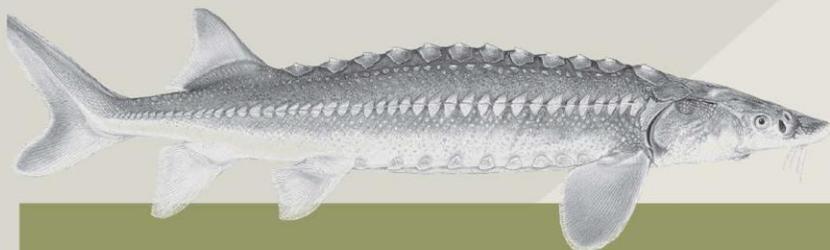
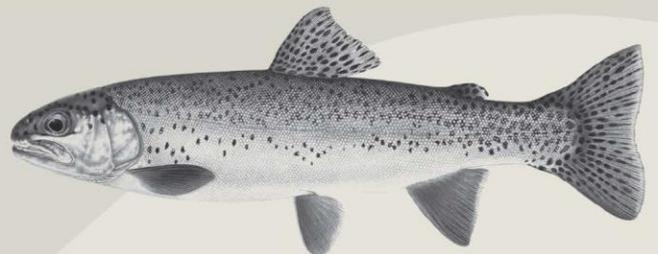
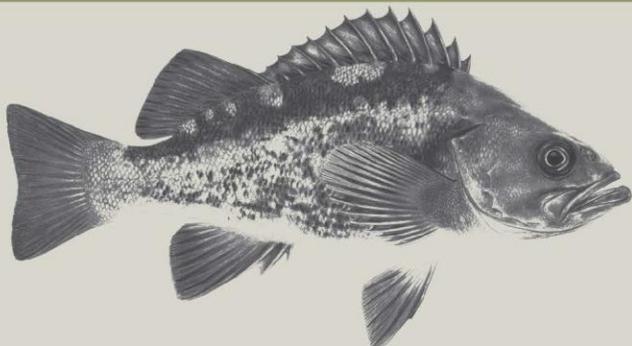


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Aerial Surveys of Bull Kelp (*Nereocystis luetkeana*) Along
the Oregon Coast in 2022 and 2024: Abundance,
Distribution, and Change Since 2010.



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February 2026

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ABSTRACT

From 2014 to 2016, an extended marine heat wave affected nearshore ecosystems along the U.S. West Coast during a period that also featured an extraordinary increase in the density of kelp-grazing purple sea urchins and the regional extirpation of the sunflower sea star, an important predator on sea urchins. The resulting shifts in nearshore kelp communities were well documented in nearby northern California, but the abundance and distribution of bull kelp had not been comprehensively assessed in Oregon since 2010.

Fixed-wing aircraft were used to conduct aerial imaging surveys of the Oregon coast and offshore reefs between the Oregon-California border and the vicinity of Depoe Bay in the fall of 2022 and 2024. The floating bull kelp canopy visible in the multispectral (four-band) 0.23 m resolution imagery was classified on a per-pixel basis as either surface kelp or subsurface kelp. Kelp canopy area totals were summarized within 5-km segments of the coast, and compared with the results of a similar survey conducted in 2010 along the south coast where the bulk of Oregon's bull kelp is found.

For the portion of the coast surveyed in 2010, results showed a 70% decrease in kelp canopy area by 2024. The most notable area of change was at Orford Reef, which in 2010 constituted almost half of that survey's total 541 hectares of kelp, but in 2022 was nearly devoid of kelp and largely overrun by purple sea urchins. Between 2022 and 2024, a remarkable resurgence of kelp along the northern portion of the study area near Depoe Bay drove a 26% increase in total kelp canopy area. However, the southern part of the coast continued to decline in 2024, resulting in a survey-wide total of 241 hectares, a very low total area compared to previously observed abundances. Maps comparing kelp locations among years found high variation in the spatial expression of the kelp canopy even within reefs retaining similar total amounts of kelp. Several sites exhibited a broadening and shallowing of the kelp distribution, particularly in 2022, to nearby locations where it had not been observed in previous high-abundance years.

Patterns of kelp distribution were compared with surveys conducted by ODFW from 1996 to 1999. While the current state of abundance is very low, results show that bull kelp, as a dynamic annual species, has demonstrated rapid regional recoveries from low abundance in the past. However, the potential long-term stability of high sea urchin abundance may currently limit the rate of kelp recolonization. Continued work is necessary to calibrate kelp survey methods across historical and contemporary surveys and produce a reliable time series of bull kelp abundance across the available datasets. Looking forward, a better understanding of the mechanisms currently affecting bull kelp abundance and distribution along the Oregon coast would help guide management efforts. These topics include relationships of kelp sporophytes and gametophytes with changing upwelling dynamics, site-specific kelp spore dispersal potential and spore limitation, and the relationship of sea urchin density to kelp recruitment and persistence in different structural habitats.

1. INTRODUCTION

Bull kelp (*Nereocystis luetkeana*) provides important habitat for many highly valued nearshore species, and bull kelp forests are designated by the Pacific Fishery Management Council as a Habitat Area of Particular Concern for salmon (PFMC 2014) and groundfish (PFMC 2025). Globally, kelp forests are important coastal habitats that support high biodiversity (Teagle et al. 2017) and are among the most highly productive marine ecosystems (Wernberg et al. 2019).

Recent climate-related changes in ocean conditions have contributed to broad-scale impacts to kelp habitats and associated biological communities in nearshore waters off Oregon. Like other areas along the U.S. West Coast, Oregon experienced a record-breaking marine heatwave beginning in 2014 (Bond et al. 2015, Rogers-Bennett and Catton 2019), precipitating a substantial shift in the nearshore marine ecosystem. Anecdotal observations of kelp beds over the past decade note widespread and substantial decline in kelp forests at major reefs off southern Oregon. The main contributing causes of kelp declines are thought to include changes in nearshore oceanography associated with warmer waters (Bond et al. 2015), historic recruitment of purple sea urchins (Groth 2023), and the complete loss of the sunflower sea star (a key predator of sea urchins) to sea star wasting syndrome (Harvell et al. 2019, Hamilton et al. 2021). However, the relative importance of mechanisms controlling bull kelp abundance in Oregon during this period are not well understood.

1.1. History of kelp monitoring in Oregon

ODFW's first statewide assessment of bull kelp off Oregon occurred in 1990 using color-infrared film aerial photography (Ecoscan Resource Data 1991). In the mid-1990's, interest in commercial kelp harvest prompted ODFW to launch a five-year (1996-2000) aerial photography survey and biomass assessment at four prominent kelp-bearing reef systems along the south coast. Kelp growth and biomass fluctuated greatly among the years surveyed (Fox et al. 1999), indicating the resource would not support a commercial harvest program. This led the state to retain the moratorium on commercial kelp harvest. Kelp monitoring was discontinued until resources became available in 2010. At that time, digital multispectral imaging technology had become accessible and feasible for small-scale projects. These imaging systems provided substantial improvements in processing capabilities and became a standard method for acquiring kelp bed imagery.

Since 2010, at least two additional methods of estimating bull kelp abundance based on satellite remote sensing have become available. Bell et al. (2020) used 30 m resolution Landsat data to reconstruct a long timeseries of emergent kelp abundance. "Emergent kelp" is a different attribute of the kelp canopy than the total floating canopy area ODFW assessed in the 1990s and in 2010. The Landsat-based data are made available online by Kelpwatch in a regularly updated, accessible form (Bell et al. 2023). During the course of our study, Cavanaugh et al. (2023) developed a methodology to create high-resolution maps of bull kelp canopies in

northern California using data from constellations of small “CubeSats” that became available in 2016. The method shows great promise for mapping Oregon kelp, but a detailed model development process would be necessary, and the data are limited to the post-2016 period, limiting the utility for assessing kelp change in Oregon since 2010. To assess the change in kelp canopy area since 2010, we implemented aerial surveys using methods that were modernized (higher resolution) but otherwise similar to the 2010 survey.

1.2. Project Goals

The 2022 and 2024 surveys provided an update on the status of this important ecological resource and began a renewed endeavor to monitor kelp beds now and into the future as the changing climate alters ocean conditions and the marine ecosystem. These surveys also support concurrent ecological research on the communities in and around Oregon kelp forests as part of a comprehensive assessment of nearshore species affected by climate-related ocean conditions (red sea urchin, abalones, sunflower sea star).

The goals of ODFW’s work on kelp ecosystems are to: (1) monitor the status of the kelp habitat resource off Oregon, (2) contribute to the development of a kelp data timeseries by combining with other potential data sources on kelp abundance such as imagery from Unmanned Aerial Vehicles (UAVs) and satellites, and (3) assess the relationships between kelp habitats and abundances of other species.

The working objective for these aerial surveys was to use a fixed-wing aircraft to acquire high-resolution multi-spectral imagery of bull kelp canopy and to map the spatial extent of the canopy, allowing quantitative comparison with prior estimates of kelp abundance, particularly the 2010 aerial survey that preceded substantial changes in Oregon’s nearshore environment.

2. METHODS

High-resolution 4-band (RGB and near-infrared) aerial images of bull kelp beds were collected during the period of peak floating canopy cover in the fall of 2022 and 2024. Flights were conducted on October 1, 2022 and September 20, 21, and 22, 2024, between the Oregon-California border and Cape Arago, and along the central Oregon coast near Depoe Bay (Fig. 1). Together these regions included almost all of Oregon’s floating kelp canopy, excluding only small areas to the north near Cape Kiwanda and Cape Lookout. In this report we use the term “floating kelp canopy” (often shortened to “kelp canopy”) to refer to the portion of bull kelp sporophytes (the large canopy-forming phase of the bull kelp life cycle) at or just under the water’s surface, as distinguished from prostrate or sub-canopy kelps that may form a completely submerged canopy near the seafloor. In this study, kelp canopy area is used as a proxy for the total abundance of bull kelp, while acknowledging that there are areas and times where some bull kelp sporophytes are not visible from above the water. Kelp canopy was classified as either surface or subsurface, and the area of kelp canopy was summarized within 5-km segments of shoreline.

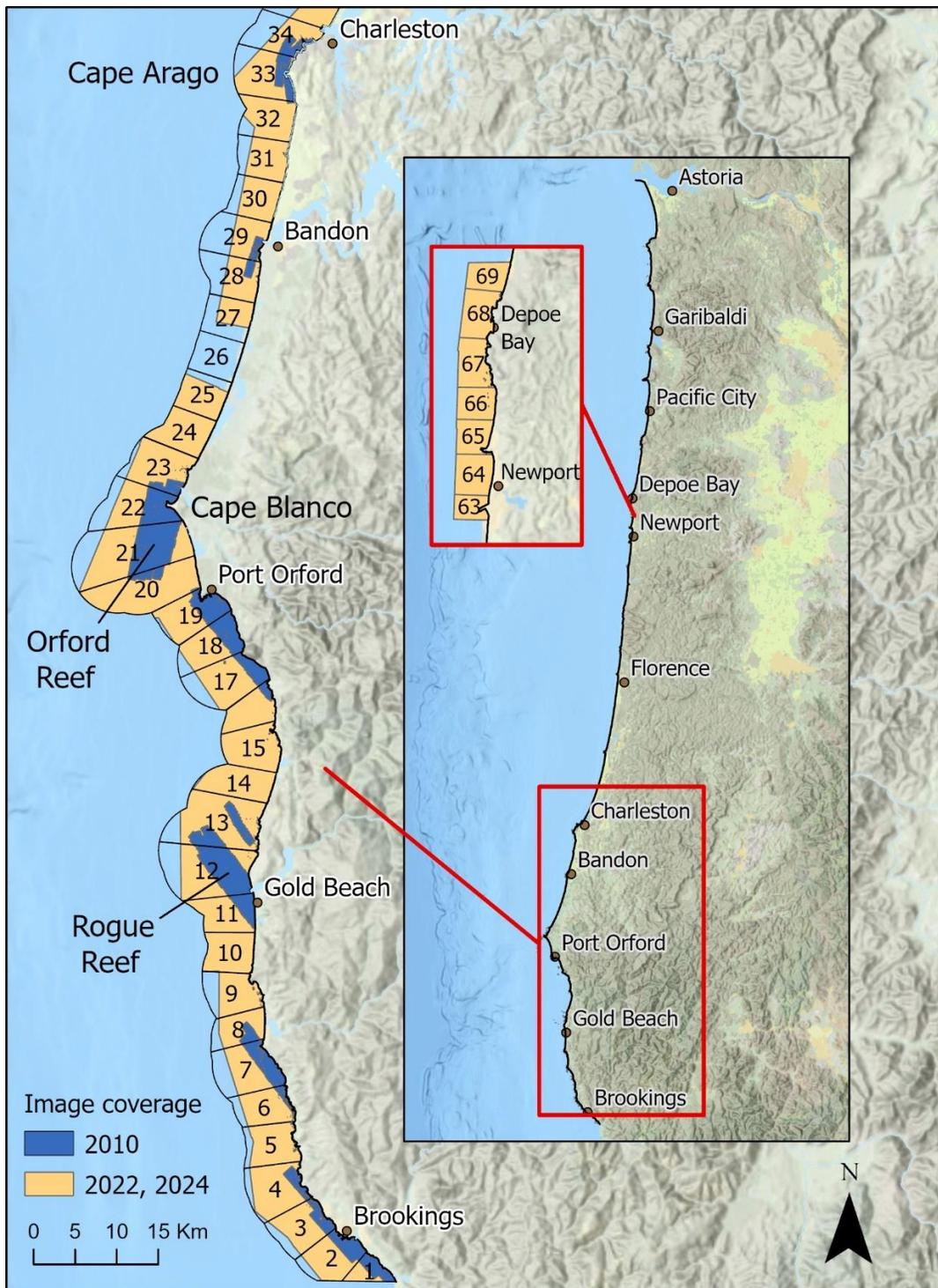


Figure 1: Image coverage of fixed-wing aerial photographic surveys conducted in 2010, 2022, and 2024 along the Oregon coast. The 2010 survey (blue polygons) covered all major kelp-bearing rocky reefs from the Oregon-California border to Cape Arago. The 2022 and 2024 surveys' broader image coverage (orange regions) included almost the entire coast south of Cape Arago, as well as the region near Newport and Depoe Bay on the central coast (shown on inset map). Analysis of kelp abundance was conducted within 5-km segments of coast, numbered south to north.

In this study, the term “surface kelp” refers to the portion of the floating kelp canopy that is just above, at, or just under the air-water interface. This portion of the kelp canopy has a relatively higher return (reflectance) in near-infrared wavelengths and a relatively lower return in red wavelengths due to the absorption and reflectance characteristics of photosynthetic vegetation. Subsurface kelp (aka submerged kelp) is the portion of the kelp canopy close to the water’s surface with lower relative returns in the near-infrared spectrum, but still distinguishable from the surrounding water. Subsurface kelp does not have a strong return in near-infrared wavelengths because these wavelengths are quickly absorbed by water. These imaging surveys are targeted at the bull kelp canopy (including the surface and subsurface portions of the canopy) and generally do not capture prostrate kelps. However, in some very shallow areas other kelps (e.g., *Egregia*, *Laminaria*, *Saccharina*, *Pterygophora*) may contribute to the spectral signal classified as subsurface kelp. The inclusion of the subsurface portion of the bull kelp canopy is an important distinction from other types of kelp surveys that strictly target the emergent (surface) portion of the kelp canopy based on strong near-infrared reflectance (e.g., KelpWatch (Bell et al. 2023), which is based on Landsat satellite images).

2.1. Image Acquisition

ODFW contracted with Ocean Imaging (OI) to collect multi-spectral imagery of kelp beds off Oregon and classify the kelp canopy observed. OI was selected for their decades of experience and expertise (40+ years) with kelp surveys along the U.S. west coast and Alaska using state of the art digital imaging technology, and for their analytical capabilities using multispectral imagery to assess surface and subsurface kelp beds. Imagery was acquired using a Vexcel UltraCam Eagle Mark 3 (UCEm3) multispectral imaging (MSI) system. The system has four channels in the red, green, blue and near-IR bands. The UCEm3 has an extremely large (449 megapixels) footprint which, in addition to allowing much higher spatial resolution than previous MSI systems, yields a wide image swath and results in complete coverage of large or far-offshore kelp beds. This reduced the need to image and mosaic multiple overlapping flight lines in some areas as was done in the 2010 survey discussed below. The system was integrated with a high accuracy DGPS/IMU unit to ensure high positioning accuracy. Specifications on the UCEm3 and wavelengths for each spectral band can be found in Appendix A.

2.2. Criteria for timing image acquisition

The following criteria were considered in deciding when to acquire imagery:

- **Tide level.** High tide levels increase the proportion of the bull kelp canopy held below the surface, either due to shorter stipe length or due to the greater effect of currents on pulling down floating stipes at higher water levels. Higher tide levels at the time of image acquisition have been associated with less classified kelp (see review in Reshitnyk

et al. 2023). This severely limits the time periods available for optimal imaging. This limitation is less constraining with wide-coverage sensors, because more area can be covered in a single low tide window.

- **Sun angle.** All imaging systems are compromised by surface glint (bright speckling from sun reflections off the water's surface), so imaging must be done at lower sun angles (40° or less). This can preclude surveying during the middle of the day. The effect of costal bluffs shading nearshore kelp beds in the morning was also a constraining factor. The aerial survey was planned to optimize the imaging conditions by scheduling flights during acceptable sun angle, moderate low tide conditions and minimal shading.
- **Sea state.** Image-based assessments can be affected by sea state and high winds or storms in the period preceding the kelp survey, especially by reducing water clarity and increasing the amount of sea foam. Large waves can introduce glint in the imagery and may cause the kelp to remain fully or partially submerged even at low tide conditions.
- **Seasonal timing.** In Oregon, bull kelp growth peaks in late summer and maximum floating canopy occurs in September/October. Surveys are targeted to capture the seasonal peak abundance as closely as possible given the available weather and tide windows. However, storms prior to the image acquisition can cause potentially large amounts of kelp to be ripped off the bed. A survey following such conditions can substantially under-represent peak abundance. OI closely monitored sea state and wind conditions in each part of the coast prior to imaging to avoid surveying under such conditions. Rain storms, heavy cloud or fog conditions, and strong upwelling winds are common occurrences off Oregon and prevented surveying on some days.
- **Water clarity.** Excessive turbidity reduces the depth penetration range of the aerial instruments. Before the planned image acquisition missions OI monitored water quality along the entire coast with NASA MODIS, VIIRS and Sentinel 3A and 3B satellite color imagery and planned to alter the survey schedule if a specific region was subject to excessively high turbidity.
- **Cloud cover.** Although clear atmospheric conditions are preferred, cloud cover above the imaging aircraft still allows accurate classification of surface and submerged kelp. Although the preference was for cloudless days, due to the tight scheduling windows to accommodate both sun angle and low tide requirements, imaging could be done in the presence of high-altitude clouds.

The aerial surveys were planned to be close to the yearly peak kelp abundance during favorable conditions (clear skies, mild wind and sea state, low sun angle) to maximize kelp canopy detection. Optimum conditions for acquiring imagery are wind speed less than 15 knots, a combined wave height of less than 7 feet, sun angle less than 40 degrees and within 2 hours of mean low tide, with an optimum tide less than 1.5 ft MLLW (mean lower low water).

2.2.1. Survey coverage and conditions

The survey area extended from Lincoln City, Oregon to the Oregon-California border, spanning approximately 206 miles of coastline. There is little kelp-bearing shallow rocky reef in the 90-mile stretch of coast between Newport and Coos Bay, and consequently images were not acquired for that portion of the coast. The survey area was segmented into five regions to accommodate survey implementation and data processing/organization (Table 1). These regions are not used as units for this kelp analysis, but simply served to organize the survey effort and the acquired images into manageable units.

Weather and ocean conditions at the major south coast reefs (Cape Arago, Cape Blanco, Orford Reef, Rogue Reef) are typically more severe than elsewhere on the Oregon coast and present challenges for acquiring aerial imagery from any platform (i.e., aircraft, UAV, satellite). Winds can be strong and persistent around the reefs during the period of peak kelp canopy, affecting sea state and whitecap formation on the water. Likewise, cloud cover and fog are also prevalent during this period. These conditions restrict the number of survey days available during optimum tide windows. The surveys were targeted for mid-September through early October, reflecting both the available tide windows and the tradeoff between premature image acquisition (before kelp reached peak growth and surface area) and the risk of losing canopy with the onset of storms in mid-late October.

Table 1. 2022 and 2024 aerial kelp survey extent and data acquisition schedule. In 2022, the flight times for the Orford, Rogue, and Brookings regions were not individually specified.

Survey Region	Extent (N. lat.)	Acquisition Date and Time (PST)		Tide Height (ft)	
		2022	2024	2022	2024
Depoe Bay	44° 35.99' - 44° 52.76'	10/1/22 12:27 – 12:37	9/21/24 9:31 – 9:47	4.2 – 5.5	1.8 – 2.1
Coos Bay	43° 1.86' - 43° 25.47'	10/1/22 11:49 – 12:10	9/20/24 9:30 – 9:42	2.85 – 3.0	1.8 – 2.1
Orford	42° 26.06' - 42° 58.15'	10/1/22 10:17 – 11:47	9/20/24 9:47 – 10:23	3.5 – 4.2	2.8 – 3.8
Rogue	42° 22.30' - 42° 33.00'	10/1/22 10:17 – 11:47	9/20/24 10:23 – 10:31 9/21/24 10:19 – 10:30 9/22/24 10:29 – 10:34	3.5 – 4.2	3.8 – 4.1 3.3 – 3.5 3.3 – 3.4
Brookings	41° 54.00' - 42° 26.78'	10/1/22 10:17 – 11:47	9/21/24 10:30 – 10:46	3.5 – 4.2	3.5 – 3.9

For the 2022 survey, optimum daytime low tides occurred only during the first five days of the survey period, which is uncharacteristic of previous kelp surveys off Oregon. Daytime low tides were marginally better in September (0.6 ft – 3.9 ft MLLW) than October (2.7 ft – 4.0 ft), but unfavorable weather, sea states, and airplane availability precluded image acquisition throughout September. Kelp imagery was captured on October 1, 2022 under clear skies, moderate wind (8-15 mph), and relatively

calm seas (combined seas at offshore buoy 4-5 feet at 12 seconds, likely smaller near shore). Tide height ranged from 2.85 ft – 5.50 ft MLLW, and was especially high during the Depoe Bay area acquisition. The Depoe Bay imagery was acquired on the afternoon of the same day that the south coast surveys were conducted, despite a tide rising beyond preferred heights, because the forecast for future weather windows was poor. Consequently there was risk that if the survey were further delayed, areas of kelp would be ripped out by large storm waves before imagery could be acquired.

In 2024, the first suitable tide window emerged in late September and coincided with suitable atmospheric and sea conditions. Kelp imagery was captured mostly across two days, on September 20 – 21, 2024, with just one flight line covering the offshore portion of Rogue Reef captured on September 22. Skies were clear and winds were generally less than 15 kts. Tide levels in the survey areas further north (Coos and Depoe regions) were around 2 ft. MLLW, which was lower than they had been for those regions in 2022. To the south (Orford – Brookings), tides were once again higher than optimal at around 3-4 ft. MLLW, and generally similar to the tides in those regions in 2022.

The image coverage (the spatial footprint of all areas captured by the aerial imagery) was similar in 2022 and 2024, with no differences for kelp interpretation. Flight path maps are presented in Appendix B, along with weather and tide data during the acquisition windows.

2.3. Image processing and kelp classification

Raw images and geo-positioning data from the UltraCam Eagle Mark 3 IMU were imported into ERDAS Imagine software. The 16-bit multispectral imagery was collected from four spectral bands (red, green, blue and near-infrared) at a spatial resolution of 0.2286 meters. Spatial accuracy of the imagery is reported to be within one meter (90% circular error). The imagery was orthorectified using digital elevation models available for the region. Individual, orthorectified scenes were then mosaicked together, where necessary, into manageable files using Esri ArcGIS 10.X/ ArcGIS Pro mosaic tools. The surface and subsurface kelp canopy were then classified using OI's proprietary neural network classification software using reflectance wavelength algorithms to optimize detection of surface and subsurface kelp. Surface and subsurface kelp classes were created using both supervised (maximum likelihood) and unsupervised (ISO Data) classification methods.

Multiple image mosaics (GeoTIFFs) were created to facilitate data processing and delivery (image clips listed in Appendix C). Thematic map classifications (surface and subsurface kelp) were generated in both ArcGIS shapefile (.shp) and GeoTIFF (.tif) formats. The data for each region were processed in the native (as collected) geographic projection, then projected to WGS 1984 UTM Zone 10N. The native projection for the Depoe Bay region was "NAD_1983_StatePlane_Oregon_North_FIPS_3601_Feet_Intl", and for the Coos Bay, Orford, and Brookings regions it was "NAD_1983_2011_StatePlane_Oregon_South_FIPS_3602_Ft_Intl".

ODFW staff conducted post-processing on the shapefiles to remove a small number of features. These decisions were based on local knowledge or datasets indicating that the seafloor was either too deep (meaning that the classified kelp was likely detached and drifting away from its

point of origin at the time of image capture) or too shallow (likely indicating intertidal algae misclassified as kelp). These edits did not meaningfully affect any area totals in this report.

2.4. Analysis of kelp abundance

Maps delineating the extent of surface and subsurface components of the kelp canopy were created using Esri ArcGIS Pro 3.0 – 3.43 software.

2.4.1. Summarizing kelp abundance by coast segments

To summarize spatial trends in kelp abundance along the coast and to facilitate site-specific kelp abundance comparisons with prior surveys, the total area of surface and subsurface kelp was aggregated within a series of approximately 5 km long segments. The segments were created by first defining points along the coast separated by 1 km (Euclidean distance, not along the shore features). At every 5th point, a line was drawn generally perpendicular to the coast. These segment dividing lines were connected with the state coastal waters boundary (i.e., 3 nm from shore or state waters emergent rocks), and with a recent high-resolution shoreline layer derived primarily from NOAA's Continually Updated Shoreline Product (CUSP) defining the mean high water line, to form a series of polygons along the coast. Some polygon dividing lines were adjusted or re-oriented to avoid splitting large kelp beds.

2.4.2. Assessing kelp distribution change since 2010

The 2022 and 2024 image coverage was broader than the prior 2010 image coverage, encompassing sections of coast that were not surveyed in 2010. Methods for the 2010 survey are summarized in Appendix D, and full details are available in Merems (2011). The key methodological difference with the 2022/2024 surveys is that the 2010 imagery had a resolution of 1 m (1 m x 1 m pixels) compared to 0.2286 m resolution of the 2022 and 2024 imagery. To analyze the change in kelp canopy between 2010 and 2022/2024, the recent survey data were divided in ArcGIS Pro into portions observed within the 2010 image coverage and portions observed outside the 2010 image coverage. Kelp change analyses between 2010 and 2022/2024 were conducted using only the portion of the 2022/2024 image coverage that occurred within the 2010 coverage.

To assess the completeness of the 2010 survey in light of the more expansive and detailed 2022 and 2024 survey data, each coast segment was classified according to whether the 2010 survey included complete coverage of the potential kelp habitat in the segment (i.e., shallow rocky substrate) as interpreted from the available seafloor data, ODFW staff's best understanding of nearshore rocky habitats, and any prior observations of kelp presence. Where the 2010 coverage was incomplete, coast segments were further categorized by whether the 2022 or 2024 survey found a substantial amount of kelp in the portion of that segment lying outside the 2010 image coverage.

Analyses of change are focused on the 2010 – 2022 comparison because this period brackets the timeframe when a major marine heat wave had extensive ecological impacts on the Oregon coast, starting in 2015, causing large reductions in kelp abundance in nearby northern California (Rogers-Bennett and Catton 2019). Subsequent change between 2022 and 2024 was assessed using the full extent of these two surveys, which had equivalent image coverage. Finally, change was assessed between 2010 and 2024 using only data within the image coverage of the 2010 survey.

2.4.3. Assessing kelp distribution change since the 1990s

We focused analysis of kelp change on the comparison between the 2010, 2022, and 2024 surveys because they used comparable methods. The only available previous aerial survey datasets (ODFW surveys conducted between 1990 and 2000) were established using methods that do not yield estimates of canopy area directly comparable with the current methods without additional studies to develop calibrations between the methods. However, comparing the overall location and extent of kelp in the 1990-2000 surveys is helpful in building an understanding of the potential distribution of kelp canopy and interpreting the spatial patterns evident in the 2022 and 2024 surveys.

In 1990, an aerial survey of the entire Oregon coast was contracted to Ecoscan using “planimeter area” of kelp beds, which measures the area of polygons enclosing the visible kelp canopy. Planimeter area for this survey was highly inclusive (i.e., biased high relative to other kelp canopy area estimation methods), because it incorporates the entire area of patchy kelp beds. The survey’s main purpose was to quantify kelp-bearing areas, and the data should be considered the maximum extent of floating kelp in 1990, a larger quantity when compared to later methods that target only the surface area of floating kelp. The 1990 survey data are not included in this report because, when contrasted with the more recent (restrictive-method) surveys, they lead to substantial overestimation of the loss of kelp area .

In 1996 through 2000, aerial surveys were conducted by ODFW at five major reefs in southern Oregon (Orford Reef, Cape Blanco Reef, Redfish Rocks, Humbug, and Rogue Reef). The 1999 kelp abundance was very high, while the other years (1996 in particular) had much lower kelp abundance. Kelp canopy surface area was quantified from color-infrared photographs by a more exclusive procedure (KIM-1 method, Foreman 1984) than the 1990 survey (i.e., excluding more open water). This method involved manually drawing polygons around patchy kelp areas, and therefore produced a larger area estimate than pixel-based methods due to the inclusion of open water within the hand-drawn polygons. The goal of these surveys was to produce a total kelp biomass estimate, in service of producing management recommendations or harvest limits on a potential commercial kelp harvest (which never materialized). Each kelp polygon was assigned a density estimate (number of individuals/ha), which was used in combination with kelp bed surface area and sampled individual weights to produce a biomass estimate (Fox et al. 1996,

Foreman 1984). At present, the 1996 – 1999 kelp polygon area is not directly comparable with the 2010, 2022, and 2024 pixel-based area, aside from qualitative comparisons of which locations supported kelp, without further work on quantitative method calibration. We created maps with survey results from 1996, 1999, 2010, 2022, and 2024 to illustrate the observed range of kelp distribution at select reefs. Due to the methodological differences described above, no assessment of change in canopy area among these years is presented here.

3. RESULTS

The image coverage for the 2022 and 2024 surveys is shown in Figure 1 along with the image coverage of the 2010 survey and the coastal segment polygons used to summarize kelp abundance for the three surveys. The 2022 total image coverage area was 183,600 ha, including all image area over water and land, and the 2024 image coverage was similar. In comparison, the 2010 image coverage was 22,200 ha.

3.1. Kelp abundance and distribution in 2022

The 2022 aerial survey classified a total of 191.6 hectares (ha) of kelp canopy between the Oregon-California border and the vicinity of Depoe Bay (Fig. 2). A hectare is 10,000 m² or approximately 2.47 acres. The kelp forests at Rogue Reef constituted the largest area (68.4 ha), representing 36% of the total. Ninety-five percent (182 ha) of the total kelp area in 2022 was found along the south coast between Cape Arago and the California border, and in this stretch of coast 91% was inside the 2010 survey's image coverage. The area just north of Rogue Reef (7.6 ha) and the central coast region near Depoe Bay (10 ha) were the primary areas where the 2022 survey detected any substantial amount of kelp outside the 2010 survey's image coverage.

In 2022, only 28% (54.3 ha) of the total observed kelp canopy was classified as surface kelp, with the remainder (137.2 ha) classified as subsurface (Fig. 3). The proportion of surface kelp appeared higher for the larger kelp forest areas, particularly Rogue Reef, but every coast segment had substantially more subsurface kelp than surface kelp. Figure 4 provides an example of surface and subsurface classifications relative to the original image. Maps displaying the 2022 digital imagery and the distribution of classified kelp canopy (surface and subsurface) along the coast are provided in Appendix E.

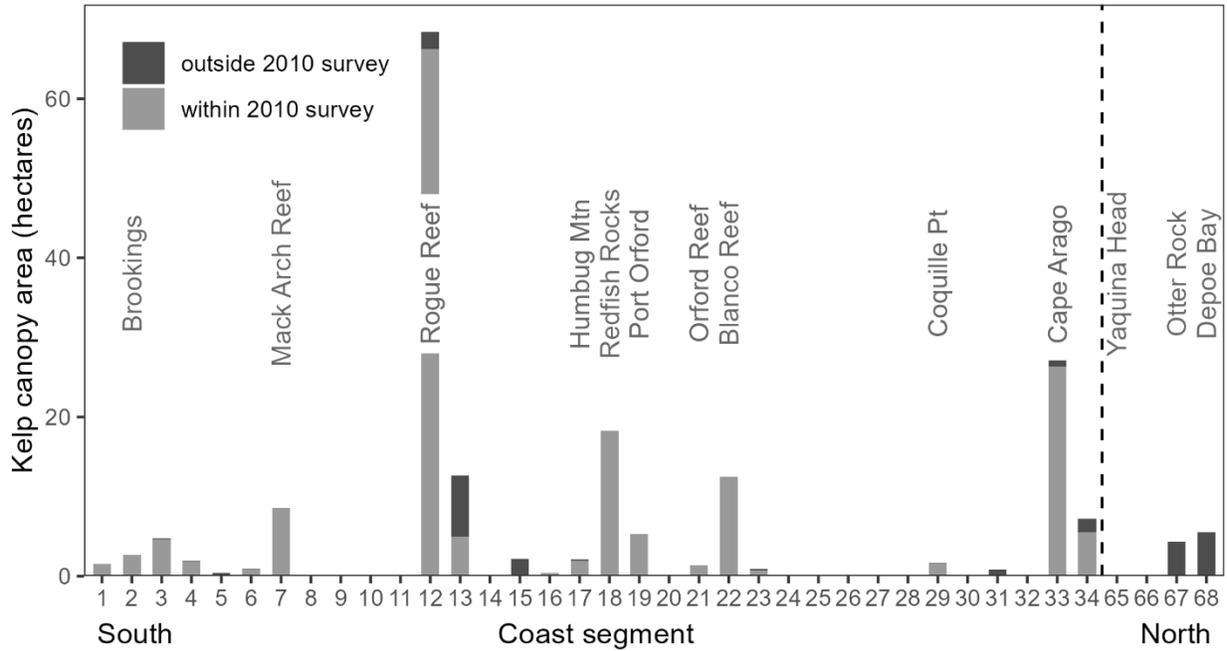


Figure 2: Total area of floating kelp canopy mapped in the 2022 survey. Data are summarized by 5-km coast segments. The stacked bars show the proportion of the 2022 kelp area that was either inside the 2010 survey’s image coverage (representing the data used for quantitative comparisons with 2010) or outside (indicating areas not imaged in 2010). The dashed vertical line represents the geographic gap with minimal habitat for kelp between Cape Arago and the Newport region.

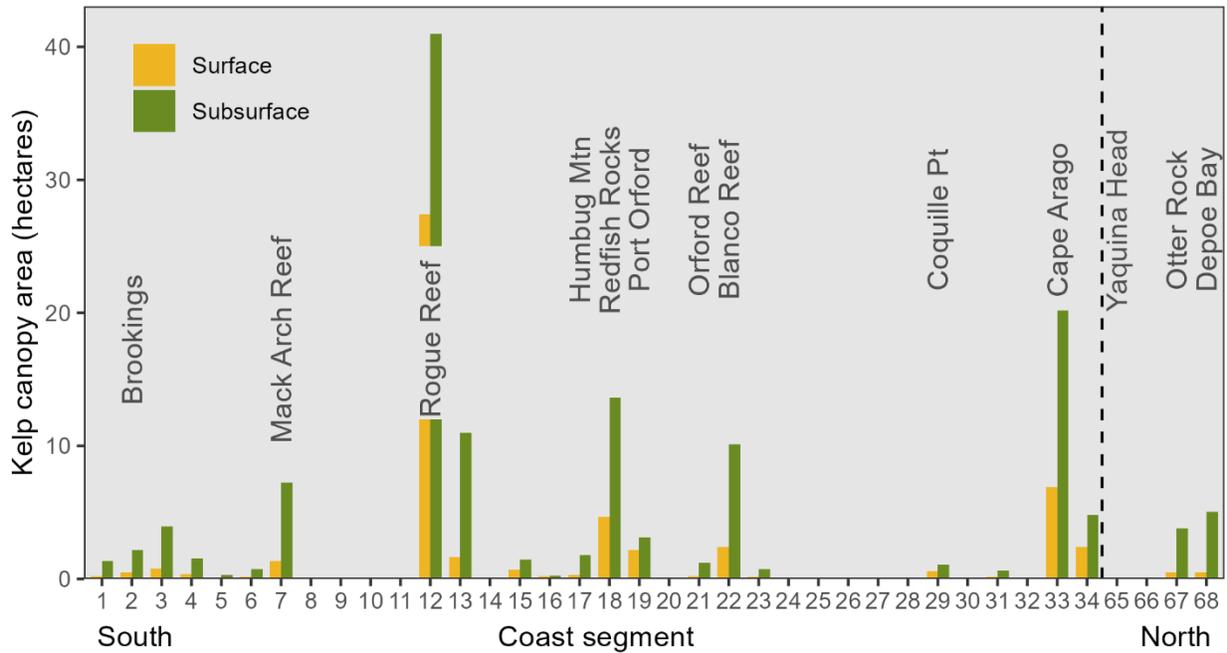


Figure 3: Total area of floating kelp canopy mapped in the 2022 aerial survey, classified as either surface kelp or subsurface kelp according to the spectral characteristics in the images. Data are summarized by 5-km coast segments. The dashed vertical line represents the geographic gap with minimal habitat for kelp between Cape Arago and the Newport region.

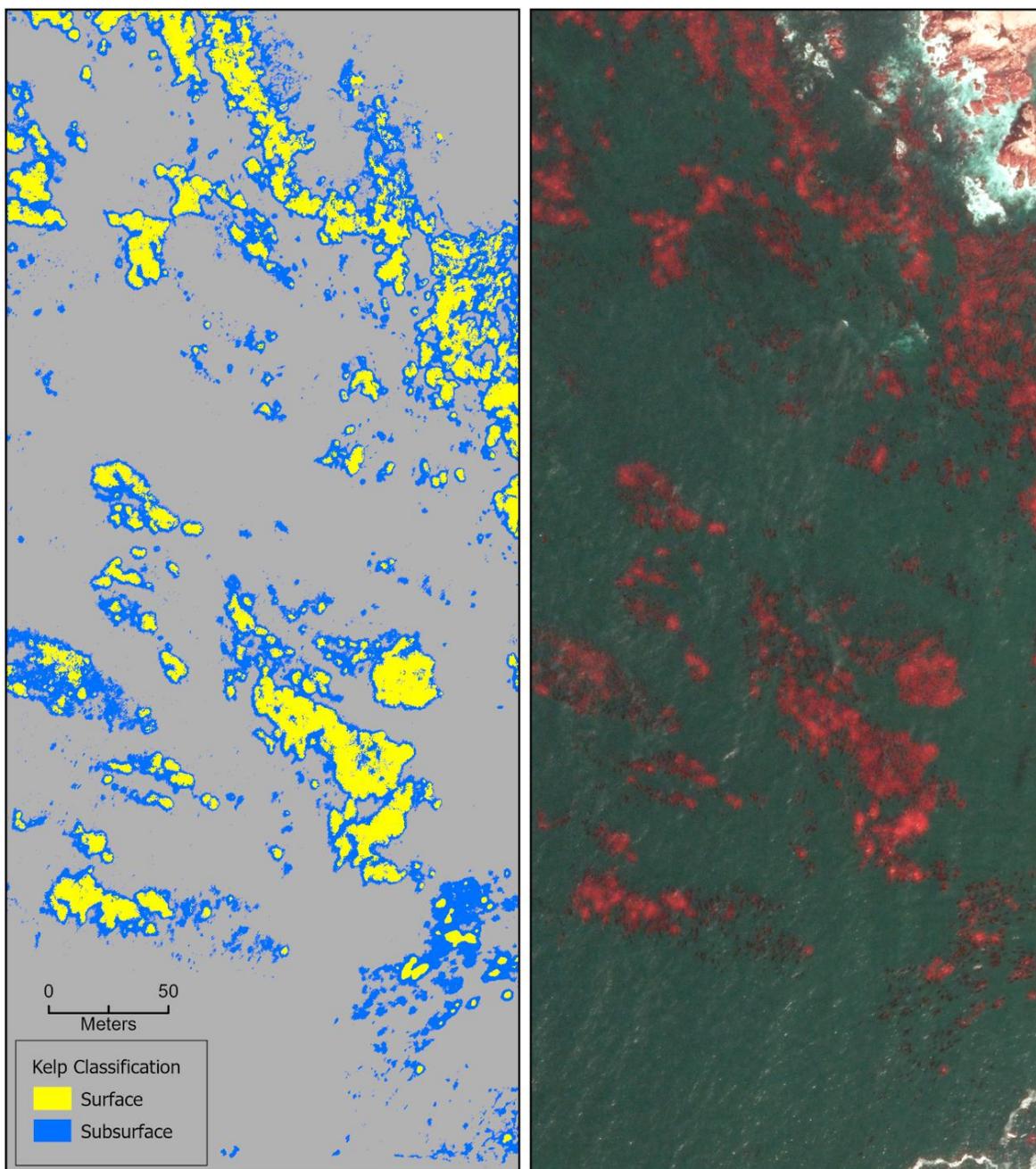


Figure 4: Example of surface/subsurface floating kelp canopy classification (left) relative to the corresponding aerial image (right) The four-band multispectral image is displayed in false color with the near-infrared band replacing the red band to highlight vegetation.

3.2. Kelp abundance and distribution in 2024

The 2024 aerial survey classified a total of 241.4 ha of kelp canopy between the Oregon-California border and the Depoe Bay region (Fig. 5). The kelp forests at Rogue Reef constituted the largest area (58 ha), representing 24% of the 2024 total, followed by Cape Arago (40.1 ha), representing 17% of the 2024 total. Of particular interest was the uncharacteristic abundance on the central coast; Otter Rock (29.4 ha) and Depoe Bay (32.8 ha) accounted for 12% and 14% of the 2024 total, respectively. Kelp was less abundant at the other major reef systems (Orford Reef, Cape Blanco Reef, and Redfish Rocks), each representing less than 10% of the annual total.

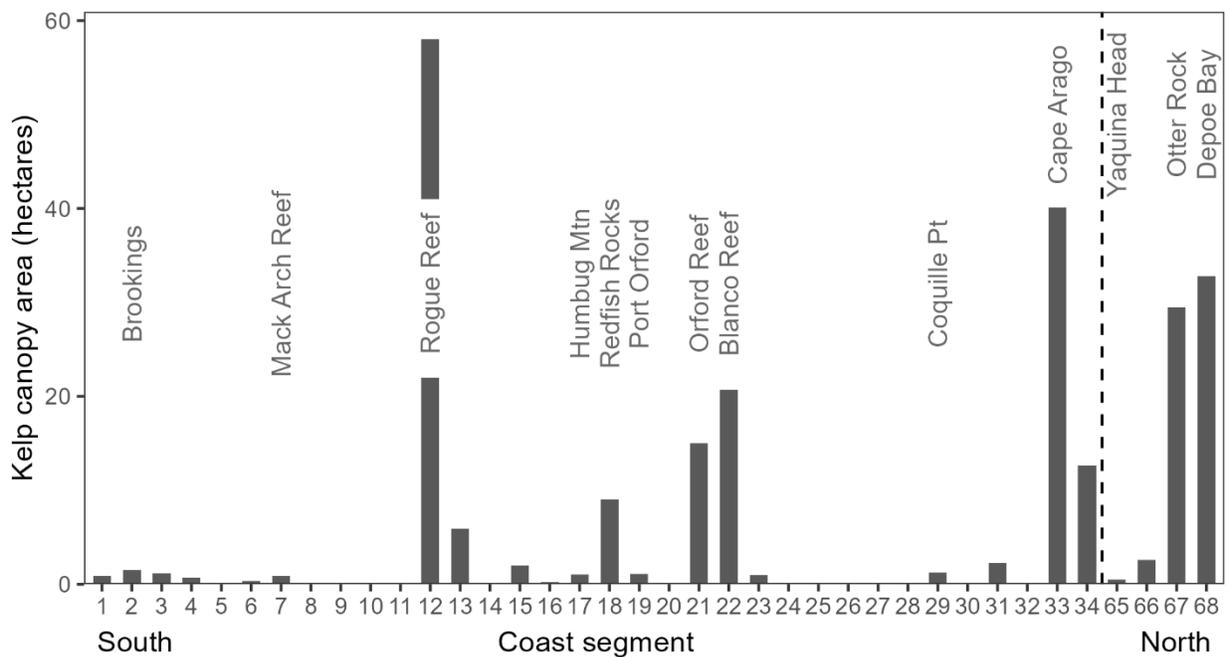


Figure 5: Total area of floating kelp canopy mapped in the 2024 aerial survey. Data are summarized by 5-km coast segments. The dashed vertical line represents the geographic gap with minimal habitat for kelp between Cape Arago and the Newport region.

In 2024, 28% (66.8 ha) of the total kelp canopy was classified as surface kelp, with the remainder (174.6 ha) classified as subsurface (Fig. 6). Every coast segment had substantially more subsurface kelp than surface kelp. The surface-subsurface classification proportion and overall pattern was very similar to the 2022 result.

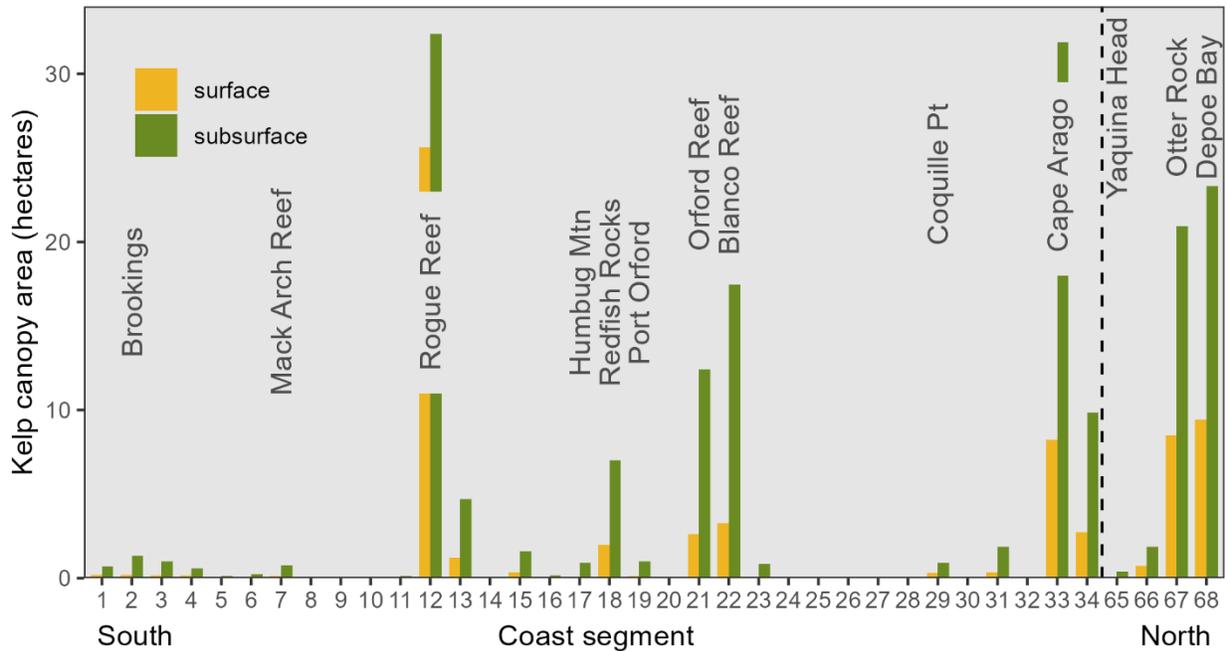


Figure 6: Area of floating kelp canopy mapped in the 2024 survey, classified as either surface kelp or subsurface kelp according to the spectral characteristics in the images. Data are summarized by 5-km coast segments. The dashed vertical line represents the geographic gap with minimal habitat for kelp between Cape Arago and the Newport region.

3.3. Change in kelp abundance and distribution between 2022 and 2024

The 2024 survey, which used the same spatial extent as the 2022 survey, showed an overall 26% increase (50 ha) in kelp canopy area over two years from 2022 (Fig. 7). Appendix F shows maps contrasting the 2022 and 2024 kelp canopy distribution. The kelp forests at Rogue Reef still constituted the largest area in 2024 (as in 2022), but a 10-ha reduction in kelp area there along with an increase in other parts of the coast (notably at Cape Arago and north of Newport) reduced Rogue Reef’s relative contribution from 36% of the total survey’s kelp area in 2022 to 24% in 2024. The increase in the northerly regions shifted the relative balance of kelp along the coast; the total kelp area found along the south coast between Cape Arago and the California border (176.1 ha in 2024) dropped from 95% of the coast-wide total in 2022, to 73% in 2024.

Many locations along the south coast dropped to near-zero amounts of kelp in 2024 (Fig. 7). No segment south of Rogue Reef, including the previous kelp stronghold of Mack Arch Reef, held more than 1.5 ha of kelp canopy in 2024, nor did either Humbug Mountain or Port Orford. There were distinct differences along the coast in the two-year change in kelp abundance between 2022 and 2024 (Fig. 8). Almost every segment from Orford Reef to Depoe Bay had an increase in kelp area, while all segments along the southern part of the coast between Port Orford and the California border featured declines.

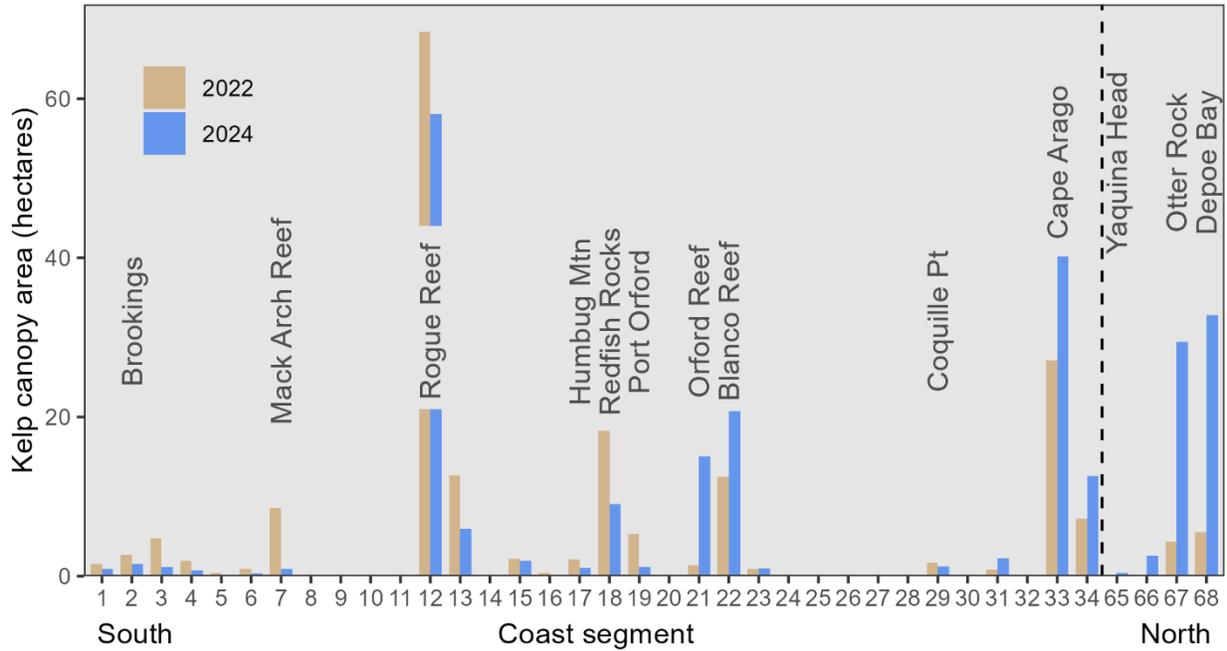


Figure 7: Total kelp canopy area in the 2022 (brown) and 2024 (blue) aerial surveys. Data are summarized by 5-km coast segments. The dashed vertical line represents the geographic gap with minimal habitat for kelp between Cape Arago and the Newport region.

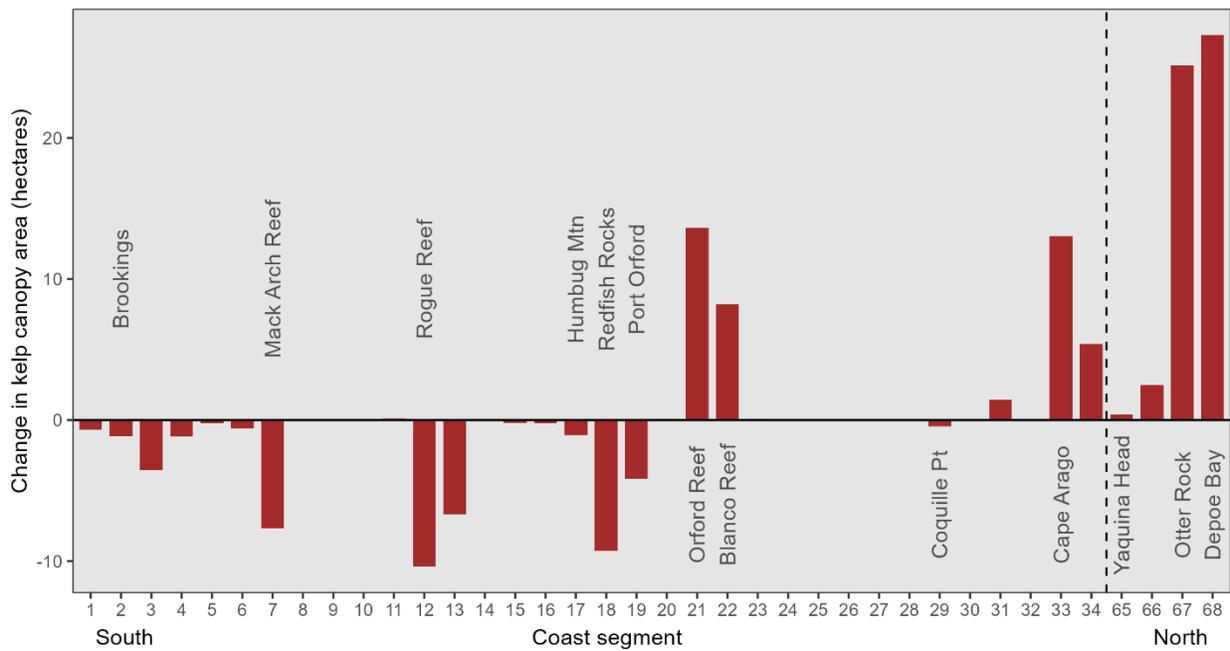


Figure 8: Change in kelp canopy area (ha) between 2022 and 2024. Data are summarized by 5-km coast segments. The dashed vertical line represents the geographic gap with minimal habitat for kelp between Cape Arago and the Newport region.

3.4. Kelp abundance and distribution in 2010

Application of the 5-km coast segment aggregation scheme to the 2010 kelp survey results (Fig. 9) allows quantitative comparison of those results with the 2022 and 2024 surveys. Figure 9 highlights the historically high contribution of Orford Reef to the total kelp abundance; 47% of the total kelp area (274 out of 541 ha) was at Orford Reef. Total kelp abundance was dominated by the large kelp forests at Orford Reef, Cape Blanco Reef, and Rogue Reef, which together constituted 72% of the total mapped kelp area in 2010.

The 2010 survey covered principle kelp-bearing areas, but a few smaller areas that may have had kelp (i.e., shallow rocky substrate) in 2010 were not surveyed. Where kelp existed in the 2022 or 2024 imagery in locations outside the 2010 survey footprint, the corresponding coast segment in Figure 9 is annotated with a "+" symbol, indicating that the actual 2010 total kelp area in that segment may have been slightly higher. If no kelp was seen in the 2022 or 2024 imagery in locations outside the 2010 survey footprint, despite the presence of known or inferred potential kelp habitat, the corresponding coast segment in Figure 9 is annotated with an "x" symbol. This

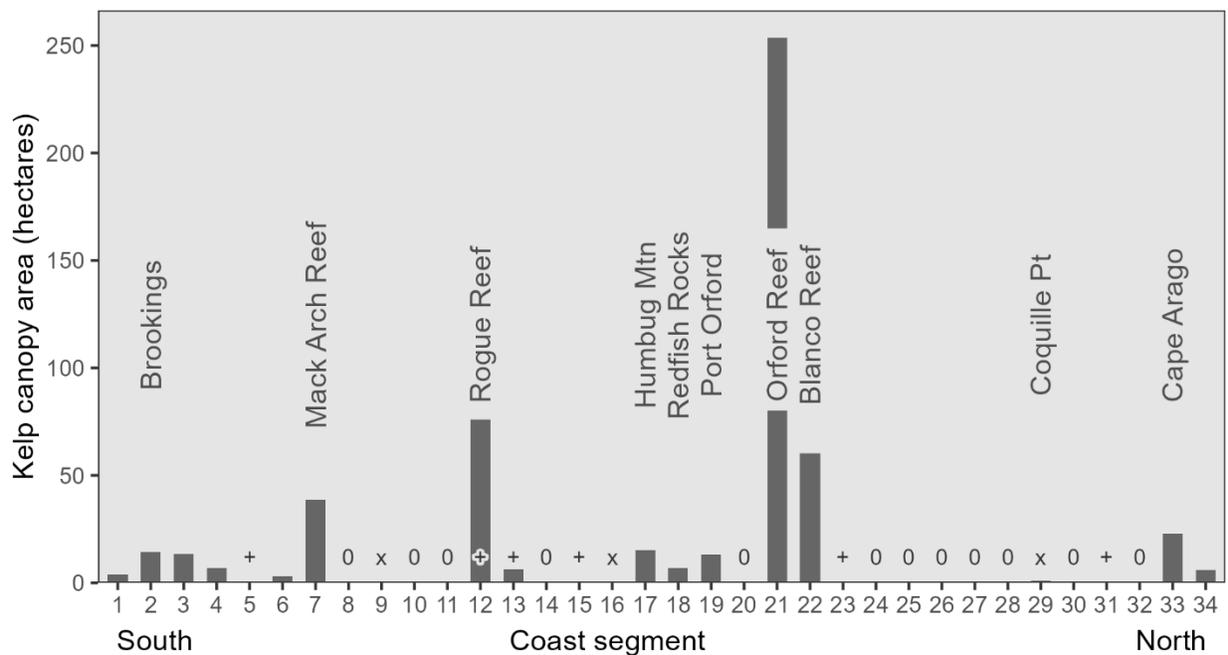


Figure 9: Total area of floating kelp canopy mapped in the 2010 ODFW aerial survey, summarized by 5-km coast segments. Segments with incomplete 2010 survey coverage are annotated as follows: 0 = negligible or no kelp habitat (i.e., very little shallow rocky substrate); x = incomplete 2010 coverage of kelp habitats, and the broader 2022/2024 surveys found no kelp; + = incomplete 2010 coverage of kelp habitats, and the 2022/2024 surveys found additional kelp.

symbol indicates lack of any direct evidence that the 2010 kelp area in the segment was too low (although it is possible that the areas not surveyed in 2010 had kelp that was not present in 2022 or 2024). For areas outside the 2010 survey footprint that are not known to hold any potential kelp habitat (i.e., sandy areas), the corresponding coast segment in Figure 9 is annotated with a “0” symbol, indicating the presumption that no additional kelp outside the survey footprint was present in 2010.

In 2010, 44% of the total kelp area was classified as surface kelp (Fig. 10), compared with 28% for 2022 and 2024. The proportion of surface kelp was lower (26%) at the largest kelp forest area, Orford Reef.

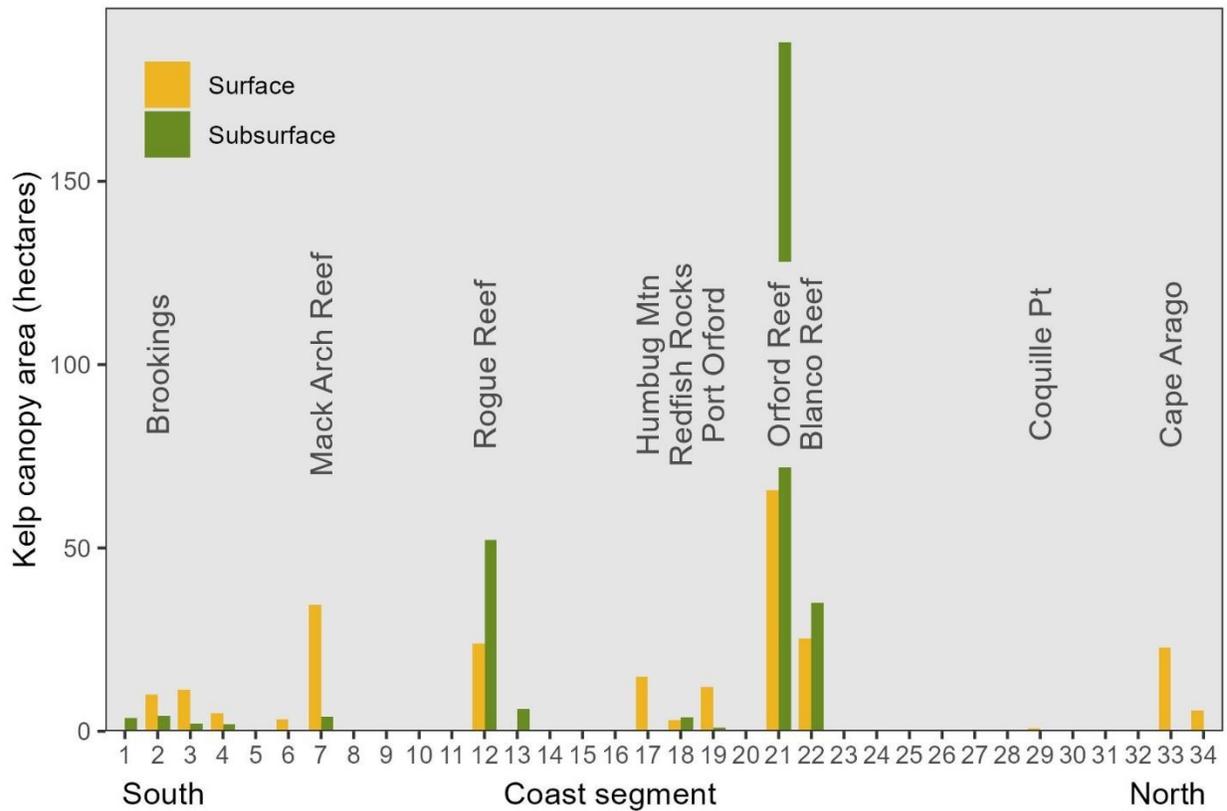


Figure 10: Total area of floating kelp canopy mapped in the 2010 aerial survey, classified as either surface kelp or subsurface kelp according to the spectral characteristics in the images. Data are summarized by 5-km coastal segments.

3.5. Change in kelp abundance and distribution between 2010, 2022, and 2024

Direct comparison of total kelp area (combined surface and subsurface classes) for 2010, 2022 and 2024 within the 2010 survey footprint is provided in Figure 11 and Table 2. The 165 ha of kelp mapped in 2022 within the 2010 survey footprint represents a 69% reduction in total area from the 2010 survey's 541 ha. In areas outside the 2010 survey image coverage at Cape Arago and southward, there were just 16.1 additional hectares of kelp observed in 2022 (approximately 3% of the 2010 total), and 14.8 ha in 2024, indicating that the 2010 survey was near-comprehensive for the section of the coast that it covered. The near-complete loss of the previously massive kelp forest at Orford Reef was by far the largest component of the 2010 - 2022 reduction, but large losses were also observed at the nearby Cape Blanco Reef, as well as at Mack Arch Reef and along the south coast near Brookings. In contrast, kelp persisted or even increased within three coast segments at Cape Arago, Redfish Rocks, and Rogue Reef. The change in total kelp abundance by coast segment between 2010 and 2022/2024 is provided in Table 2.

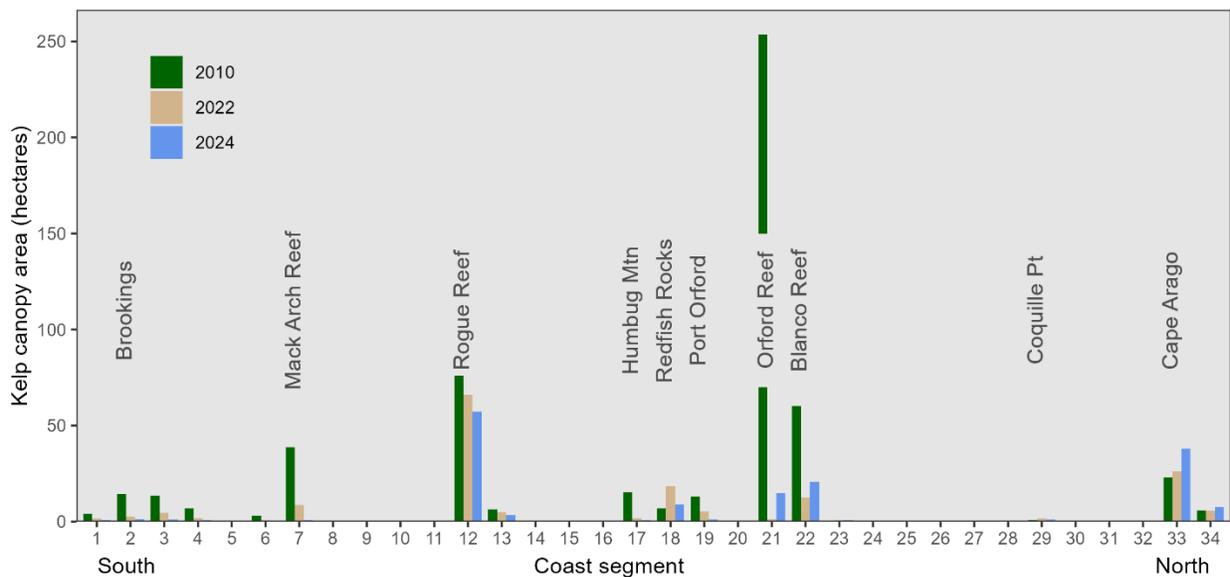


Figure 11: Kelp canopy area (ha) in 2010, 2022, and 2024, limited to the extent of the 2010 survey's image coverage between the California border and the vicinity of Cape Arago. Data are summarized by 5-km coast segments. See Figure 7 for the full extent of the 2022 and 2024 surveys.

The modest increases between 2022 and 2024 at a few sites along the south-central coast did not change the overall picture of kelp loss; over the entire 2010 – 2024 study period, kelp abundance within the image coverage of the 2010 survey (Cape Arago southward) decreased by 70%, from 541 ha to 160 ha, a loss of 381 ha (Table 2, Fig. 12).

Table 2: Floating kelp canopy area by survey year and coast segment (see segment locations in Figure 1). Change in kelp area was calculated only for the portion of the 2022/2024 survey coverage that was within the 2010 image coverage. "NA" indicates the 2010 survey did not include the segment. Segments south of Cape Arago not represented in the table (segments 8 - 11, 14, 20, 24 - 28, 30, and 32) all have minimal shallow rocky seafloor and no kelp was observed in 2010, 2022, or 2024.

Seg. #	Seg. name	Total kelp area (ha)			Kelp area (ha) within 2010 image coverage				Kelp area (ha) outside 2010 image coverage	
		2010	2022	2024	2022	2024	2010 – 2022 change	2010 – 2024 change	2022	2024
1		4.1	1.5	0.9	1.5	0.9	-2.5	-3.2	0.0	0.0
2	Brookings	14.2	2.7	1.5	2.6	1.4	-11.6	-12.8	0.1	0.1
3		13.4	4.7	1.1	4.7	1.1	-8.8	-12.3	0.1	0.0
4		6.8	1.9	0.7	1.9	0.7	-5.0	-6.1	0.0	0.0
5		NA	0.4	0.1	NA	NA	NA	NA	0.4	0.1
6		3.2	0.9	0.3	0.9	0.3	-2.3	-2.8	0.0	0.0
7	Mack Arch	38.6	8.6	0.9	8.6	0.9	-30.0	-37.7	0.0	0.0
12	Rogue Reef	76.0	68.3	58.0	66.2	57.3	-9.8	-18.7	2.1	0.7
13		6.4	12.6	5.9	5.0	3.4	-1.4	-3.0	7.6	2.5
15		NA	2.2	2.0	NA	NA	NA	NA	2.2	2.0
16		0.0	0.4	0.2	0.4	0.2	0.4	0.2	0.0	0.0
17	Humbug Mtn.	15.2	2.1	1.0	1.9	0.7	-13.3	-14.5	0.2	0.3
18	Redfish Rocks	6.9	18.3	9.0	18.3	9.0	11.4	2.1	0.0	0.0
19	Port Orford	13.0	5.3	1.1	5.3	1.1	-7.7	-11.8	0.0	0.0
21	Orford Reef	253.7	1.4	14.9	1.4	14.9	-252.3	-238.8	0.0	0.0
22	Blanco Reef	60.2	12.5	20.6	12.5	20.6	-47.7	-39.6	0.0	0.0
23		0.0	0.9	0.9	0.7	0.8	0.7	0.8	0.1	0.1
29	Coquille Pt.	0.8	1.7	1.2	1.7	1.2	0.9	0.4	0.0	0.0
31		0.0	0.8	2.1	0.0	0.0	0.0	0.0	0.8	2.1
33	Cape Arago	22.8	27.1	40.1	26.3	37.9	3.5	15.1	0.8	2.2
34		5.9	7.2	12.2	5.6	7.6	-0.3	1.8	1.6	4.6
Segs 1 – 34 TOTAL		541.2	181.5	174.8	165.4	160.1	-375.9	-381.2	16.1	14.8
64		NA	0.0	0.4	NA	NA	NA	NA	0.0	0.4
65	Yaquina Head	NA	0.1	0.5	NA	NA	NA	NA	0.1	0.5
66		NA	0.1	2.6	NA	NA	NA	NA	0.1	2.6
67	Otter Rock	NA	4.3	29.4	NA	NA	NA	NA	4.3	29.4
68	Depoe Bay	NA	5.5	32.8	NA	NA	NA	NA	5.5	32.8
Segs 64 – 68 TOTAL			10.0	65.6					10.0	65.6
All segs TOTAL			191.4	241.4					26.1	80.4

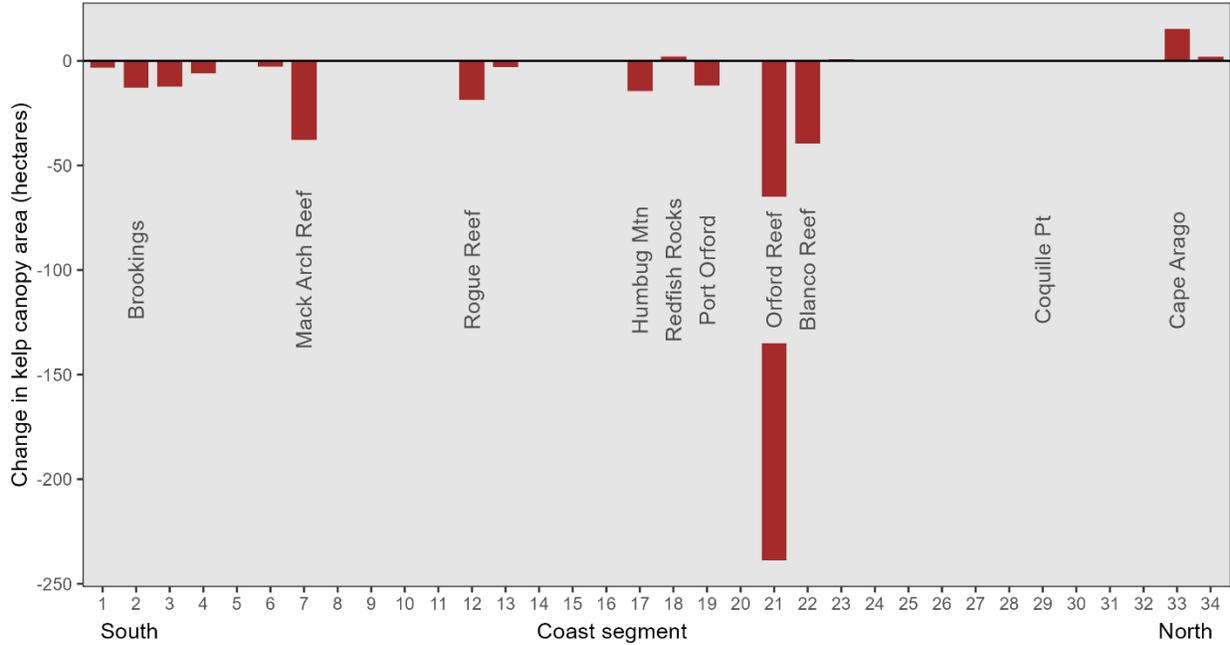


Figure 12: Change in kelp canopy area (ha) between 2010 and 2024, limited to the extent of the 2010 survey’s image coverage between the California border and the vicinity of Cape Arago. Data are summarized by 5-km coast segments.

In addition to changes in total abundance, examination of the location of kelp present in 2010 and 2022 reveals substantial spatial shifts in kelp distribution between years, even within individual kelp forests. Appendix G provides maps contrasting the kelp canopy (surface and subsurface kelp combined) for 2010 and 2022 showing each year and the area shared in the two years. Appendix H provides similar maps contrasting 2010 and 2024. Figure 13 presents examples at four key sites contrasting the kelp distribution in 2010, 2022, and 2024. A common pattern emerged across multiple regions, with surprisingly little kelp area shared between the two surveys even in regions that retained a similar total abundance of kelp. At Rogue Reef in particular, there was a shoreward and shallower shift in distribution at the main reef complex. Furthermore, the 2022 (and 2024 in some cases) distributions frequently featured a broader spread of patchy kelp, often in a shallower and/or more shoreward location.

3.6. Comparison with 1990s kelp surveys

Maps showing examples of the comparative distribution of kelp canopy in 1996, 1999, 2010, 2022, and 2024 are presented in Figure 14.

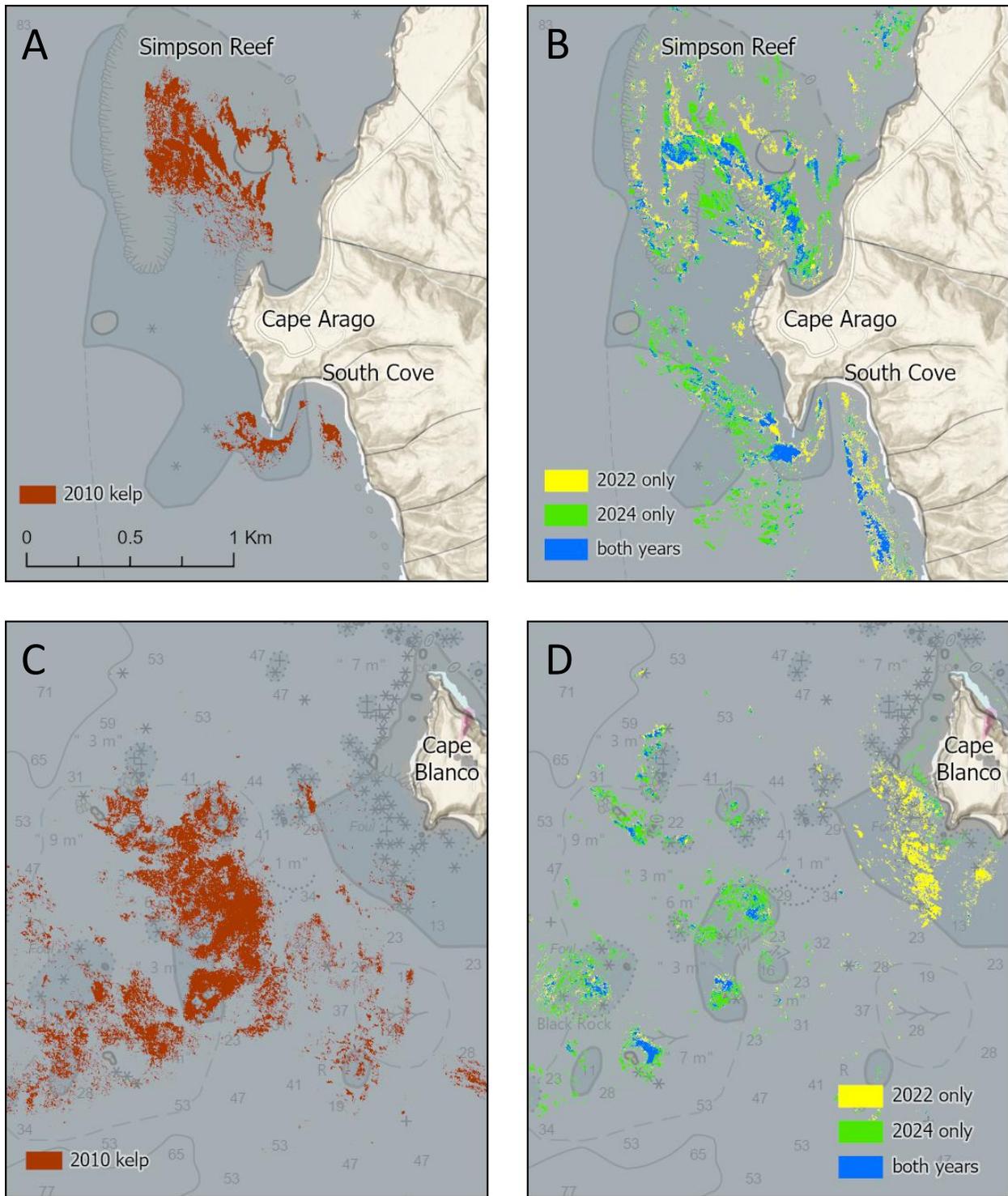


Figure 13: Floating bull kelp canopy distribution in 2022 and 2024 (right panels) relative to the prior ODFW aerial survey in 2010 (left panels) overlaid on a nautical chart. Panels A and B: Cape Arago Reef (near Coos Bay). Note that a small area of giant kelp (*Macrocystis pyrifera*) was present at Simpson Reef in 2010. Panels C and D: Cape Blanco Reef (near Port Orford). Scale is constant across panels. (continued on next page)

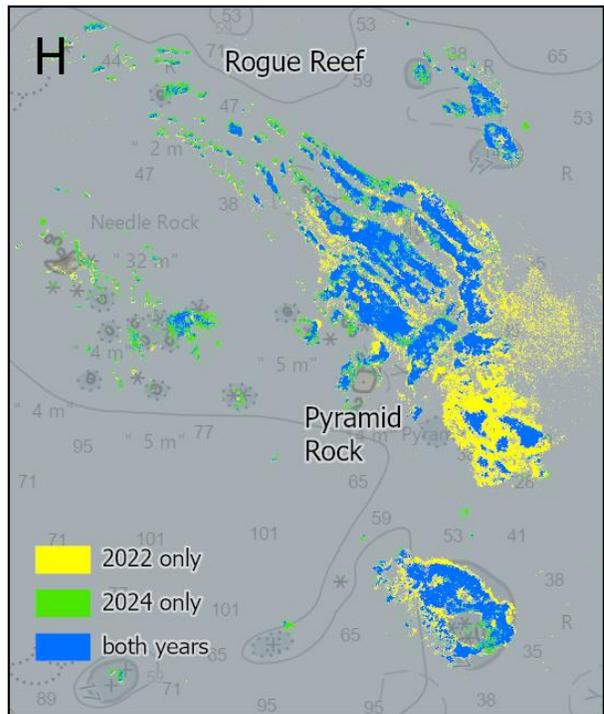
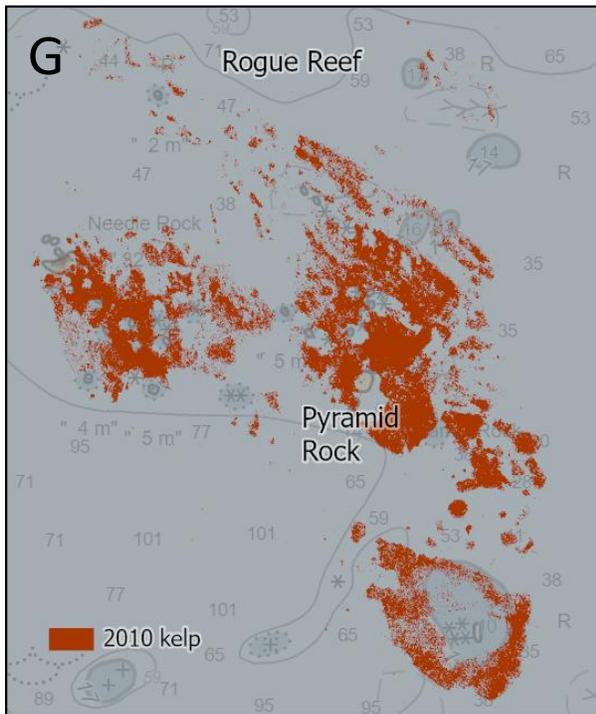
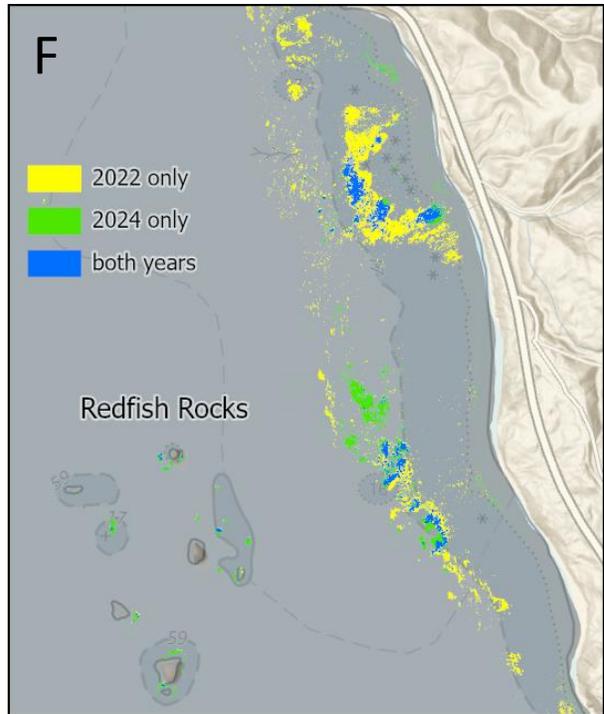
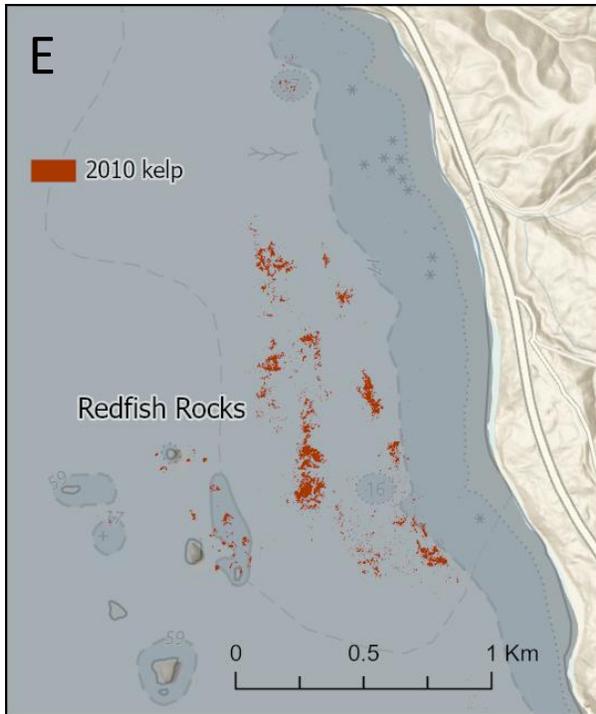


Figure 13 (continued): Floating bull kelp canopy distribution in 2022 and 2024 (right panels) relative to the prior ODFW aerial survey in 2010 (left panels). Panels E and F: Redfish Rocks (near Port Orford). Panels G and H: Rogue Reef (near Gold Beach). Scale is constant across panels.

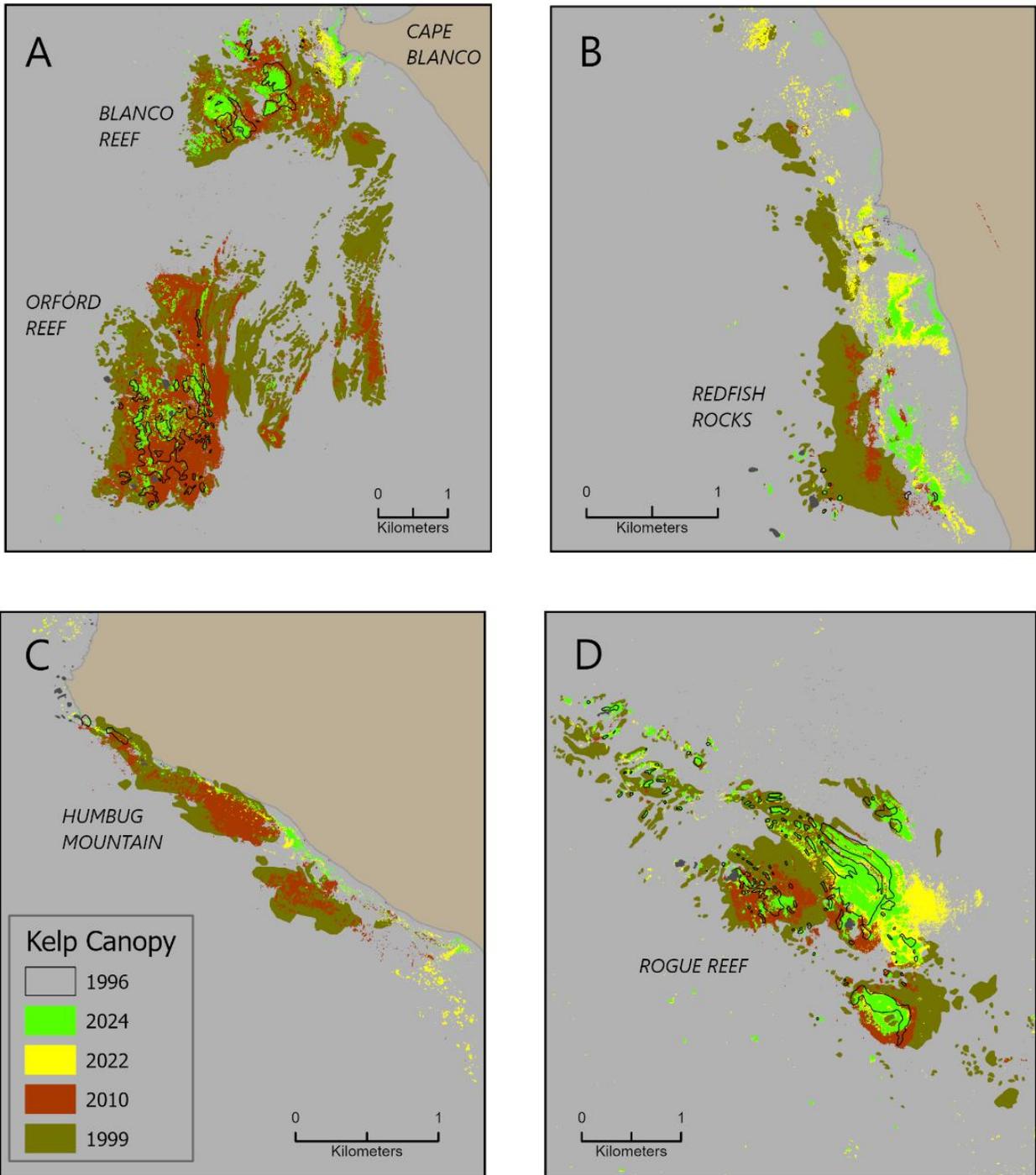


Figure 14: Kelp canopy distribution changes at four south coast regions across five select years of ODFW surveys. Layers are displayed (opaquely) in the order shown in the legend to maximize their visibility, with 1996 on top because it had the smallest coverage. The 1996 and 1999 kelp beds were hand-delineated from photographic prints, while the 2010, 2022 and 2024 kelp beds were digitally classified from digital images (see Methods). Also see Appendices and Figure 13 for detailed comparisons.

4. DISCUSSION

The 2022 and 2024 aerial surveys of Oregon's floating kelp canopy found 191 and 240 hectares, respectively, of kelp visible from the air, representing a dramatic reduction from the prior survey conducted in 2010. Within the limits of the image coverage jointly assessed by all three surveys, this represents an approximately 70% reduction across the 14-year study period from 2010 to 2024. This reduction was dominated by the near-total loss of the state's largest kelp bed at Orford Reef, which had constituted almost half of the 2010 survey's 541 ha total area. Other locations retained more kelp across the study period but exhibited within-reef distributional shifts with remarkably little area in common between the surveys, illustrating the highly dynamic nature of this annual kelp's distribution. The areas retaining relatively more kelp included Cape Arago, Redfish Rocks, and Rogue Reef (although Rogue Reef had declined 25% by 2024).

There was a striking regional coherence in the direction of kelp change between 2022 and 2024 (Fig. 8, showing area loss in the south and expansion in the north). The mechanisms causing coherence are unknown, but the pattern suggests sensitivity to broad-scale oceanographic factors, consistent with Oregon's nearshore oceanographic context in which the geomorphology of Cape Blanco plays a prominent role in separating upwelling and transport regimes to the north and south (Barth et al. 2000). Equally notable is just how small the remaining kelp area in the southern part of the coast became by 2024. Many locations along the south coast held almost no kelp in 2024 (Fig. 11, Table 2). No segment south of Rogue Reef, including the previous kelp stronghold of Mack Arch Reef, held more than 1.5 ha of kelp canopy in 2024, nor did either Humbug Mountain or Port Orford. The consequences of the low regional kelp abundance across the far south coast are unknown, but seem likely to include low future patch recolonization rates due to limited density of spores dispersing from sources within the region. The current low abundance highlights the importance of better understanding the relationship between spore supply and yearly kelp recruitment along Oregon's open coast.

4.1. Mechanisms contributing to declines in kelp abundance

Comparisons with the 2010 kelp abundance provide a reference point for understanding changes across the decade that included the regionally influential 2014 – 2016 marine heat wave (Siedlecki et al. 2016), a dramatic increase in purple sea urchin (*Strongylocentrotus purpuratus*) abundance (Groth 2023), and a second marine heat wave in 2019 (Amaya et al. 2020). These multiple processes make it difficult to infer the relative importance of the mechanisms affecting kelp abundance, and in fact our study is not intended to draw conclusions about the individual effects of marine heat waves or sea urchin grazers. Additionally, it is important to recognize that historic observations from as recently as 1999 indicate a much more expansive potential distribution of bull kelp, meaning that 2010 did not represent a particularly high point in kelp abundance against which to compare the modern abundance. In this context, the recent

observation of only 240 hectares of kelp across almost all of Oregon's kelp-bearing coastline represents a very low-abundance condition relative to bull kelp's potential distribution. Additional work is necessary to quantitatively compare this abundance with 1996 (previously the lowest observed year) at select south coast reefs where data is available from the 1990s surveys.

This study did not explicitly examine ecological factors potentially responsible for the decrease in kelp abundance since 2010. However, data from ODFW surveys show a dramatic, historically unprecedented explosion of kelp-grazing purple sea urchins at Orford Reef during this period (Groth 2023). The enabling conditions for the high abundance of purple sea urchins included a marine heat wave (Rogers-Bennett and Catton 2019) and a coast-wide extirpation of a primary sea urchin predator, the sunflower sea star *Pycnopodia helianthoides*, due to Sea Star Wasting Syndrome (Gravem et al. 2021, Hamilton et al. 2021) concurrent with and extending beyond the marine heat wave. While regional sea urchin density change is well quantified at select index sites (Groth 2023), the spatial extent of high purple sea urchin densities across the coast is not well delineated. Spatially broader sea urchin data in close proximity to both declining and persisting kelp sites would be helpful in relating urchin densities to kelp changes. Such data could also help address the question of what factors enable kelp to persist despite the presence of locally high sea urchin densities. Ongoing work at ODFW is seeking to better understand purple sea urchin abundance across the kelp-bearing regions of the south coast.

Despite widespread warmer waters during the past decade, cursory examination of temperature records from available offshore buoys along the Oregon coast do not clearly indicate substantial exceedance of critical thermal thresholds for bull kelp. Documented thresholds include 18 °C for germination failure (Muth et al. 2019), 16 – 18 °C for reduced/eliminated production of microscopic sporophytes (Weigel et al. 2023), and between 16 and 21 °C for adult sporophyte blade metabolic stress (Fales et al. 2023). Temperature may also interact with nutrient availability to affect bull kelp performance (Fales et al. 2023), and long-term temperature changes well below characteristic stress thresholds have been shown to lead to dramatic reductions in bull kelp abundance (Schiel et al. 2004). In fact, the warm water temperatures associated with recent northern California bull kelp declines had a mean near 14 °C and peaked at 17.4 °C (Rogers-Bennett and Catton 2019). In Washington, kelp canopy reductions on the open coast were associated with only brief exceedance of 16 °C mean temperatures (Claar et al. 2025). As both temperature and nutrient supply are tightly correlated with upwelling events (Garcia-Reyes et al. 2014), nutrients may be an important part of the mechanism by which marine heat waves affect bull kelp in our region, with temperature potentially being an indicator variable rather than a primary direct stressor. Ocean temperature could potentially also have indirect effects via the influence of oceanographic variables on invertebrate recruitment (e.g., sea urchins, sea stars, encrusting organisms that compete for benthic settlement space) and algal epiphytes. In addition to a better understanding of the thermal responses of Oregon's populations of bull kelp (which may be distinct from better-studied Salish Sea populations), more data on water temperature at kelp-bearing shallow reefs (as opposed to offshore buoy data) is needed to determine whether temperatures may have direct effects on kelp abundance. Globally, ocean

warming is having increasing effects on kelp ecosystems (Smale 2020), especially for species like bull kelp that are near the warm edge of their species' distribution (Shi et al. 2026)

Bull kelp is an annual species that exhibits high interannual variability in abundance. The mechanisms that produce this variability off Oregon are poorly understood, but potentially include the magnitude and timing of spore production, the physical processes that affect the transport of spores and sori (the spore-producing structures located along the blades of the adult sporophytes) and the resulting location and extent of spore retention on shallow rocky reefs, competition for settlement space on suitable rocky surfaces, survival of developing gametophytes, and environmental factors such as water clarity and temperature that may affect sporophyte growth and eventual surface expression. The implication of high variability is that trends in abundance are difficult to detect, and this study's comparison of two years separated by over a decade cannot be interpreted to imply a steady trend of loss.

4.2. Factors affecting potential kelp recovery

Despite this study's overall observation of dramatic reductions, rapid increases in kelp abundance have been noted in the past, including a remarkable six-fold expansion to a potentially historic high point in the Depoe Bay region between 2022 and 2024. Anecdotal site-specific observations suggest the 2023 abundance in this region was even higher than that documented in 2024, implying an exceptional one-year increase between 2022 and 2023. Likewise, in prior studies (Fox et al. 1996, Fox et al. 1999) ODFW documented a dramatic increase at select south coast reefs between 1996 and 1999, when major reef systems increased from the lowest to the highest abundance recorded. These observations demonstrate bull kelp's capacity for rapid abundance and distributional changes when conditions allow and when spore sources are available.

The current low kelp abundance, however, can be expected to limit the rate of kelp recruitment by reducing spore availability. Burnett et al. (2024) modeled coastal spore transport in bull kelp using bimodal release heights and predicted two clusters of dispersal distances. Spores released from abscised sori on the seafloor were predicted to disperse mostly less than 1 m from the source (median distance of 0.75 m, with some traveling many kilometers). Spores released from intact sporophytes in the surface canopy were predicted to disperse between 100 m and 20 km (median 2.2 km). They predicted 34% of bull kelp spores settling within 10 m, twice the proportion found for giant kelp (*Macrocystis pyrifera*), a perennial species, and concluded that local retention is more important for local population persistence of bull kelp than for giant kelp. They also highlight the expectation, deriving from the work in Reed et al. (2006) on giant kelp, that kelp spore supply increases with proximity to large extant kelp forests. Along with the observation that a minimum density of spores is necessary to allow the subsequent gametophyte (sexually reproductive) life stage to successfully generate new sporophytes, these analyses suggest that kelp regrowth for very large reef systems largely denuded of kelp (like Orford Reef, spanning > 5 km) will likely face spore supply constraints. Meanwhile, the

potentially long-term persistence of purple sea urchin grazers may continue to constrain kelp recovery at urchin-dominated sites. Together, these factors suggest currently little likelihood of bull kelp abundance naturally increasing rapidly along the south coast, compared to historical observations of rapid kelp bed expansion.

4.3. Distributional shifts and inferences about mechanisms driving kelp distribution

The observed spatial shift in the location of kelp beds in 2022 and 2024 relative to 2010 may provide useful insights to help infer what ecological mechanisms are controlling bull kelp abundance and distribution, or at least to generate hypotheses that could be further investigated. The working hypothesis explaining the decade's kelp loss is that a large pulse of purple sea urchins (Groth 2023), released from predation by the sunflower sea star which was extirpated by Seastar Wasting Syndrome (Gravem et al. 2021), grazed down the kelp. This mechanism was well supported in explaining the kelp loss in nearby northern California (Rogers-Bennett and Catton 2019), and could contribute to direct consumption of kelp sporophytes, kelp loss due to severed stipes, and subsequent limitation of the spore production that annually drives kelp forest regeneration. In Oregon, observations of abundant purple sea urchins are consistent with grazer constraints on local kelp abundance, most dramatically documented at Orford Reef where divers observed historically high purple urchin abundance (Groth 2023) while the kelp canopy was essentially lost (this study).

However, grazing effects alone cannot fully explain the distributional shifts in kelp beds observed in 2022 and 2024. Several sites show kelp appearing in 2022 and 2024 in locations that did not hold kelp in 2010, and sometimes did not hold kelp even in 1999. Examples are evident for Cape Arago (Fig. 13 C and D), Redfish Rocks (Fig. 13 E and F; also Fig. 14 B), Humbug Mountain (Fig. 14 C), and Rogue Reef (Fig. 13 G and H; Appendix G shows additional kelp in 2022 extending beyond the area shown in Fig. 13 H). We interpret these observations as examples of spore dispersal varying among years and resulting in different suitable habitat patches being occupied each year. While sea urchin grazing may explain the absence of kelp in a particular patch, spore dispersal is necessary to explain the appearance of kelp in a patch of suitable habitat that was uninhabited the year before (assuming that grazer distributions are not also shifting rapidly among years). As kelp cannot evade grazing sea urchins, there is no obvious grazing-related mechanism that would result in kelp bed expansion/relocation as we see in 2022.

The observation that spatial patterns of distribution shift among years (as opposed to simply expanding and contracting within a stable area) highlight the influence of physical processes affecting the release, transport, retention, and settlement of kelp sori and/or spores. These processes may include a variable wave climate affecting the timing of release of sori from mature kelp sporophyte blades, variable transport of sori before deposition, potential resuspension of sori on the seafloor, and a highly variable tidal flow that could carry spores in

many directions. This net transport, potentially affected by multiple factors with high inter-annual variability, could help explain the kelp spatial shifts that varied among locations among the three years of this study.

In addition to grazing and spore dispersal, depth may affect kelp's changing distribution. While we did not conduct an explicit depth analysis, many of the areas that lost kelp since 2010 are deeper than those holding "new" kelp. On its own, this observation raises the question of whether light limitation (implicitly due to reduced water clarity) at deep sites, or possibly other depth-related physiological constraints, may have constrained kelp development in 2022/2024 relative to 2010. Data to relate any changes in light availability at depth to kelp changes is currently lacking, so at present this idea cannot be rigorously evaluated. Still, if light availability was constraining kelp to shallow areas, the question arises why the "new" shallow regions holding kelp in 2022/2024 were not already populated with kelp in 2010, if they represent lower-stress areas for kelp. Future observational and experimental investigation of the roles of spore transport and physiological limitation at reef sites along the Oregon coast would be useful in understanding the factors constraining bull kelp abundance and distribution.

4.4. Methodological considerations affecting kelp detection and classification

The difference in proportions of surface and subsurface kelp between the 2010 and 2022/2024 surveys is likely to be influenced by the difference in image resolution between the surveys and probable differences in the kelp classification algorithms used. The analyses conducted in 2010 using 1 m pixels were less likely to be able to segregate subsurface vs subsurface kelp, compared to the more advanced analyses conducted in 2022 and 2024 using 0.23 m pixels, particularly for the small, patchy kelp distribution generally seen in locations outside Oregon's major reef systems.

Additionally, the 2022 and 2024 images were collected mostly at higher water levels, potentially resulting in a higher proportion of subsurface kelp classification and less overall kelp detected (Timmer et al. 2024). Further, water level is not the only consideration in whether kelp is classified as surface or subsurface. Faster currents (which can be especially prevalent for the offshore shoals at Orford, Cape Blanco, and Rogue reefs due to their location and exposure) can quickly submerge the bull kelp canopy even where the length of the stipes is much greater than the water depth (Britton-Simmons et al. 2008, Timmer et al. 2024). Similarly, calm conditions can allow the blades to lay flat at the surface, maximizing the near-IR spectral returns, while wavy conditions can cause more blades to be pushed below the surface, with only the portion near the pneumatocyst exposed. Further complicating the relationship between water level, currents, and kelp detectability, bull kelp blades themselves are not buoyant but are brought near the surface by the pneumatocyst and held horizontally by moving water. During tidal periods of low current, blades can hang more vertically in the water column, reducing the area at the surface and therefore the infrared reflectivity and the likelihood of classification as kelp.

Consequently, caution should be taken in making any ecological inferences from the surface/subsurface classifications, especially in comparisons across surveys. Rather, these classifications may be useful in identifying core and fringing portions of beds, or shallower and deeper areas, where the two categories are present. Generally, we analyze overall kelp abundance as the sum of the surface and subsurface components. This is an important distinction from other kelp classification methods (e.g., satellite imagery) that rely more heavily on the infrared signal and therefore are likely to produce results most similar to this survey's surface-only classification.

Regarding the impact of high water levels and increased image resolution on the total kelp canopy area in 2022/2024, we consider the total kelp canopy area metric to be less sensitive than the surface vs. subsurface classification to these survey changes, but the potential for methodological bias toward lower abundance for the 2022/2024 surveys does exist. Quantifying the magnitude of this potential bias relative to the expected high interannual variation in kelp abundance is an important topic for future work. Aggregating and reclassifying the 2022/2024 images at 1 m resolution, restricting to sites where water levels were most similar across surveys, and comparing the resulting change from 2010 with the change reported in this study may provide insights into any methodological bias. Additional research into the detectability of floating kelp at Oregon's primary kelp forests under different field conditions (water depth, current speed, wave condition) is warranted to improve the accuracy of kelp abundance comparisons across existing and future surveys.

4.5. Comparison with 1996- 1999 ODFW aerial kelp survey data

At Orford Reef, the small amount of kelp present in 2022 and 2024 had some overlap with the distribution observed in the lowest prior year, 1996, suggestive of core "refuge" areas in the interior portion of the shallow reef system. Likewise at nearby Cape Blanco Reef, there was some interior remnant reef area, but in 2022 and 2024 kelp also occupied a very nearshore area that had not served as a refuge in 1996. At Redfish Rocks, a substantial shoreward shift is apparent in the 2022 and 2024 distributions, a pattern that was not shared in the 1996 low-abundance year. It is particularly striking that 2022's "stable" total kelp abundance in this region (stable compared to 2010, at least) masks a major shift in distribution to shallow nearshore areas that were not occupied even in the high-abundance years of 1990 and 1999, and the disappearance of kelp from portions of the area's shores (e.g., the coves near Port Orford). This shoreward shift, which was also observed in 1998, is suggestive of a physical transport mechanism that may have deposited kelp spores closer to shore than was previously observed in the region. Rogue Reef shared an element of the above patterns, with several core regions persisting that were also occupied during the 1996-1998 low kelp years there, and also an inshore shift in abundance not seen in prior surveys.

Comparison of this study's results with those from the 1996-2000 ODFW surveys is limited at present to comparing only the location and extent of kelp canopy, rather than quantitative

comparison of kelp canopy area, because those early surveys used different kelp classification methods. Future work is planned to develop appropriate calibration methods allowing direct quantitative comparison across the surveys. Additional material summarizing the prior ODFW survey approaches and preliminary work comparing among various kelp data sources is available through ODFW's [Marine Habitat Project website](#).

4.6. Comparison with other sources of kelp abundance data

The development of kelp mapping methods using image data from satellites, including Landsat (Bell et al. 2020, Hamilton et al. 2020) and Planet (Kavanaugh 2026) has provided valuable resources for examining long term changes in kelp distribution. In particular for LandSat, KelpWatch (Bell et al. 2023) has provided an accessible portal to kelp abundance data that is particularly valuable for time periods before aerial surveys were available and for parts of the world where more high-resolution imagery is not available. Recent attention to this resource (e.g., Frieder et al. 2025) has highlighted contrasts among various sources of kelp distribution data. Reshitnyk et al. (2023) and others (e.g., Cavanaugh et al. 2021, Schroeder et al. 2019) have provided excellent summaries of considerations appropriate to various kelp mapping approaches, which are not necessary to duplicate here except to briefly address issues pertaining to differences between this study's results and patterns observed in the KelpWatch data.

Comparison of total kelp abundance estimates for Oregon from KelpWatch with this study's results shows a substantial difference in magnitude, with ODFW's estimates on the order of 20-fold higher. This scale discrepancy is partially explained by a number of factors. First, the features of the kelp bed mapped by the two approaches are different. Whereas the aerial surveys target all floating kelp canopy visibly detectable from the air, KelpWatch's detection algorithm explicitly targets only emergent kelp, the portion of bull kelp's stipes, pneumatocysts, and blades that physically break the water's surface and therefore provide strong infrared returns without absorption by intervening water. Second, LandSat's 30 m pixels may be insensitive to low-density, patchy areas of kelp (Hamilton et al. 2020, ODFW unpublished analysis), which are characteristic of many of Oregon's bull kelp beds. This patchiness contrasts with the large beds of giant kelp in southern California on which the KelpWatch algorithm was developed and assessed. Finally, the timing of the observations is different, as each year KelpWatch produces four aggregated quarterly estimates that each incorporate data across three months, while the ODFW surveys were timed each year to fall near the single yearly peak biomass.

The important distinction is that KelpWatch is focused on objective methodological consistency over time in classifying emergent kelp to produce an unbiased timeseries specific to emergent kelp. Meanwhile the ODFW methodology used optimized survey timing, proprietary classification models (Ocean Imaging) that were locally customized within different regions, and a degree of professional judgement in optimizing the detection of the full extent of the visually

observable bull kelp canopy. Detailed analysis of the consequences of these methodological differences is beyond the scope of this report, but ongoing work is focused on determining quantitative relationships between the methods to better understand and interpret kelp abundance trends over time. In cases where the methods offer different conclusions about kelp abundance trends, focused work is necessary to determine whether they can be tied to potential differences between emergent kelp trends and whole-canopy trends (perhaps due to field conditions at the time of image acquisition), or if other methodological artifacts are responsible.

4.7. Considerations for future kelp monitoring and management

Oregon's kelp forests are currently at a very low state of abundance relative to our best understanding of historical conditions (this study, Frieder et al. 2025), a result of severe and continuing regional declines. This increases the importance of understanding the ecological mechanisms affecting kelp persistence and potential recovery. It also highlights the importance of continuing to monitor bull kelp using methods that are appropriate and sensitive to the currently prevailing kelp bed condition (i.e., small, patchy, fringing, shallow). While ODFW does not have an explicitly defined kelp monitoring program or direct management authority over bull kelp, the importance of kelp as habitat for ODFW-managed fisheries species and prey necessitates ongoing monitoring and further understanding kelp habitats. We intend to continue acquiring high-resolution airborne imagery to extend the observations in the current study. These data will likely be necessary for evaluating an emerging range of potential region-specific management scenarios (McPherson et al. 2021) that may include direct kelp enhancement actions (e.g., kelp spore distribution, kelp outplanting), indirect ecosystem manipulations (e.g., sea urchin culling, sea urchin predator reintroduction), and the possible development of more targeted monitoring and management frameworks.

In addition to much fundamental work documenting the relationships between bull kelp abundance and environmental conditions (e.g., Mora-Soto et al. 2024, Berry et al. 2021, Pfister et al. 2021), new research is revealing important mechanisms that affect the persistence of the currently diminished stocks (Ricart et al. 2025, Starko et al. 2022, Starko et al. 2024). More work is needed assessing the applicability of this literature specifically to Oregon's bull kelp beds, which exist in an open-coast, reef-dominated physical environment that is somewhat distinct from the complex mosaic of habitats in which much of the existing work was done. To this end, the development of yearly data on kelp abundance and distribution, accompanied by closely-tied environmental covariates, would greatly benefit the understanding of Oregon's kelp dynamics and responses to changing ocean conditions. In parallel, further analytical work enabling direct comparison and evaluation of multiple data sources and surveys on kelp abundance and distribution (e.g., ODFW 1990-2000 surveys, KelpWatch, other satellite data sources, any emerging UAV data) is timely and will help provide a better foundation for emerging management initiatives.

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LIST OF APPENDICES

Appendices are available [HERE through ODFW's Data Clearinghouse](#) (or search the ODFW Data Clearinghouse for 2026-02, the number of this Science Bulletin).

Appendix A: Technical specifications of the survey camera.

Appendix B: Flight maps for the 2022 aerial kelp survey.

Appendix C: Organization of the 2022 image mosaics, and the image clips used to facilitate analysis.

Appendix D: Methods used in the 2010 kelp survey.

Appendix E: Maps displaying the 2022 distribution of floating kelp canopy along the Oregon coast, classified into surface and subsurface categories. Three files: Depoe Bay region; Cape Arago to Sisters Rock; Rogue Reef to CA border.

Appendix F: Maps displaying the comparative distribution of floating kelp canopy in 2022 and 2024 along the Oregon coast. Classified kelp is overlaid on the 2024 false-color survey imagery and nautical chart. Three files: Depoe Bay region; Cape Arago to Sisters Rock; Rogue Reef to CA border.

Appendix G: Maps displaying the comparative distribution of floating kelp canopy in 2010 and 2022 along the Oregon coast between Cape Arago and the California border. Classified kelp is overlaid on the 2022 false-color survey imagery and nautical chart. One file.

Appendix H: Maps displaying the comparative distribution of floating kelp canopy in 2010 and 2024 along the Oregon coast between Cape Arago and the California border. Classified kelp is overlaid on the 2024 false-color survey imagery. Two files: Cape Arago to Sisters Rock; Rogue Reef to CA border.

Appendix I: Spatial data (zipped polygon shapefiles) providing the locations of the floating kelp canopy classified in the 2010, 2022, and 2024 aerial surveys (see included metadata).



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