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RESEARCH ARTICLE

Using unoccupied aerial vehicles to map and monitor changes in emergent kelp canopy after an ecological regime shift

Vienna R. Saccomanno[1], Tom Bell[2], Camille Pawlak[3], Charlotte K. Stanley[1], Katherine C. Cavanaugh[3], Rietta Hohman[4], Kirk R. Klausmeyer[1], Kyle Cavanaugh[3], Abby Nickels[4], Waz Hewerdine[4], Corey Garza[5], Gary Fleener[6] & Mary Gleason[1]

[1]The Nature Conservancy, Sacramento, California, USA
[2]Woods Hole Oceanographic Institution, Woods Hole, Massachusetts, USA
[3]University of California, Los Angeles, California, USA
[4]Greater Farallones Association, Greater Farallones National Marine Sanctuary, San Francisco, California, USA
[5]California State University, Monterey Bay, California, USA
[6]Hog Island Oyster Company, Marshall, California, USA

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Correspondence
Vienna R. Saccomanno, The Nature Conservancy, Sacramento, CA, USA.
Tel: +1 415-777-0487; Fax: +1 916-442-2377; E-mail: v.r.saccomanno@tnc.org

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Abstract

Kelp forests are complex underwater habitats that form the foundation of many nearshore marine environments and provide valuable services for coastal communities. Despite their ecological and economic importance, increasingly severe stressors have resulted in declines in kelp abundance in many regions over the past few decades, including the North Coast of California, USA. Given the significant and sustained loss of kelp in this region, management intervention is likely a necessary tool to reset the ecosystem and geospatial data on kelp dynamics are needed to strategically implement restoration projects. Because canopy-forming kelp forests are distinguishable in aerial imagery, remote sensing is an important tool for documenting changes in canopy area and abundance to meet these data needs. We used small unoccupied aerial vehicles (UAVs) to survey emergent kelp canopy in priority sites along the North Coast in 2019 and 2020 to fill a key data gap for kelp restoration practitioners working at local scales. With over 4,300 hectares surveyed between 2019 and 2020, these surveys represent the two largest marine resource-focused UAV surveys conducted in California to our knowledge. We present remote sensing methods using UAVs and a repeatable workflow for conducting consistent surveys, creating orthomosaics, georeferencing data, classifying emergent kelp and creating kelp canopy maps that can be used to assess trends in kelp canopy dynamics over space and time. We illustrate the impacts of spatial resolution on emergent kelp canopy classification between different sensors to help practitioners decide which data stream to select when asking restoration and management questions at varying spatial scales. Our results suggest that high spatial resolution data of emergent kelp canopy from UAVs have the potential to advance strategic kelp restoration and adaptive management.

Introduction

Kelp forests are complex habitats found along 25% of the world's coastlines and form the foundation of many nearshore marine environments. Kelp forests also provide valuable services for coastal communities (Wernberg et al., 2019), are important nursery and foraging habitat for numerous key ecological species (Holbrook et al., 1990; Steneck et al., 2002), and can help buffer shorelines from storms (Arkema et al., 2013). Globally, the four dominant kelp genera (*Macrocystis*, *Nereocystis*, *Ecklonia* and *Laminaria*) contribute an estimated $684 billion per

year in fisheries production, nutrient cycling and carbon removal services (Eger et al., 2021). Despite their ecological and economic importance, increasingly severe threats and stressors to kelp forests have resulted in declines in kelp abundance in many regions over the past few decades (Krumhansl et al., 2016).

The nearshore marine habitat along the North Coast of California, USA is generally dominated by canopy-forming bull kelp (*Nereocystis luetkeana*) forests and hosts biodiverse and productive ecosystems. However, a perfect storm of stressors that began around 2013 resulted in massive and sustained declines in the abundance of bull kelp in this region. In late 2013, a record-breaking marine heatwave (MHW) (Bond et al., 2015; Gentemann et al., 2017; Oliver et al., 2018) took hold of the northeast Pacific Ocean and brought temperature anomalies that were associated with an unprecedented regional decline in the abundance of bull kelp (McPherson et al., 2021; Rogers-Bennett & Catton, 2019). The MHW impacts on kelp were magnified by a dramatic increase in the density of herbivorous purple sea urchin (*Strongylocentrotus purpuratus*) that coincided with substantial declines in the population of the sunflower sea star (*Pycnopodia helianthoides*), a primary predator of kelp-grazing sea urchin (Duggins, 1983), due to the outbreak of sea star wasting disease (Burt et al., 2018; Hamilton et al., 2021; Harvell et al., 2019; McPherson et al., 2021; Miner et al., 2018; Rogers-Bennett & Catton, 2019). The result was an ecological regime shift along 350 km of coastline from healthy kelp forests to urchin barrens, an alternative stable state maintained by multiple feedback mechanisms that challenge the natural recovery of kelp to historical average abundances (Cavanaugh et al., 2011; Dayton, 1985; Filbee-Dexter & Scheibling, 2014; Lauzon-Guay et al., 2009; Ling et al., 2009). The regime shift impacted over 150 species important to coastal tribes, as well as the commercial red urchin and the recreational red abalone fisheries (Hohman et al., 2019; McGinnis et al., 2004).

Given the significant and sustained loss of kelp on the North Coast, interventions such as active kelp forest restoration and adaptive management are likely necessary tools to reset the ecosystem (Eger et al., 2022; Walters, 1986). Strategic implementation of kelp restoration projects often requires conservation practitioners to utilize geospatial data on kelp dynamics across a variety of spatiotemporal scales. Because canopy-forming kelps (Order: *Laminariales*) are distinguishable in airborne and satellite imagery, remote sensing is an important tool for documenting changes in canopy area and biomass to meet these data needs (Bell et al., 2020; Cavanaugh et al., 2011; Jensen et al., 1980; Schroeder et al., 2019). Remotely sensed data availability for monitoring surface canopy-forming kelps (hereafter referred to as 'emergent kelp canopy') is steadily increasing and the selection of these data to inform management should match the efforts' objectives and spatial scale (Cavanaugh, Bell, et al., 2021).

To manage kelp resources and track commercial harvest, the California Department of Fish and Wildlife (CDFW) conducted high-resolution airplane-based occupied aircraft vehicle (OAV) surveys of kelp canopy along the California coastline from the Mexico to Oregon borders. The first OAV survey was conducted in 1989 and the second in 1999. Annual surveys were conducted in at least some regions of the state between 2002 and 2016 (Aerial Kelp Surveys, 1989); surveys did not take place from 2017 to 2018, and were attempted but only partially completed in 2019 and 2020. While the CDFW OAV data are useful for monitoring changes in kelp canopy over time at a regional scale, there are several limitations inherent in these data. Importantly, the spatiotemporal coverage is inconsistent across years due to various factors that impacted the surveys such as inclement weather, limited funding, malfunctioning equipment and smoke from wildfires (N. Eddy, personal communication, Oct 19, 2020; Hohman et al., 2019) making them unreliable for consistent time series analysis at the local level (see SI for further discussion on OAV data limitations).

Satellite imagery has emerged as another remote sensing tool to track the regional dynamics of kelp canopy (Bell et al., 2020; Cavanaugh et al., 2011; Finger et al., 2021; Hamilton et al., 2020). While satellite imagery provides data on the dynamics of emergent kelp canopy across large regions since the mid-1980s (Bell et al., 2020; Cavanaugh et al., 2011; Hamilton et al., 2020), the spatial, spectral and temporal resolutions of satellite imagery can present several limitations. First, emergent kelp canopies that are adjacent to the coast or offshore rocks are missed due to the reflectance properties of these terrestrial features within overlapping pixels (Hamilton et al., 2020; Nijland et al., 2019). Second, since most satellite imagery is not collected on demand, acquisition may occur during suboptimal periods, such as cloudy days or during high tidal height and/or current speed conditions, which can submerge the emergent kelp canopy below the sea surface (Britton-Simmons et al., 2008; Cavanaugh, Cavanaugh, et al., 2021). Third, the often moderate pixel resolution necessitates the use of a classifier to assign the class of each coastal pixel, for example, as kelp or seawater, to avoid erroneous detection of kelp canopy due to breaking waves, sun glint and/or floating debris that increases the reflectance of near-infrared light. The conservative nature of many classifiers may lead to the misclassification of sparse kelp canopies as seawater, thus missing small refugia that may be important to restoration efforts during periods of low canopy cover.

Local-scale monitoring of emergent kelp canopy dynamics, especially sparse canopy, requires remote

sensing tools that provide high spatiotemporal resolution. Small unoccupied aerial vehicles (UAVs) are becoming increasingly useful tools in conservation, and are being used for aquatic ecosystem monitoring (Haskins et al., 2021), wildlife management and enforcement (Jiménez López & Mulero-Pázmány, 2019). In recent years, UAVs have been utilized to capture spatially and spectrally complex intertidal macroalgal communities (Rossiter et al., 2020), monitor invasive aquatic vegetation (Bolch et al., 2021) and provide a non-invasive way to observe marine fauna (Bevan et al., 2016; Colefax et al., 2018; Hensel et al., 2018; Hodgson et al., 2013; Schaub et al., 2018). Monitoring emergent kelp canopy with UAVs provides flexibility in the timing of data collection relative to OAV and satellite imagery. UAVs are a nimble tool that can be deployed rapidly, allowing a pilot to survey at ideal tidal, sun angle and wind conditions, as well as peak biomass. This flexibility in turn facilitates the characterization of seasonal and interannual kelp dynamics to better understand the effect of disturbance from storms and marine heatwaves (Cavanaugh, Cavanaugh, et al., 2021; Thomsen et al., 2019), and inform restoration and management efforts. With very high-resolution (VHR) sub-meter imagery, UAVs can capture small or sparse kelp beds and differentiate between near-shore kelp beds and land, addressing detection challenges associated with satellite imagery (Fig. S1). And while certain environmental conditions such as wind, clouds, sun glint and deep water detection (Kellaris et al., 2019) can limit the use of UAV imagery in monitoring macroalgal communities, novel automated canopy detection algorithms have been shown to be highly accurate and the assessment of the influence of tides and currents has recently improved data collection and processing methods (Cavanaugh, Cavanaugh, et al., 2021). Finally, relatively low start-up costs and pilot training requirements also make UAV-based conservation monitoring highly accessible (Evans et al., 2015; Mlambo et al., 2017; Weissensteiner et al., 2015).

We conducted UAV surveys at 36 priority kelp forest sites along the North Coast of California in 2019 and 2020 to fill a key data gap for kelp managers and restoration practitioners working at a local scale. With over 4,300 hectares surveyed between 2019 and 2020, these surveys represent the two largest marine resource-focused UAV surveys conducted in California to our knowledge. These surveys are the first VHR assessments of emergent kelp canopy since 2016 for the majority of the priority kelp forest sites along the North Coast and provide documentation of further decline and, in some cases, potential resilience (*i.e.* recovery after disturbance (Cavanaugh et al., 2019; Hodgson et al., 2015)). We present a repeatable workflow for consistent kelp surveys and data capture, creating orthomosaics, georeferencing data, classifying emergent kelp canopy in UAV imagery and creating VHR kelp canopy maps that can be used to assess changes in kelp canopy coverage over space and time at a level of spatiotemporal resolution previously unachieved by traditional OAV and satellite imagery. We illustrate the impacts of spatial resolution on emergent kelp canopy classification in imagery from both the Landsat satellite sensor and a UAV to help practitioners decide which data stream to select when asking restoration and management questions at varying scales. Our results suggest that high spatial resolution data on local-scale spatiotemporal patterns of emergent kelp canopy from UAVs have the potential to advance strategic kelp restoration and adaptive management.

Materials and Methods

Study area

The study area includes approximately 90 km of nearshore rocky habitat in Northern California along Sonoma and Mendocino counties (38°N–39°N) that has been historically dominated by bull kelp forests (Fig. 1). The mean tide level in the study area is approximately 0.84 m with a mean tidal range of approximately 1.27 m (NOAA Tides and Currents, n.d.). The coastal ocean environment is largely determined by wind-driven coastal upwelling that typically brings cold, nutrient-rich waters to the ocean's surface, which stimulates the growth of bull kelp (Springer et al., 2007). An annual species, bull kelp in the study area typically grows in sea surface temperatures (SST) between 10° and 14°C (García-Reyes & Largier, 2012) on wave-exposed rocky reefs from the low intertidal (3 m) out to 20 m, with maximum depths of about 40 m (Springer et al., 2007). With an upper thermal tolerance of approximately 17°C, bull kelp exhibits strong spatial and temporal variability in distribution and abundance (Springer et al., 2007).

The abrupt and persistent shifts in SST and nutrient conditions associated with the MHW in the northeast Pacific Ocean were beyond the physiological thresholds of optimum bull kelp growth and reproduction (McPherson et al., 2021). Mean SST anomalies from 2014 to 2015 during the MHW event were approximately two standard deviations warmer, with extreme SST anomalies reaching three to four standard deviations above the long-term mean distribution (McPherson et al., 2021).

Priority survey site selection

We selected sites for UAV emergent kelp canopy surveys using a prioritization framework for kelp recovery efforts based on data from OAV surveys, subtidal surveys, areas of cultural significance, areas of economic significance, accessibility and proximity to marine protected areas

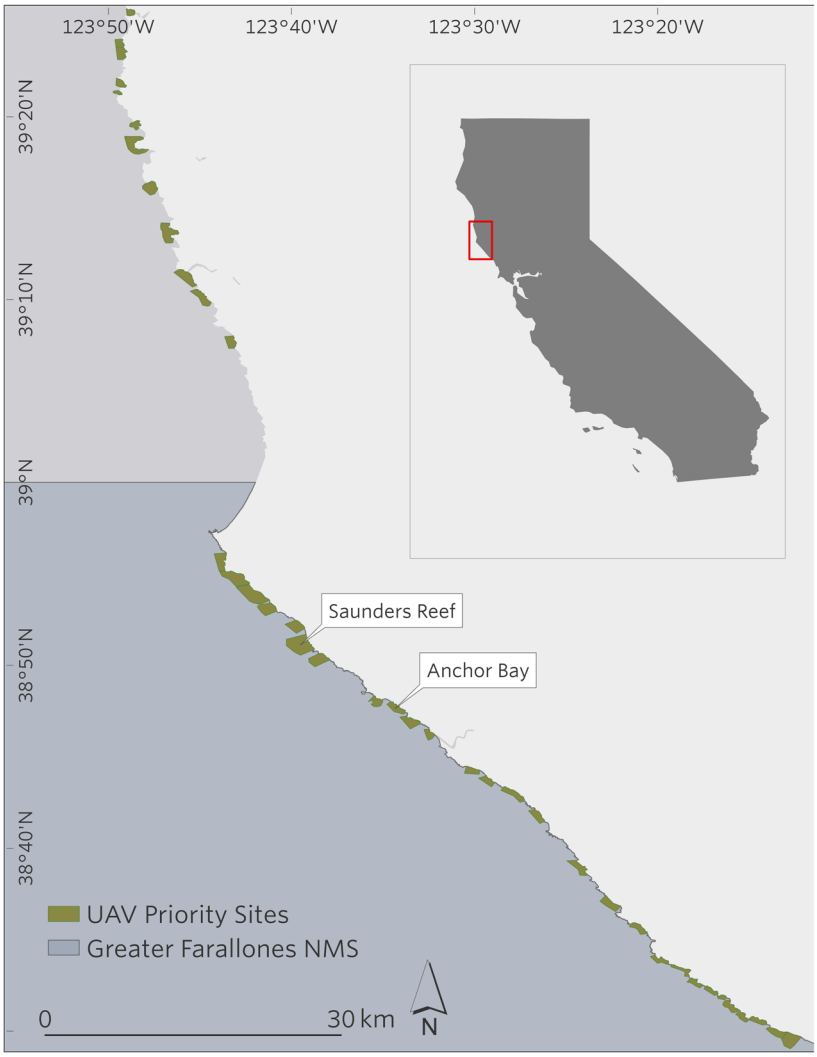

Figure 1. Study area extent and UAV priority sites along the North Coast of California. Case study sites Saunders Reef and Anchor Bay are denoted with callouts. Basemap source: Esri.

(MPAs) (Hohman et al., 2019). A total of 37 sites were identified in Mendocino and Sonoma Counties (*i.e.* the 'North Coast'), hereafter referred to as 'priority sites' (Fig. S2). Ten of the sites are in actively managed state MPAs and 27 are in the Greater Farallones National Marine Sanctuary (GFNMS) (Fig. 1). Thirty-six of the 37 sites were surveyed with UAVs between 2019 and 2020, with 21 sites surveyed in both 2019 and 2020. The average priority site area was 1 km^2 (range 0.2–1.7 km^2).

UAV flights, timing and environmental sources of variation and error

Due to the 90 km stretch of coastline within which the noncontiguous priority sites are located, numerous pilots participated in data collection and we developed a repeatable workflow building upon the efforts of Cavanaugh, Cavanaugh, et al. (2021) to ensure data consistency. We obtained state and federal permits to allow UAV use in restricted areas and we established criteria for UAV launch sites (*e.g.* public coastal access, no large obstacles, flat area with minimal ecological impact potential and located mid-way in the survey area to maintain telemetry link between the UAV and controller). We used small UAV platforms from the same manufacturer and each pilot selected their own flight software. Pilots flew at an altitude of 120 m above mean sea level with a minimum front and side overlap of 75%, nadir angle of the sensor, auto white balance and UAV speeds between 10 and 12 m/s. The image processing softwares used were Agisoft Metashape, DroneDeploy and Pix4D; all orthomosaics were reviewed by expert annotators and when

output orthomosaics were incomplete or contained significant defects, the imagery was reprocessed using at least one of the two other software options (see SI for detailed workflow; Table S2).

All UAV pilots acquired imagery using the built-in Red-Green-Blue (RGB) sensor. We coordinated flights to coincide with the annual peak biomass of bull kelp, which typically occurs in late summer/early fall on the North Coast. Our team surveyed during the lowest tide series of the month and aimed to survey at the lowest tide of the day, as tidal height and surface currents have been shown to impact the amount of kelp canopy exposed on the water surface (Britton-Simmons et al., 2008), and these impacts can vary regionally (Cavanaugh, Cavanaugh, et al., 2021). Because sun angle, wind and weather conditions varied significantly throughout the data collection process, surveys were not restricted to a specific daily tidal height or current speed; data were collected when field conditions allowed for stable UAV launch and landing and this structure resulted in random sampling throughout the tidal range within and between years, addressing sampling bias in our data (see SI for detailed discussion on the potential influence of tides).

Kelp detection, classification and quantification

We identified kelp pixels in each UAV image using a band combination between the red and blue bands (Red - Blue), which has been shown to best distinguish kelp from water in RGB-UAV imagery relative to other RGB vegetation indices (Cavanaugh, Cavanaugh, et al., 2021). Before applying a threshold to our image, we manually masked all terrestrial objects (*e.g.* land and intertidal rocks). Due to radiometric and spectral variability present in the imagery, we manually selected thresholds to distinguish kelp from seawater. For individual sites with high levels of spectral variability due to turbidity, sun glint or other artifacts, a single threshold could not be used for kelp identification because the threshold varied throughout the image within a site (Cavanaugh, Cavanaugh, et al., 2021). For these sites, we gridded images into subsets (ranging from 1000 × 1000 m areas to 5000 × 5000 m areas, depending on the level of variability), and each grid was assigned a unique threshold. As a result, multiple thresholds were used for classification for these sites. We mosaicked the classified grids back to their original extent (Fig. S3) and manually reviewed all classified mosaics for quality assurance. We used binary classification values (*i.e.* 'Kelp' or 'Not Kelp') except for mixed-species marine algal beds and the occasionally blurred image, which were assigned 'No Data' values. We worked in a GIS environment to determine the area of kelp at a given site by multiplying the number of kelp pixels by the area of the pixels (ArcGIS Pro 2.7).

Comparison to multi-decadal Landsat data

To give multi-decadal temporal context to the UAV surveys, we examined long-term trends in kelp canopy dynamics along the North Coast using Landsat satellite imagery (see SI for data accessibility). The primary benefits of using Landsat data include high temporal resolution, long-term coverage (1984-present) and large spatial coverage (Bell et al., 2020; Cavanaugh et al., 2011; Hamilton et al., 2020). The maximum extent of UAV survey area overlap between 2019 and 2020 was used to clip the Landsat emergent kelp canopy data such that the exact same area was compared for each priority site between the Landsat and UAV datasets ($n = 36$) (Fig. 6). To control for differences in available reef habitat between priority sites, we selected the maximum area of kelp canopy (m^2) that occurred within a site in each year and normalized that amount by the historical maximum extent of emergent kelp canopy (*i.e.* the cumulative area within a site where kelp was ever observed between 1984 and 2020) to produce a time series of annual, proportional coverage values. We also used Landsat emergent kelp canopy data to produce maps of canopy persistence at our case-study sites (Fig. 7), where relative persistence was defined as the number of years from 1984 to 2020 in which a pixel contained kelp canopy (Bell et al., 2020). Maps of emergent kelp canopy for case-study sites during a given year used the maximum canopy area observed (Fig. 7).

Comparison to historical OAV data

We used the high-resolution CDFW OAV survey data collected annually from 2002 to 2016 to assess changes in emergent kelp canopy over time relative to the UAV data. While the OAV data have a different spatial and spectral resolution (2 m and RGB + NIR, respectively) compared with the UAV data (~0.03 m and RGB, respectively), they are the only high-resolution data available for the region to assess trends over time. The spatiotemporal coverage of the OAV surveys was irregular and the associated metadata do not consistently differentiate between when data were not collected in an area (*e.g.* due to cloud cover) and when there was no kelp detected in an area (see SI for further discussion on OAV data limitations). Therefore, we only selected years with North Coast regional OAV data (Table S1) that spatially overlapped with the UAV priority sites based on the OAV survey extent coordinates. The maximum extent of UAV survey area overlap between 2019 and 2020 was used to clip the OAV emergent kelp canopy data such that the exact same area

was compared for each priority site in the OAV and UAV combined dataset (hereafter referred to as the 'high-resolution dataset'). To control for differences in available reef habitat between survey sites, we normalized the annual peak kelp area by the historical maximum extent of emergent kelp canopy (*i.e.* the cumulative area within a site where kelp was ever observed in available years from 2002 to 2020 in the high-resolution dataset) to produce a dataset of annual, proportional coverage values. Therefore, max extent estimates between the high-resolution and Landsat data are specific to the dataset. We used the WGS 1984 geographical coordinate system for all data in this dataset. To account for the differences in spatial resolution when investigating local, relative occurrence patterns, we resampled the UAV data to 2 m to match that of the OAV data; we then ran the high-resolution dataset of emergent kelp for each case study site through the Count Overlapping Feature geoprocessing tool in ArcGIS Pro 2.7 to obtain the number of years a given pixel was classified as "kelp".

Spatial statistics

We examined the interquartile range of emergent kelp canopy values for both Landsat and the high-resolution data at the priority sites between years to understand statistical dispersion given the natural interannual variability of kelp forest ecosystems. For the Landsat dataset, we collated emergent kelp canopy data across all 36 priority sites by year (Fig. 6); for the high-resolution dataset, we collated emergent kelp canopy data by year for the 36 priority sites where canopy data were available (Table S1). Spatial statistics were conducted in R V4.1.1 (R Core Team, 2021; Wickham et al., 2019) and are available in the data repository.

Case study sites

With 36 priority sites and over 4,300 hectares surveyed with UAVs between 2019 and 2020, we selected two, representative priority sites to serve as case study locations, Saunders Reef and Anchor Bay (Fig. 1); both sites were surveyed in 2019 and 2020, and represent the upper and lower bounds of priority site area (1.5 and 0.4 km^2, respectively), cover the two core site types (coastal and cove, respectively) and capture the range of kelp canopy dynamics and trends observed in the region (refugia and sustained decline, respectively). We use these sites to investigate the performance of the UAV imagery and associated classifications, understand local trends and kelp canopy status and compare UAV emergent kelp canopy classifications to that of Landsat. A full summary of findings by priority site can be found in Table S1.

Results

UAV survey extent and tides

We surveyed 25 priority sites encompassing 2,075 hectares of priority bull kelp habitat in 2019, and 32 priority sites encompassing 2,198 hectares in 2020. Between the 2019 and 2020 surveys, there were 21 overlapping priority sites representing a spatial footprint of 1,297 hectares of priority bull kelp habitat (Table S1). We used tidal data at the time of UAV launch to explore the interquartile range of tidal height across all priority sites surveyed in both 2019 and 2020 and found that the median tidal height between 2019 and 2020, 1.17 m and 1.1 m, respectively (n = 21, Fig. S4), was comparable; the IQR was less than 1 m of tidal height in each year (IQR 2019 = 0.94–1.35 m; IQR 2020 = 0.59–1.45 m). Tidal height (m) in 2019 (1.17 ± 0.35 [mean ± SD]) and 2020 (1.1 ± 0.53) did not differ significantly ($t(40) = 0.56$, $P = 0.571$, $n = 21$) for each year (see SI for further analysis on the potential influence of tides).

Local trends using high-resolution dataset

We used the high-resolution dataset to understand annual emergent kelp canopy trends from 2002 to 2020 across the 36 non-contiguous priority sites (Fig. 2) and constructed spatial occurrence patterns within case study sites over time (Figs. 4 and 5). We found that the median emergent kelp canopy coverage since the 2013 onset of coincident stressors has consistently remained below that of preceding years where higher-resolution data are available (Fig. 2; Table S1). From the most recent complete OAV survey in 2016 to the first UAV survey in 2019, we found that emergent kelp canopy decreased in all but two priority sites and that there was an overall decrease in emergent kelp canopy of 85.8% from 2016 to 2019 (Table S1). We found that emergent kelp canopy area increased in every priority site surveyed in both 2019 and 2020 (n = 21), although the increase at several sites was minimal and may not reflect true increases given the sources of variability in this system that impact the amount of kelp canopy exposed on the water's surface (Britton-Simmons et al., 2008)(Table S1).

Priority site case studies using the high-resolution dataset

Using the high-resolution dataset, we explored site-specific spatiotemporal trends in emergent kelp canopy within and between our case study sites and observed between-site variation (Fig. 3) that suggests that certain

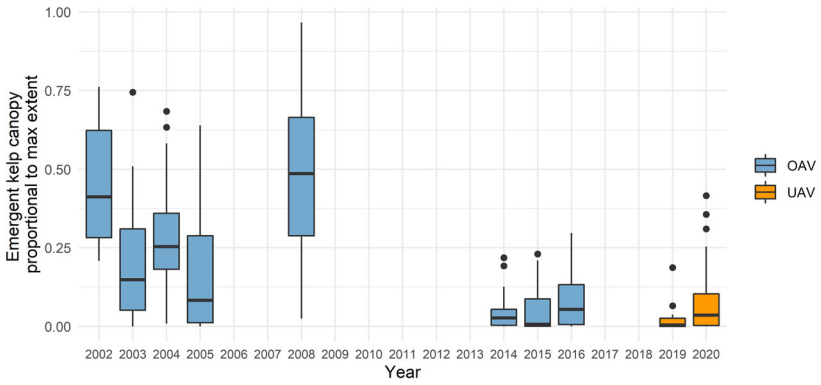

Figure 2. Interquartile range of emergent kelp canopy coverage proportional to maximum extent observed in the high-resolution dataset across all priority sites (n = 36). The figure includes all years with available high-resolution OAV data and UAV data.

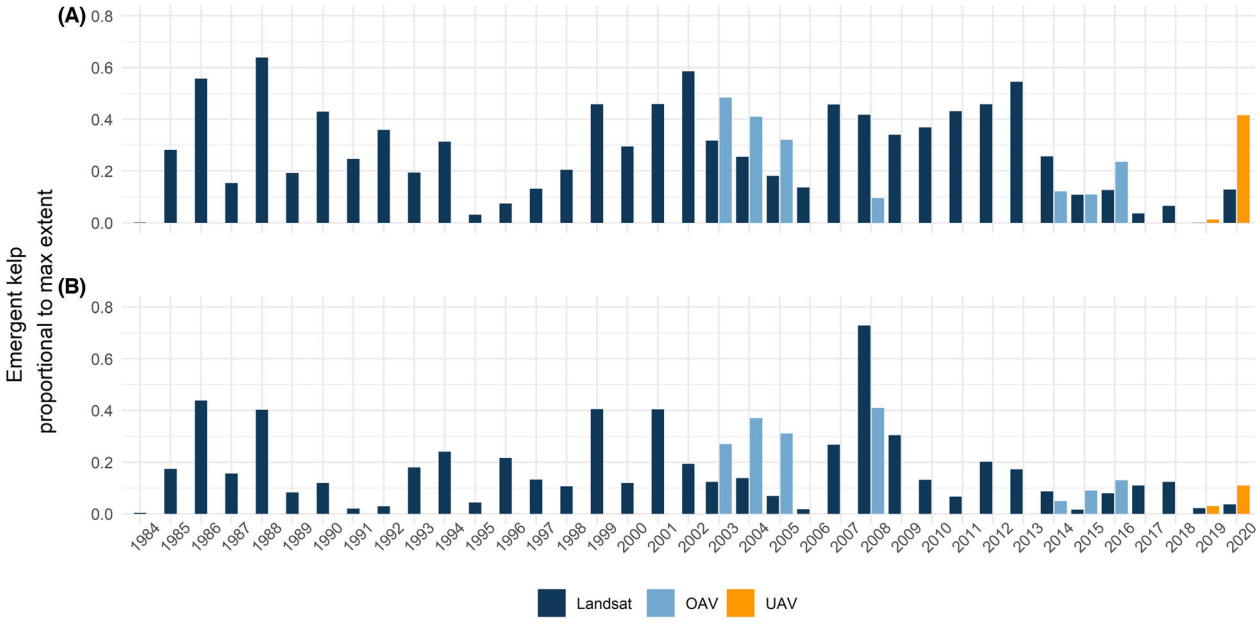

Figure 3. Emergent kelp canopy proportional to the maximum extent of observed kelp within Saunders Reef (A) and Anchor Bay (B) using the high-resolution and Landsat datasets. Maximum extent estimates are relative to each dataset.

sites exhibit more resilience to extreme stressor events (Fig. 4) relative to other sites (Fig. 5). While the regional trend in emergent kelp canopy along the North Coast since the onset of coincident stressors has been a sustained lack of emergent kelp canopy relative to historical coverage (Figs. 2 and 6), several priority sites exhibited signs of potential local recovery in the 2020 UAV surveys. UAV surveys and classification of emergent kelp canopy at Saunders Reef suggest that 2019 was a historically low kelp year for this site, but that some recovery might have occurred in 2020 with the second highest emergent canopy coverage in the high-resolution dataset, albeit temporal coverage is discontinuous (Fig. 3a). It is possible that the lower tides in 2020 relative to 2019 account for some of this increase (Table S3). Landsat data were used to place the 2020 UAV kelp area data at Saunders Reef in greater historical context and illustrate that, while there was indeed an uptick in emergent kelp canopy in 2020, this priority site historically has had high emergent kelp canopy coverage proportional to the max extent and 2020 was a moderate year relative to other years in the time series with 78% of the previous years on record having higher canopy coverage than 2020 (Fig. 3a). Spatializing the emergent kelp in the high-resolution dataset at Saunders Reef shows regions of kelp occurrence and suggests this priority site is a historically strong location for kelp,

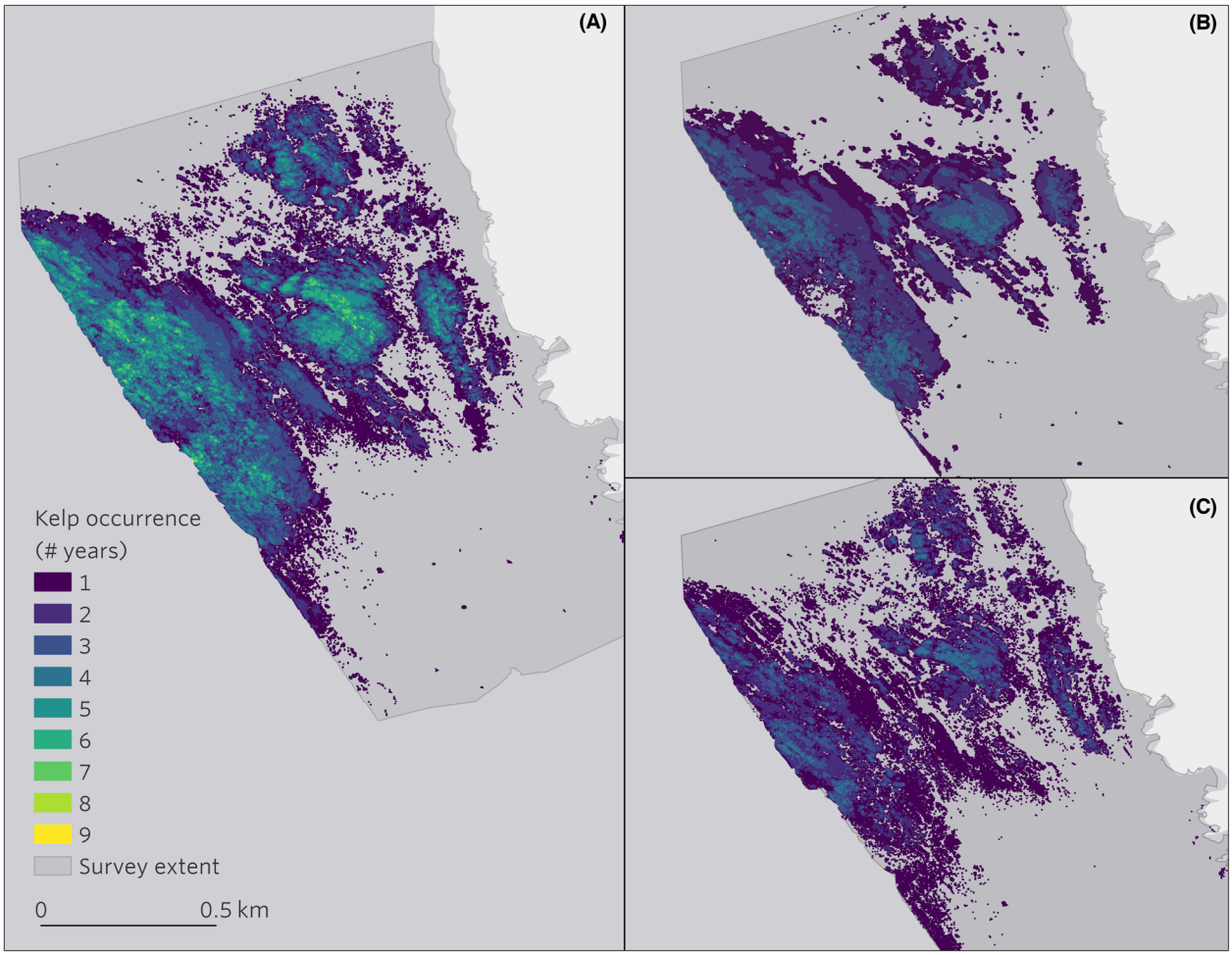

Figure 4. Spatial occurrence of emergent kelp canopy at Saunders Reef using the high-resolution dataset. Colored pixels represent areas where kelp has been observed, where variation in color represents the count of occurrence in years (not necessarily consecutive). A = full dataset with high-resolution classifications; B = pre-onset of coincident stressors (2003, 2004, 2005, 2008); C = post-onset of coincident stressors (2014, 2015, 2016, 2019, 2020). Basemap source: Esri.

with canopy reoccurring in select locations in the reef in eight out of the nine years of data (Fig. 4a). Additionally, we detected areas of kelp occurrence post-coincident stressors where kelp had not been previously detected by OAV sensors (Fig. 4c). Unfortunately, we do not know if these are novel areas of kelp occurrence or if the resolution and/or methodology of the OAV surveys resulted in undetected kelp.

UAV flights and classification of emergent kelp canopy at Anchor Bay align with the regional trend in that there has been a sustained lack of kelp recovery at this site since 2014. In 2019, there was historically low area of emergent kelp canopy and little indication of recovery in 2020 (Fig. 3b). Tides were higher at this site during the 2020 UAV surveys than they were during the 2019 surveys (Table S3). Spatializing the emergent kelp canopy data using the high-resolution dataset at Anchor Bay to investigate regions of kelp occurrence also suggests that this priority site has had minimal kelp recovery since the onset of coincident stressors (Fig. 5c). Landsat data were used to place the observed lack of kelp recovery at Anchor Bay in greater historical context and illustrate that 2019 and 2020 were indeed low years for emergent kelp canopy coverage and that this site has not experienced a strong uptick since 2008 (Fig. 3b).

Regional trends using Landsat

While the high-resolution dataset is helpful for understanding near-term, local-scale emergent kelp canopy dynamics, these data are of limited value for assessing long-term, regional-scale change. Landsat data were used

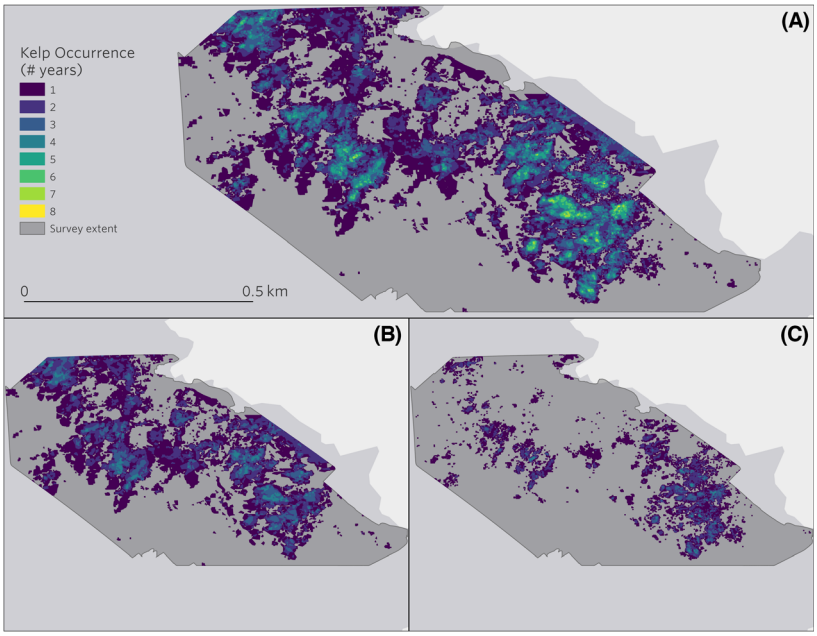

Figure 5. Spatial occurrence of emergent kelp canopy at Anchor Bay using the high-resolution dataset. Colored pixels represent areas where kelp has been observed, where variation in color represents the count of occurrence in years (not necessarily consecutive). A = full dataset with high-resolution classifications; B = pre-onset of coincident stressors (2003, 2004, 2005, 2008); C = post-onset of coincident stressors (2014, 2015, 2016, 2019, 2020). Basemap source: Esri.

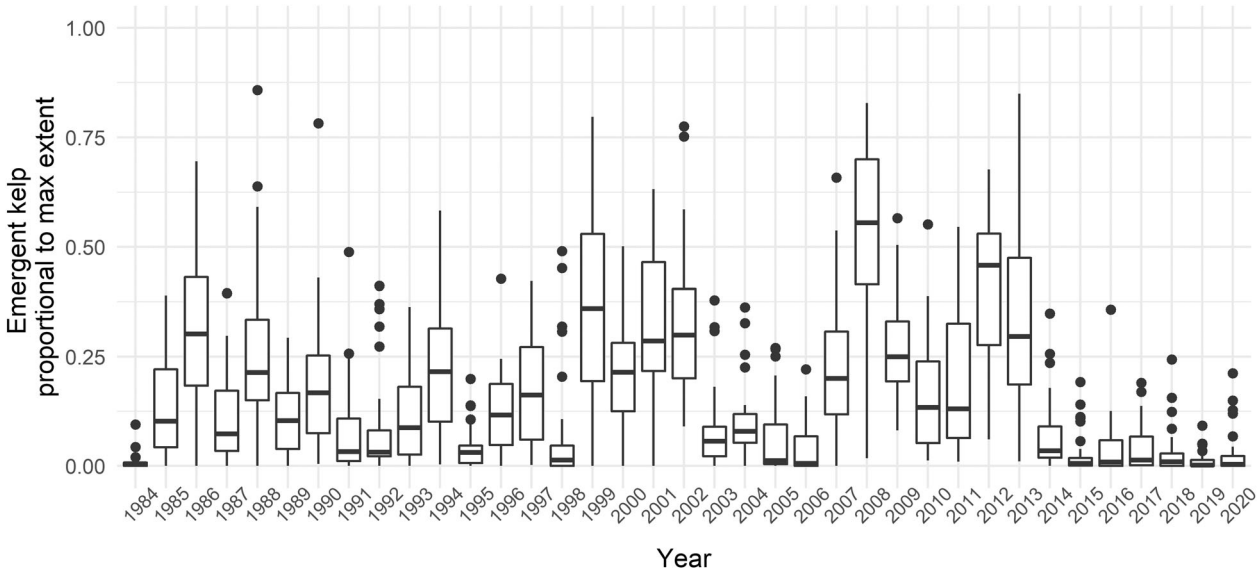

Figure 6. Interquartile range of emergent kelp canopy across the 36 priority sites proportional to the maximum observed extent within a priority site observed in the Landsat time series.

to bridge this gap and suggest a significant and sustained loss of kelp within priority sites from 2014 to 2020 compared to the historic emergent kelp canopy area (1984–2013). The period since the 2013 onset of coincident stressors is the first within the record with sustained loss for more than four years and emergent kelp canopy consistently under 15% of average historical levels (Fig. 6). The most severe decline in kelp after the onset of coincident stressors was in 2019 (Fig. 6) when kelp coverage was only 3.6% of the historic average emergent kelp

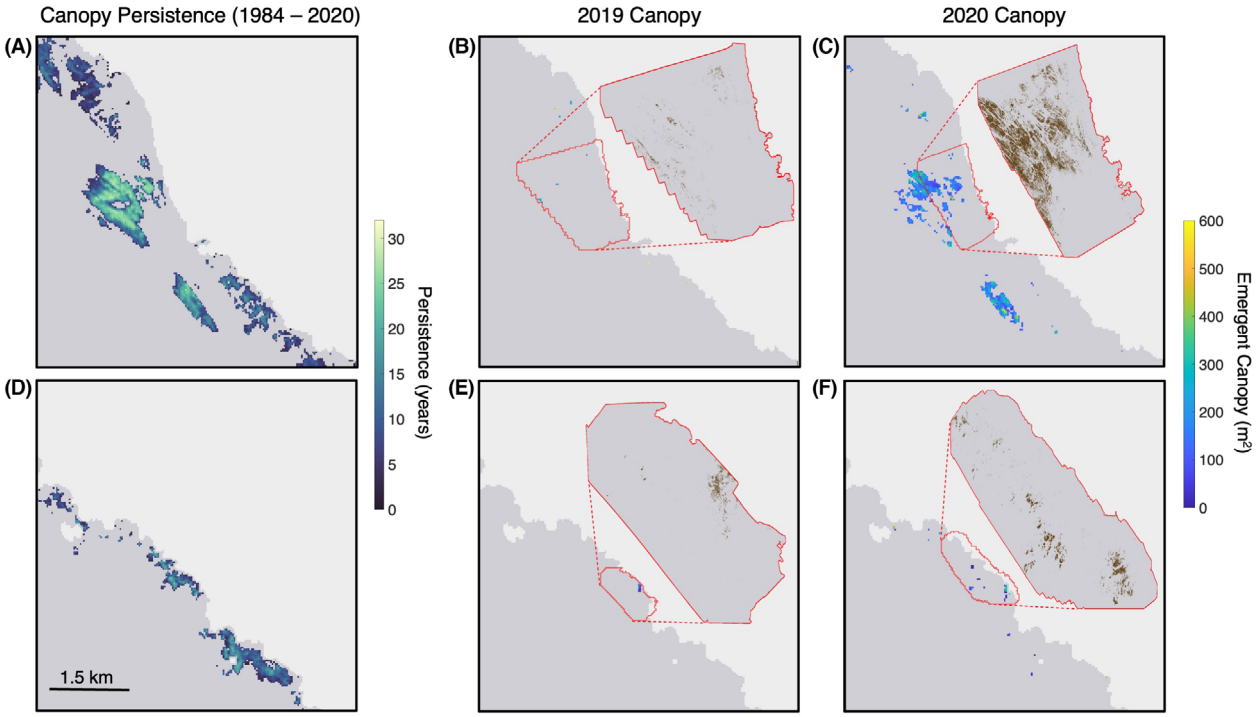

Figure 7. Landsat and UAV emergent kelp canopy classification and persistence at Saunders Reef (top row) and Anchor Bay (bottom row) at peak biomass in 2019 and 2020, where red outlines demark the UAV survey extent. A and D show annual persistence using Landsat data, the number of years where emergent kelp canopy was present across all years from 1984 to 2020. The 2019 (B and E) and 2020 (C and F) canopy maps display the emergent kelp canopy area identified through Landsat and the enhanced insets in the upper right of each panel show the UAV emergent kelp canopy classification in brown for that year. See Figure 1 for location of case study sites relative to the study area.

canopy cover, with a slight increase to 9.7% of historic levels in 2020.

While Landsat data are helpful for understanding long-term, regional-scale kelp canopy dynamics, the 30 m sensor resolution is often too coarse to accurately assess local-scale, nearshore emergent kelp canopy spatial patterns (Finger et al., 2021; Hamilton et al., 2020). A comparison between Landsat and UAV emergent kelp canopy classifications in case study sites illustrates the differences in resolution between these sensors and the ability of UAVs to detect sparse emergent kelp canopy, a common feature in the North Coast region since 2014. Many areas of sparse kelp canopy were missed by the Landsat sensor, suggesting that the <0.1 m spatial resolution of UAVs is a better fit to understand local, site-level emergent kelp canopy dynamics of this system (Fig. 7).

Discussion

Our analysis indicates that remote sensing methods using UAVs to map and monitor emergent kelp canopy provide unparalleled insights into the spatial dynamics of kelp at a local scale. While the Landsat data indicate low regional-scale resilience (Fig. 6), the UAV data suggest that there are pockets of potential recovery at the local level. Using the UAV data, we illustrate considerable local-scale spatial variability in kelp occurrence at North Coast priority sites which, coupled with the region's prevalent sparse canopy, supports the use of a UAV platform to document local patterns of loss or potential recovery. While determining the causal mechanism(s) for variability in emergent kelp canopy between sites is beyond the scope of this study, it is possible that local-scale biotic and abiotic processes may influence the recovery of kelp from extreme disturbance events (Edwards, 2004; McPherson et al., 2021) and that VHR data can be used to map fine-scale spatiotemporal patterns and locate remnant kelp that could serve as refugia and a local source of spore production during periods of low canopy cover. This information in turn can be used to inform strategic, local restoration efforts to defend kelp strongholds that can otherwise be difficult to locate.

We illustrate the impacts of spatial resolution on emergent kelp canopy classification between the Landsat sensor and that of a UAV to help practitioners decide which data stream to select when asking restoration and management

questions at varying scales. The use case for UAV surveys of emergent kelp canopy at local scales is compelling. When comparing classified kelp in Landsat and UAV imagery at the same site during a similar timeframe, we found that many areas of sparse canopy that were detected by the UAV were not detected by the Landsat sensor (Figs. 7 and S1); this suggests that higher spatial resolution data are needed to understand local trends in emergent kelp canopy dynamics in regions characterized by sparse kelp coverage. Furthermore, when comparing historical OAV emergent kelp canopy surveys with UAV surveys within case study sites, we mapped novel areas of kelp canopy in 2019 and 2020 (Fig. 4c) even though these were both historically low kelp abundance years (Fig. 6). Due to the moderate resolution resampling of the OAV data we do not know if these are indeed new areas of kelp growth, or if kelp was missed by the OAV sensor, which inherently limits our confidence in these potential signs of recovery. Thus, when selecting remote sensing tools for local-scale kelp restoration and management purposes, UAVs are a compelling platform to capture fine-scale dynamics.

While small UAVs are a nimble tool and provide data with exceptional spatial resolution, this tool is not yet cost- nor time-effective when surveying large regions (*e.g.* state wide); UAVs have notable limitations including visual line of sight requirements, telemetry link limitations (often 3–7 km), maximum flight altitude restrictions (120 m without a waiver), wind speed thresholds (approximately 45 km/h for small quadcopters), reliance on batteries with finite charge and other physical and technological limitations. Given these limitations and challenges, surveys in the present study were not restricted to a specific daily tidal height. This is an important limitation because tidal height has been shown to impact the amount of kelp canopy exposed on the water surface (Britton-Simmons et al., 2008; Cavanaugh, Cavanaugh, et al., 2021). While differences in tidal height at the time of the surveys may influence our estimates of change between years, the range of tidal heights across the 2019 and 2020 surveys was comparable and therefore site-level biases are likely addressed when pooling changes across all sites (see SI for further discussion). Additionally, the necessity of an accessible launch site for UAVs limits which areas can be surveyed, making it difficult to census a population or survey sites without a viable launch site. For example, Fig. 7c illustrates that kelp was present beyond the perimeter of the UAV priority site but, due to the above-mentioned UAV limitations, this area was unable to be surveyed. Finally, the imagery collected with three-channel digital cameras that come standard with low-cost UAV platforms is more sensitive to the misclassification of submerged kelp and previous work suggests that multispectral imagery (*e.g.* imagery collected by Landsat or a multispectral UAV payload) produces higher accuracy classifications (Cavanaugh, Cavanaugh, et al., 2021). However, when used in conjunction with other remote sensing platforms like satellites, UAVs with standard sensors can supplement time series with VHR data and capture narrow temporal intervals (*e.g.* low tide, post-fire, post-storm) to enhance ecological monitoring (Mohamad et al., 2019; Pádua et al., 2020; Turner et al., 2016).

While our UAV priority sites primarily contain bull kelp and are located along the North Coast of California, the methods presented here are applicable for remote sensing of canopy-forming kelp forests with UAVs in other geographies. As global interest in actively restoring kelp forests continues to increase (Eger et al., 2020; Eger et al., 2022), these results suggest that high spatial resolution emergent kelp canopy data from UAVs can be used to guide strategic management efforts by informing restoration site and technique selection. For example, in systems where herbivory is an issue, VHR imagery can illustrate where kelp strongholds are located and therefore guide where techniques such as removing overabundant grazers should be deployed. Furthermore, repeat VHR UAV surveys of restoration areas with control sites can allow practitioners to monitor and evaluate the potential efficacy of restoration efforts. The ability to produce VHR data on local-scale spatiotemporal patterns of emergent kelp canopy using UAVs has the potential to advance strategic kelp restoration and adaptive management on the North Coast of California and around the world.

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Author Contributions Statement

VRS, TB, KyC, and RH conceived the idea for the manuscript. VRS led the development and writing of the

manuscript. VRS, CP, and KaC led data processing and management. VRS, TB, KaC, CS, and KK led spatial and statistical analyses. VRS, TB, KaC, CS, AN and WH led creation of figures and tables. All authors contributed critically to the drafts and gave final approval for publication.

Conflict of Interest

All authors declare that they have no conflicts of interest.

Data Accessibility Statement

The data that support the findings of this study are openly available in Dryad at https://doi.org/10.5061/dryad.n02v6wwzs

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Appendix S1 Supporting Information.