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Remote Sensing Tools for Mapping and Monitoring Kelp Forests along the West Coast

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Cover photo: Aerial image of kelp canopy at Del Mar Landing, California. Photo: Warren Hewerdine/Greater Farallones Association

About the National Marine Sanctuaries Conservation Series

The Office of National Marine Sanctuaries, part of the National Oceanic and Atmospheric Administration, serves as the trustee for a system of underwater parks encompassing more than 620,000 square miles of ocean and Great Lakes waters. The 15 national marine sanctuaries and two marine national monuments within the National Marine Sanctuary System represent areas of America's ocean and Great Lakes environment that are of special national significance. Within their waters, giant humpback whales breed and calve their young, coral colonies flourish, and shipwrecks tell stories of our nation's maritime history. Habitats include beautiful coral reefs, lush kelp forests, whale migration corridors, spectacular deep-sea canyons, and underwater archaeological sites. These special places also provide homes to thousands of unique or endangered species and are important to America's cultural heritage. Sites range in size from less than one square mile to almost 583,000 square miles. They serve as natural classrooms and cherished recreational spots, and are home to valuable commercial industries.

Because of considerable differences in settings, resources, and threats, each national marine sanctuary has a tailored management plan. Conservation, education, research, monitoring, and enforcement programs vary accordingly. The integration of these programs is fundamental to marine protected area management. The National Marine Sanctuaries Conservation Series reflects and supports this integration by providing a forum for publication and discussion of the complex issues currently facing the National Marine Sanctuary System. Topics of published reports vary substantially and may include descriptions of educational programs, discussions on resource management issues, and results of scientific or historical research and monitoring projects. The series facilitates integration of natural sciences, socioeconomic and social sciences, education, and policy development to accomplish the diverse needs of NOAA's resource protection mandate. All publications are available on the Office of National Marine Sanctuaries website.

Disclaimer

Report Availability

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Abstract

Kelp forests grow in nearshore rocky subtidal areas along the Pacific Coast from Alaska to Baja California, and within four federal marine protected areas along the West Coast: Olympic Coast, Greater Farallones, Monterey Bay, and Channel Islands national marine sanctuaries. Kelp forests are highly dynamic ecosystems with growth and distribution influenced greatly by ocean conditions, ecological dynamics, environmental stressors, and anthropogenic impacts. There is a critical need to better understand regional variations of kelp forest response to certain stressors, particularly to increasing frequency, duration, and intensity of marine heatwaves, which may elicit large-scale ecosystem threshold shifts and changes in species range and distribution along the West Coast.

Management agencies are tasked with understanding these dynamics and planning effective adaptive management strategies for resource protection, conservation, and restoration. Bull kelp and giant kelp, two main foundational species, form canopy layers at the ocean's surface that are detectable by various remote sensing tools.

Remote sensing technology is a valuable tool on both a broad and fine scale, with varying spatial and temporal capabilities. These technologies can measure kelp canopy extent to analyze past ecosystem dynamics, evaluate status and trends, and assess response to management efforts. Analyzing kelp forest dynamics at a local level is valuable for fine-scale restoration and conservation efforts, yet there are significant benefits to developing adaptive management of kelp forests and associated resources at a regional level with a coordinated and complementary approach facilitated between resource managers.

Accessibility of remote sensing technologies has vastly improved in recent years, yet there is a limited understanding among resource managers of the capabilities of each platform, including coverage, resolution, cost, practical applications, and availability of data on kelp canopy cover. This report highlights several tools and data portals that are available to resource managers to effectively communicate and collaborate across the West Coast for timely and efficient decision-making. We will also evaluate the capabilities and practical applications of satellite imagery, plane-based aerial imagery, and uncrewed aerial systems, with specific recommendations to increase the capacity of resource managers to acquire data and support analysis conducive to adaptive management of kelp forests. These data will be presented through remote sensing case studies of three national marine sanctuaries in California while highlighting important applications and key areas of coordination between management agencies and partners relevant to the West Coast Region.

Key Words

kelp forest, kelp canopy, bull kelp, giant kelp, remote sensing, drone, uncrewed aerial systems, satellite imagery, Landsat, PlanetScope, Olympic Coast National Marine Sanctuary, Greater Farallones National Marine Sanctuary, Monterey Bay National Marine Sanctuary, Channel Islands National Marine Sanctuary, California Department of Fish and Wildlife, The Nature Conservancy

Chapter 1:
Kelp Forests and National Marine Sanctuaries Along the West Coast

Figure 1. Thick canopy of giant kelp near Andrew Molera State Beach in Monterey Bay National Marine Sanctuary. Photo: Josh Pederson/NOAA

Kelp forests are found in nearshore rocky subtidal areas in temperate seas around the world. Along the West Coast of North America, kelp forests can be found from Alaska to Baja California and exist within four national marine sanctuaries. These vibrant ecosystems are composed of tiers similar to terrestrial forests, with a canopy layer that forms on the ocean's surface and several layers of subcanopy, understory, and benthic algal growth. Bull kelp (*Nereocystis luetkeana*) and giant kelp (*Macrocystis pyrifera*) are the dominant large canopy-forming brown macroalgal species along the West Coast and are considered foundation species, or species that provide biogenic habitat for kelp forest ecosystems (Krumhansl et al., 2016). One or both of these species are found within Olympic Coast (OCNMS), Greater Farallones (GFNMS), Monterey Bay (MBNMS), and Channel Islands (CINMS) national marine sanctuaries. Giant kelp and bull kelp coexist in mixed-species kelp forests in MBNMS in central California, as well as in OCNMS in Washington. Giant kelp is dominant within the CINMS in southern California, while bull kelp is dominant within GFNMS in northern California. National marine sanctuaries offer an excellent opportunity to present case studies for kelp forest mapping and monitoring, as they are areas of protected ocean space where state and federal management overlap. The case studies presented in this report focus on sanctuaries in California; however, we identify resources and potential applications for OCNMS. These case studies and applications address the ONMS Strategic Goal 1: to ensure healthy and resilient sanctuaries and other marine protected areas, as well as Goal 2: to deepen our understanding of sanctuaries by using remote sensing tools to increase our understanding of kelp forest dynamics and identify opportunities to supplement monitoring of kelp forest habitat.

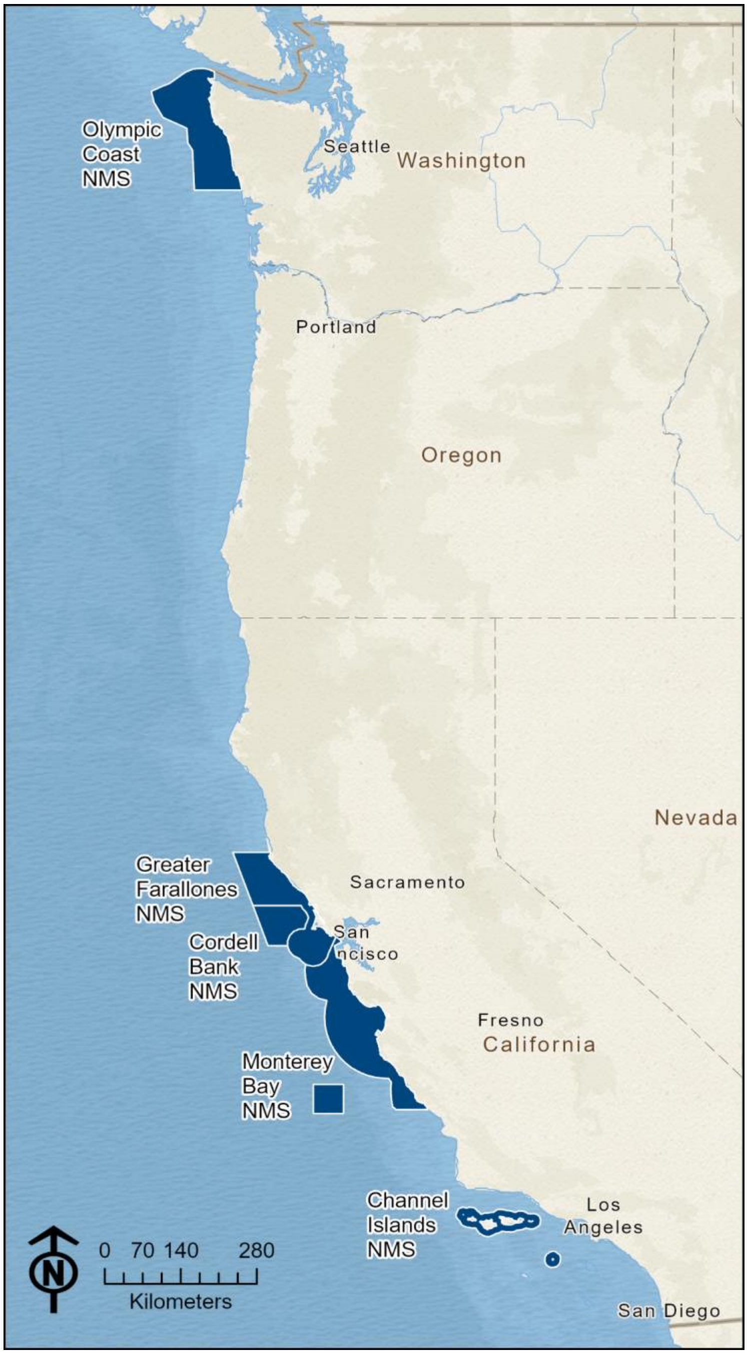


Figure 2. West Coast of the United States, stretching from the Canadian-U.S. border to the Mexico-U.S. border. Five national marine sanctuaries in California and Washington are found in this region. Kelp forests are found in four sanctuaries where boundaries contain nearshore habitats.

Kelp forests along the North Pacific Coast in California and Washington are naturally dynamic ecosystems, yet there are certain ocean conditions and environmental stressors that may cause prolonged or multi-year suppression of kelp forest growth. Kelp typically thrives in cold, nutrient-rich water; thus, regional growth is greatly influenced by the frequency, intensity, and duration of marine heatwaves that create warmer water and lower nutrient conditions (Filbee-Dexter et al., 2020). Increased urchin densities can elicit a shift from kelp forest to urchin-dominated conditions, or urchin barrens, areas characterized by lower biodiversity and high urchin density. Urchin barrens have been observed throughout California with increasing frequency over the past decade, and in 2014, extensive barrens formed along approximately 350 km of the northern California coastline (Rogers-Bennet & Catton, 2019). Short-term stability and long-term resilience of kelp forests are strengthened by the presence of key species that consume urchins, such as sea otters (*Enhydra lutris*), sunflower stars (*Pycnopodia helianthoides*), spiny lobsters (*Panulirus interruptus*), and fishes such as the California sheephead (*Semicossyphus pulcher*). These predators can keep urchin populations in check and maintain balance in the ecosystem (Caselle et al., 2018; Smith et al., 2021).

Ecological, Economic, and Cultural Significance

Kelp forests support diverse and productive ecological communities, and provide vital ecosystem services including primary production, carbon storage and export, and foundational habitat for ecologically and economically important species. Kelp forests also support cultural resources and practices important to Indigenous tribes and nations, provide raw material for commercial harvest and industry, and enhance recreational activities and ecotourism (Hutto et al., 2021; Jones at al., 1994; Pfister et al., 2019; Schiel & Foster, 2015). Kelp forests are biodiversity hotspots that provide habitat, structure, and food for hundreds of species (North, 1971), including those that are commercially, recreationally, and culturally important.

Kelp forests and associated ecosystem services are intricately interwoven with economic and cultural ties to coastal communities. Kelp forests contribute an estimated annual value of $684 billion globally and over $50 billion regionally along the West Coast (Eger et al., 2021). In northern California, a dramatic decline of kelp forests, beginning in 2014, resulted in the collapse of the commercial red sea urchin fishery in the region, an estimated annual ex-vessel value of $3 million, and the complete closure of the recreational red abalone fishery, an estimated annual non-commercial value of $44 million (Reid et al., 2016). Along the West Coast, kelp forest ecosystems support diverse marine resources that have sustained and inspired traditional Indigenous lifeways (Calloway et al., 2020). Kelp also plays a prominent role in traditional subsistence knowledge and is used in fishing, hunting, food preparation, and storage. Declining kelp beds can be viewed as a sign of ecological disruption as well as an impending cultural loss since the two are closely intertwined in Indigenous culture. Decline of kelp forests also has significant impacts on recreational activities such as kayaking, fishing, and scuba diving.

State and Federal Kelp Forest Policies and Management Practices

Management of kelp forests and associated resources is accomplished at both federal and state levels to varying degrees along the West Coast. At the federal level, the Pacific Fishery Management Council identified canopy-forming kelp as a Habitat Area of Particular Concern

(HAPC) for Pacific Coast groundfish within Essential Fish Habitat designated by NOAA's National Marine Fisheries Service. HAPCs are considered high-priority areas for conservation, management, and research because they are important to ecosystem function, sensitive to human activities, stressed by development, or are rare. These areas provide important ecological functions and may be especially vulnerable to degradation. HAPCs are designated based on either specific habitat types or discrete areas. Kelp forests are also recognized as important habitats within national marine sanctuaries.

At the state management level, there are recreational and commercial fisheries along the West Coast for both bull kelp and giant kelp. In California, the California Fish and Game Commission is the decision-making body that establishes policies and regulations, and the California Department of Fish and Wildlife (CDFW) is charged with implementing and enforcing the regulations set by the commission, including the management of recreational and commercial harvest of kelp and other marine algae. Recreational take is not formally monitored; however, regulations limit recreational harvesters to a 10-lb wet weight daily bag limit in the aggregate for all species allowed (14 California Code of Regulations [CCR] 30; 14 CCR 30.10). Commercial kelp and other marine algae harvest requires the purchase of an annual Commercial Kelp Harvesting License and regulations specify allowable harvest methods and harvest areas (14 CCR 165; 14 CCR 165.5). Kelp harvested for non-human consumptive purposes is managed through 87 administrative kelp beds that span the California coastline and the Channel Islands (14 CCR 165; 14 CCR 165.5). The Oregon Parks and Recreation Department allows recreational harvest of marine algae with an allowable take of a one-gallon volume container per day and a limit of three gallons during the calendar year. In addition, Oregon regulations for recreational harvest include allowable harvest methods and seasons (Oregon Administrative Rules 736-021-0090). In Washington, recreational take is managed by the Department of Natural Resources and recreational harvest of kelp is allowed with a license and limited to 10 lbs wet weight per day (Kilgo et al., 2019).

Restoration and Conservation Initiatives

Since the dramatic decline of kelp forest habitat along the northern coast of California in 2014, there has been momentum to advance conservation practices, initiate adaptive management measures, and support restoration of degraded kelp forest ecosystems along the West Coast. The following plans include recommendations and strategies for remote sensing technologies to map and monitor kelp forests at state and local levels.

- The **Sonoma-Mendocino Bull Kelp Restoration Plan** is a guidance document, based on recommendations from the Greater Farallones Sanctuary Advisory Council, that outlines strategies and priorities for kelp restoration, research, monitoring, and community engagement (Hohman et al., 2019). This plan includes recommendations and strategies to develop a long-term coordinated kelp canopy monitoring program using a combination of remote sensing tools, including uncrewed aerial systems (UAS) and satellite imagery, to characterize broad-scale and fine-scale kelp forest dynamics and restoration efficacy.
- The **Interim Kelp Action Plan for Protecting and Restoring California Kelp Forests**, released by the California Ocean Protection Council in partnership with

CDFW, outlines priorities for action on research and monitoring, policy development, restoration, and community engagement (California Ocean Protection Council, 2021). This plan identifies several areas where remote sensing efforts are currently being implemented, including an effort led by the Greater Farallones Association to align mapping and monitoring protocols for sanctuaries and a comparison of PlanetScope imagery to aerial surveys of kelp canopy led by The Nature Conservancy and the University of California Los Angeles (UCLA).

- The **Kelp Restoration and Management Plan**, currently in development, will provide an adaptive, climate-ready approach to managing California's kelp forest ecosystems in the face of changing ocean conditions. The plan's development is being led by CDFW, in partnership with the California Ocean Protection Council. In addition to a harvest management framework and other fishery management plan elements required by the Marine Life Management Act, the plan will include an innovative framework for ecosystem-based management of kelp forests, and a Restoration Toolkit that will provide guidance and best practices on kelp restoration strategies. The Kelp Restoration and Management Plan will also identify a statewide kelp forest monitoring plan, which will include subtidal and remote-sensing data sources. The plan is being developed in response to priorities set forth by the California Ocean Protection Council and CDFW for the management, protection, recovery, and restoration of kelp forests in the face of changing ocean conditions.

In May 2023, a floating kelp indicator for all of Washington State, including OCNMS, was released with the first statewide assessment of floating kelp. This work, performed in a collaboration of many diverse partner organizations and individuals, is intended to guide science and management. The Washington Department of Natural Resources continues to monitor floating kelp within OCNMS, but a kelp conservation plan that addresses kelp forests within the sanctuary does not currently exist. The **Puget Sound Kelp Conservation and Recovery Plan** provides a research and management framework for coordinated action to improve understanding of kelp forest population changes and declines, while also working to implement and strengthen recovery and protective measures (Calloway et al., 2020). However, this plan does not address kelp forests found on the outer coast within OCNMS, and managers have identified a need to determine management pathways to protect and conserve these habitats within the sanctuary.

West Coast Region Kelp Forest Data Gap Analysis Summary

In 2021, the West Coast Region Kelp Team—a conglomeration of representatives from four national marine sanctuaries—led an effort to identify ongoing monitoring efforts across sanctuaries, specifically to address priorities and key areas of information and data gaps relevant for resource managers. Priorities that emerged included an understanding of:

1) how best to conduct annual assessments of kelp forest ecosystem health;
2) where, how, and by whom data are collected within sanctuary boundaries and throughout the region;
3) how and when to access data efficiently and in a timely manner for management purposes;

4) mechanisms to ensure management questions that can be supported through collaboration and effective communication; and
5) the appropriate spatial and temporal scales of data needed to inform specific management and restoration decisions.

Sanctuary partners, including state agencies, academic groups, and NGOs, collect most data used for monitoring and decision-making processes. There is a need to better understand how to strategically leverage partnerships and resources to ensure consistent data collection, analysis, and availability of data. Monitoring and research priorities stem from direct management needs; thus, sanctuary resource managers identified the necessity of clear communication from leadership on critical questions that need to be addressed and corresponding timelines. One key information gap that emerged was the need to improve understanding of practical applications and accessibility of remote sensing data and identifying pathways to be more cohesive and communicative across the region among sanctuaries and partners. This report aims to address this information gap by providing guidance for accessing data from remote sensing tools and outlining case studies that demonstrate practical applications for remote sensing data in mapping kelp forest canopies. These priorities align with the management needs of the state of California, and this report focuses on a strong collaboration between agencies to use these remote sensing tools for various levels of resource protection, regulation, conservation, and restoration.

Chapter 2:
Assessment and Comparison of Remote Sensing Tools

Remote Sensing to Map and Monitor Kelp Forests

Remote sensing is the process of obtaining information about objects or areas from a distance by using sensors that measure reflected energy from physical characteristics (National Ocean Service, 2023). Special cameras collect remotely sensed images, which can provide information and data about these physical characteristics. Canopy-forming kelp species are spectrally distinct, as they form large, floating surface layers that can be distinguished by differences in their wavelengths from the surrounding habitat with airborne and satellite imagery (Figure 3; Figure 4). Other nearshore species, such as feather boa kelp (*Egregia menziesii*), sea palm (*Postelsia palmaeformis*), and stalked kelp (*Pterygophora californica*), form limited surface canopy or above-water growth layers. This is relevant, as species differentiation is an important consideration when mapping and monitoring surface canopy via remote sensing methods. In any single kelp forest, there may be multiple canopy-forming species, making it challenging to determine cover of each species. Some species, such as bull kelp, also have much less biomass at the surface of the ocean for remote sensing tools to detect compared to giant kelp. Remote sensing platforms with higher resolution are more likely to be able to distinguish spectrally distinct nuances between species.

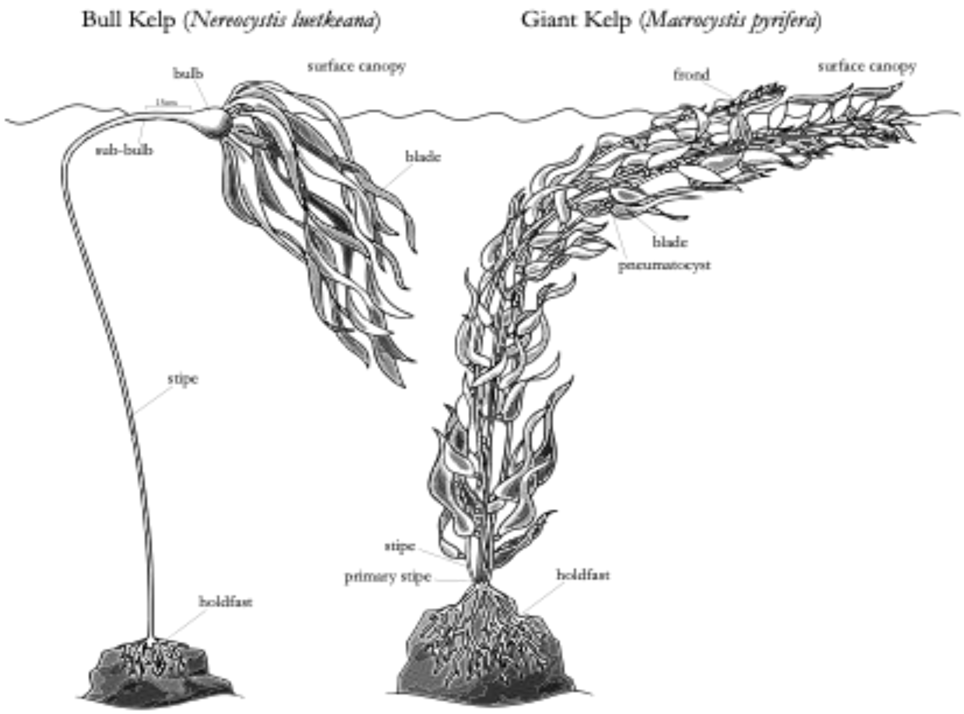


Figure 3. Relevant morphometric characteristics of bull and giant kelp adult sporophytes show the extent of the fronds of both species that reach the surface of the ocean and are thus spectrally distinct. Image: Niky Taylor/University of California Santa Cruz

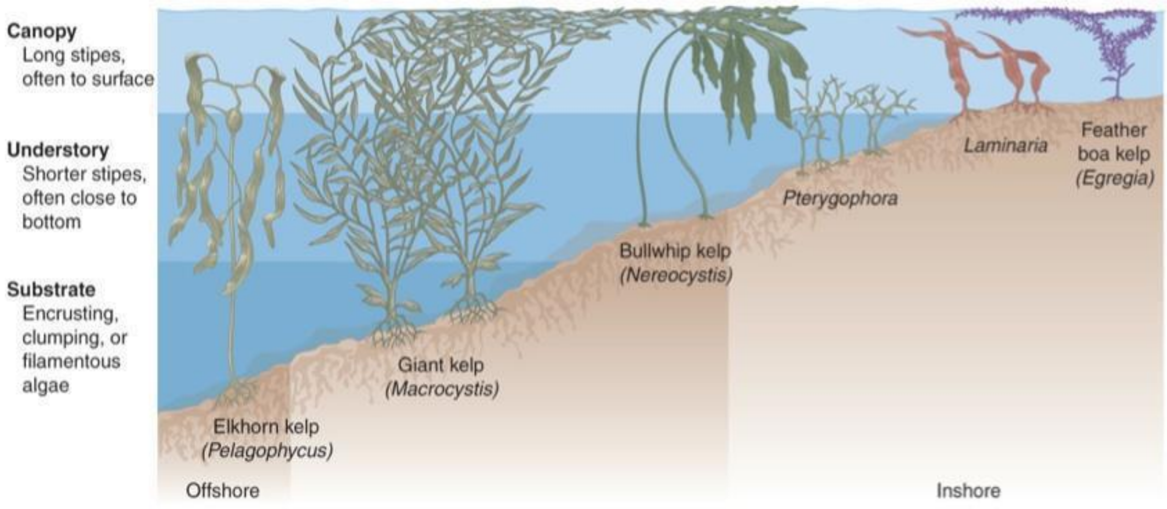


Figure 4. General structure of a West Coast kelp forest showing associated algal species that reach the surface of the ocean and may be detected by remote sensing. Image: Morrissey, 2018

Availability of remote sensing data has increased over the past decade, and we now have access to data sets that span a range of spatial, temporal, and spectral coverage, and resolutions (Cavanaugh et al., 2021). There are significant differences in these data sets that need to be considered. Each may be used in different ways to answer management questions and contribute to decision-making processes by resource managers.

We outline how remote sensing tools can be accessed, how often data may be acquired and processed, what benefits and constraints there are with using these data to inform state and federal management, and which tools may be best suited for specific management applications. To assess and demonstrate the capabilities of each platform, we have described case studies for three national marine sanctuaries along the West Coast that have kelp forests within their boundaries, focusing on three main platforms: Landsat, PlanetScope, and UAS. We also mention applications and accessibility for plane-based aerial surveys; however, in some regions (i.e., Northern California), these data have not been available for several years.

Lastly, we provide recommendations and applications for expanding use of remote sensing resources and data for mapping and monitoring kelp forests, detailing specific pathways for assessment of kelp restoration and conservation projects, outlining opportunities and specific applications for expanded monitoring and community-based science, facilitating regional collaboration among agencies and partners, and aligning remote sensing priorities for agencies and partners to maximize the benefits of a coordinated approach to management of kelp forests.

Remote Sensing Platform Overview

In this section, we will discuss the capabilities, limitations, and applications for UAS, Landsat and PlanetScope satellites, and historical plane-based surveys of kelp canopy. For all remote sensing platforms, imagery is taken by various types of cameras—red/green/blue (RGB), multispectral, and hyperspectral. Each camera may vary in resolution and ability to detect kelp canopy layers and environmental factors such as cloud cover, water currents, glint from the sun, and wind waves. These factors influence imagery and detectable kelp canopy cover (see Table 2). Once imagery is captured, visible kelp canopy cover must be classified (identified manually or via an automated detection method) to distinguish it from surrounding features. Classified kelp cover can then be transcribed as shapefiles and quantified to determine kelp area at the surface of the ocean within the survey area.

Uncrewed Aerial Systems

Uncrewed aerial vehicles (UAV), commonly known as a drones, are aircraft without a human pilot, crew, or passengers. UAV are a component of a UAS, and also include a ground-based controller and communication with the UAV. Throughout this report, we will refer to these systems as UAS. We will only discuss the applications for small UAS, or drones that weigh less than 55 lbs, as defined by the Federal Aviation Administration (FAA).

Mapping and monitoring of nearshore kelp, particularly on a small scale with sparse canopy, requires high spatiotemporal resolution that may be challenging to achieve with moderate-resolution satellite imagery. UAS have been increasingly used in recent years to capture fine-scale, high-resolution kelp canopy data (Saccomanno et al., 2022). Use of UAS allows for flexibility in timing of data collection, allowing the pilot to survey during the peak growth season under ideal conditions, including low tide and low sun angle to maximize canopy expression and reduce glint on the water from the sun’s rays, respectively.

These attributes make UAS particularly useful tools in the assessment of kelp restoration projects to measure success, kelp harvest events to monitor take, and areas of pollution to evaluate potential degradation. UAS allow a quick response to capture the impact of certain events, such as storm disturbances and oil spills. UAS are also highly accessible and affordable, with relatively low costs for equipment and pilot training, and allow for the expansion of opportunities at a local scale for monitoring kelp if access to satellite imagery is limited (Evans et al., 2015; Weissensteiner et al., 2015; Mlambo et al., 2017). However, the time and labor required to conduct UAS surveys and process imagery limits spatial and temporal coverage of these data (Cavanaugh et al., 2021), although automated methods for classification are vastly increasing in efficiency. A variety of sensors can be mounted on UAS; visible and near-infrared multispectral cameras are mostly used for kelp and macroalgal mapping purposes (Tait et al., 2019; Bell et al., 2020). UAS can generally capture imagery with finer than one centimeter resolution if needed.

Aerial Plane-based Surveys

CDFW historically facilitated aerial plane-based surveys of kelp forests along the California coast. Plane-based kelp surveys were conducted in 1989 and 1999, and near-annual surveys were flown between August and October from 2002 to 2016. Although CDFW strived for annual statewide surveys, budget constraints, weather conditions, and equipment malfunction prevented coverage of the entire coastline in 2006 and 2009–2013. The CDFW surveys ended in 2016 due to budget constraints and a limited number of contractors available to perform the specialized monitoring. In 2019 and 2020, The Nature Conservancy (TNC) funded and managed aerial plane-based surveys; however, poor visibility due to wildfire smoke made most imagery of the Northern California coast unusable. When available and as detailed in the annual metadata, CDFW included aerial survey data from other sources to provide a more complete dataset prior to the cessation of these surveys in 2016. As technology advanced, different camera systems and processing software were used over time; however, all datasets include two-meter spatial resolution imagery that contains RGB and near-infrared spectral bands. Descriptions of the image collection, processing, and resulting datasets are available on CDFW's webpage as GIS shapefiles and can be found on MarineBIOS, an online interactive mapping tool used for relevant marine spatial planning (California Department of Fish and Wildlife [CDFW], 2023) and each individual year can be downloaded separately.

In addition to the historical plane-based surveys conducted by CDFW, plane-based aerial giant kelp surveys have been and continue to be conducted quarterly in southern California as required by National Pollutant Discharge Elimination System permits for ocean dischargers. Monitoring began in 1983 with aerial giant kelp surveys conducted by the Region Nine Kelp Survey Consortium for San Diego and southern Orange counties. In 2003, monitoring by the Central Region Kelp Consortium increased the coverage area to include Ventura, Los Angeles, and northern Orange counties. Annual reports depicting maximum kelp coverage, descriptions of the kelp beds, and oceanographic data can be found on the Southern California Bight Regional Aerial Kelp Surveys webpage (*Southern California Bight Regional Aerial Kelp Surveys*) from 2010 to 2016 (as of June 2023).

Data from CDFW's aerial plane-based surveys was used extensively by CDFW to inform the planning process for state marine protected areas throughout California and was initially used to assess extensive kelp forest loss in northern California from 2014–2016. The two-meter resolution of the data from plane-based surveys is valuable, as it allows the detection of small patches of bull kelp canopy. However, surveys conducted annually cannot reflect seasonal variation in growth. As these data are no longer collected, we do not have a specific case study example in this report using these data, but they are referenced for comparison.

In restoration planning for GFNMS sites, aerial plane-based surveys are of great value despite missing data after 2016. Existing layers, in conjunction with Landsat and UAS data, can be used to determine areas of historical persistence to identify areas with potentially higher restoration potential (Hohman et al., 2019). Examining persistence maps of identified restoration sites yields information about the habitat and potential characteristics that may increase natural resilience (Figure 5).

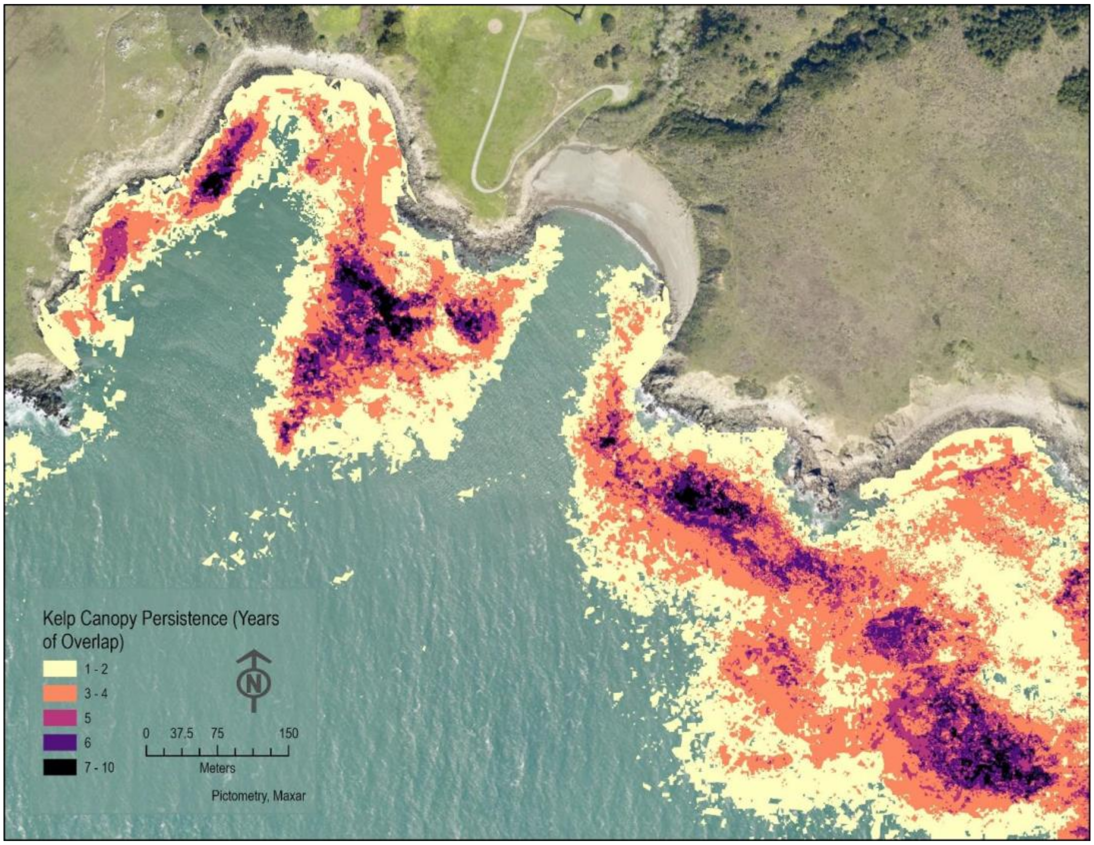


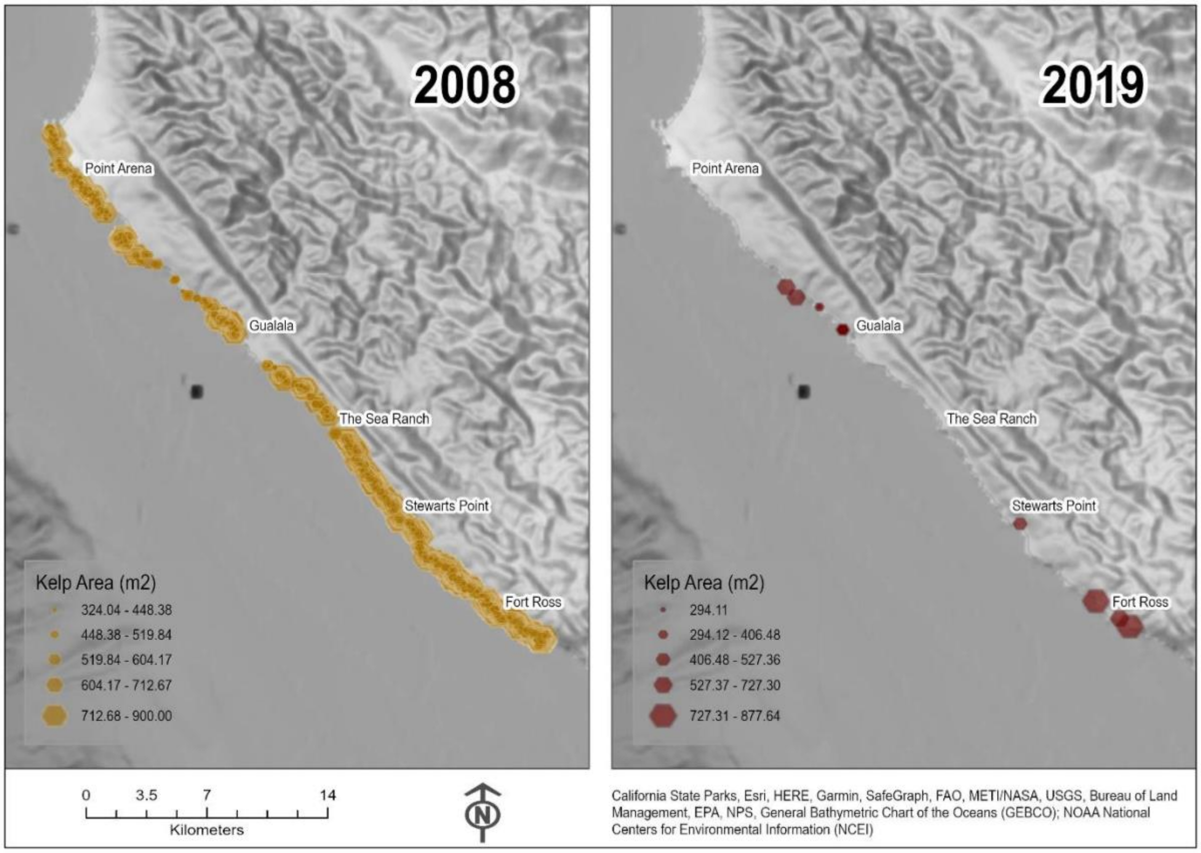
Figure 5. Persistence map of Fort Ross Cove in GFNMS, an identified kelp restoration site, showing areas of high historical persistence (7–10 years), medium persistence (5 years) and low persistence (1–2 years) for the years when data was collected between 2002–2016. Source: CDFW

PlanetScope

PlanetScope, operated by Planet, is a constellation of approximately 130 satellites that orbit the poles every 90 minutes to image the entire land surface of the Earth every day. PlanetScope satellite imagery provides high-resolution multispectral data that can detect floating kelp canopy, including small, nearshore kelp beds (Cavanaugh et al., 2023). PlanetScope provides imagery at near-daily resolution from 2016–present. This imagery provides four spectral bands (blue, green, red, near-infrared) at a three-meter spatial resolution.

Landsat

The Landsat Program, funded by NASA and the U.S. Geological Survey, provides the longest continuous space-based record of Earth's land in existence. Landsat data are used in many ways by various entities to make informed decisions about Earth's resources and environment. Kelp canopy data derived from Landsat have been built into a seasonal time series of kelp canopy area biomass across 1500 km of the California coastline from 1984 to present (Bell et al., 2020). Recently, Landsat was shown to be a valuable tool in enabling broad remote measurement of bull kelp canopy to confirm recent extensive losses in northern California (McPherson et al., 2021), as Landsat imagery shows a drastic decline between 2008, a good year for kelp growth, and 2019, when very little kelp was observed (Figure 6). Additionally, Landsat data were used to inform a Fish and Game Commission decision to temporarily close commercial bull kelp harvest for a three-year period beginning January 1, 2023, in Sonoma and Mendocino counties due to the extensive losses. Landsat imagery has a 30-meter spatial resolution and tends to be too coarse to distinguish small patches of kelp (<150 m² area), particularly in the nearshore area where it can be confused with land masses.



California State Parks, Esri, HERE, Garmin, SafeGraph, FAO, METI/NASA, USGS, Bureau of Land Management, EPA, NPS, General Bathymetric Chart of the Oceans (GEBCO); NOAA National Centers for Environmental Information (NCEI)

Figure 6. Landsat imagery confirms the dramatic difference of kelp forest canopy cover in northern California and GFNMS between 2008 and 2019. Source: Santa Barbara Coastal Long Term Ecological Research (SBC LTER)

Remote Sensing Challenges

The remote detection of kelp is influenced by numerous physical and biological factors (Cavanaugh et al., 2021), which may determine the sensor characteristics needed to accurately map kelp canopy cover in specific locations. Important factors for the West Coast include multiple species (i.e., bull kelp, giant kelp) of surface-canopy-forming kelps, extent of kelp cover, complex bathymetry, coastline morphologies, glint, shadowing in areas of steep coastal topography, and, most importantly, nearshore oceanographic conditions such as currents, tides, wave height, and phytoplankton blooms. Most of the challenges for remote sensing of kelp canopy increase in severity from south to north along the West Coast. These challenges include greater cloud cover, higher amplitude of tides and currents, more complex topography, steeper bathymetry, greater turbidity, and lower sun angles in the more northern regions, which can exacerbate shadowing along the coast. In addition, fringing kelp beds, which require higher spatial resolution to detect, are more common in central California and throughout Washington.

Table 1. Remote sensing platforms evaluated for kelp canopy mapping applications. Source: Cavanaugh et al., 2021; Schroeder et al., 2019

Remote Sensing Platform	Spatial Resolution	Temporal Resolution	Applications	Limitations	Cost
UAS imagery	3 to 10 cm	Flexible, determined by user	• Local mapping and monitoring at high resolution • Monitoring and assessment of restoration projects • Involving user groups and stakeholders in monitoring	• Limited spatial coverage • Labor for collection and processing imagery • Coastal accessibility • FAA flight restrictions • Training required for individual pilots • Data acquisition limited by weather, smoke from wildfires, and other environmental conditions	Varies depending on spatial coverage, but relatively inexpensive to train pilots, acquire UAS, travel, and map individual sites (<$10 depending on scale, to start a program)
Plane-based aerial imagery	10 cm to 2 m	Determined by user, ceased in north-central California due to cost	• Regional monitoring at high resolution • Estimation of harvestable biomass and regulation of harvest	• Data acquisition limited by weather, smoke from wildfires, and other environmental conditions	$100k–200k to cover 200–300 miles of coastline, depending on resolution, area surveyed per mile of coastline, and specificity of acquisition windows
PlanetScope	3 m global	Daily, 2016–present	• High-resolution monitoring of kelp abundance from 2016 onward; weekly-to-monthly timescales • Standardized regional monitoring • Detecting impacts of heatwaves and other disturbances	• Lower radiometric accuracy (greater interference) than some other satellite-based sensors • Expensive	Annual license fee of >$15k
Landsat	30 m	Eight-day repeat with launch of Landsat 9 in 1999; 16-day repeat for 1970s to present time series	• Regional to global monitoring from late 1970s onward at seasonal timescales • Long-term retrospective surveys • Documenting decadal trends • Detecting impacts of climate change on kelp abundance	• Resolution is relatively low compared to other satellite platforms, which may limit use in some regions. • The Landsat program spans multiple decades and includes multiple sensors. As a result, sensor degradation and calibration among sensors must be accounted for.	Free access on SBC LTER website; however, labor involved with image processing will vary

Chapter 3:
Case Studies in West Coast Sanctuaries

Case Study 1: Using UAS and Plane-based Imagery for Restoration Site Assessment in GFNMS

From 2019–2022, a collaborative effort among federal, state, academic, and nonprofit groups was launched in northern California to map all sites within the Sonoma-Mendocino Bull Kelp Recovery Plan using UAS. This effort is now estimated to be the largest marine mapping project to use drones in California, and likely the west coast of North America (Saccomanno et al., 2022). Sites were selected using a prioritization framework based on data from aerial surveys, subtidal survey sites from multiple organizations, areas of cultural significance, areas of economic significance, and accessibility and proximity to marine protected areas (Hohman et al., 2019). A total of 37 sites were identified, 10 of which were within state marine protected areas and 27 of which were located within GFNMS (Figure 7). Ten sites were located along the Mendocino County coastline outside of the sanctuary.

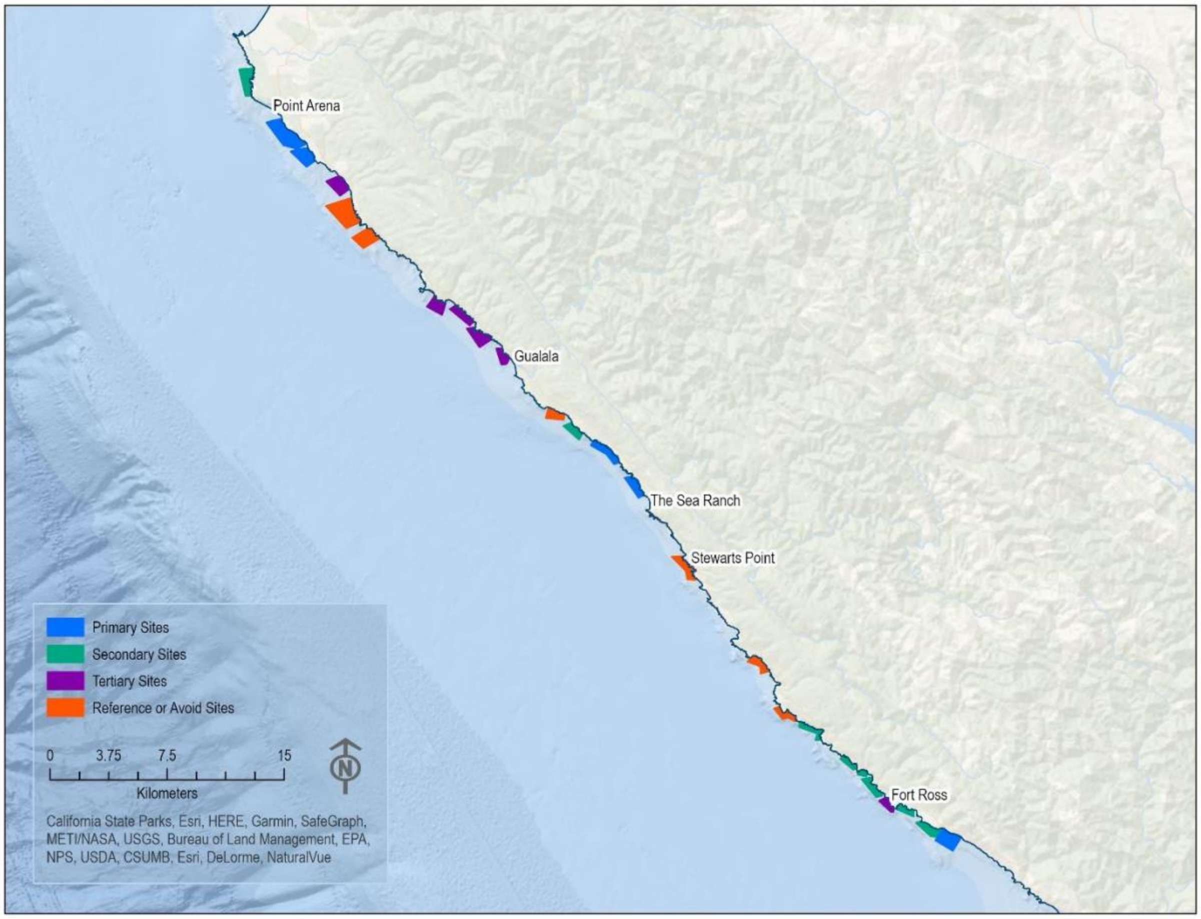


Figure 7. Locations and priority levels of kelp recovery sites in GFNMS identified in the Sonoma-Mendocino Bull Kelp Restoration Plan and mapped using UAS. Source: Hohman et al., 2019

Flight planning software was used to plan and execute autonomous flights to capture imagery with the desired spatial resolution and front- and side-overlap, which determine altitude and flight line spacing. The UAS surveys captured two-dimensional images, which were photogrammetrically orthorectified (geometric distortion corrected and the imagery color balanced) to produce a seamless image product from multiple images and create an orthomosaic data set (see Saccomanno et al. [2022] for methods).

For this project, all terrestrial objects such as land and intertidal rocks were manually masked and selected to help distinguish kelp from seawater using a spectral thresholding process. For individual sites with high levels of spectral variability due to turbidity, glint, or other artifacts, a single threshold could not be used for kelp identification, because the optimal threshold varied throughout the image within a site. For these sites, images were gridded into subsets ranging from 1000 x 1000 m areas to 5000 x 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. The classified grids were mosaicked back to their original extent and all classified mosaics were manually reviewed for quality assurance. Binary classification values—“Kelp” or “Not Kelp”—were used except for mixed-species (bull and giant kelp) marine algal beds and the occasional blurred image, which were assigned “No Data” values. The area of kelp at a given site was determined using GIS software by multiplying the number of kelp pixels by the area of the pixels.

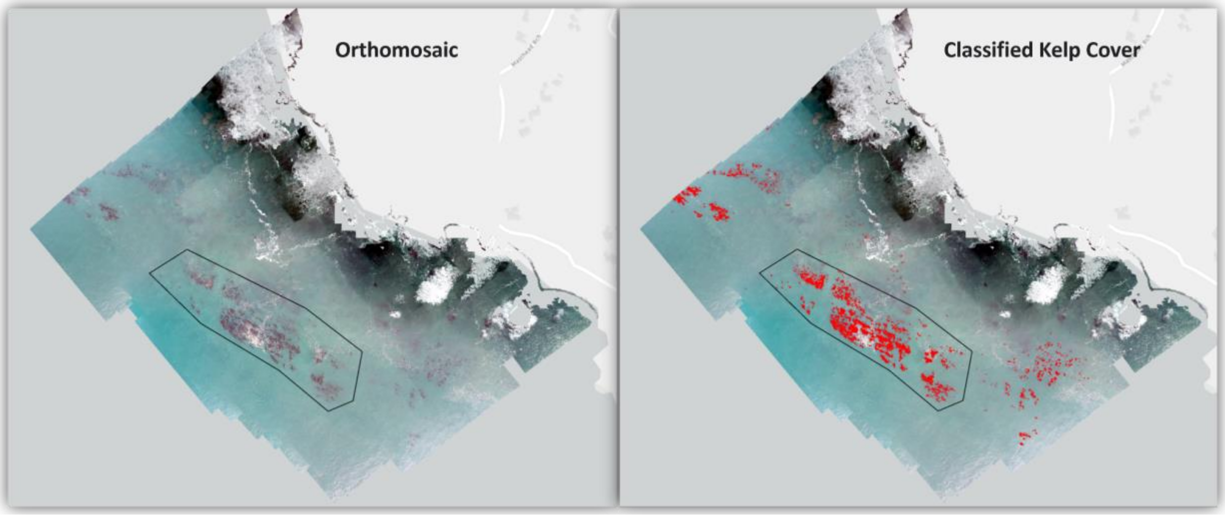


Figure 8. Classification of kelp canopy cover for a drone mosaic at Del Mar, Sonoma County. Source: Greater Farallones Association

The resulting high-resolution data set from the northern California coast was mapped to understand annual emergent kelp canopy trends over the last two decades across all sites and construct spatial occurrence patterns within priority sites over time. Data from the 2019–2022 UAS surveys were then overlaid with historical plane-based surveys at priority kelp restoration sites in GFNMS to create high-resolution maps of areas where kelp canopy is persistent through time and may indicate areas of resilience (Figure 9). These maps allow for the visualization of sparse patches of kelp canopy in the nearshore environment during very low biomass conditions following the extensive loss of kelp forests in GFNMS. More recently, auto classification methods have allowed for classification of kelp canopy with much less manual guidance in a significantly shorter amount of time (Denouden & Reshitnyk, 2023).

Primary kelp restoration strategies include focusing restoration efforts at key areas along the coastline that demonstrate persistence despite low nutrient and urchin barren conditions, and protecting areas of new kelp forest growth from urchin grazing to enhance availability of bull kelp spores. Persistence maps (Figure 9) reveal fine-scale areas where kelp occurs most frequently during extended kelp loss events, allowing researchers, resource managers, and restoration practitioners to focus recovery efforts on these areas. Kelp mapping in the late spring of 2021 also informed restoration planning by identifying areas where young bull kelp growth occurred at priority sites. Knowing areas of early season kelp forest growth will further inform fine-scale site selection and is essential for protecting new kelp forest growth from urchin encroachment.

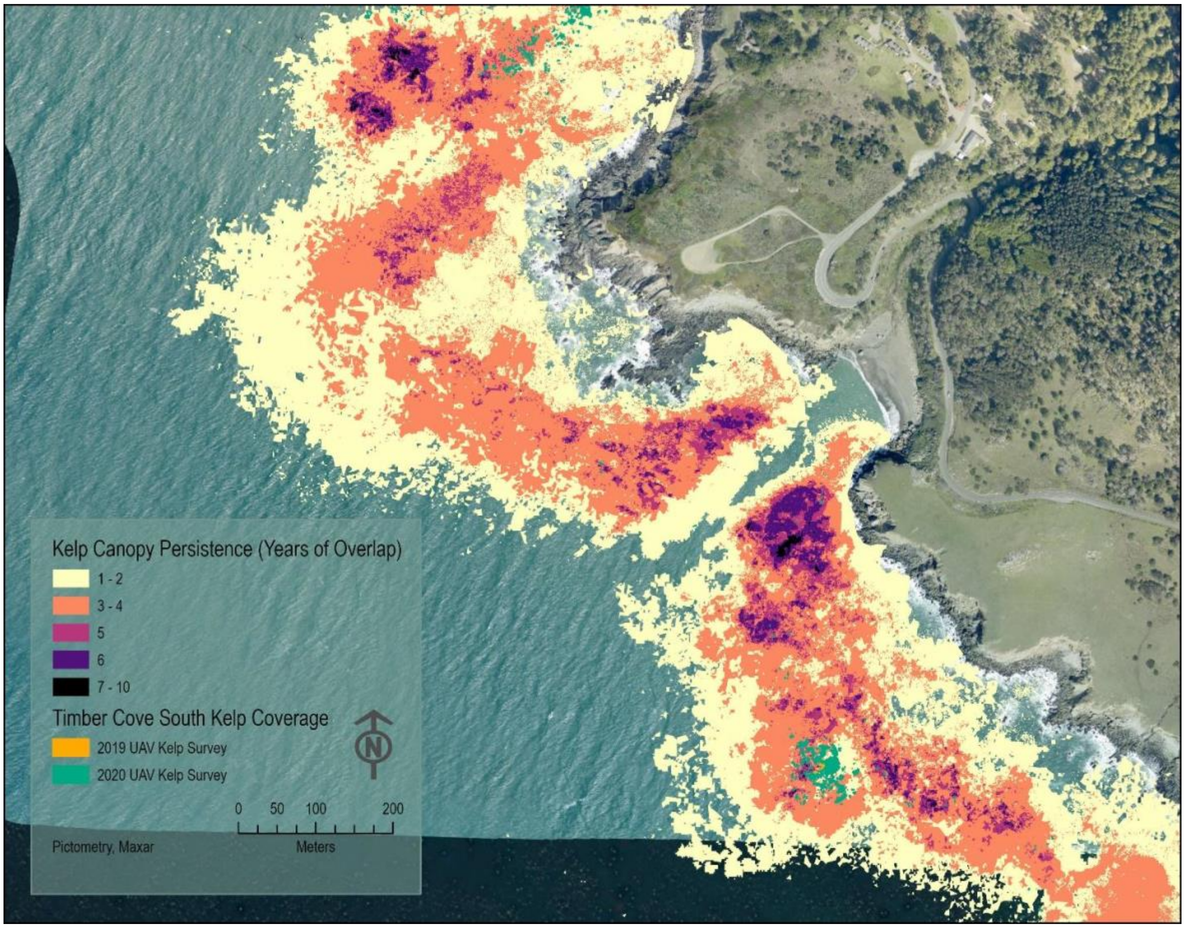
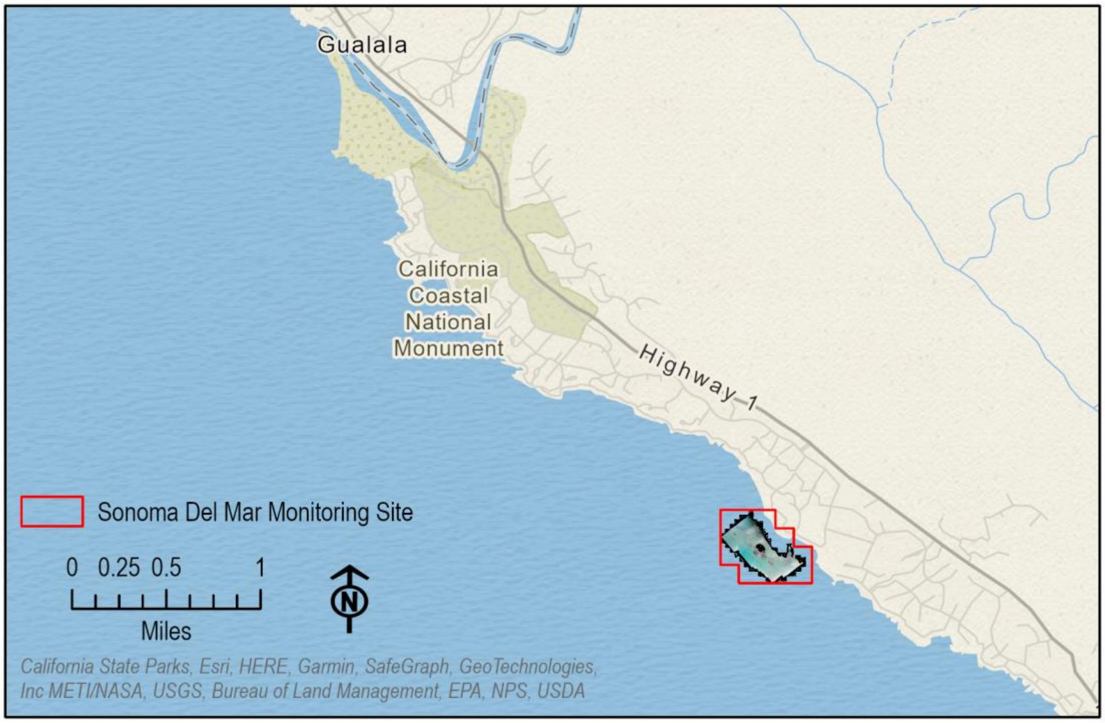


Figure 9. Kelp persistence map showing data from plane-based aerial surveys overlapped by data from drone surveys from 2019–2020 at Timber Cove along Sonoma County in GFNMS. Source: CDFW; TNC

Kelp Cover Analysis Over Seven-foot Tidal Range

While small UAS are excellent tools with flexible deployment opportunities and are able to generate data with exceptionally high spatial resolution, their usage is not yet cost-efficient nor time-effective when surveying relatively large regions (Saccomanno et al., 2022). UAS have limitations in the field that include visual line of sight requirements, telemetry link distances (often 3–7 km), maximum flight altitude restrictions (120 m without a waiver), wind speed thresholds (approximately 45 km/h maximum wind speed for small quadcopters and 20 km/h for permitted areas), accessibility to coastal areas where UAS can be launched, reliance on batteries with finite charge (maximum flight time approximately 28 minutes/battery for a Phantom 4 Pro), 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 et al., 2019). While differences in tidal height at the time of the surveys may influence estimates of change between years and may translate to a conservative measurement in emergent kelp, these data still inform the location of kelp refugia on fine spatial scales. To date, there has not been a comprehensive study on the influence of tidal height and currents on kelp canopy along the northern California coast. To address this question, we conducted a small study at one site in Sonoma County where kelp canopy cover was mapped over a seven-foot tide range.



California State Parks, Esri, HERE, Garmin, SafeGraph, GeoTechnologies, Inc METI/NASA, USGS, Bureau of Land Management, EPA, NPS, USDA

Figure 10. Location of the study area at Del Mar, Sonoma County.

We conducted an analysis of percent kelp canopy cover to determine if, and to what degree, kelp cover changed over a tide cycle. Using 2020 RGB drone imagery collected at the Sonoma Del Mar monitoring site (Figure 10), we compared percent kelp cover throughout the tide cycle. Drone imagery was collected using a Phantom 4 Pro equipped with a 20 MP RGB camera. Imagery was classified using Kelp-O-Matic.[1] Over the course of seven hours, the maximum tide height was 7.2 feet, and fell to as low as -0.3 feet at slack tide.

As a point of reference, measurement of kelp was limited to a core area, which is clearly visible within each of the geoTIFFs used in our analysis. A polygon was drawn to delineate this kelp core area and was overlaid on each of the six geoTIFFs (Figure 11). The areal extent of kelp observed on the ocean surface within the kelp core area ranged from 4,006 to 2,418 square meters. This is nearly a 40% change in cover throughout the study period (7 hours). It is important to note that, at a glance, this kelp core area appeared fairly uniform across the six images. The overall difference in kelp cover across flights was evaluated within the kelp core area (Table 2).

Table 2. Total kelp cover, percent cover, and difference in kelp cover between flights within the core area.

Flight #	Tide Level at End of Flight (ft)	Kelp Cover Within Core Area (m^2)	Percent Kelp Cover Within Core Area	Difference in Kelp Cover (%) Within Core Area Between Flights
1	7	2,585.10	9.03%	N/A
2	7.2	2,418.87	8.71%	-0.32% ↓
3	5.8	2,674.52	9.63%	0.92% ↑
4	3.2	3,181.49	11.46%	1.83% ↑
5	1.3	3,603.60	12.98%	1.52% ↑
6	-0.3	4,006.07	14.43%	1.45% ↑

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[1] Kelp-O-Matic was released under the MIT license and was co-created at the Hakai Institute by Taylor Denouden and Luba Reshitnyk.

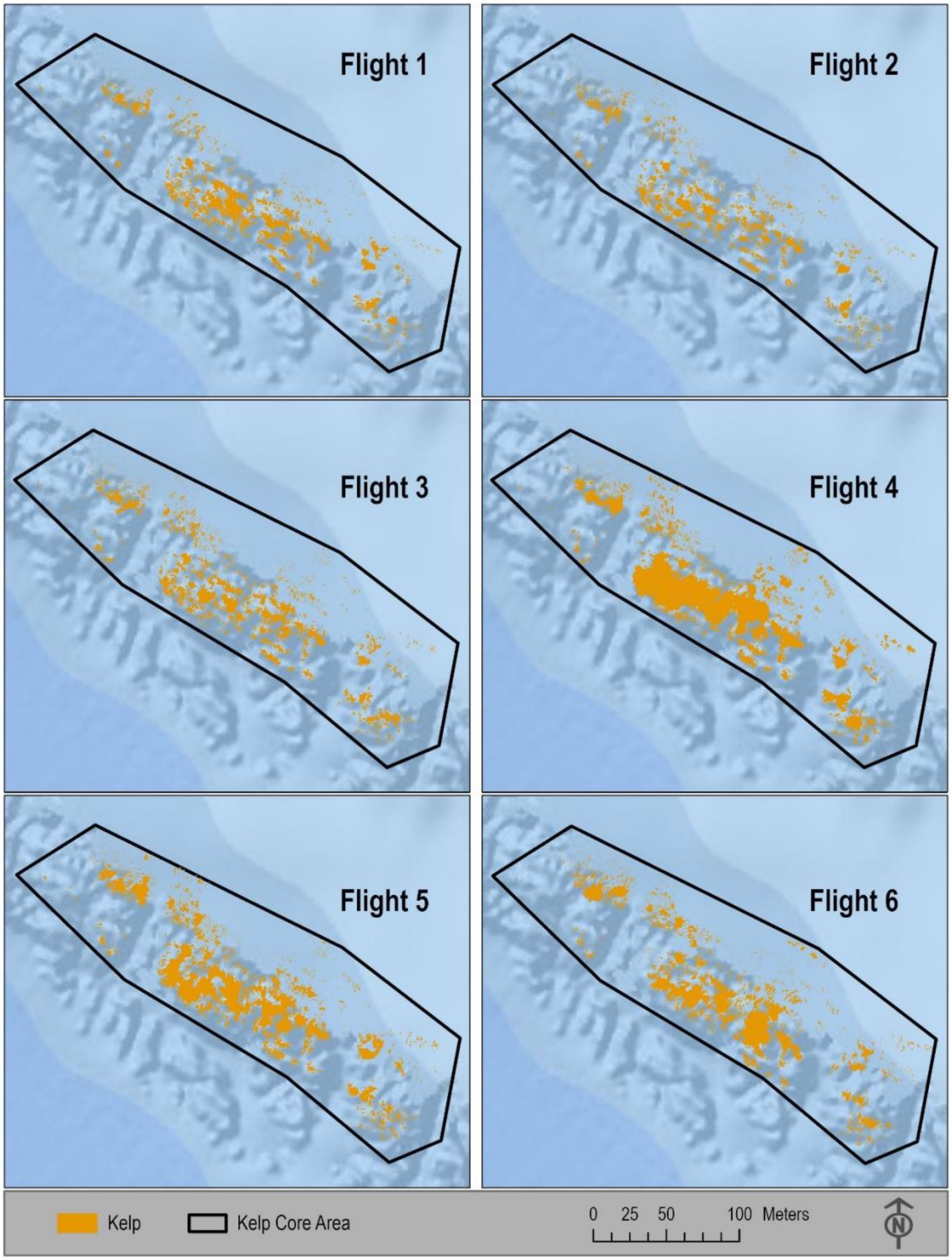

Figure 11. Percent kelp cover within the core kelp area for each flight of the tidal range analysis.

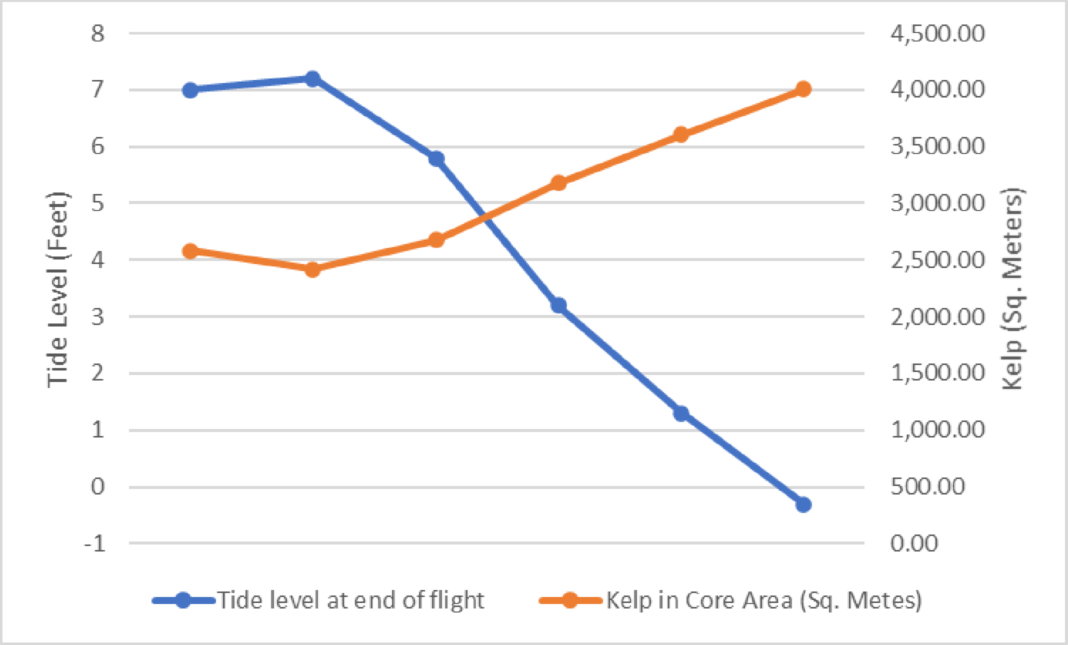

Figure 12. Tide level at the end of each flight and kelp cover within the core area.

These results indicate that tidal range has a substantial impact on detection of bull kelp canopy extent, and that tides should be one of the main considerations when planning field work and deploying UAS to map canopy, particularly for kelp restoration projects where kelp canopy cover may indicate degrees of restoration success. This was a small study and should be replicated across several sites within the same time period to verify the exact range of percent change in kelp cover due to tides. Future studies should also examine the influence of nearshore currents, as they likely also have a significant impact on surface kelp canopy expression. There should also be consideration of the limitations of other remote sensing platforms, including satellite imagery, as there may be little to no flexibility in considering tidal cycles when imagery is collected with those methods. For example, taking the maximum or average kelp canopy cover across a season may help account for the effect of tides and currents, given high temporal resolution opportunities.

Case Study 2: UAS comparison to Landsat in GFNMS

While Landsat data are helpful for understanding long-term, regional-scale kelp canopy dynamics, the 30-meter sensor resolution is often too coarse to accurately assess local-scale, nearshore canopy spatial patterns. Comparison between Landsat and UAS emergent kelp classifications in Saunders Reef and Anchor Bay, two priority sites for monitoring in GFNMS, illustrates the differences in resolution between these sensors and the ability of UAS to detect sparse kelp canopy, a common feature in this region since 2014 (Figure 13). Many areas of sparse kelp canopy were missed by the Landsat sensor, suggesting that the less than 0.1-m spatial resolution of UAV is a better fit to understand local, site-level, sparse kelp canopy dynamics of this system. However, Landsat can detect kelp canopy outside of the boundaries of UAS flights, as demonstrated here, and can show persistence of kelp canopy over three decades (Saccomanno et al., 2022).

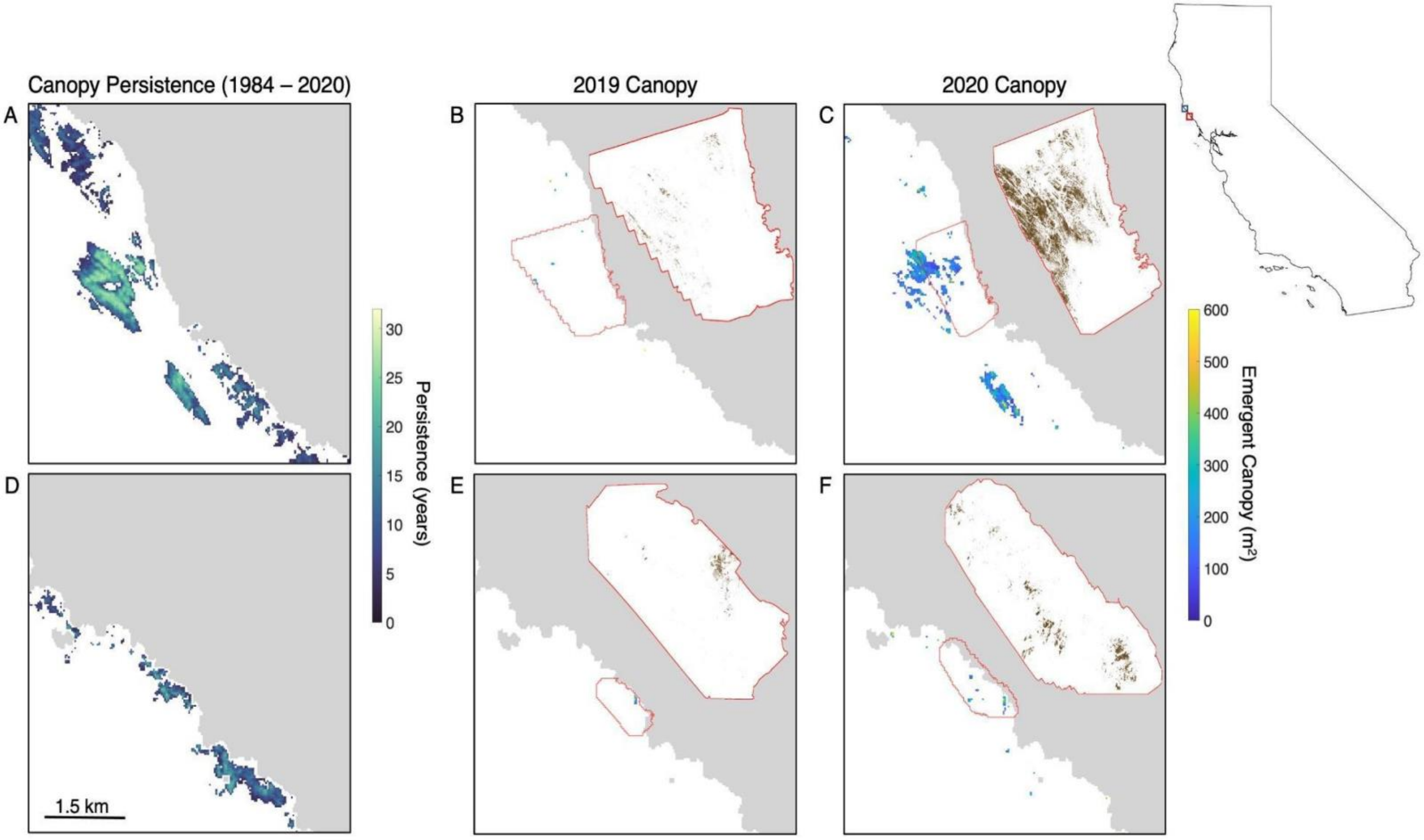

Figure 13. Landsat and UAS emergent kelp classification and persistence at Saunders Reef (top row; northernmost box on state map) and Anchor Bay (bottom row; southernmost box on state map), two priority sites within GFNMS, at peak biomass in 2019 and 2020, where outlines indicate UAS survey extent. Images A and D display relative persistence using Landsat data, showing the number of years with kelp canopy across all surveyed years, 1984–2020. The 2019 (B, E) and 2020 (C, F) canopy maps display the kelp area identified through Landsat and the insets in the upper right of each panel illustrate the UAS emergent kelp classification for that year. Image: Saccomanno et al., 2022

Case Study 3: PlanetScope Assessment in GFNMS

A semi-automated method was developed for mapping giant and bull kelp canopy from PlanetScope imagery (Cavanaugh et al., 2023) and was applied to map kelp canopy extent in GFNMS between 2016 and 2020 (PlanetScope launched in 2016). Imagery was preprocessed to standardize spectral reflectance across the different sensors in the PlanetScope constellation. PlanetScope images were manually classified to create training data for a two-class Naïve Bayes classifier[2], which was applied to obtain the probability of pixels containing kelp in each image. Weekly images were acquired during the months of September and October, as these months tend to represent the maximum canopy extent in GFNMS, each year from 2016–2020 (Figure 14). Monthly average kelp probabilities were calculated for each pixel and used a threshold of 0.5 to transform these probabilities into binary maps of kelp canopy for each month. A composite of kelp canopy in September and October was created for each year, resulting in annual maps of kelp canopy (Figure 15). These kelp canopy maps were clipped to GFNMS boundaries. For more details on PlanetScope image processing methodology and validation, see Cavanaugh et al. (2023). Between 2016–2020, bull kelp canopy extent in GFNMS averaged 0.6 km^2. Canopy area remained around 0.5 km^2 from 2016 to 2018, before declining to 0.15 km^2 in 2019. Canopy area then increased to 1.3 km^2 in 2020.

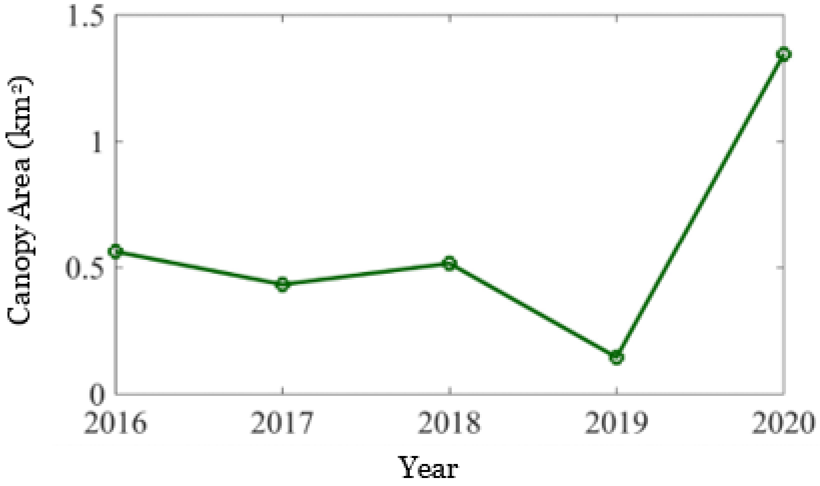

Figure 14. Time series of kelp canopy area in GFNMS as measured from PlanetScope imagery. Data from PlanetScope were only available after 2016, as that is when the satellites were launched.

The analysis of kelp canopy dynamics in GFNMS confirms the results of previous studies that documented a collapse in kelp abundance along the coast of northern California beginning in 2014. PlanetScope data show that kelp canopy in this region remained at historically low levels through 2019. In 2020, kelp canopy area in GFNMS was more than twice as high as it had been in any of the previous four years, indicating an increase in kelp cover. The actual canopy area was still well below average kelp extent prior to the collapse (see Landsat case study below). For this analysis, data were combined from September and October to create annual composite maps of kelp canopy. However, PlanetScope now provides near daily imagery, so it is possible to

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[2] A probabilistic machine learning model used for classification tasks that is based on the Bayes theorem.

use these methods to generate canopy data with higher temporal frequency in the form of seasonal or monthly maps.

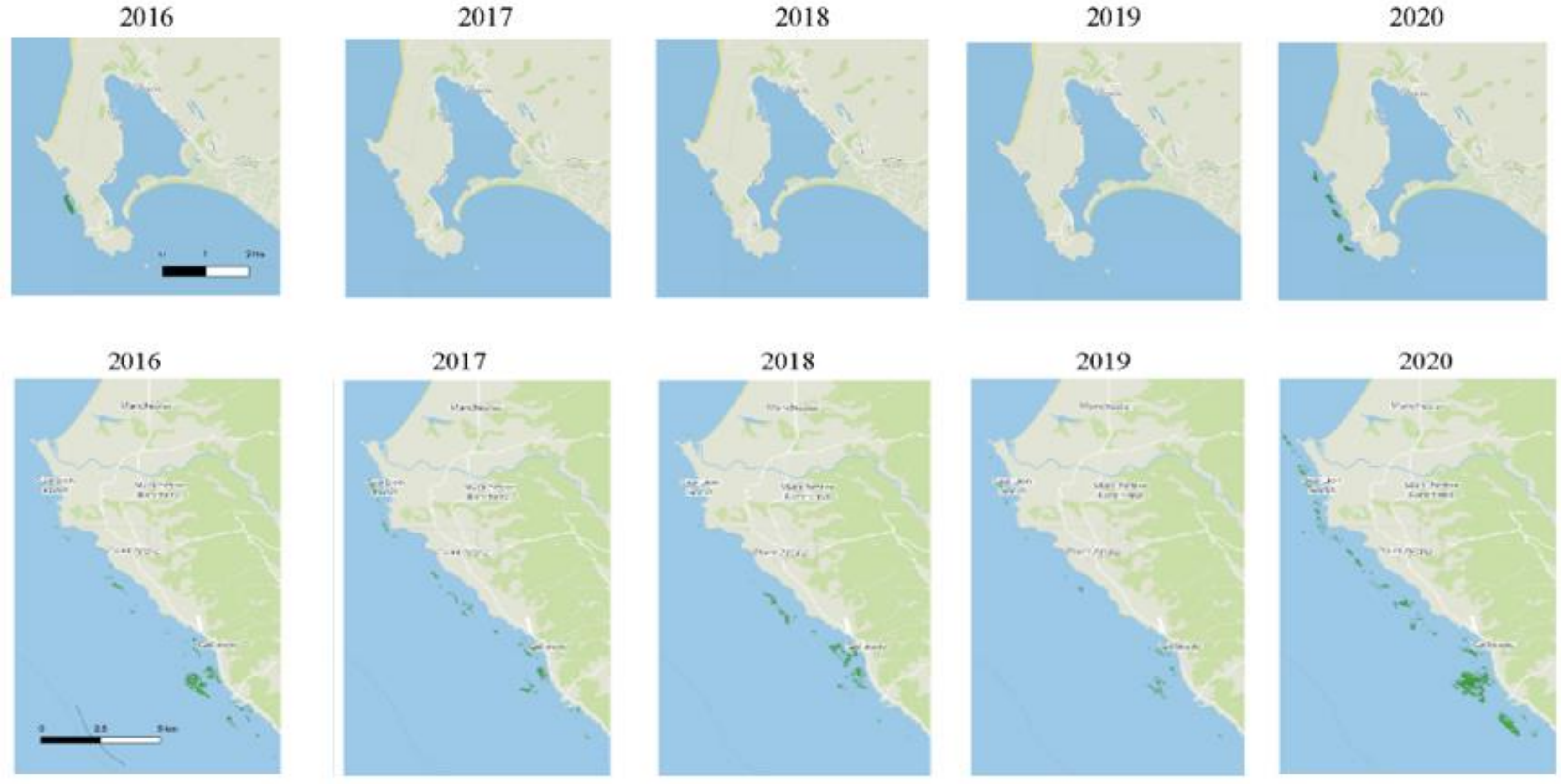


Figure 15. Annual maps of kelp canopy (offshore dark green shading) around Point Arena (top row) and Bodega Bay (bottom row) derived from PlanetScope imagery.

PlanetScope satellite imagery provides a valuable tool for monitoring bull kelp canopy that can complement high-resolution aerial surveys and long-term Landsat data. While 3 m PlanetScope imagery has somewhat coarser resolution than the aerial surveys, canopy area data from PlanetScope aligns well with aerial plane-based survey data (Cavanaugh et al., 2023). As a result, PlanetScope data could be used to continue this valuable high-resolution time series. While Landsat satellite imagery provides an excellent long-term dataset (1984–present), the 30-m resolution of Landsat is insufficient for identifying some of the smaller, nearshore patches of kelp found in this region.

Case Study 4: Landsat Time-Series in California Sanctuaries

Landsat kelp canopy area data from 1984–2020 were used to create time series and mapped annual persistence for GFNMS, MBNMS, and CINMS. Kelp canopy area was determined using classified 30 x 30 m Landsat pixels, where a classified pixel equals 900 m^2 of canopy area and is summed through time. Quarters of each year where greater than 40% of pixels were obscured by clouds were removed from the analysis. Regional maps were created where kelp containing Landsat pixels were binned into 2 x 2 km cells; all cells with less than 20 pixels of visible kelp habitat were removed from the analysis. Annual persistence was calculated as the number of years (out of 37 years) where kelp was observed at least once during a year. Insets show kelp canopy persistence at the native 30 x 30 m pixel scale.

In GFNMS, Landsat confirmed a pattern of high interannual variability, as bull kelp is an annual species (Figure 16). There was a marked decline following 2014, with low kelp cover persisting for several years. There was a small increase in 2020–2021; however, kelp growth was extremely low in the sanctuary in quarter three of 2022 and remains far below historical persistence.

In MBNMS, there was some interannual variability; however, the mixed giant kelp and bull kelp forests in the sanctuary remained relatively stable over time (Figure 17). However, Landsat imagery of Monterey Peninsula revealed that some areas of kelp forests have declined dramatically since 2018 (Figure 18). This demonstrates the value of examining remote sensing data, especially long-term data sets with Landsat, to evaluate fine-scale kelp dynamics as well as broad scale mapping and monitoring.

In CINMS, data showed somewhat high decadal variability and relatively low recent persistence, although low abundance was also observed in the 1990s (Figure 19). Overall, these case studies demonstrate the importance of understanding regional kelp dynamics and trends and provide data that can be compared to long-term environmental conditions to better understand kelp forest response to stressors across the state.

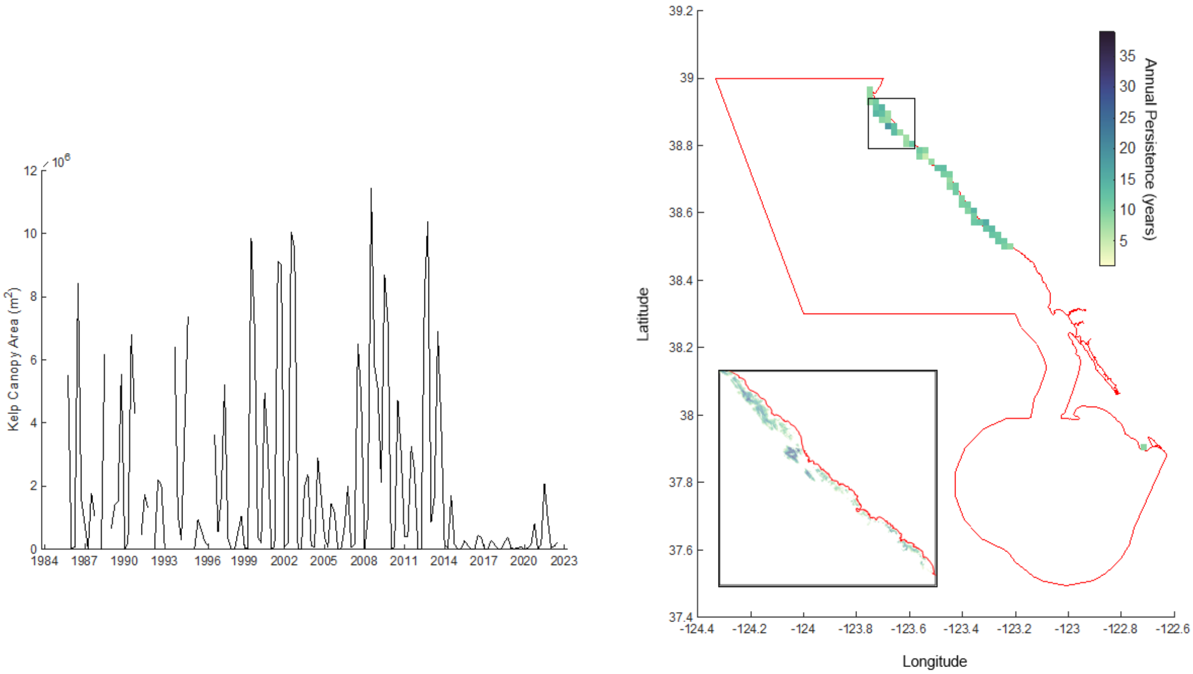


Figure 16. Time series and persistence of kelp canopy in GFNMS using Landsat data. The red outline shows the boundaries of GFNMS. Source: SBC LTER

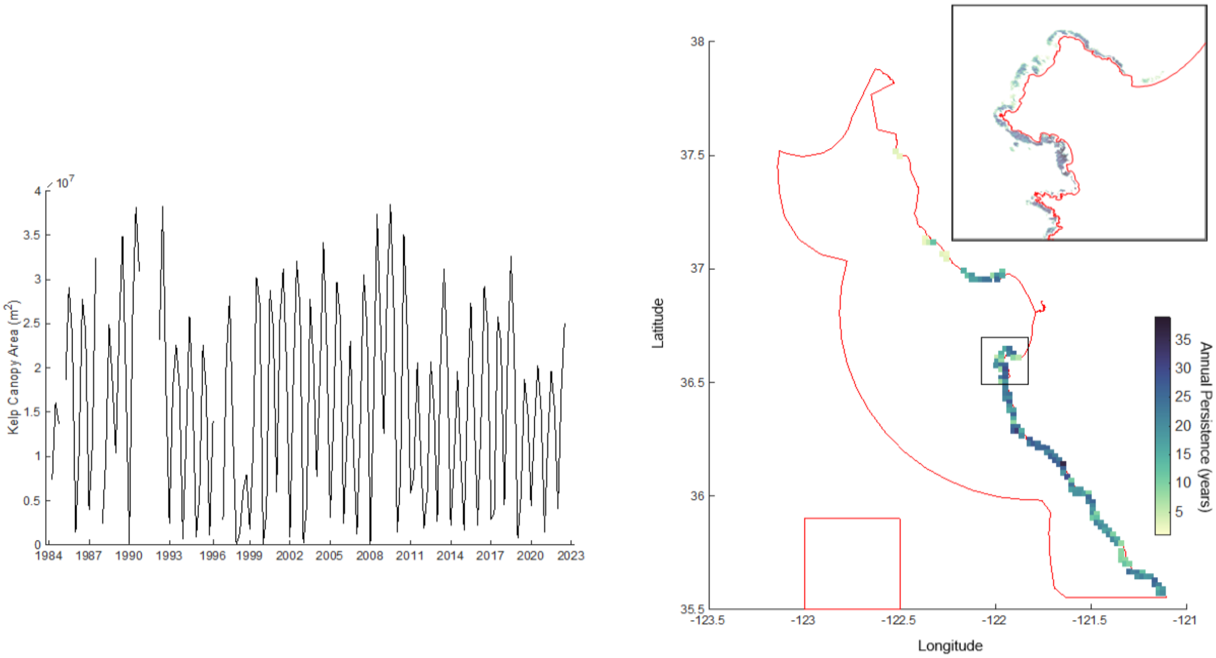


Figure 17. Time series and persistence of kelp canopy in MBNMS using Landsat data. The red outline shows the boundaries of MBNMS. Source: SBC LTER

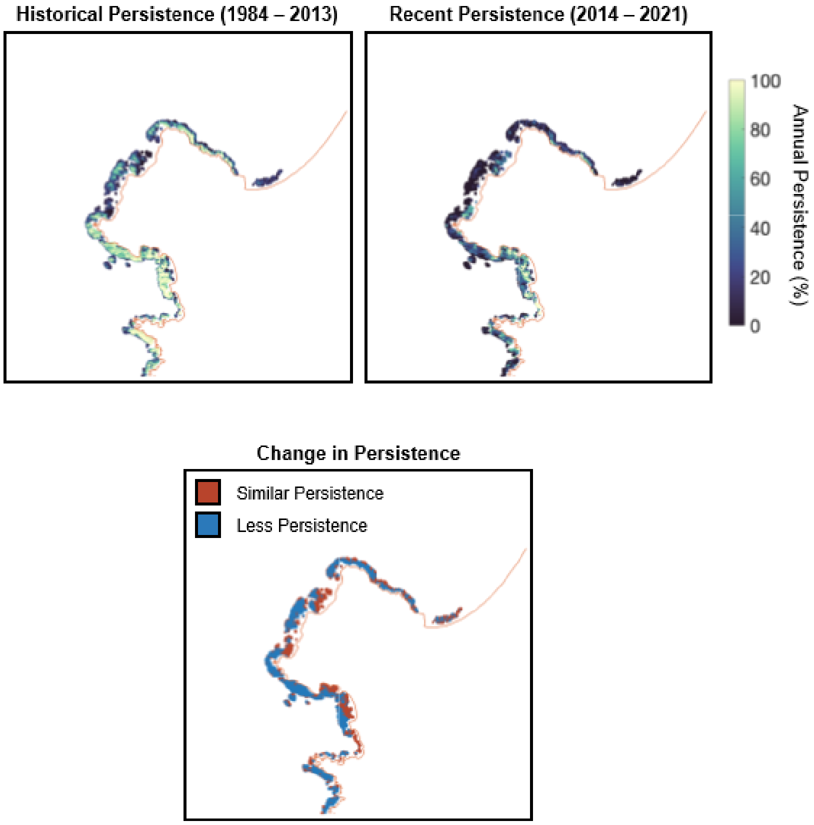


Figure 18. Historical annual persistence of kelp canopy around the Monterey Peninsula from 1984–2013. Recent persistence of kelp canopy from 2014–2021. The change in kelp canopy persistence between the two periods, where areas that show less recent persistence are shown in blue and areas with similar persistence to historical data are shown in red. Image: Bell et al., 2023

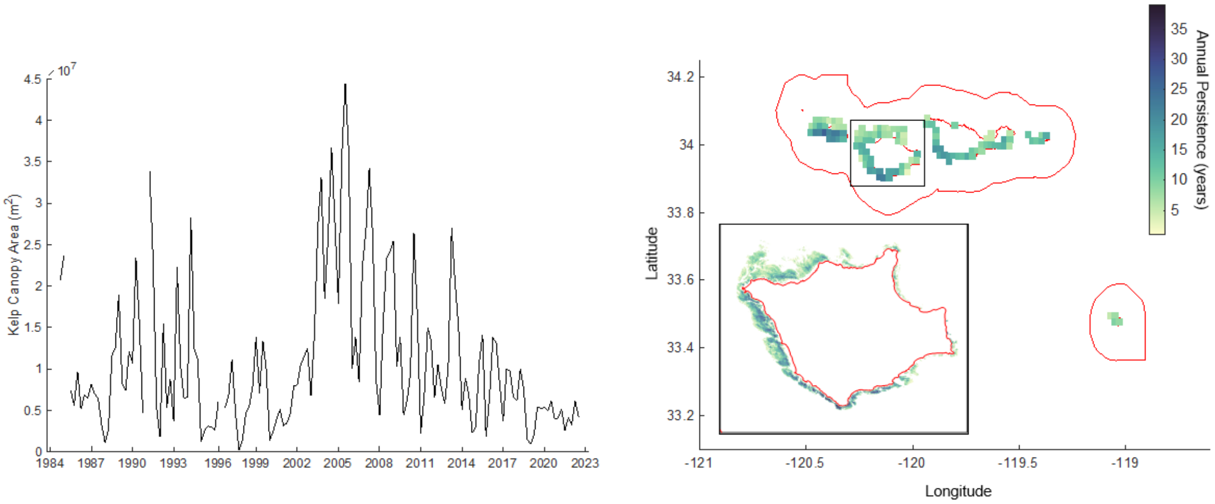


Figure 19. Time series and persistence of kelp canopy in CINMS using Landsat data. The red outline shows the boundaries of CINMS. Source: SBC LTER

Remote Sensing Platform Comparison and Validation

Each of the tools described above requires rigorous ground truthing at multiple locations to ensure validation of kelp canopy features estimated over large areas from satellite or aerial imagery (Cavanaugh et al., 2021). Thus, it is ideal to have multiple complementary sources of remote sensing data, each taken within similar spatial and temporal extents in order to validate kelp canopy calculations accurately. Kelp canopy presence, extent, and species composition can be assessed by field observations or surveys by small UAS. Canopy biomass can be assessed by evaluating the relationship between remote estimates of canopy density and field estimates of canopy biomass. An additional consideration for pairing field measurements with imagery is that the kelp canopy is a “moving target,” constantly shifting its position and distribution with changing tides and currents. Some studies have attempted to account for these variations using spatial smoothing to account for the shifting canopy in validation imagery (Hamilton et al., 2020). This is an important consideration for all ground truthing activities since field validation is rarely achieved simultaneous to satellite image acquisition.

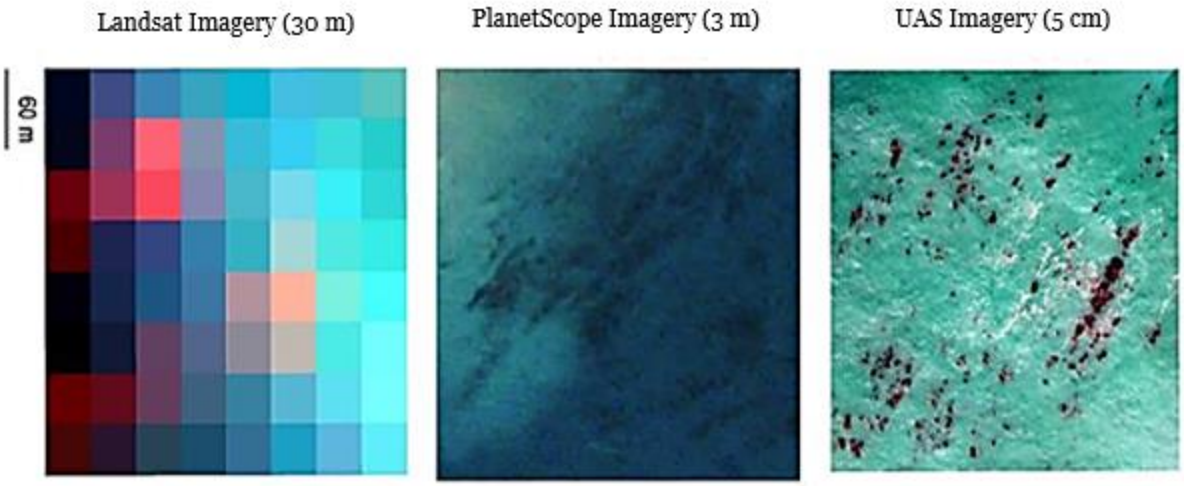


Figure 20. Landsat, PlanetScope, and UAS spatial resolution comparison with imagery collected at the same geolocation within a similar time frame. Landsat imagery is false color, with spectral bands shown as near-infrared, red, and green, rather than red, green, and blue.

Saunders Reef is one site in GFNMS that has demonstrated consistently higher kelp persistence than any other surveyed sites. We examined UAS, Landsat, and PlanetScope imagery for this reef within a relatively close time frame in 2020 (Figure 20). By reviewing the outputs, we see that both Landsat and PlanetScope can capture a much greater area, while the UAS is limited by telemetry link boundaries. However, when comparing kelp canopy extent within the boundaries of the UAS survey, results show that the UAS yielded significantly greater kelp cover (236,750 m^2) when compared to either PlanetScope (149,328 m^2, 37% less area than UAS) or Landsat (143,100 m^2, 40% less area than UAS) for the same area. This demonstrates the expected limitations of each platform—greater coverage at lower resolution versus high spatial resolution at small spatial scales.

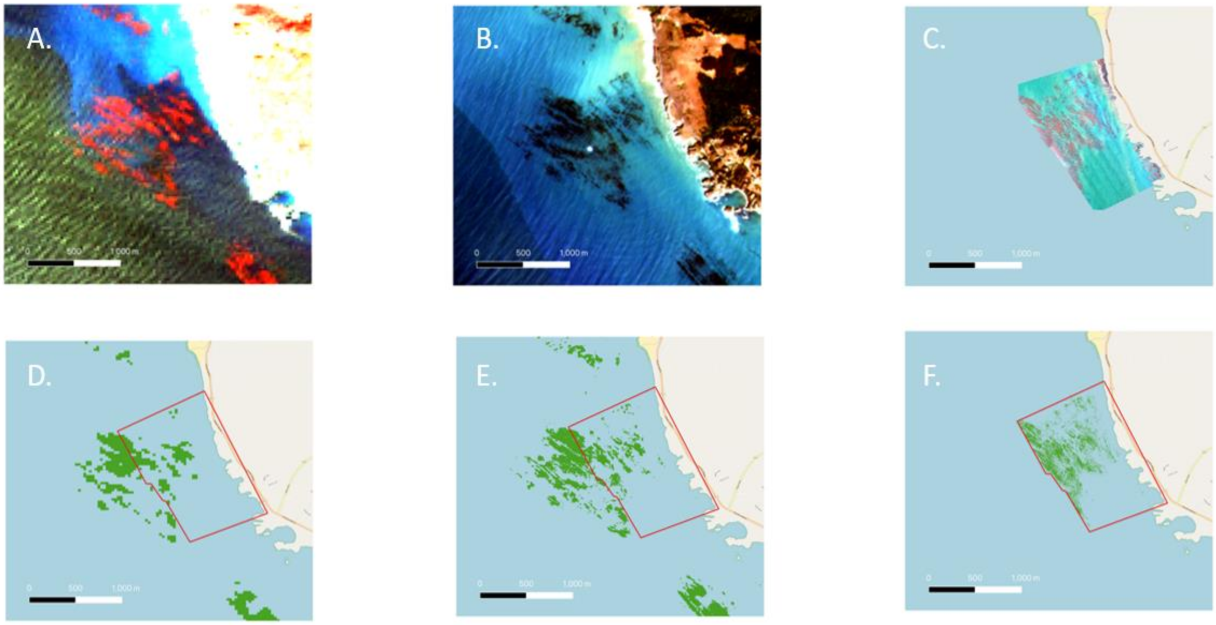


Figure 21. Imagery of Saunders Reef in September/October 2020 from (A) Landsat, (B) PlanetScope, and (C) Phantom 4 Pro drone and (D–F) kelp canopy classified from each image. Red outlines show the boundary of the UAS survey area. Kelp canopy calculated within the red boundaries was as follows: Landsat: 143,100 m^2, PlanetScope: 149,328 m^2, UAS: 236,750 m^2.

In conclusion, the remote sensing platforms highlighted in these case studies have different applications at varying spatial and temporal scales to meet various needs for restoration and conservation. The greatest confidence in outcomes from these data comes from using multiple sources simultaneously to provide validation and answer questions at the site level as well as at the regional level. Particularly for restoration, each platform has significant benefits, as well as limitations, at each stage of the planning and implementation process. Because of the significant overlap in state and federal management areas, it is recommended that these groups collaborate closely in identifying specific remote sensing tools and data that should be used at each spatial-temporal scale, and collaborate on acquisition and analysis of these data, particularly on a regional level.

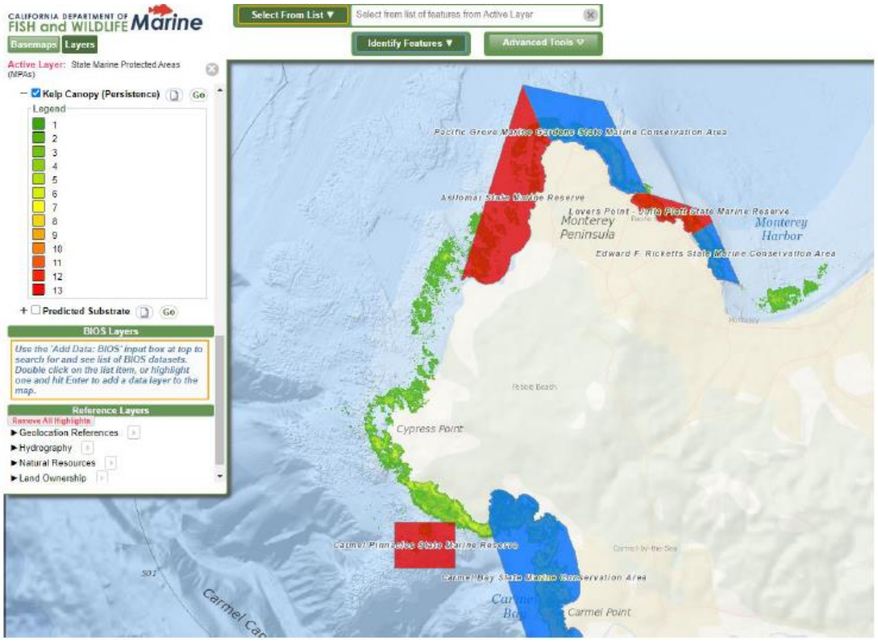
Chapter 4:
Resources for Current and Historical Data

Existing Data, Accessibility of Data Portals, and Repositories

California Department of Fish and Wildlife: Shapefiles

Shapefiles of aerial kelp surveys are available on the CDFW webpage (CDFW, 2023). The webpage provides the 1989, 1999, 2002–2006, and 2008–2016 aerial kelp surveys as downloadable shapefiles that include corresponding metadata describing the survey collection methods, location, and dates of imagery acquisition. The surveys do not distinguish between giant and bull kelp, although some years beginning in 2008 distinguish between surface and subsurface canopy. The webpage also provides an administrative kelp bed boundary layer.

California Department of Fish and Wildlife: MarineBIOS



Use the 'Add Data: BIOS' input box at top to search for and see list of BIOS datasets. Double click on the list item, or highlight one and hit Enter to add a data layer to the map.

Figure 22. MarineBIOS is a marine spatial planning tool that allows multiple layers of marine management and habitat data to be displayed, including kelp canopy persistence from occupied airborne surveys and marine protected areas. Image: CDFW

CDFW offers an interactive map for referencing relevant marine resource spatial planning data. This tool, MarineBIOS (CDFW, 2023), can be used for looking up the boundaries and regulations of marine protected areas or investigating the attributes of benthic and intertidal habitat information. MarineBIOS hosts a kelp canopy persistence layer derived from the aerial plane-based surveys conducted by CDFW in 2002–2006, 2008–2010, and 2013–2016, the administrative kelp bed boundaries, state and federal marine protected areas, and various other marine management and habitat data (Figure 22). Kelp classification layers from UAS surveys on the northern California coastline may be added to this database in the future.

Santa Barbara Coastal Long Term Ecological Research

The Santa Barbara Coastal Long Term Ecological Research (SBC LTER) Program is an interdisciplinary program established in 2000 to understand the ecology of coastal kelp forest ecosystems (Santa Barbara Coastal Long Term Ecological Research, 2023). SBC LTER is based at the University of California, Santa Barbara (UCSB) Marine Science Institute, and is part of the National Science Foundation's Long Term Ecological Research Network, a program established in 1980 to support research on long-term ecological phenomena. Their research is focused on the nearshore waters of southern California, where ocean currents and climate are highly variable with seasonal and longer-term cycles, including the El Niño-Southern Oscillation and the Pacific Decadal Oscillation. SBC LTER's principal study domain is a 10,000 square kilometer area of the northern portion of the Southern California Bight that includes the Santa Barbara Channel and the steep coastal watersheds, small estuaries, and sandy beaches that border the channel.

SBC LTER manages a time series of kelp canopy cover from Landsat 5, 7, 8, and 9 (each a separate satellite) collected since 1984. These data are published quarterly in the form of NetCDF files of giant and bull kelp biomass. Canopy area (m^2) data are given for individual 30 x 30-meter pixels for all coastal areas of Baja California, Mexico; California; Oregon; and Washington, including offshore islands. Biomass data (wet weight, kg) are given for individual 30 x 30-meter pixels in the coastal areas extending from near Año Nuevo, California through the southern range limit in Baja California, Mexico, representing the range where giant kelp is the dominant canopy-forming species. Estimates of canopy area are derived from the fractional cover of kelp canopy determined from satellite surface reflectance. Estimates of kelp canopy biomass are derived from the relationship between giant kelp fractional cover determined from satellite surface reflectance and empirical measurements of giant kelp canopy biomass in long-term SBC LTER study plots obtained using scuba. The different Landsat sensors were calibrated to each other using simulated Landsat data derived from hyperspectral imagery. Data are organized into a single NetCDF file and contain the quarterly area and biomass means for each Landsat pixel across the three sensors. Relevant metadata, such as number of Landsat estimates from which the mean was derived, the number of estimates from each sensor, standard error for each quarterly estimate, spatial coordinates, and date, are all included in the file on the SBC LTER website.

Kelpwatch

Kelpwatch is a user-friendly online tool that hosts the latest kelp distribution data for canopy-forming kelp species using the SBC LTER kelp canopy cover time series derived from Landsat imagery. Kelpwatch gives users the ability to assess long-term, large-scale, and seasonal trends in kelp canopy cover from Baja California, Mexico to the U.S.-Canadian border from 1984–present. Kelpwatch allows users to quantify and visualize how kelp canopy has changed over time. Researchers and resource managers can also download ready-to-use kelp data to answer their unique questions, advance the science around kelp forest ecosystems, and develop science-based management plans. Kelpwatch was collaboratively developed by TNC, UCLA, UCSB, and Woods Hole Oceanographic Institution.

This tool is expanding in both time and space and will host kelp canopy data from global geographies where canopy-forming kelps are found. Data will be added iteratively over the next three years from locations including but not limited to: British Columbia, Southeast Alaska, Falkland Islands, Peru, Tasmania, New Zealand, and Chile.

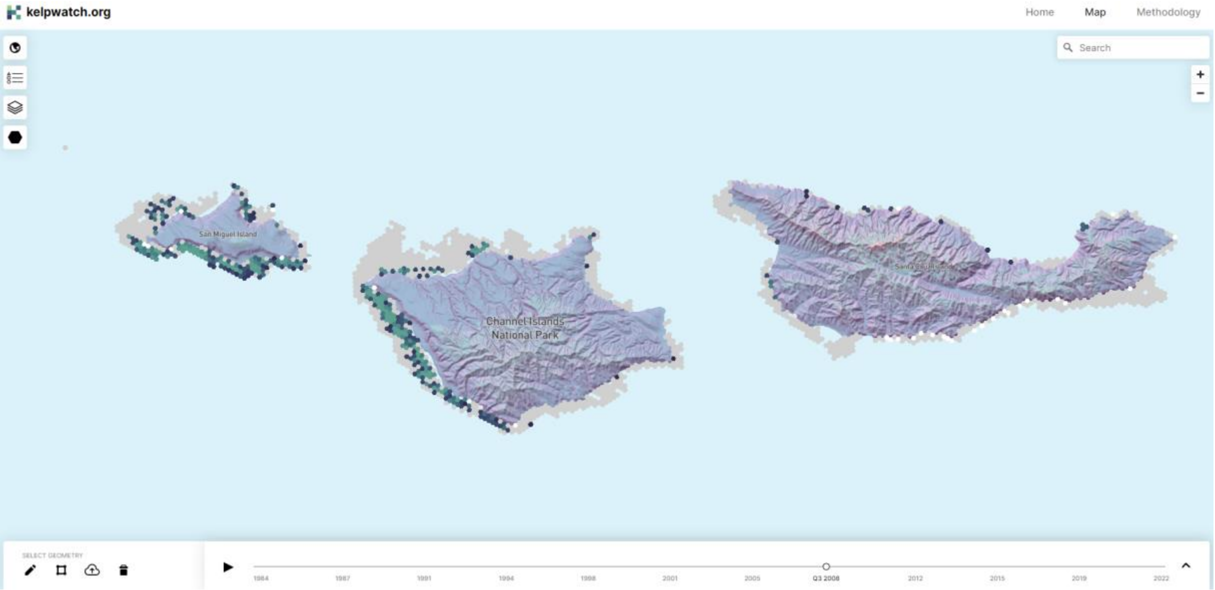


Figure 23. Kelpwatch data portal depicting kelp canopy extent via Landsat in 2008 at San Miguel, Santa Rosa, and Santa Cruz islands in CINMS. Image: Kelpwatch

Washington State Department of Natural Resources

The Washington State Department of Natural Resources Nearshore Habitat Program has conducted plane-based annual aerial surveys of floating kelp canopy extent since 1989. Two species of canopy-forming kelp are monitored: bull kelp (*Nereocystis luetkeana*) and giant kelp (*Macrocystis pyrifera*). The website houses GIS data for annual kelp inventories on the outer coast and Strait of Juan de Fuca within OCNMS from 1989–2021 at the time of this report and links to a Washington Marine Spatial Planning mapping application, a dynamic interactive mapping tool with various data layers showing human uses, marine life habitat, and physical oceanography of Washington's coastal waters (Washington State Department of Natural Resources, 2023). The site also hosts a blog summarizing floating kelp dynamics, annual monitoring reports, and a story map of current and historical floating kelp distribution.

Annual monitoring and quantification of the floating kelp canopy has been conducted since 1989 by the Washington State Department of Natural Resources and in collaboration with OCNMS since 1995. Although canopy cover changes every year, these kelp beds are generally considered stable, and the area covered by floating kelp has been increasing along the outer coast and western portion of the Strait of Juan de Fuca (Berry et al., 2021). This increase may be influenced by changes in oceanographic conditions. In contrast, extensive logging of the Olympic Peninsula, an area of very high rainfall, has markedly increased sediment loads in rivers in the past and a loss of kelp beds near river mouths may be caused by increased silt and reduced light penetration (Office of National Marine Sanctuaries, 2008).

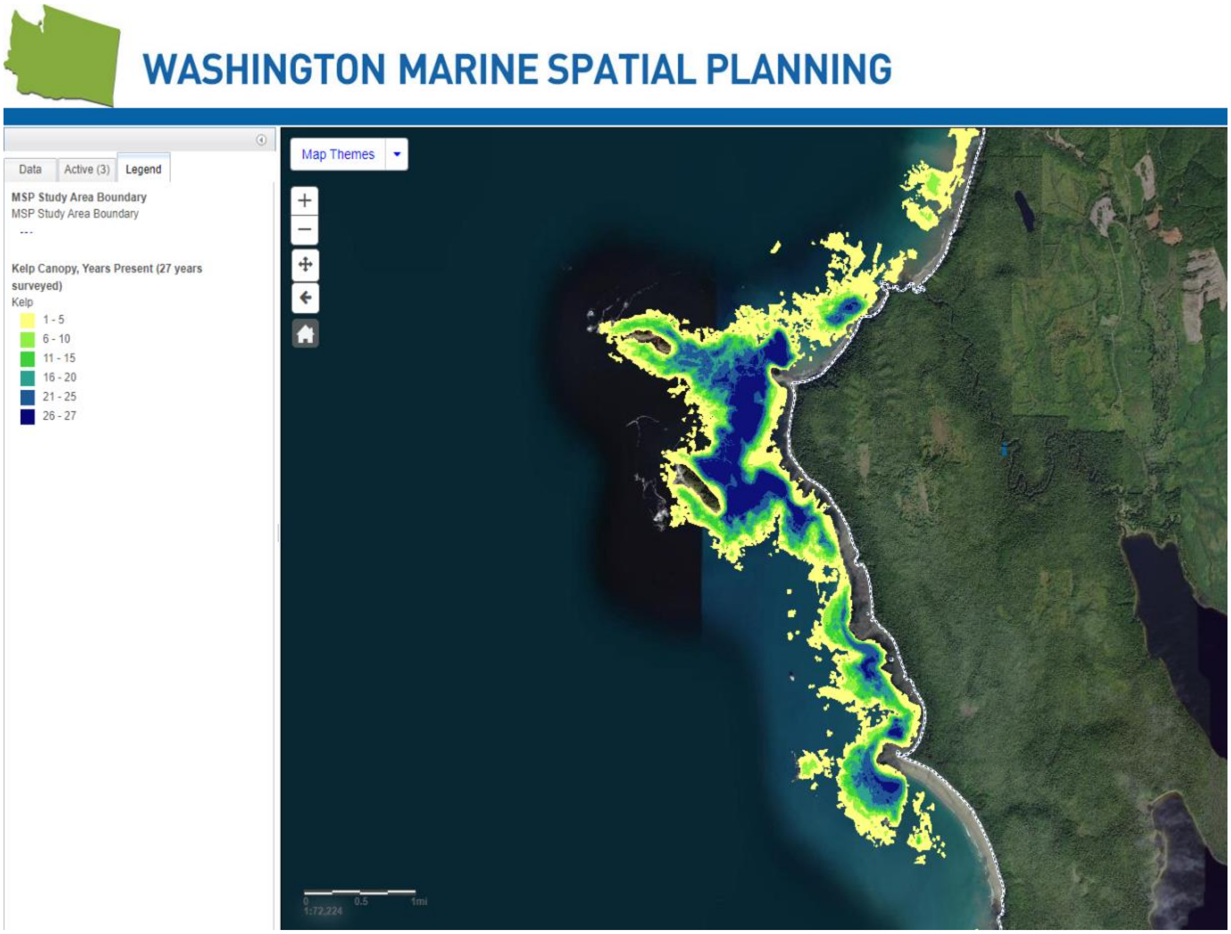


Figure 24. The Washington Marine Spatial Planning mapping application depicts kelp canopy persistence over 27 years. Image: Washington State Department of Natural Resources

Chapter 5:
Applications for Current and Future Management in California

Data on Commercial Kelp Harvest in California

Historically in California, CDFW managed the commercial kelp harvest industry with data from plane-based (crewed) aerial surveys. There were significant limitations to using these data, primarily that they were relatively expensive, data collection was inconsistent, and data were collected only during one time frame throughout the growth season.

More recently, CDFW has begun to use Landsat data (sourced from SBC LTER data portal) to evaluate statewide status of kelp canopy cover. For tracking kelp canopy extent, consistent and timely data on kelp cover across a range of spatial scales (e.g., region, county, administrative kelp bed) is essential to understanding the status of kelp resources and for informing potential management actions. Kelp canopy data derived from Landsat are uploaded to the SBC LTER portal on a quarterly basis, offering an excellent opportunity to use this resource for timely management. However, if considering harvest at smaller spatial scales (e.g., site, forest), it may be ideal to use canopy data derived from PlanetScope or UAS sources to map harvest sites before and after harvest, which could then be compared to reported harvest weight. Such an assessment may contribute to field validation of other remote sensing tools to better understand estimates of kelp biomass in the canopy layers. Here, validation refers to the process of assessing the uncertainty of higher-level, satellite-sensor-derived products by analytical comparison to reference data, which is presumed to represent the true value of an attribute.

Applications:

- Track kelp canopy within harvest regions using Landsat and PlanetScope data sourced from SBC LTER and UCLA
- Use UAS to map sites before and after harvest

Assessment of Kelp Restoration and Conservation Projects

As efforts to advance kelp restoration gain momentum in California, there is a critical need to better understand ecosystem responses to such efforts on both a fine and broad scale. This is particularly true in northern California, where bull kelp is an annual species that expresses less surface biomass than giant kelp and thus nearshore patches are relatively small and ephemeral. A high-resolution tool that can map kelp throughout the growth season is essential. UAS may be used to gather data on the centimeter scale; capture sparse, low-density kelp; detect early season growth; and allow users to time their collection for ideal conditions.

These data are essential in ongoing restoration planning in GFNMS to create persistence maps and identify key areas to focus restoration efforts. However, it should be considered that field surveys on the north coast especially require significant planning, involve a great deal of time traveling between sites, and can be severely limited by weather. Drone surveys may be more consistent and reliable in other regions, such as central and southern California, to capture more consistent data at specific sites. Data processing is also labor intensive for a relatively small spatial and temporal scale and can take several months. However, a newer semi-autoclassification method developed by the Hakai Institute can create analysis-ready maps in just hours (Denouden & Reshitnyk, 2023). With near-daily images available 30 days after collection, PlanetScope can provide consistent information throughout the growth season, barring cloudy days, and for a large regional extent. No field labor is necessary; however, the platform license and labor to process data can be relatively expensive and potentially fluctuate from year to year. Exploration of PlanetScope as a mapping tool for kelp canopy is also relatively new and there isn't a framework in place yet to access publicly available data regularly. The potential for management use is high if funding and accessibility are better understood.

It is also incredibly important to understand historical trends and dynamics at the site and region level, an analysis that can be best achieved with a long time series. A critical part of restoration planning is understanding which areas have the greatest need for restoration efforts and which areas are most likely to successfully respond to these efforts. Landsat has the longest-running time series of any remote sensing platform, with quarterly kelp canopy data from 1985 to present for the entire West Coast. Even with moderately low spatial resolution (i.e., 30 m), Landsat still detects areas where large areas of kelp cover have occurred consistently over time. Restoration efforts are more likely to be successful in areas where there is greater kelp persistence, indicating greater ecosystem resilience. However, floating kelp can also be persistent in fringing nearshore beds—a potential blindspot in Landsat imagery—and vitally important for population connectivity.

Applications:

- Deploy UAS for targeted site-level field surveys of new and ongoing restoration projects to capture very high-resolution data of sparse or fringing nearshore kelp for discrete projects
- Build a framework to acquire consistent kelp canopy data from PlanetScope at the regional level to collect data that tracks seasonal growth at finer scales to build understanding of kelp canopy dynamics
- Use Landsat, in conjunction with PlanetScope, to identify areas of offshore persistence and investigate historical trends and dynamics to inform restoration and conservation planning

Opportunities For Expanded Monitoring and Community-based Science

UAS offer a unique opportunity to engage with the public and with community-based science programs. Members of the public and particularly of coastal communities with FAA small UAS pilot certifications have expressed an interest in becoming involved in kelp canopy mapping efforts. Field data collection is straightforward, and protocols have been developed to standardize surveys; these would likely easily transfer to a public training program. This type of program would need careful guidance to ensure standardization of data collection and processing, as well as make certain that guidelines surrounding FAA regulations and local wildlife disturbance are being met.

Other sanctuary programs may benefit from being engaged in kelp canopy mapping efforts with UAS. Beach Watch is a community-based science program that engages over 150 citizen scientists to monitor beaches spanning 339 km of the California coast. Beach Watch surveys paired with UAS surveys would increase understanding of beach wrack biomass (how much kelp washed ashore), as UAS also capture beach imagery and may contribute to our understanding of distribution of beach wrack in relation to nearby kelp beds. Beach Watch surveys gather data on presence and amount of reproductive sori, allowing us to determine whether the associated increase in biomass from reproductive fronds could be detected via remote sensing. There is also an opportunity to collaborate with the Long-term Monitoring and Experiential Training Program for Students (LiMPETS) program. Ideally, kelp mapping via UAS is conducted at low tide and could provide data to LiMPETS, such as reef structure, algae biomass, and even densities of certain invertebrates. LiMPETS can validate these measurements with field surveys, providing data on algal species identification and densities of urchins to inform restoration planning.

In addition, there is a significant opportunity to engage in expanded monitoring efforts outside of state and federal programs. In 2021–2022, scientists from the Kashia Band of Pomo Indians collaborated with the Greater Farallones Kelp Restoration Project and TNC to establish a new kelp mapping site at the Kashia Coastal Reserve using UAS. The intent is to build capacity for Kashia to map this site on their own moving forward, supporting autonomy over data collection and processing. This model could be used in the future with other tribes to enhance marine resource management that supports cultural resources and practices. There are also likely many coalitions and coastal community groups interested in expanding monitoring efforts along the coast.

Applications:

- Explore opportunities to engage with the public using UAS to map kelp canopy, with careful guidance on methods, protocols, and permitting
- Engage with sanctuary-based projects such as Beach Watch and LiMPETS to explore the potential uses of UAS that coincide with kelp canopy surveys
- Identify potential opportunities for expanded monitoring efforts with tribes, coastal coalitions, and community groups

Regional Communication and Collaboration

A key area of coordination for resource managers is understanding indicators, trends, and thresholds for kelp forest loss and recovery. Although there are basic regional differences in kelp forest composition and structure, it would be beneficial to share research findings, data, and information to help contribute to a greater understanding of kelp forest response to significant stressors and the success of restoration and conservation efforts. Remote sensing platforms, particularly Landsat and PlanetScope, allow us to investigate these responses at a broad scale. As kelp forests are found along the entire West Coast, resource managers, practitioners, and researchers would benefit from connecting on a regular basis to discuss, coordinate, and synthesize new and ongoing research and management outcomes. There is already an effort to coalesce some of these data, and the Kelp Forest Alliance is in the process of building out an open access central Kelp Mapping Repository in coordination with TNC.

Whether the goal is monitoring kelp canopy extent or identifying key areas for restoration and conservation efforts, coordinating data collection among agencies would improve efficiency and cost-effectiveness, as well as better establish standardized methods and strong lines of communication across agencies. State and federal management agencies use the same remote sensing tools and synthesize the data at different spatial and temporal scales to meet the needs of their respective resource authorities. Many areas in California have overlapping state and federal jurisdictions, and these groups already collaborate closely on several kelp forest restoration and research projects; both types of agencies have identified that it is a priority to determine pathways to gather data on a timely and consistent basis.

At the management level, it would be beneficial to develop and implement standardized methods and protocols for data acquisition, packaging, processing, and end product dissemination, including visualization. Supporting multiple levels of management with a streamlined data analysis and process workflow may be more appealing to potential funding sources and likely more sustainable over the long term. It is also important, however, to identify key distinctions between data processing for management decision purposes and approaches for exploring new research ventures.

Applications:

- Establish a repository for data with remote sensing resources
- Expand and enhance regular lines of communication and collaboration among agencies and partners across the region to connect and share information and data
- Identify the most efficient and cost-effective pathways for acquiring remote sensing data on a frequent and consistent basis
- Use opportunities and co-develop workflows to increase governmental or internal capacity to acquire and process data with standardized methods
- Package data with consistent language and distinguish between data used for management decisions versus new research

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Glossary of Acronyms

CCR	California Code of Regulations
CDFW	California Department of Fish and Wildlife
CINMS	Channel Islands National Marine Sanctuary
FAA	Federal Aviation Administration
GFNMS	Greater Farallones National Marine Sanctuary
HAPC	Habitat Area of Particular Concern
LiMPETS	Long Term Monitoring and Experiential Training for Students
MBNMS	Monterey Bay National Marine Sanctuary
OCNMS	Olympic Coast National Marine Sanctuary
RGB	red/green/blue
SBC LTER	Santa Barbara Coastal Long Term Ecological Research
TNC	The Nature Conservancy
UAS	uncrewed aerial systems
UAV	uncrewed aerial vehicles
UCLA	University of California Los Angeles
UCSB	University of California Santa Barbara

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