dept. of Fish and Game (CDFG) and the Alaska Dept. of Fish and Game (ADFG) (Stekoll, et al. 2006) for managing and monitoring kelp resources in their respective states.

Previous kelp surveys conducted by ODFW indicate that kelp beds occur predominantly in the southern third of Oregon's nearshore ocean from Cape Arago to the California border, with few kelp beds to the north (Fox, et al (1996), Fox, et al. (1998), Miller, et al. (1997)). In years of low abundance, kelp beds can be extremely sparse. Based on local fishermen's knowledge, they assessed 2010 to be a low-abundance year. Prior to committing resources to a full coastwide survey, ODFW staff flew a reconnaissance survey aboard a U.S. Coast Guard helicopter in advance of the DMSI survey to assess kelp beds on the north coast and choose the northern extent of the survey. The only notable kelp bed north of Cape Foulweather (Depoe Bay) was a single bed at Cape Lookout, however we felt this did not warrant extending the aerial survey north of Cape Foulweather (Figure 1).

Surveys were planned for early-mid fall when mature plants reach the water surface and kelp canopy reaches its maximum spatial extent. Aerial and vessel surveys were scheduled to co-occur during the same survey window to minimize bias caused by plant growth, decay or plant drift. Several environmental conditions were monitored to ensure high quality imagery and successful at-sea surveys. We relied on OI's expertise to determine suitable conditions for the aerial survey (i.e., adequate cloud ceiling, sun angle, tide level, wind speed and sea state), however as tide level is the only environmental parameter that is predictable well in advance, survey date ranges were initially selected based on tide level (-0.7 to +1.9 feet). Three suitable tide windows were available; September 5 -11, September 22-23 and October 5 -9. OI tracked the environmental conditions within these windows of opportunity and selected survey dates accordingly. Suitable conditions did not align until October 5.

2.2. Vessel Survey Planning

Three commercial fishermen were selected to conduct the at-sea survey for ground-truthing the digital imagery. These individuals were selected based on their knowledge and familiarity with nearshore reefs, aptitude for collecting scientific data, availability, and size of vessel. The at-sea surveys were initially planned at six nearshore reefs between Cape Foulweather and Chetco River (CA border). Sampling was systematically distributed equally among 4 "Biomass Areas" at each reef. Fishermen were assigned to one or two reefs each and given detailed sampling instructions. Within each Biomass Area, fishermen were instructed to haphazardly choose 3 sampling stations representing 3 subjective kelp bed density levels; very dense, moderately dense and sparsely dense, for a total of 12 sampling sites per reef. The fishermen were to position their vessels inside a bed of uniform density and away from the edge of the bed. The sampling station was a visual rectangle that extended parallel to the vessel from bow to stern and perpendicular out 20 feet across the water surface (Figure 2). The boat would be anchored and compass heading maintained during sampling. Fishermen positioned themselves midpoint between bow and stern on either the starboard or port railing and recorded the GPS location on hand-held Garmin GPS units. From this position, the fishermen would count every kelp bulb floating on the surface within this sampling rectangle. They would then haphazardly select and cut 10 kelp plants retaining the blades and bulb with 12 inches of stipe (stem) for subsequent morphometric measurements by ODFW biologists.

3. Results

3.1. Aerial Survey Data Acquisition and processing

Unfavorable environmental conditions prevented the execution of aerial surveys during the September tide window. Aerial surveys were conducted during the October tide window on October 5 and 6, though environmental conditions were less than ideal. Tides were outside the desired range because survey flights had to be delayed until the fog cleared. Tides ranged from +4.36 feet to +1.57 feet on October 5 and +5.35 to +1.12 on October 6. The average wind speed on October 5 was 10mph (North) with a max wind speed of 24mph and on October 6 the average wind speed was 6mph (NNW) with a max wind speed of 15mph. Visibility was 10 miles on both days. Survey altitude was 6,500 feet resulting in a ground resolution of 1.0 meter.

The aerial survey was conducted from a Partnavia PN68 Observer aircraft, owned and operated by the Oregon Department of Forestry (ODF). The survey was flown from Cape Arago to the Oregon-California Border (Figure 3). Intense fog and low cloud ceiling impeded visibility and prevented the survey from continuing north to Cape Foulweather as initially planned. The area between Cape Foulweather and Cape Arago does not support kelp beds of any significance, so the only notable loss of survey coverage was off Cape Foulweather.

The products generated were digital raster image files: kelp imagery in ERDAS IMAGINE raster file format, kelp classifications in both ArcGIS raster and shapefile formats, surface and subsurface kelp canopy in both ArcGIS raster and shapefile formats, kelp biomass classifications (kg/m2) in ArcGIS shapefile format, and metadata for all of the above. The DMSC

Imagery was captured with 60% overlap.

Each DMSC frame collected was geo-referenced using a direct geo-referencing program based off of position data logged both by the DMSC imager and Oxford Technologies DGPS/IMU unit. Each frame location was carefully compared to Microsoft Virtual Earth aerial imagery to ensure correct geo-location. Spatial geo-reference adjustments were performed on each DMSC image when necessary to within +/- 4 meters CE 90.

3.2. Vessel Survey Results

Three of the six reefs originally planned for vessel surveys plus one additional reef were sampled on October 6, 7, 8 and 14. Surveys were completed at Orford Reef (two surveys), Blanco Reef, Redfish Rocks Reef, and Rogue Reef. Rough ocean conditions resulted in the termination of vessel surveys at Cape Arago and Mack Arch Reefs. Cape Foulweather was not surveyed because the aerial survey was cancelled north of Cape Arago due to poor atmospheric visibility and rough ocean conditions. The participating fishermen sampled twelve stations at both Blanco and Redfish Rocks reefs, 24 stations at Orford Reef (two surveys), and 9 stations at Rogue Reef. Rough ocean conditions prevented completing all 12 stations at Rogue reef. ODFW biologists obtained morphometric measurements (sub-bulb diameter, blade weight, and the combined weight of blade, sub-bulb plus stipe segment) from 573 kelp plant samples. A Microsoft Access database of morphometric measurements and vessel density counts was created by ODFW staff and populated with the field data. These data, in conjunction with aerial survey imagery data, were subsequently used for the biomass calculation.

A critical component for calculating the kelp biomass estimate from the multispectral imagery is the correlation of the imagery's spectral signal with field samples of plant density and plant weights obtained from the same geographic position (i.e., within the rectangular sampling sites.) If the Biomass Area cannot be accurately geo-located, a significant amount of "noise" is introduced into correlation analysis between the density and biomass of the kelp within the Sampling Area and the spectral signature in the DMSI imagery (from which the biomass estimate is extrapolated).

As evidenced by the fishermen's GPS tracking data, it appeared that vessel position at the sampling rectangle was not maintained in many cases and most of the sampling effort occurred outside the pre-assigned sampling rectangle despite two of the vessels having anchored (Figure 4). Clusters of track points indicate a sampling area far greater in size than the intended sampling area of 20' x 30'. In many cases, sampling appears to have spanned anywhere from 30 to 60 meters in what often seemed to be a north-south direction. The actual time spent conducting the sampling is also problematic for areas sampled less than 6 minutes, which we surmise to be too short for conducting both kelp counts and plant cuttings. At some sites, the clusters of track points where sampling appears to have occurred did not overlap with the spectral signal for kelp beds in the multispectral imagery, so actual sampling location was further questioned.

It is plausible that at these locations the fisherman chose to sample kelp on an isolated, single rock outcrop supporting a small kelp patch that did not register in the imagery. Large swell, wind, and current no doubt contributed to the fisherman's inability to maintain a constant position at the sampling site. Other contributing factors for such extreme deviations have not been determined, but could be attributed to "multi-path" errors (i.e. GPS signal "bouncing" off of nearby objects) or interruption of the satellite connection when the GPS unit was placed in the wheelhouse while cutting plants. The Garmin GPS unit with WAAS-enabled positioning rectification has an inherent error of 2-4 meters but this would have contributed little to the overall positional error.

3.3. Vessel (Field) Data Analysis

Fishermen selected their sampling sites in kelp beds based on their qualitative assessment of bed density (sparse, medium and dense). Once the site was selected, fishermen counted plants within this visual rectangular sampling area. The qualitative and calculated measures of bed density appear similar for all areas sampled when graphically compared (Figure 5). Among beds classified as "dense", kelp density at Rogue Reef was less than half (0.35 plants/m2) the density at the other three reefs where densities ranged from 0.77 to 0.91 plants/m2.

Morphometric measurements (sub bulb diameter and the combined weight of blades plus bulb) were obtained for subsequent conversion to whole plant weight. The relationship between blade weight and whole plant weight has been shown to be highly correlated for kelp beds in southeast Alaska at $R2 = 0.98$ (Stekoll, et al. 2006). Sub-bulb diameter and whole plant weight was also well correlated, $R2 = 0.88$. We determined that sub-bulb diameter was the most reliable metric for our samples because several samples had lost some of their blades, likely a result of release of most sori structures (reproductive structures on blades) and an early fall storm that further stripped off the blades. Sub-bulb diameter was consistent among reefs, with slightly smaller structures at Redfish Rocks Reef (Figure 6).

The regression equation for sub-bulb diameter is as follows:

$$\text{Plant weight} = 0.038e0.125x$$

3.4. Digital Imagery Classification and Analysis

3.4.1. Imagery calibration methods adaptation

To counteract the positioning error unknowns as described in Section 3.2, OI expanded the area to be correlated with each field sampling position by a radius of 3 boat-lengths from the given GPS position. Within this circular area, the mean of pixels in the upper quartile of reflectance values was used to correlate with the field-collected kelp parameters. Some of the correlations achieved through this strategy are statistically significant and are being further refined. Figure 7 exemplifies this approach and the correspondence of kelp reflectance variability to sampled areas within a kelp bed having different density (and hence biomass) characteristics.

3.4.2. Mosaic generation

Mosaics were generated for each of the major kelp bed priority areas as well as the smaller, more isolated beds. Kelp canopy both on the water surface and submerged is visible in the image mosaics (Figures 8a – h). Thematic GIS layers classifying the kelp canopy and submerged kelp were generated from the image mosaics. An example of the transformation from image to classification to biomass estimate is presented for Blanco Reef in Figures 9 through 11.

3.4.3. Kelp Classification Methods

Submerged and Exposed Combined Classification: Following the creation of DMSC image mosaics for each of the kelp bed priority regions as well as a few small, isolated beds, thematic GIS layers were created showing submerged and exposed kelp as a single class and as two separate classes. The single-class combined product was created using ERDAS Imagine's ISODATA unsupervised classification function. The inputs to the classification routine included each of the four DMSC bands (band 1 centered at 451 nm, band 2 centered at 551 nm, band 3 centered at 675 nm and band 4 centered at 780 nm) as well as the band-ratio image product of log of band 4 and log of band 1 (ln band4 / ln band1) and a modified NDVI image product using bands 1 and 4 (band4 – band1 / band4 + band1). Using the 4-banded imagery along with the image products above, the resulting thematic map was then manually edited to reclassify misclassified pixels.

Classification Showing Submerged and Exposed Kelp as Separate Classes: In order to generate a classification product with submerged kelp and exposed kelp separated into two distinct classes, the DMSC band 4 (near-IR at 780 nm), band 1 (blue at 451 nm) and the band 4 over band 1 ratio product were closely analyzed. Reflectance signatures in the near-IR part of the electromagnetic spectrum are traditionally used to isolate live vegetation in multispectral imagery. Exposed (and some submerged) kelp therefore show a very strong reflectance signature in the DMSC band 4. However, light in the near-IR part of the spectrum will show the largest attenuation coefficient – meaning that light of this wavelength will be absorbed by water and scattered by particles faster in the water column than the red, green and blue wavelengths. The DMSC band 1 showing reflectance in the blue part of the spectrum has the lowest attenuation coefficient meaning that light (and resulting reflectance) will penetrate (and be reflected back) deeper in the water column. While knowing the exact attenuation coefficient and hence the depth penetration of light for these bands was impossible to determine for these coastal waters during data acquisition without precise field measurements, the depth penetration of band 4 (near-IR) was estimated to be roughly one meter. Visual comparison analysis of DMSC band 4, band 1, the band4/band1 ratio product and bands 4-2-1 displayed as "RGB" for each kelp bed mosaic resulted in determination of a digital number (DN) cut-off in the band4/band1 ratio image which could then be applied to the raster image. The single-kelp class product was first used to mask out any non-kelp pixels in each mosaic. The DN cut-off was then used to separate the single-kelp classification into two distinct classes, exposed and submerged (Figure 10).

3.4.4. Density calculation and Biomass Estimate

A preliminary biomass index product was created by binning the median biomass values as computed for each of the 57 field sampling stations using the 'sub-bulb' measurement equation (Stekoll, et. al) into four groups as well as binning the modified reflectance values within each of the 600 sq. ft., 640 sq. ft. and 660 sq. ft. sample areas using the DMSC lnB4 / lnB1 image ratio product into four groups. Biomass index ranges were then assigned based on DN cut-offs (Figure 11). The cutoff ranges for each class were chosen to approximately evenly span the density and weight distribution ranges encountered in the multispectral reflectance vs. field parameters for each station. This method however relied heavily on analyst interpretation and little quantitative correlation information between the biomass data and kelp reflectance.

Errors in the field data precluded the use of the field samples for any accuracy assessment of this method. Additionally, an acceptable correlation between kelp bulb counts (density) and the DMSC imagery or imagery products could not be established at most of the sampling sites beyond the preliminary attempt discussed above. This is also true for any correlation to total plant weight as computed from the equation developed by Stekoll, et al. (2006). Total kelp biomass, therefore, could not be more quantitatively determined from the DMSC reflectance data.

Final error estimation will be performed by evaluating the field-derived kelp parameters against image-derived parameters over sampling stations not used in the original calibrations. The field-derived variables available for error assessment of the image-derived product are: 1) a plant density count within a visually estimated (by the fishermen) area in the vicinity of the logged GPS location; 2) the weight of part of a limited number of plants within that area; 3) the diameter of sub-bulb of the sampled plants which can be related to total plant weight through an equation in published scientific literature (Stekoll, et al., 2006). The image-derived parameters most likely represent variations in kelp plant density and frond size. The derived kelp biomass parameter and its error of estimate are thus estimated indirectly, but appear to maintain correspondence trends to the gathered field measurements and findings in Stekoll, et al. (2006).

3.4.5. Comparison with historical kelp survey data

The spatial distribution of kelp canopy was compared between current and historical ODFW surveys (Figures 12a-g). In the 1990's surveys kelp beds were visually delineated by hand from photographs, which is somewhat subjective and not easily repeatable. In particular, hand-delineation of beds generalized the spatial resolution of the canopy and canopy edges, and the minimum mapping unit was relatively large. The automated classification methods applied to the digital imagery quantitatively classified kelp on the water surface based on quantitative reflectivity values and at a resolution of 1 meter. Not unexpectedly, density and boundaries of the delineated and classified kelp beds are visually very different from one another (Figures 12a-g).

Differences in the density and biomass extraction methods from these distinctly different imagery sources introduced additional challenges for direct comparison with historical kelp data. For these reasons and, more importantly, for the positional errors of the sampling locations previously described, quantitative comparisons were not justified and were not attempted. If the positional errors can be rectified and result in statistical correlations between field sample data and the DMSI imagery, then comparative analyses with historical data would be more plausible.

For the purpose of direct comparison of morphological characteristics between current and historical surveys we repeated plant weighing methods from the 1990's, weighing the entire upper portion of the plant (blades, bulb plus 10cm of stipe). Plant structures were collected and weighed from 4 of the 5 reefs sampled in the 1990s, and where kelp is most prevalent (Table 1). Plant weights for Blanco and Orford reefs were within the range of historical weights. Plants at Redfish Rocks Reef and Rogue Reef were lower and higher, respectively than weights in previous years. Overall, average plant weight of all reefs sampled in 2010 was within range with the average plant weights from the 1990's surveys.

4. Discussion

It became profoundly clear in this project that to achieve accurate biomass estimates using remote sensing technology and imagery, it is critical to have accurate positioning of biomass field samples for subsequent correlations with the DMSI imagery. Field density estimates must be obtained within the bounds of an identifiable sampling area in order to classify kelp bed density in the multi-spectral imagery. Our study design was modeled after the Alaska study where they used SCUBA divers to obtain density counts at the base of the plant on the seafloor where their position is not affected by ocean swell or surface current. Divers mark their sampling positions with tethered buoys that are then visible in the imagery, providing precision geo-location of sampling effort.

Our modification to this method employed fishermen with experience working in rough ocean conditions with the expectation that they could maintain vessel position relatively well during sampling. However, as we learned, this was more challenging than expected, although we do not know to what extent the error was attributed to the position and placement of the GPS (e.g,. in the wheelhouse without a clear view of satellites). Having a scientist aboard one or more vessels would have informed us of these challenges early on in the project and we might have rectified the problems on the spot. One approach to improve the delineation of the actual area sampled in the future would be to record GPS track points at a more frequent interval (e.g., 10s) and clearly marking start and stop sampling points. At a minimum, this would have allowed us to better account for the error during data processing. We are committed to continued work with the contractor to resolve vessel positional data and produce a credible biomass estimate.

The other complicating factor for this project was unfavorable weather and ocean conditions that persisted through fall. Dense, low-lying fog was the major contributor to reducing our opportunity to obtain the aerial imagery. Strong wind and white caps also impeded the survey, although the DMSI classification program was able to deal with this 'noise' in the data quite successfully. Vessel surveys were quite challenged by the rough conditions. Oregon's nearshore ocean is highly exposed to swell and wind making it very difficult to maintain a position long enough to complete such precision field sampling. Seasonal weather patterns can be highly variable from year due to climatic fluctuations (e.g., El Nino, La Nina), so it is impossible to predict the chances of success of a survey like this very far in advance. We accept this uncertainty and plan to the best of our ability, and will continue to do so in the future.

Even without a reliable biomass estimate, this project was successful at acquiring superior imagery and ecologically-meaningful classification layers for ~90% of Oregon's kelp resource, and for beginning the process of improving historical methods of kelp assessment.

5. References

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Stekoll, M.S., L.E. Deysher, M. Hess. 2006. A remote sensing approach to estimating harvestable kelp biomass. Journal of Applied Phycology, 18: 323-334

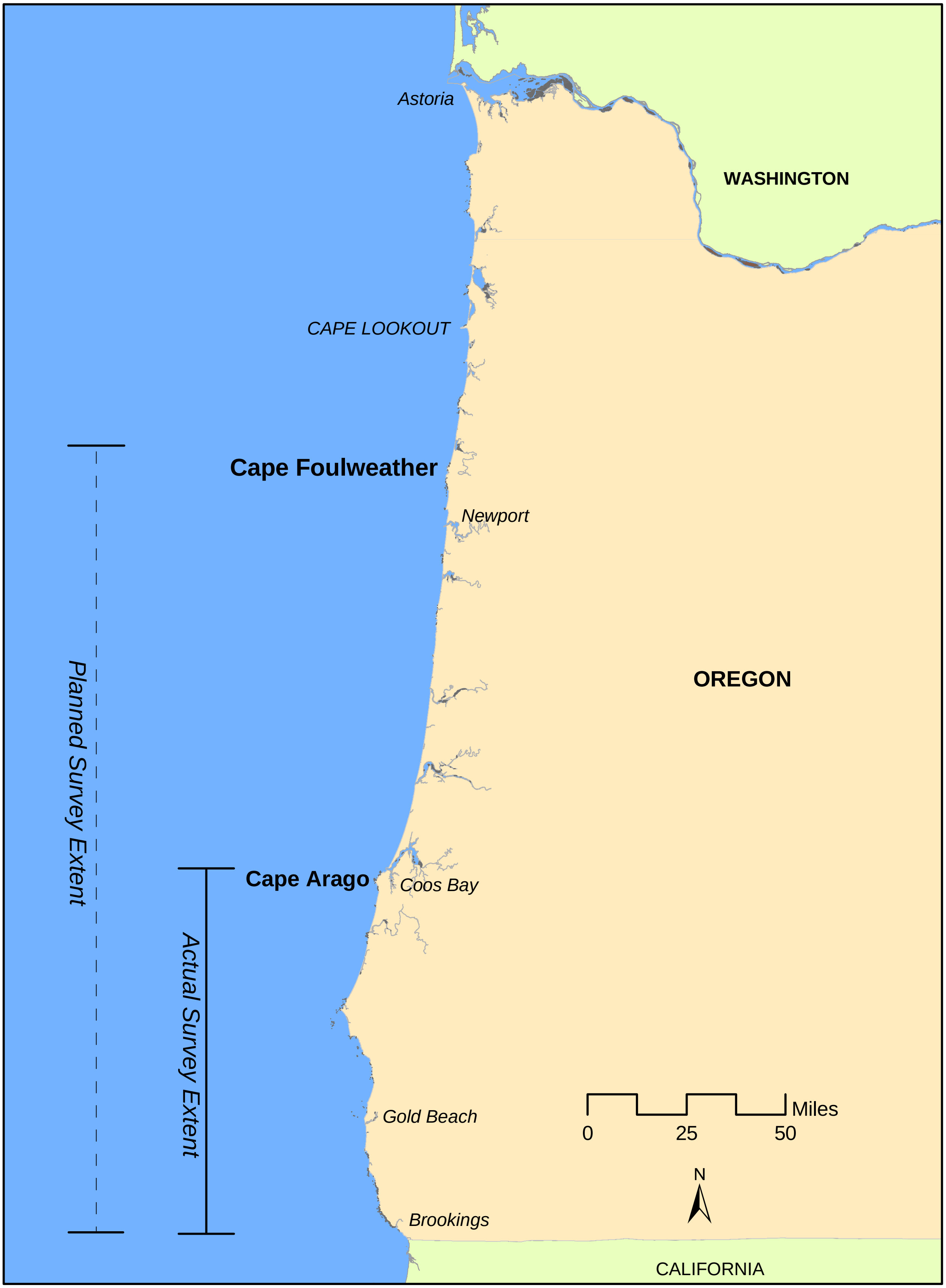

Figure 1. The kelp biomass study was intended to extend from Cape Foulweather (Depoe Bay) to Brookings. Unfavorable weather and environmental conditions restricted the survey to two days, limiting the extent of coverage. Cape Arago was the northern -most extent of the survey.

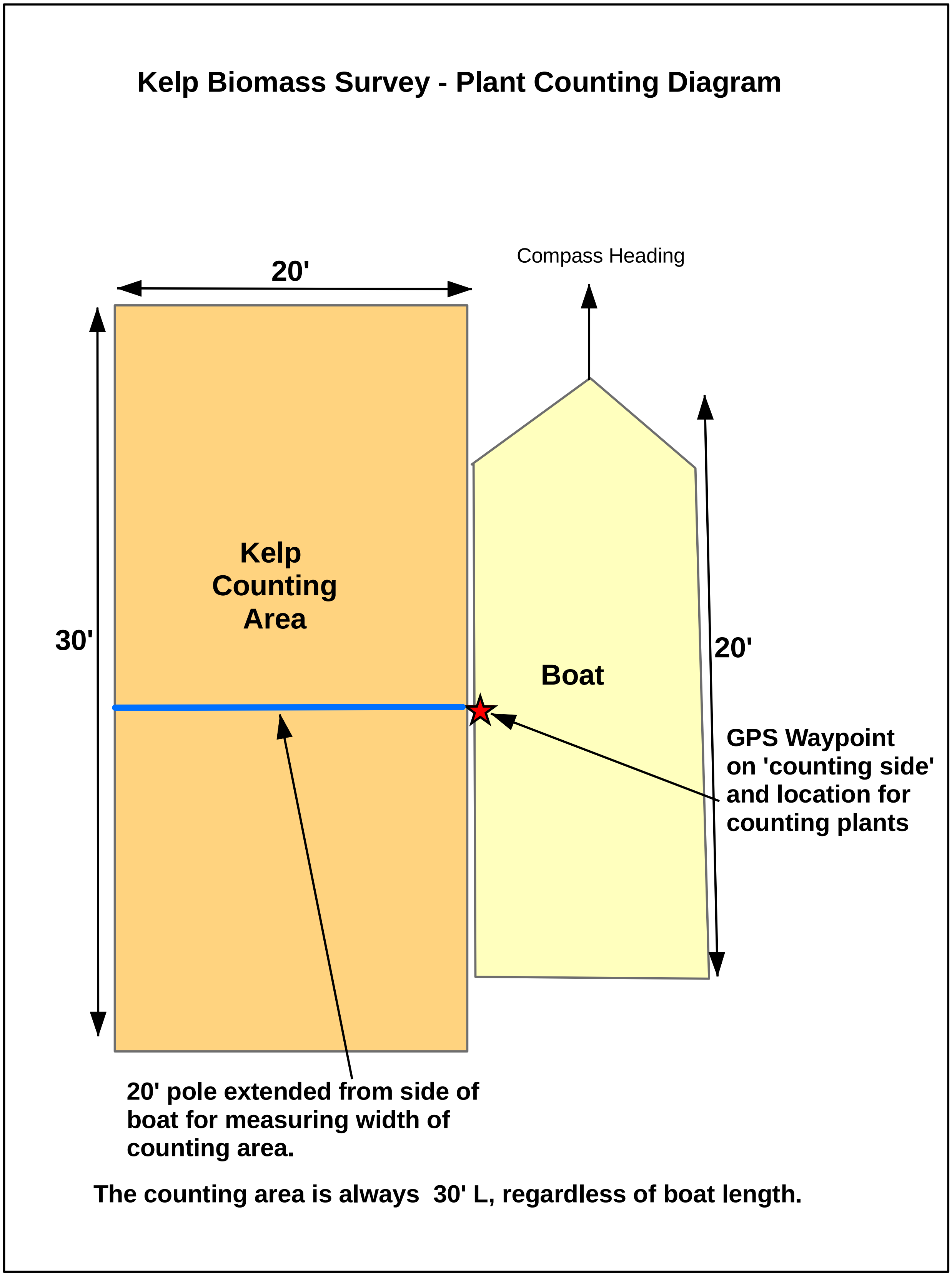

Figure 2. Diagram of at-sea sampling stations for obtaining kelp biomass parameters (plant counts and plant structure samples).

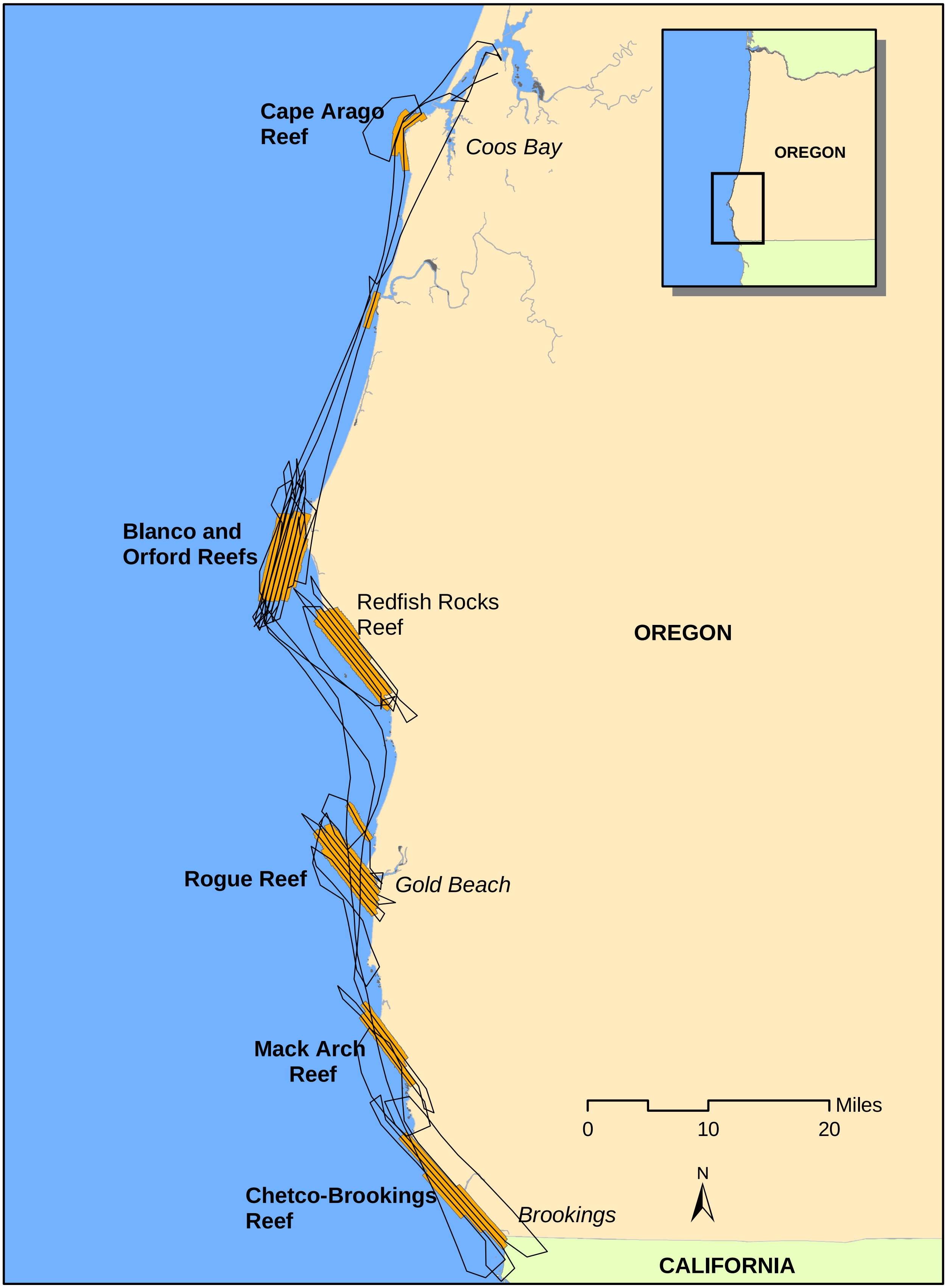

Figure 3. Study area of kelp biomass survey showing flight paths (black lines) on October 5 and 6, 2010 from Cape Arago to Brookings. Kelp beds visible from the aircraft were imaged with a Digital Multispectral Imagery camera. Imagery extent is represented by orange polygons.

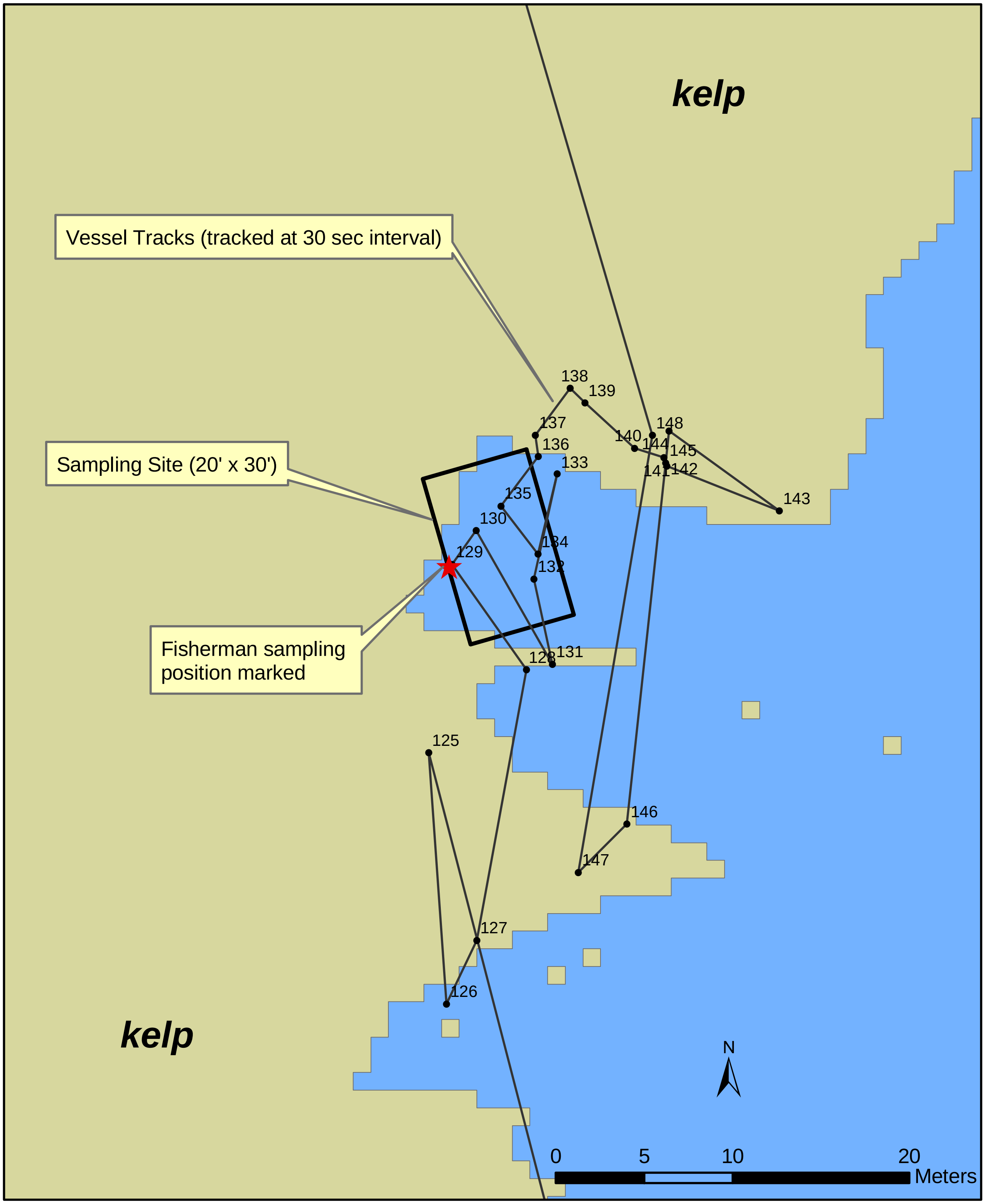

Figure 4. Example of vessel positional error during at-sea sampling of kelp density counts and plant structure samples. The geographic position was marked at the onset of sampling (red star), but the GPS tracking system (black lines) shows the vessel unable to maintain its position in the sampling site.

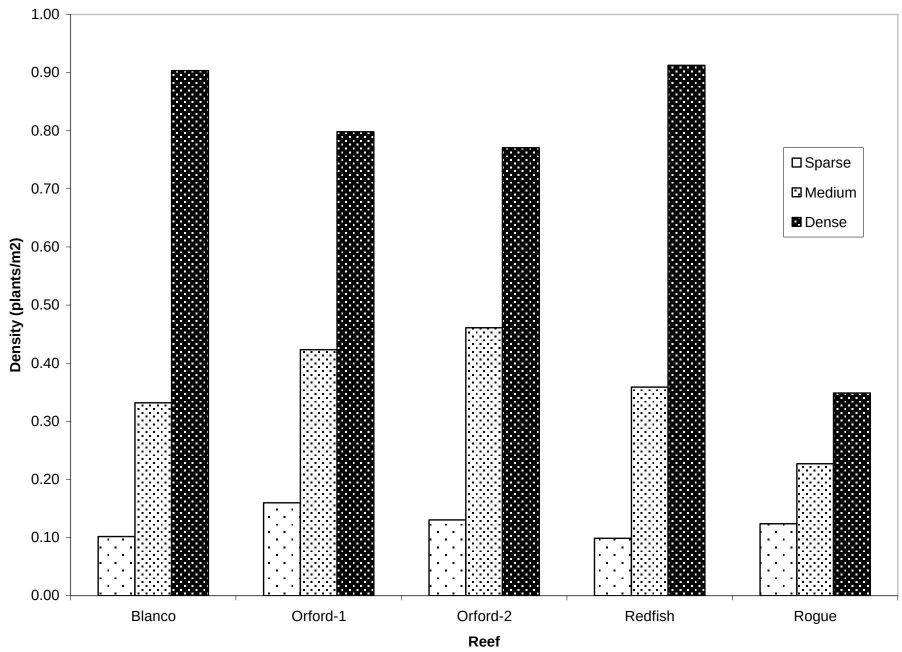

Figure 5. Comparison of fisherman's *qualitative* density assessment (i.e., sparse, medium, dense) of sampling sites and *calculated* density (no. plants/m^2) within Biomass Area Sampling sites.

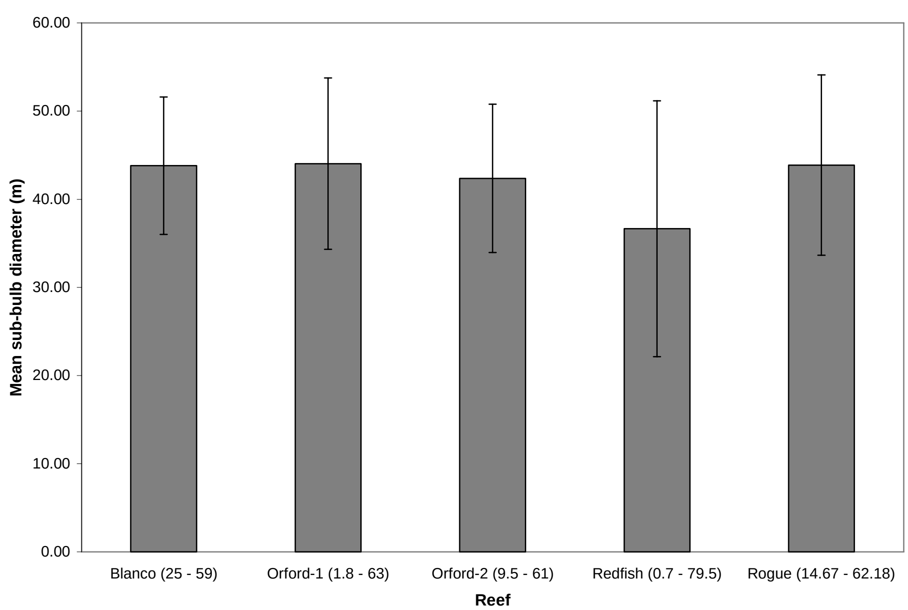

Figure 6. Mean sub-bulb diameter of kelp samples for each sampling effort. Error bars denote standard deviation among the samples.

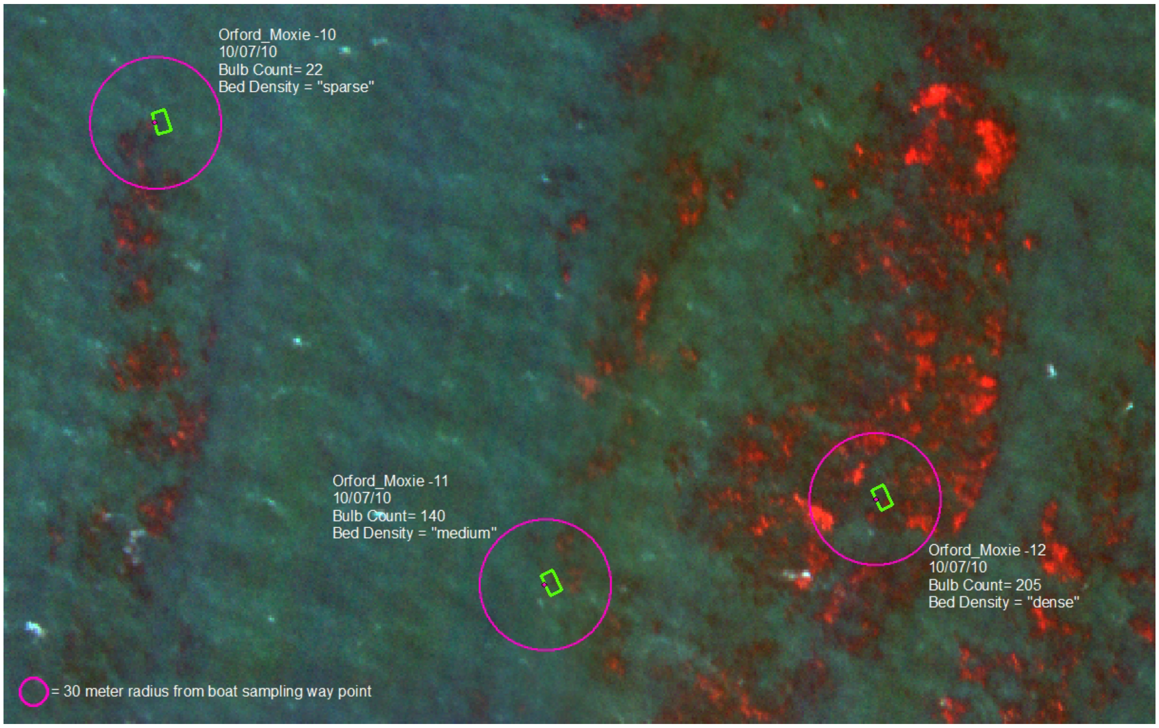

Figure 7. Sampling locations of three stations representing sparse, medium and dense concentrations of kelp within a single bed. The red dot is the GPS-logged position, green rectangle is the estimated sampling area location, and purple circle represents 3 boat lengths of the GPS point. Note that while the GPS point and estimated rectangle are not directly over kelp features, they closely abut kelp concentrations whose reflectance and spatial density characteristics agree with the ship-based plant counts and subjective bed density assessments.

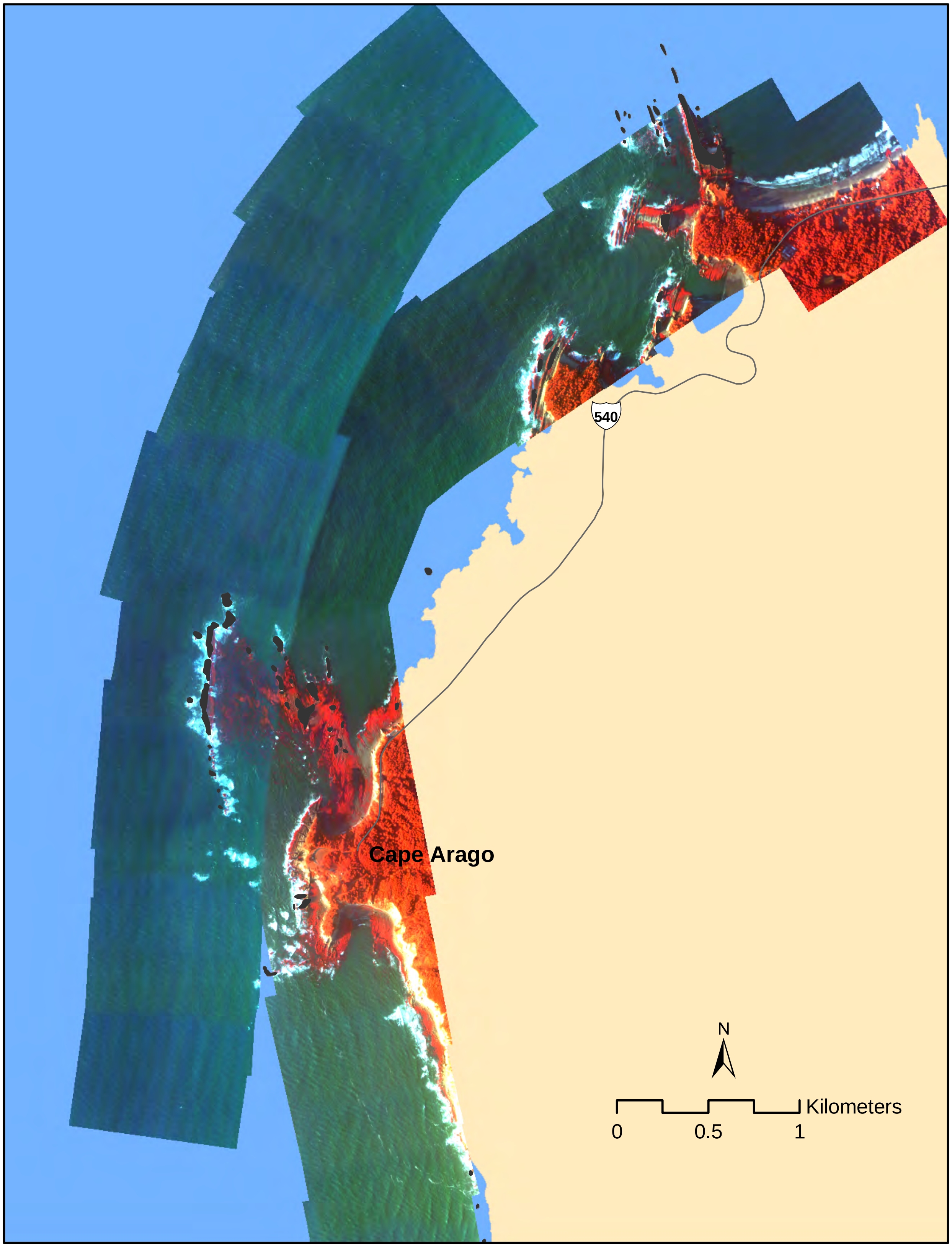

Figure 8a. Digital multispectral imagery mosaics of kelp canopy at Cape Arago Reef. Reflectance signatures in the near-IR part of the electromagnetic spectrum isolate live vegetation. Exposed (and some submerged) kelp show a very strong reflectance signature in the DMSC band 4. Depth penetration was estimated to be roughly one meter.

Figure 8b. Digital multispectral imagery mosaics of kelp canopy at Coquille Reef. Reflectance signatures in the near-IR part of the electromagnetic spectrum isolate live vegetation. Exposed (and some submerged) kelp show a very strong reflectance signature in the DMSC band 4. Depth penetration was estimated to be roughly one meter.

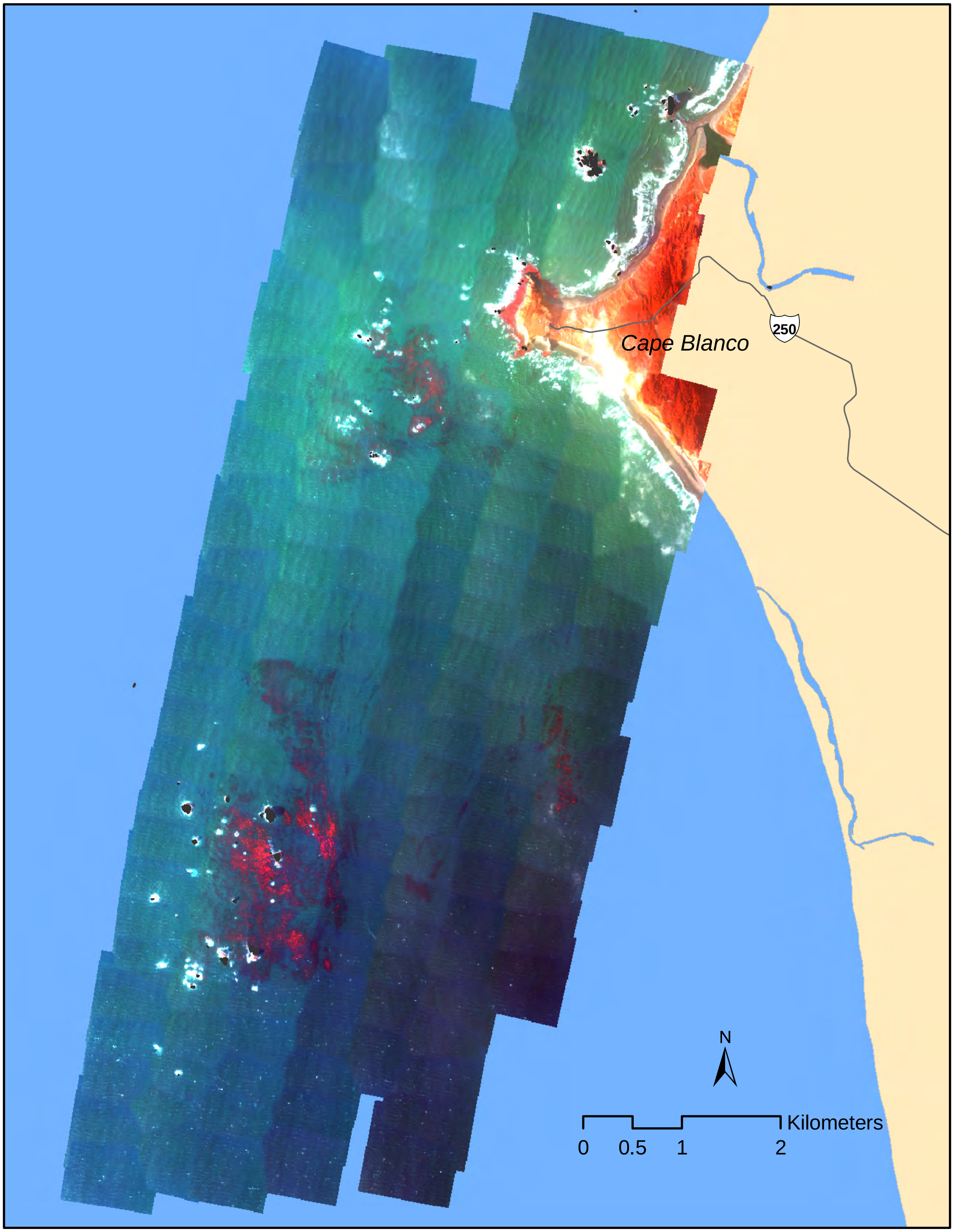

Figure 8c. Digital multispectral imagery mosaics of kelp canopy at Blanco and Orford Reefs. Reflectance signatures in the near-IR part of the electromagnetic spectrum isolate live vegetation. Exposed (and some submerged) kelp show a very strong reflectance signature in the DMSC band 4. Depth penetration was estimated to be roughly one meter.

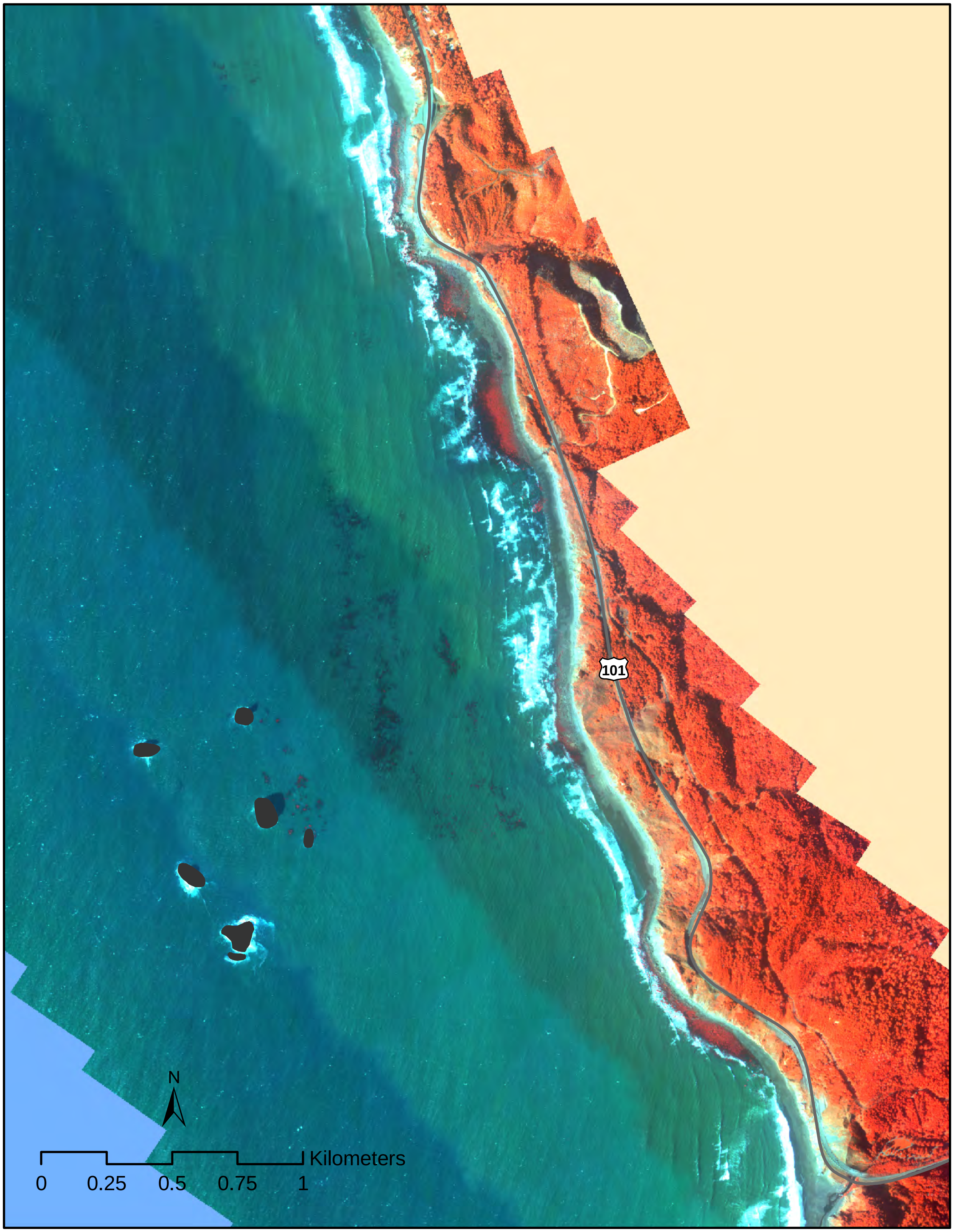

Figure 8d. Digital multispectral imagery mosaics of kelp canopy at Redfish Rocks and Humbug Mountain. Reflectance signatures in the near-IR part of the electromagnetic spectrum isolate live vegetation. Exposed (and some submerged) kelp show a very strong reflectance signature in the DMSC band 4. Depth penetration was estimated to be roughly one meter.

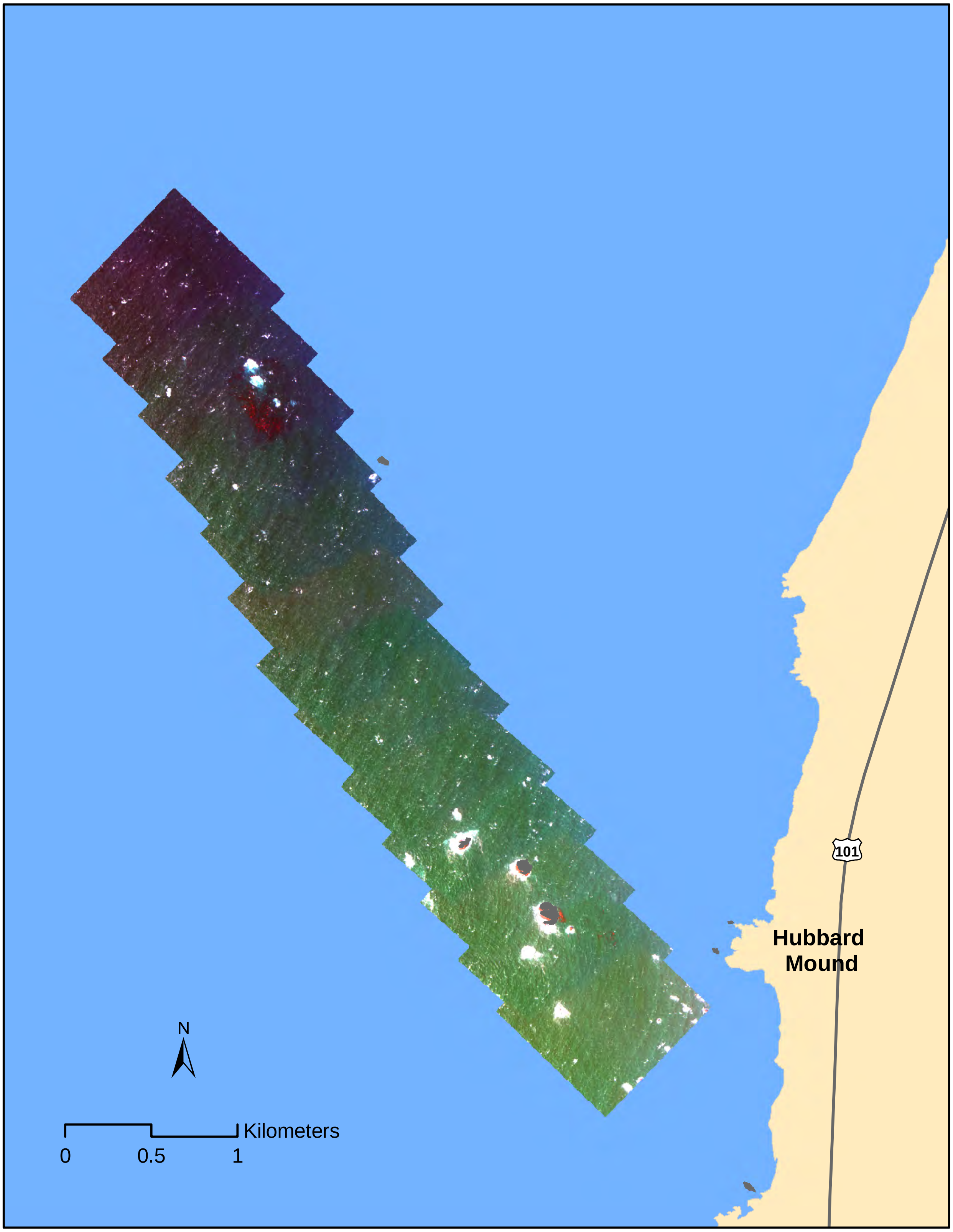

Figure 8e. Digital multispectral imagery mosaics of kelp canopy at a shallow reef north of Gold Beach. Reflectance signatures in the near-IR part of the electromagnetic spectrum solate live vegetation. Exposed (and some submerged) kelp show a very strong reflectance signature in the DMSC band 4. Depth penetration was estimated to be roughly one meter.

Figure 8f. Digital multispectral imagery mosaics of kelp canopy at Rogue Reef. Reflectance signatures in the near-IR part of the electromagnetic spectrum solate live vegetation. Exposed (and some submerged) kelp show a very strong reflectance signature in the DMSC band 4. Depth penetration was estimated to be roughly one meter.

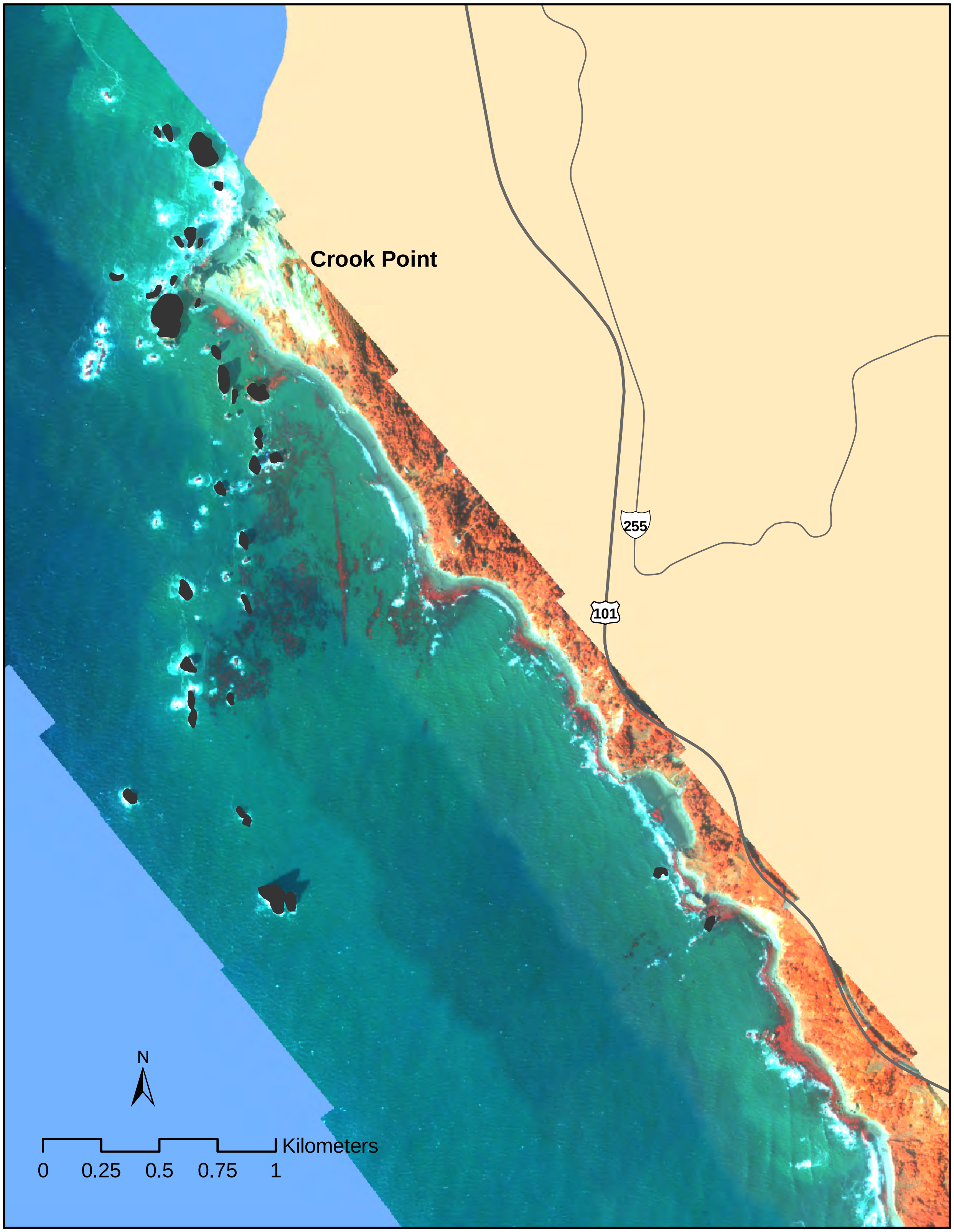

Figure 8g. Digital multispectral imagery mosaics of kelp canopy at Mack Arch Reef. Reflectance signatures in the near-IR part of the electromagnetic spectrum solate live vegetation. Exposed (and some submerged) kelp show a very strong reflectance signature in the DMSC band 4. Depth penetration was estimated to be roughly one meter.

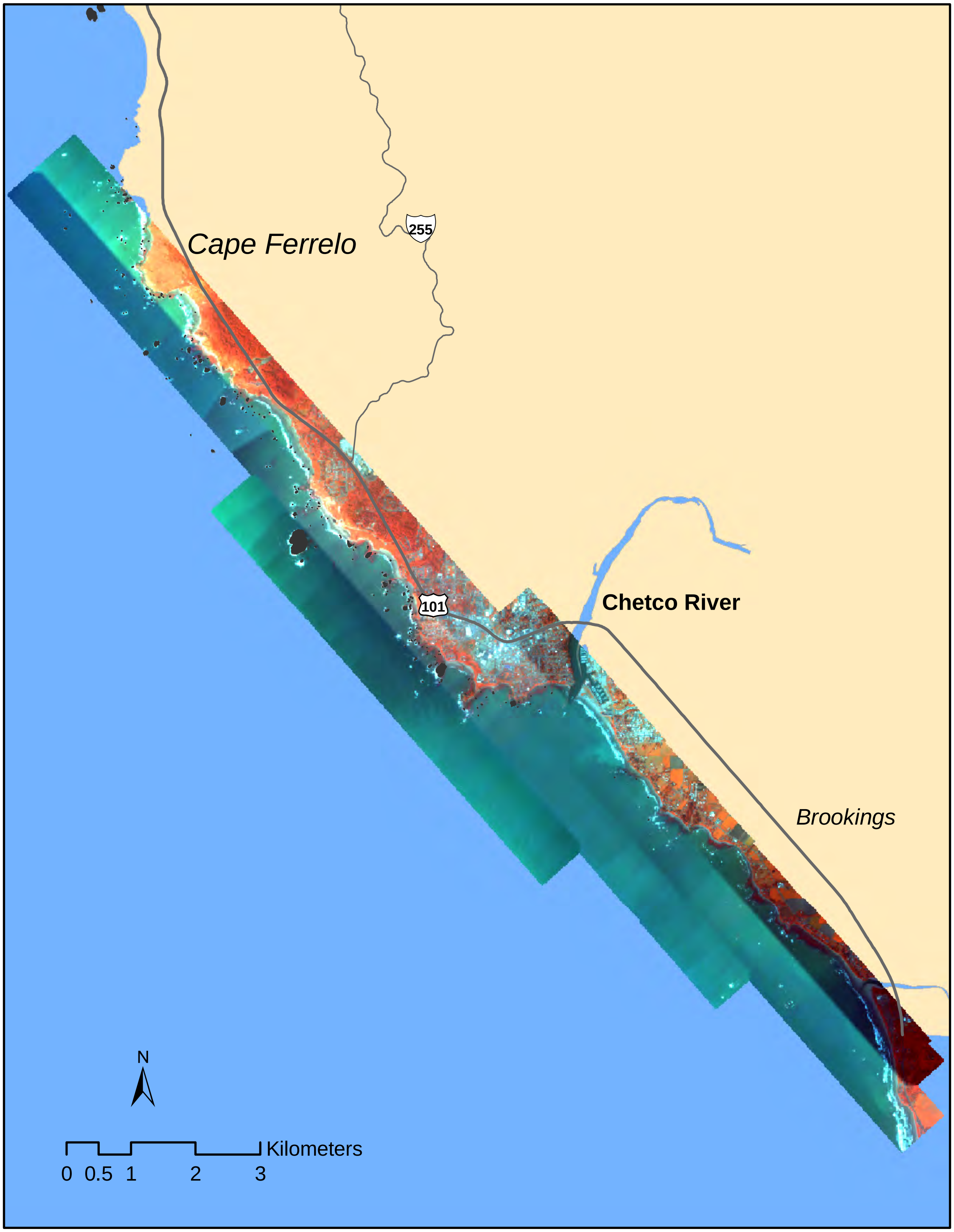

Figure 8h. Digital multispectral imagery mosaics of kelp canopy off Brookings. Reflectance signatures in the near-IR part of the electromagnetic spectrum solate live vegetation. Exposed (and some submerged) kelp show a very strong reflectance signature in the DMSC band 4. Depth penetration was estimated to be roughly one meter.

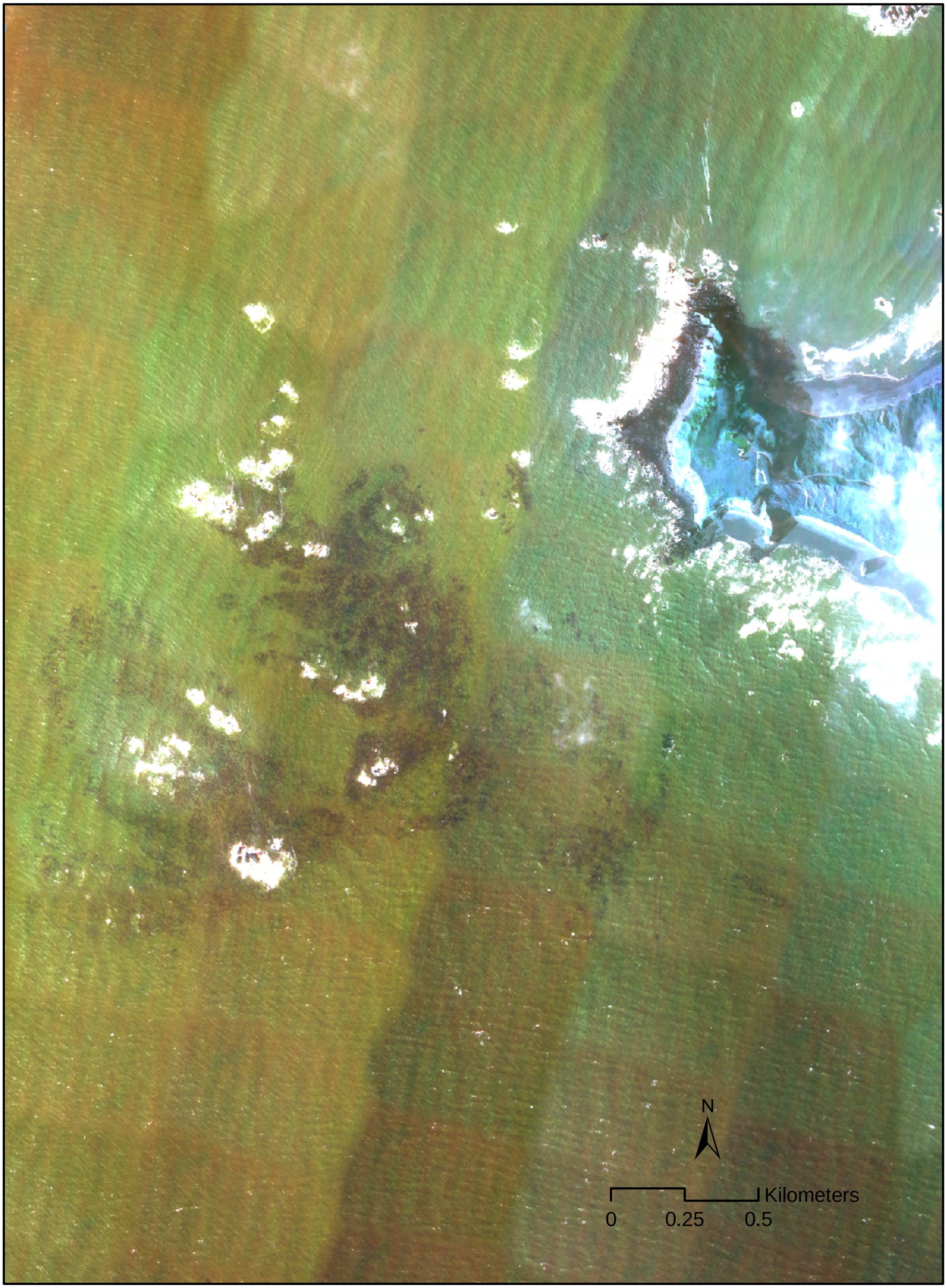

Figure 9. Digital multispectral imagery mosaic at Blanco Reef prior to classification of kelp beds. Kelp is visible as dark patches on and below the surface.

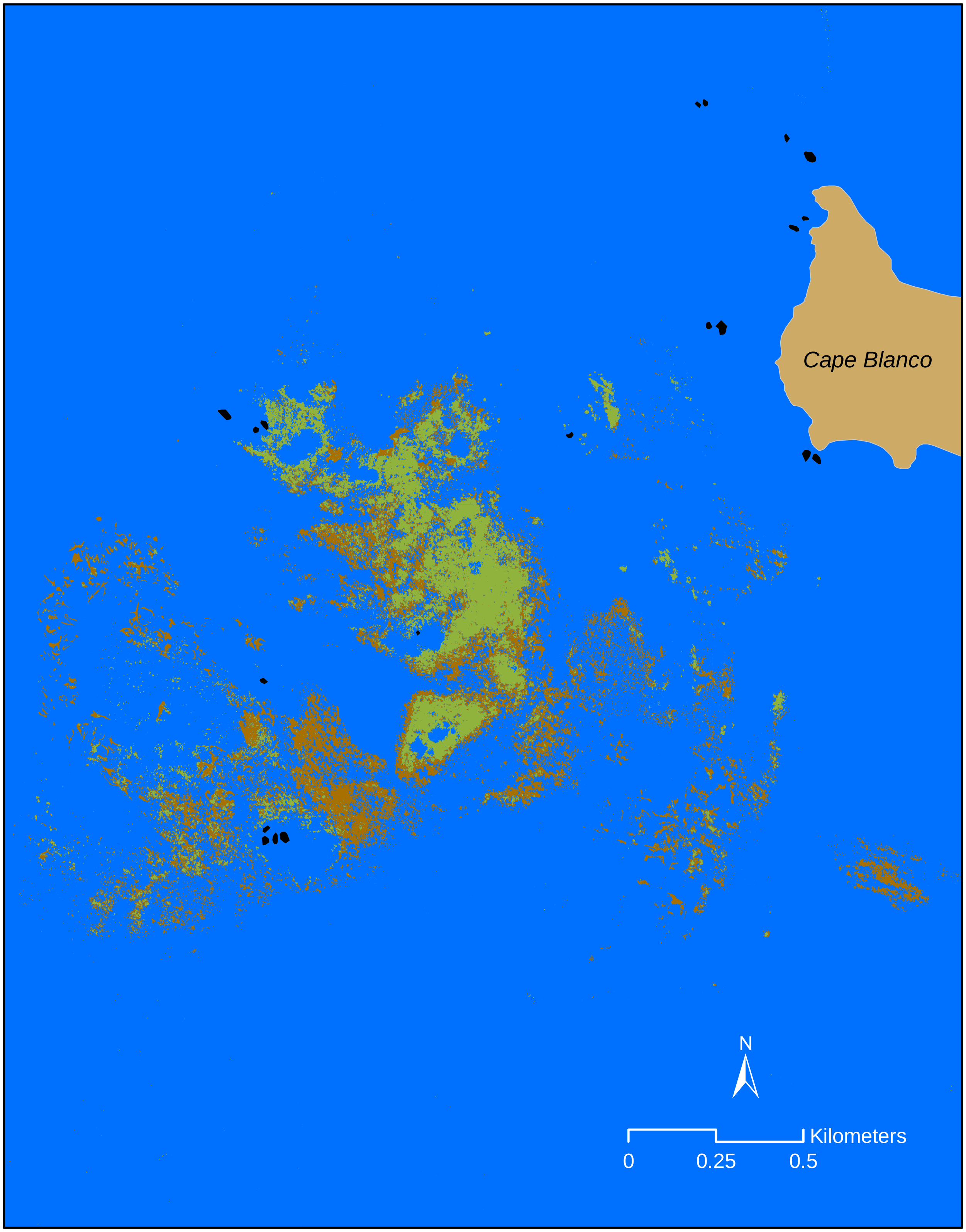

Figure 10. Multispectral imagery is classified into exposed and submerged kelp by comparing attenuation coefficients of DMSC bands 4 and 1 and other techniques. Exposed (green) and submerged (brown) kelp is visible in this example of Blanco Reef.

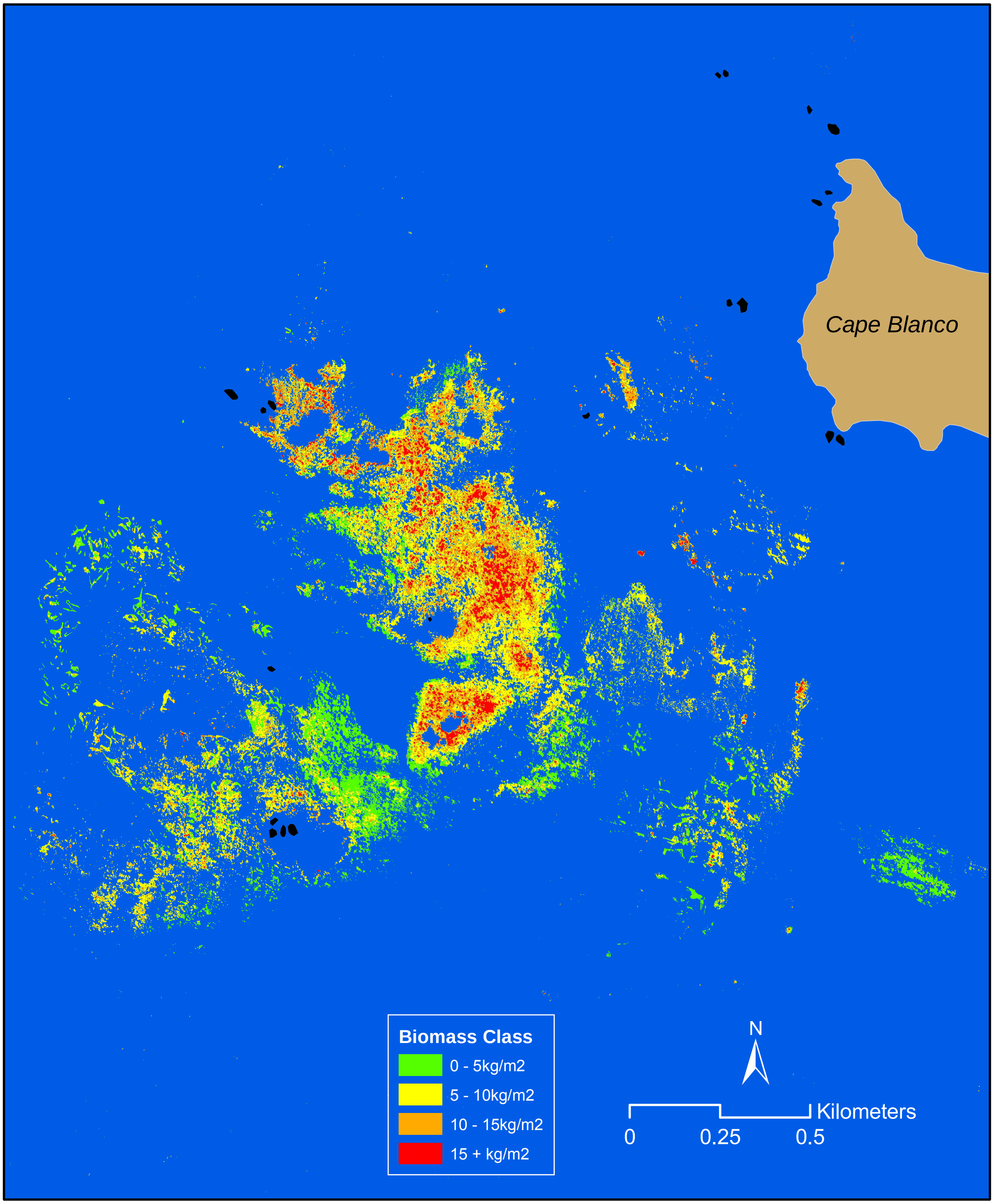

Figure 11. A preliminary biomass index product created by binning the median biomass values as computed for each of the 57 field sampling stations using the 'sub-bulb' measurement equation (Stekoll, et. al) . Biomass index ranges were assigned. Ranges for each class were chosen to evenly span the density and weight distribution ranges encountered in the multispectral reflectance vs. field parameters for each station.

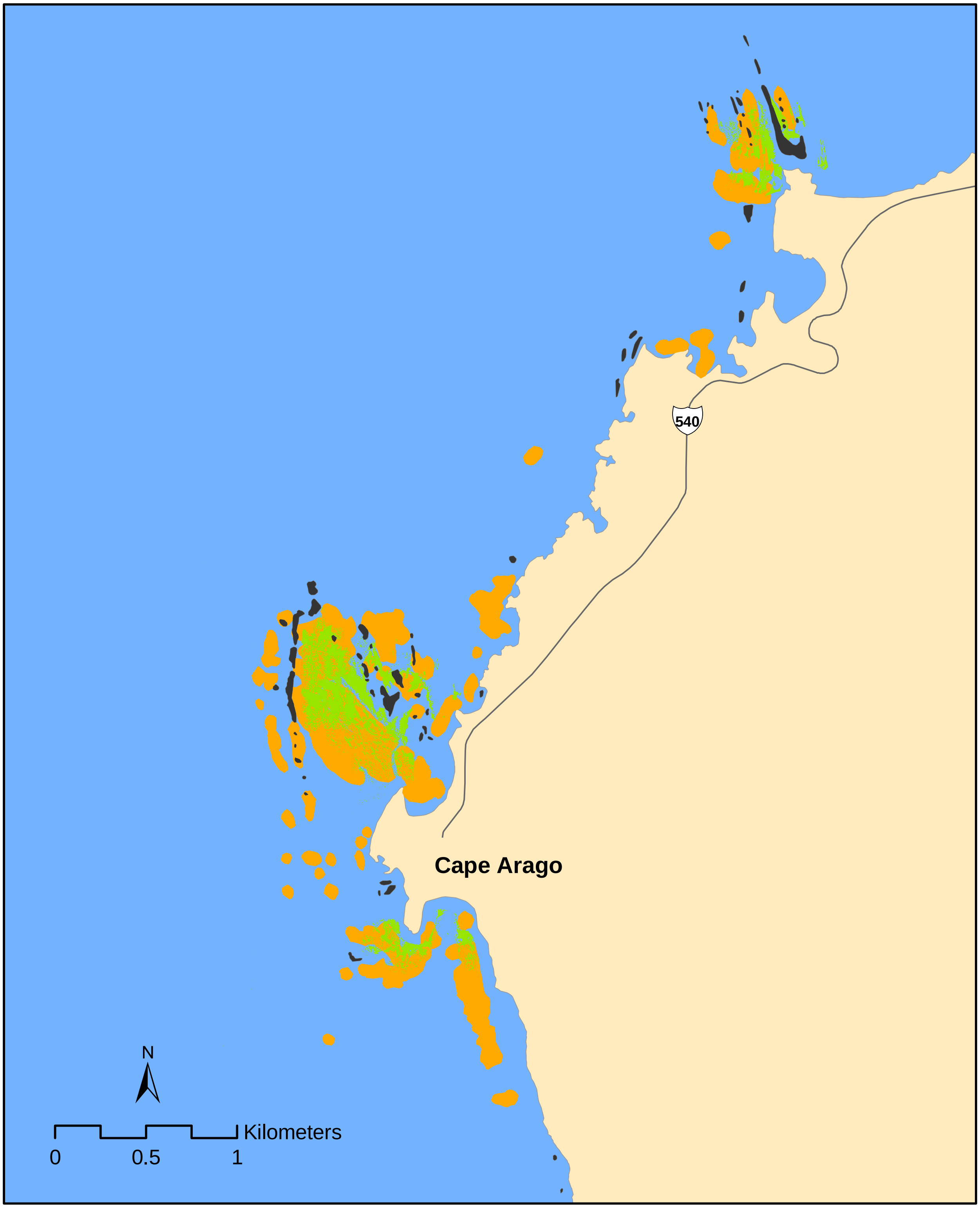

Figure 12a. Comparison of maximum kelp canopy extent at Cape Arago from all kelp surveys in Oregon. A single coastwide survey in 1990 (orange polygons) is overlaid with the kelp canopy of this current survey (green polygons). The1990 kelp beds were delineated from near-infrared photography using methods that do not differentiate beds at the resolution of DMSI methods, so bed density is not comparable between survey types in this image.

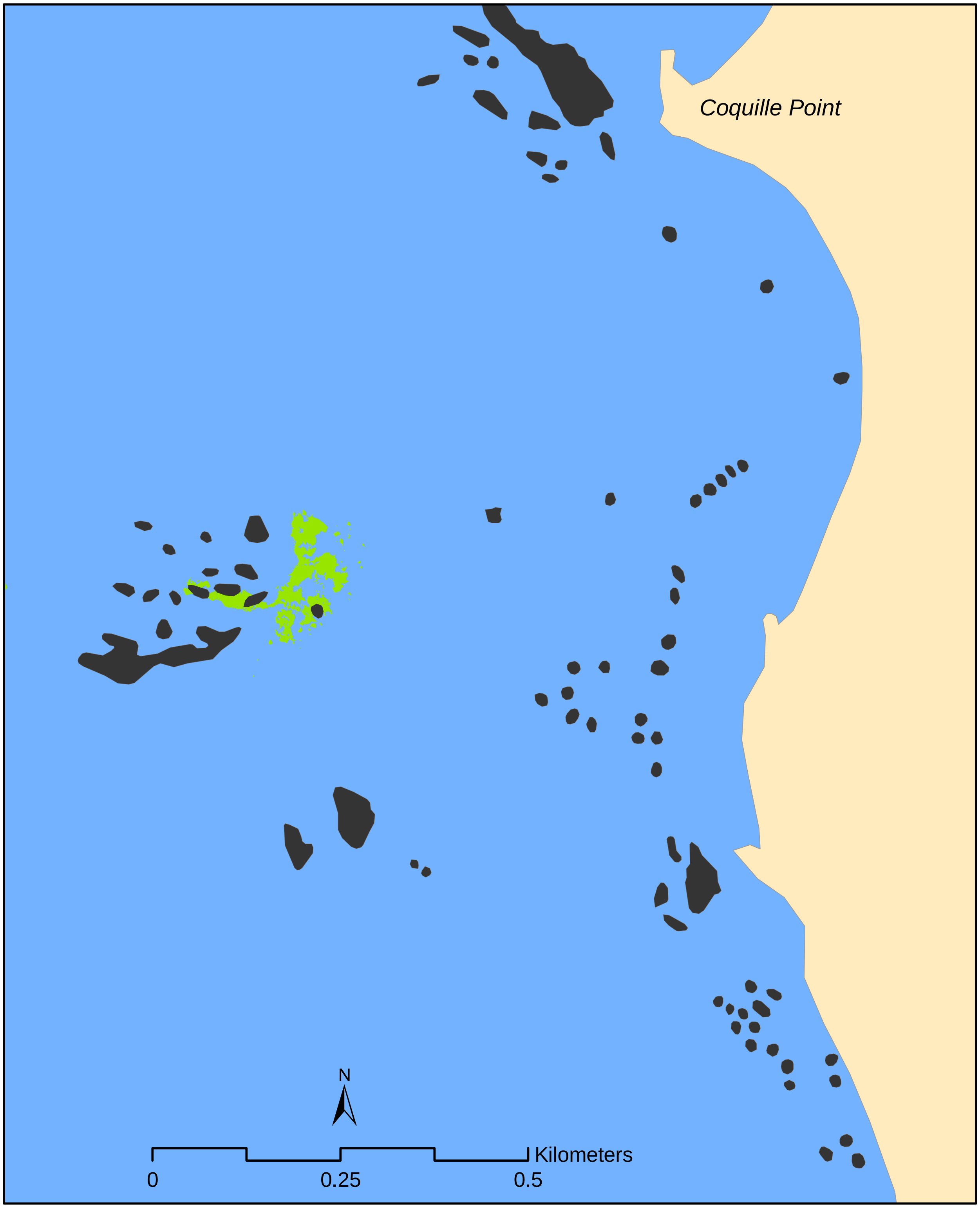

Figure 12b. Comparison of maximum kelp canopy extent at Coquille Reef from all kelp surveys in Oregon. A single coastwide survey in 1990 (orange polygons) is overlaid with the kelp canopy of this current survey (green polygons). No kelp was present at Coquille Reef in the 1990 survey.

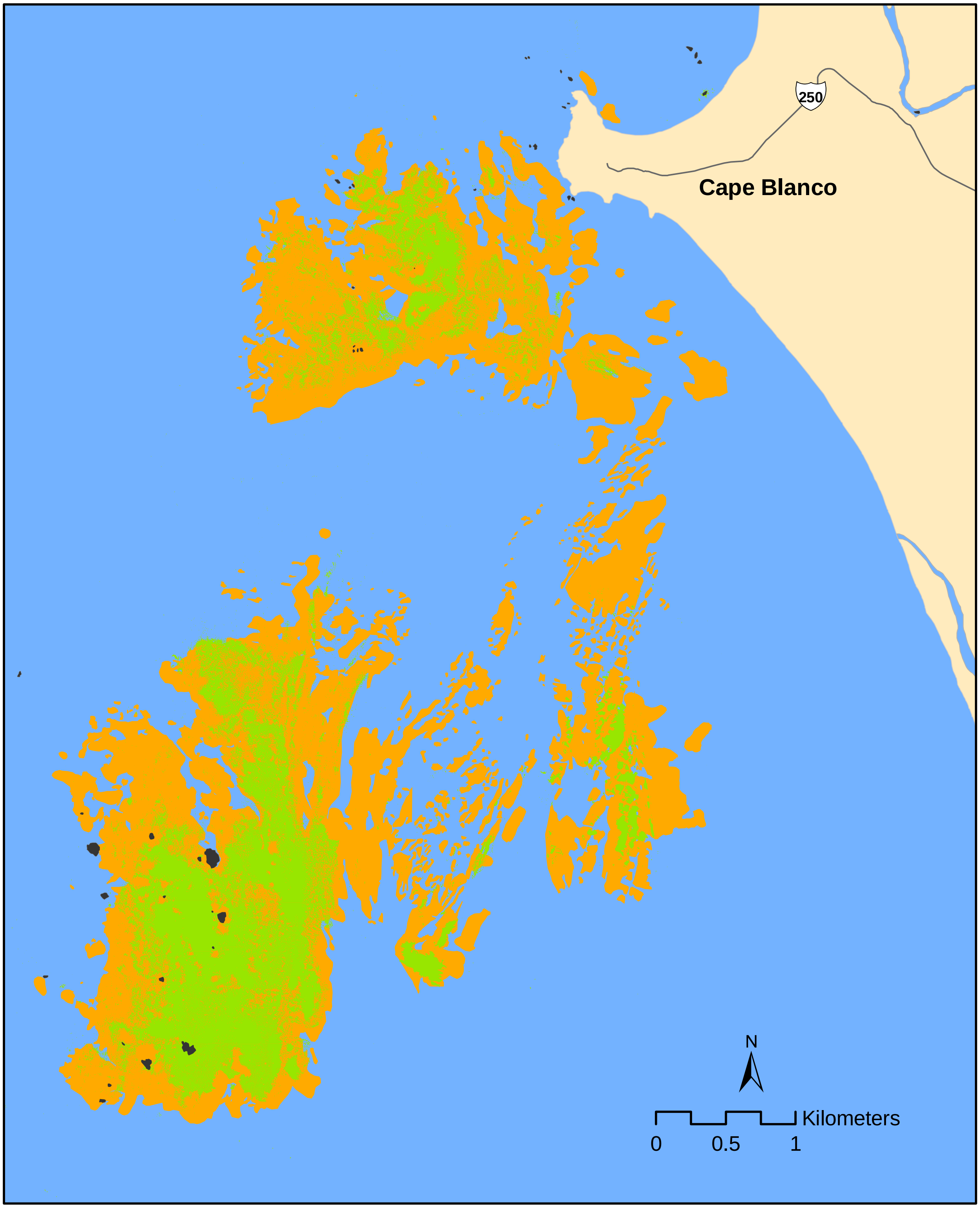

Figure 12c. Comparison of maximum kelp canopy extent at Blanco and Orford reefs from all kelp surveys in Oregon. A single coastwide survey in 1990 is merged with 5 annual south-coast regional surveys from 1996-99 (orange polygons) and is overlaid with the kelp canopy of this current survey (green polygons). The1990-99 kelp beds were delineated from near-infrared photography using methods that do not differentiate beds at the resolution of DMSI methods, so bed density is not comparable between survey types in this image.

Figure 12d. Comparison of maximum kelp canopy extent at Redfish Rocks and Humbug Mountain reefs from all kelp surveys in Oregon. A single coastwide survey in 1990 is merged with 5 annual south-coast regional surveys from 1996-99 (orange polygons) and is overlaid with the kelp canopy of this current survey (green polygons). The1990-99 kelp beds were delineated from near-infrared photography using methods that do not differentiate beds at the resolution of DMSI methods, so bed density is not comparable between survey types in this image.

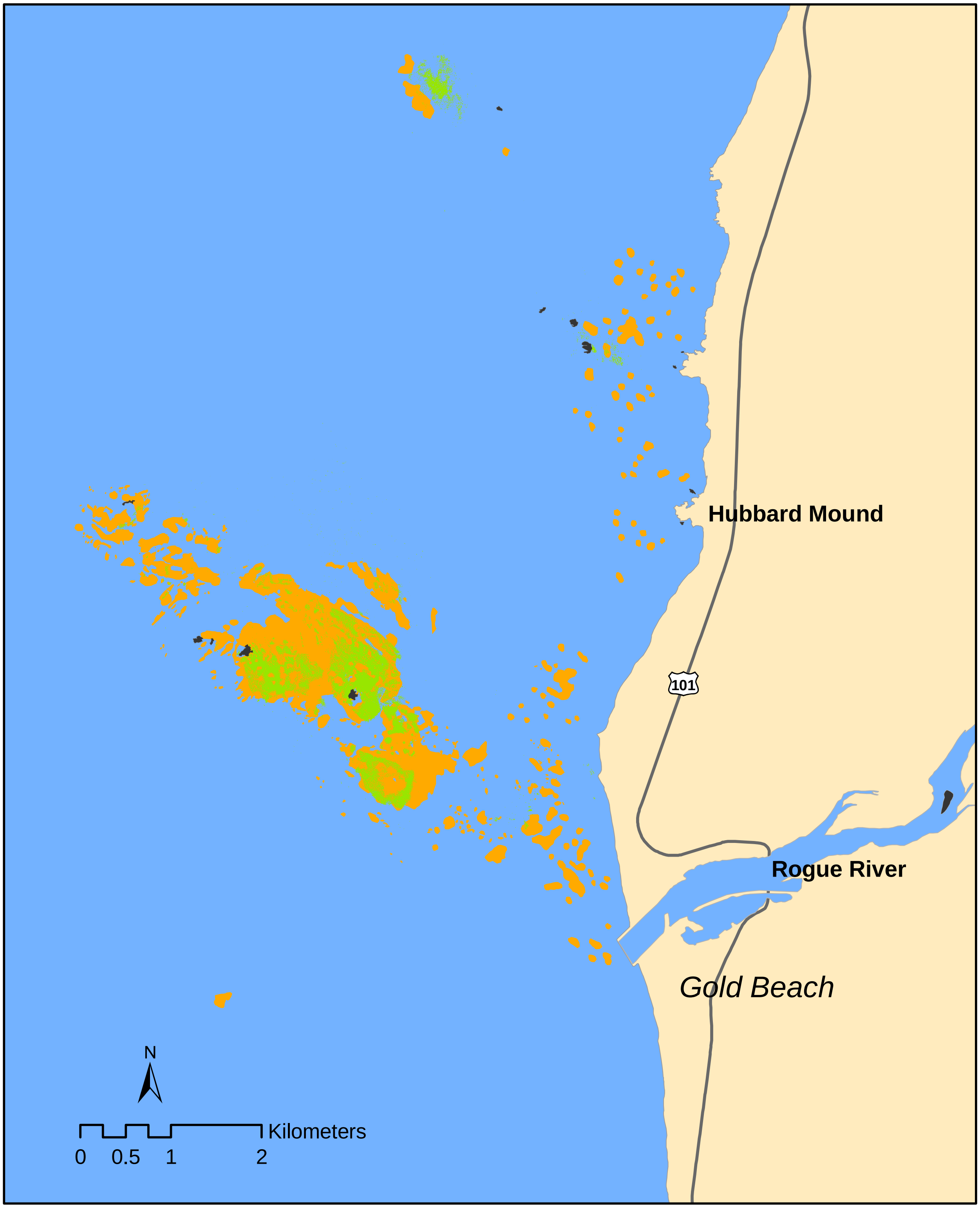

Figure 12e. Comparison of maximum kelp canopy extent at Rogue Reef and a nearby shallow reef from all kelp surveys in Oregon. A single coastwide survey in 1990 is merged with 5 annual south-coast regional surveys from 1996-99 (orange polygons) and is overlaid with the kelp canopy of this current survey (green polygons). The1990-99 kelp beds were delineated from near-infrared photography using methods that do not differentiate beds at the resolution of DMSI methods, so bed density is not comparable between survey types in this image.

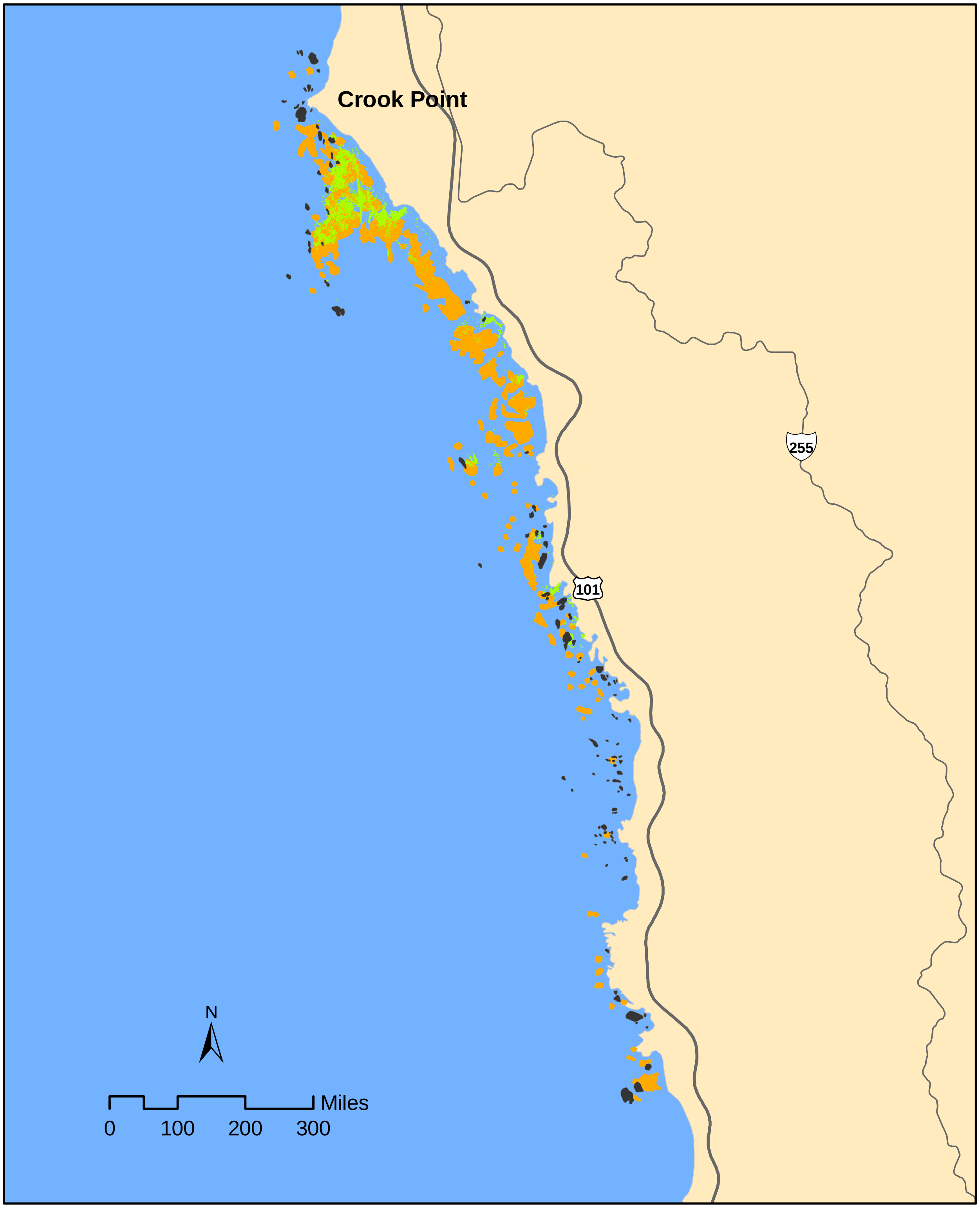

Figure 12f. Comparison of maximum kelp canopy extent at Mack Arch from all kelp surveys in Oregon. A single coastwide survey in 1990 (orange polygons) is overlaid with the kelp canopy of this current survey (green polygons). The1990 kelp beds were delineated from near-infrared photography using methods that do not differentiate beds at the resolution of DMSI methods, so bed density is not comparable between survey types in this image.

Figure 12g. Comparison of maximum kelp canopy extent at Cape Ferrelo from all kelp surveys in Oregon. A single coastwide survey in 1990 (orange polygons) is overlaid with the kelp canopy of this current survey (green polygons). The1990 kelp beds were delineated from near-infrared photography using methods that do not differentiate beds at the resolution of DMSI methods, so bed density is not comparable between survey types in this image.

Table 1. Mean weight of kelp structure (bulb, blades, stipe portion) for historical (1996, 1997, 1998, 1999) and current (2010) samples at reefs where kelp is most prevalent.

Reef * Year	Mean Plant Wt.	n
Blanco * 1996	5.04	44
Blanco * 1997	2.51	102
Blanco * 1998	3.12	75
Blanco * 1999	2.06	70
Blanco * 2010	**2.72**	**120**
Orford * 1996	5.61	72
Orford * 1997	3.82	102
Orford * 1998	3.16	72
Orford * 1999	3.11	71
Orford * 2010	**3.64**	**242**
Redfish * 1996	2.19	60
Redfish * 1997	2.03	99
Redfish * 1998	2.10	72
Redfish * 1999	1.58	70
Redfish * 2010	**1.33**	**120**
Rogue * 96	not sampled	n/a
Rogue * 97	not sampled	n/a
Rogue * 98	2.60	71
Rogue * 99	2.94	71
Rogue * 2010	**3.32**	**92**

Year	Mean Plant Wt.	n
1996	5.41	176
1997	2.97	383
1998	2.96	290
1999	2.77	353
2010	**2.92**	**573**