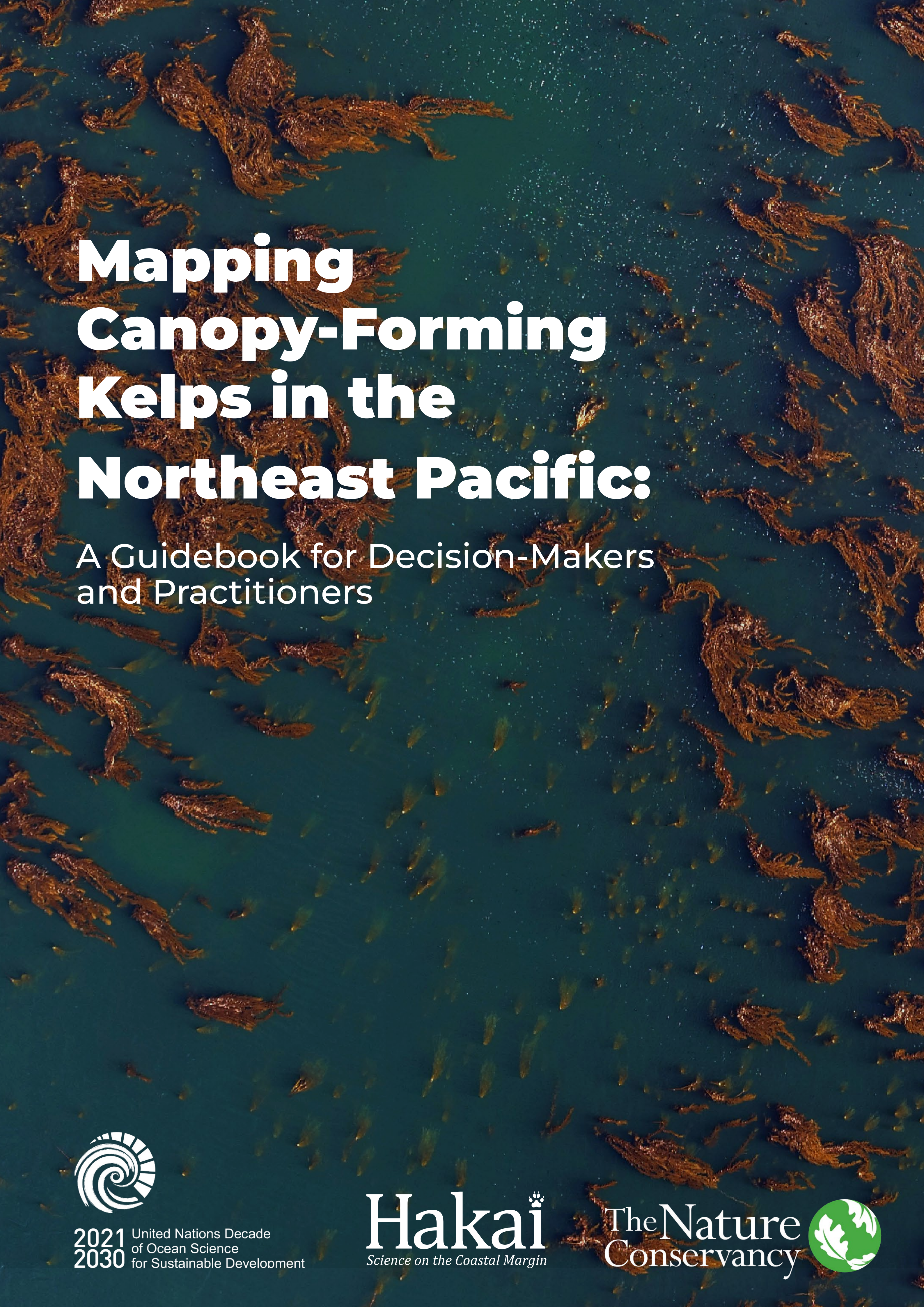


Mapping Canopy-Forming Kelps in the Northeast Pacific:

A Guidebook for Decision-Makers and Practitioners

2021 2030 United Nations Decade of Ocean Science for Sustainable Development

Hakai
Science on the Coastal Margin

The Nature Conservancy

Executive Summary

Surface canopy-forming kelps (Order: Laminariales) provide the foundation for coastal marine ecosystems that are recognized for their ecological and economic value as well as their cultural importance to First Nations. (Kobluk et al., 2021, Wernberg et al., 2019; Holbrook et al., 1990; Dayton, 1972). Along the coastlines of Northeast Pacific, giant kelp (*Macrocystis pyrifera*) and bull kelp (*Nereocystis luetkeana*) form beds and forests that are naturally dynamic and threatened by both local and global stressors. Tools are needed by many groups and organizations to reliably track changes in kelp presence, distribution, abundance, and health at different spatial scales. Optical remote sensing is a powerful tool to monitor canopy-forming kelps that float at the ocean's surface (Gendall et al., 2023; Cavanaugh et al., 2021; Bell et al., 2020; Schroeder et al., 2019; Cavanaugh et al., 2011; Jensen et al., 1980) and the availability of imagery collected by remote sensing tools has increased dramatically in recent years. However, the optical remote sensing platform used (e.g., drones, planes or satellites) must match management objectives and be appropriate for a given area's unqiue constraints. The challenges that someone in Alaska faces for mapping kelp are likely quite different from those faced by someone mapping kelp in California (see examples in Cavanaugh et al., 2021).

This guidebook provides an overview of optical remote sensing as it relates to mapping giant kelp and bull kelp. We describe optical remote sensing platforms and sensors pertinent to mapping and monitoring attributes of bull kelp and giant kelp beds — kelp presence/absence, density, species, and health. Recommendations found in this guidebook can also reasonably be applied to other floating, emergent canopy-forming kelp species (i.e., other species that float at the ocean's surface). This guidebook provides monitoring guidance via infographics developed by an international community of kelp remote sensing experts (see box below). We illustrate a user-friendly framework based on the latest remote sensing science for matching a kelp monitoring objective(s) to the desired spatial scale and environmental setting.

The goal of this guidebook is to help you select the best remote sensing tools and data for your science and/ or management directives related to mapping emergent kelp canopies.

The International Kelp Mappers Community of Practice was originally convened in 2019 by The Nature Conservancy, San Francisco, California. Since this inaugural meeting, the community has grown to nearly 60 members spanning three countries across the northeast Pacific. This community of practice meets annually to discuss advances in the state-of-the-art of remote sensing platforms (e.g., drones, occupied aircraft, and satellites), identify opportunities to collaborate, and set science-based objectives for kelp mapping for the coming year. Previous conveners and meeting hosts include The Nature Conservancy, California; Hakai Institute; University of California, Los Angeles; University of California, Santa Barbara; Woods Hole Oceanographic Institute; and University of Victoria, Canada.

Lead authors:

Luba Reshitnyk, Vienna Saccomanno, Tom W. Bell, Kyle C. Cavanaugh

Suggest citation for document

Reshitnyk, L., Saccomanno, V., Bell, T.W., Cavanaugh, K.C. (2023). Mapping Canopy-Forming Kelps in the Northeast Pacific: A Guidebook for Decision-Makers and Practitioners. The Hakai Institute, Heriot Bay, BC, Canada. doi: 10.21966/7ze4-x883

Contributors

Lead authors

Luba Reshitnyk (1)
Vienna Saccomanno (2)
Tom W. Bell (3)
Kyle C. Cavanaugh (4)

Design team

Mercedes Minck (1)
Josh Silberg (1)

Reviewers

Danielle Claar (8)
Maycira Costa (9)
Norah Eddy (2)
Keith Holmes (1)
Henry Houskeeper (4)
Tristin McHugh (2)
Romney McPhie (1)

Contributing Authors

Romina Barbosa (9)
Krista Bohlen (5)
Jake Burton (6)
Jarrett Byrnes (7)
Katherine Cavanaugh (4)
Danielle Claar (8)
Gina Contolini (11)
Maycira Costa (9)
Tyler Cowdrey (8)
Megan Davis (10)
Danielle Denley (20)
Rebecca Flores-Miller (11)
Lianna Gendall (9)
Heidi Hirsh (12)
Rietta Hohman (13)
Henry Houskeeper (4)
Margot Hessing-Lewis (1)
Lynn Lee (6)
Melanie Leung (4)
Scott Marion (14)
Rebecca Martone (19)
Meredith McPherson (15)
Alejandra Mora-Soto (9)
Ondine Pontier (1)
Toby Robinson (16)
Isaac Rosenthal (7)
Gillian Rowan (17)
Marie-France Roy (17)
Sarah Schroeder (9)
Max Stanley (16)
Sen-Huy Tan (1)
Markus Thompson (18)
Brian Timmer (9)
Emelly Villa (4)
Jennifer Yakimishyn (5)

1. Hakai Institute, PO Box 25039, Campbell River, BC, V9W 0B7, Canada
2. The Nature Conservancy in California, 830 S Street, Sacramento, CA, 95811, USA
3. Woods Hole Oceanographic Institution, 86 Water St, Falmouth, MA 02543, USA
4. UCLA Department of Geography, Bunche 1156, Los Angeles, California, 90095, USA
5. Pacific Rim National Park Reserve, PO Box 280, 2040 Pacific Rim Highway, Ucluelet, British Columbia, V0R 3A0, Canada
6. Gwaii Haanas National Park Reserve, National Marine Conservation Area Reserve, and Haida Heritage Site, 60 Second Beach Road, Skidegate, British Columbia, V0T 1S1, Canada
7. University of Massachusetts Boston, College of Science and Mathematics, 100 Morrissey Blvd, Boston, MA, 02125, USA
8. Washington Department of Natural Resources, 1111 Washington St SE, Olympia, WA, 98504, USA
9. Spectral Lab, Department of Geography, University of Victoria, PO Box 1700 STN CSC, Victoria, BC, V8W 2Y2, Canada
10. Department of Integrative Biology, Oregon State University, 4575 SW Research Way Room 2008. Corvallis, OR, 97333, USA
11. California Department of Fish and Wildlife, 619 Second Street, Eureka, 95501, California, USA
12. Atlantic Oceanographic & Meteorological Laboratory, Department of Commerce, 707 Continental Circle #1139, Mountain View, CA, 94040, USA
13. NOAA Greater Farallones National Marine Sanctuary (Headquarters), 991 Marine Drive, The Presidio, San Francisco, CA, 94129, USA
14. Oregon Department of Fish & Wildlife, 3150 Main St B, Springfield, OR, 97478, USA
15. UC Santa Cruz, Biological and Satellite Oceanography Lab, 1156 High St, Santa Cruz, CA 95064, USA
16. Barnacle Foods, 5015 Short St, Juneau, AK 99801, USA
17. Redd Fish Restoration Society, 286 Main St, Ucluelet, BC, V0R 3A0, Canada
18. Thalassia Environmental, Quadra Island, BC, Canada
19. Ocean Decade Collaborative Center for the NE Pacific. P.O. Box 25039, Campbell River, BC, V9W 0B7, Canada
20. Ministry of Water, Land and Resource Stewardship, PO Box 9012 Stn Prov. Govt., Victoria, BC, V8M 9L6, Canada

Title Page Image. Luba Reshitnyk, Hakai Institute

Acknowledgements

The authors and contributors of this guidebook predominantly live and work across the coast of the northeast Pacific — an incredibly diverse and beautiful coastal landscape which has been home to Indigenous peoples since time immemorial. We encourage our readers to engage with the Indigenous communities in the areas where they live and work and to be aware of and implement the FAIR and CARE Principles for Indigenous Data Governance.

The structure of the infographic tables used to create the infographics in this document was based on the marine remote sensing toolkit (Roelfsema et al., 2017) which highlights remote sensing tools and applications to a suite of different environmental features. We would like to thank Dr. Chris Roelfsema and Dr. Stuart Phinn for providing the rubric that was adapted for the work presented in this guidebook (Appendix 1).

We would like to thank the participants of the 2022 Kelp Mappers Meeting breakout sessions whose input informed the creation of the infographics found in this guidebook. Thank you to our colleagues who provided additional review and feedback to the guidebook. In addition, we would like to thank Adrienne Mason for providing copy editing services.

Image: Hakai Institute

Contents

How to Use This Document

Mapping and monitoring changes in kelp forest canopy through space and time is essential for informing kelp monitoring, conservation, management and restoration. However, with so many remote sensing imagery sources and analytical methods available, identifying the appropriate remote sensing tool for a given time and place may feel quite daunting.

> The **goal** of this guidebook is to help decision-makers, managers, researchers, and restoration practitioners select the best optical remote sensing tool(s) to create spatial datasets (i.e.,maps) of giant kelp (*Macrocystis pyrifera*) and/or bull kelp (*Nereocystis luetkeana*) canopy floating on the ocean surface.

The members of the Kelp Mappers Community of Practice have identified four kelp mapping objectives:

Presence/absence/extent: Is kelp present or absent at a given place and time? If present, what is the area of canopy at the ocean's surface (e.g., m^2 of canopy kelp)?

Species: What species of kelp is present (bull kelp and/or giant kelp) in a given place and time and what is the species' extent in a given area (e.g., m^2 of giant kelp)?

Density/biomass: How much kelp is present at a given place and time (e.g., kg/m^2, tonnes/ha)?

Health: What is the health of kelp at a given place and time? For example, quantitative health assessments such as carbon to nitrogen ratios and, pigments or qualitative assessments such as visual observations of kelp health status (e.g., bryozoan cover).

We generated one infographic for each of the four kelp mapping objective to help you identify the remote sensing tool appropriate for the spatial scale of your monitoring work (Figure 1). To understand the infographics, we have divided this document into two sections:

(1) a background section which provides key principles about optical remote sensing and tools related to mapping kelp.

(2) the infographics which guide you through the tool selection process.

While we aim to be as comprehensive as possible, we also wanted to make this guidebook user-friendly by limiting content to the fundamentals of kelp mapping and monitoring. Therefore, we focus on **annual** kelp canopy surveys for giant kelp and bull kelp. Please see Appendix 1 if you have different temporal monitoring needs.

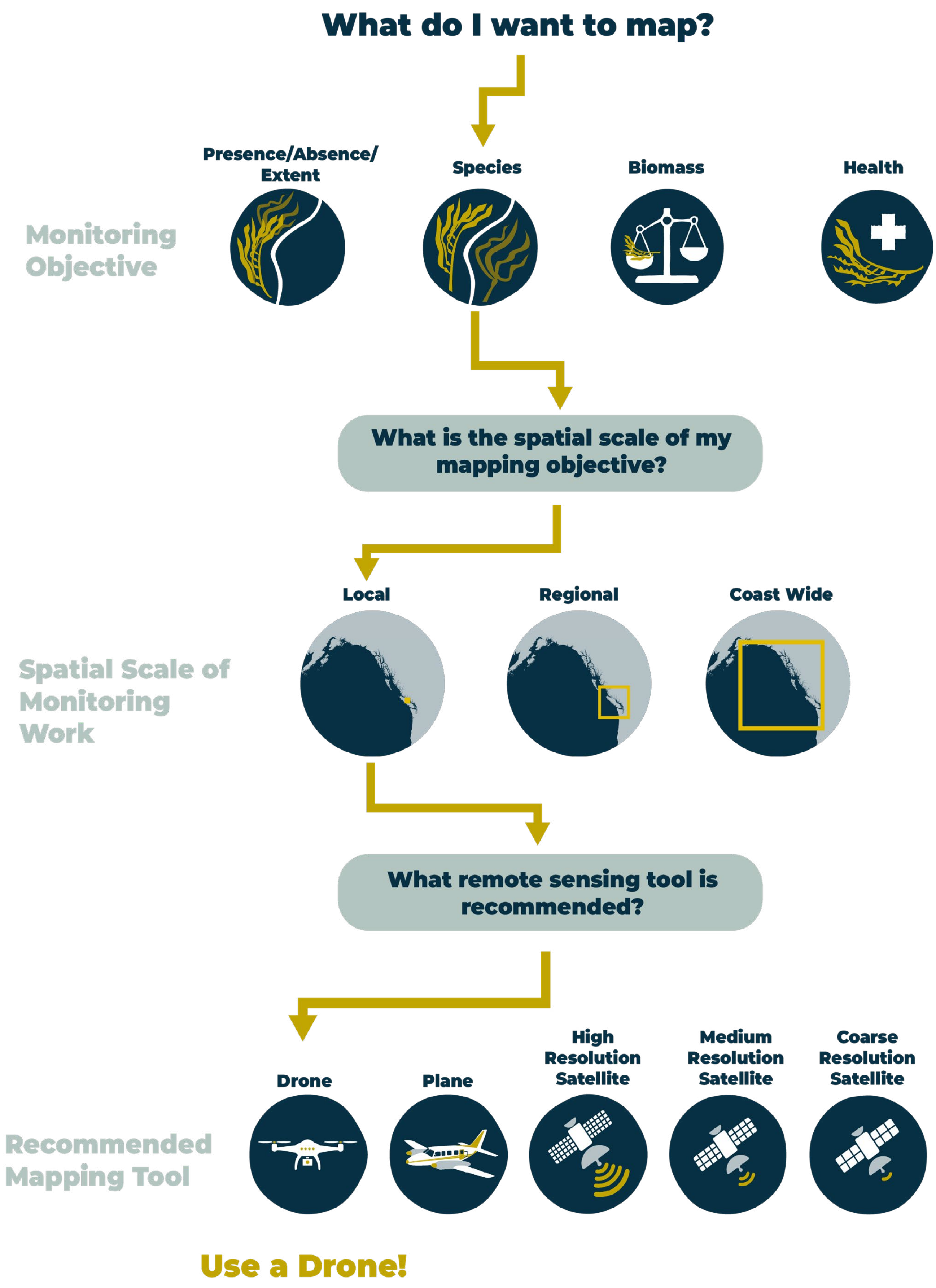


Figure 1. An example of how to use the infographics in this guidebook.

Background

Surface canopy-forming kelps (Order: Laminariales) provide the foundation for coastal marine ecosystems that are ecologically, culturally, and economically important (Wernberg et al., 2019; Holbrook et al., 1990; Dayton, 1972). Along the coastlines of northeast Pacific, giant kelp (*Macrocystis pyrifera*) and bull kelp (*Nereocystis luetkeana*) form beds and forests that are naturally dynamic and threatened by both local and global stressors (Krumhansl et al., 2016) (**Figure 2**).

Giant kelp and bull kelp differ in both their morphology (how they look) and their life cycles. **Giant kelp** is a perennial species, typically living from three to five years. Each plant is made up of multiple fronds attached at a holdfast (a kelp's "root") with blades with small buoyant pneumatocysts. An individual giant kelp can reach tens of meters in length and lies across the sea surface on a calm, low tide (**Figure 3**).

Bull kelp is an annual species — each bull kelp typically only lives for one year. A bull kelp plant consists of a long, smooth, tubular stipe attached by a root-like holdfast. Each bull kelp has a single pneumatocyst (a bulb) from which blades grow. Bull kelp blades are not buoyant so the ends of the blades will submerge below the ocean surface (**Figure 3**).

Figure 2. Generalized distribution of giant kelp (*macrocystis pyrifera*) and bull kelp (*nereocystis leutkeana*) across the Northeast Pacific.

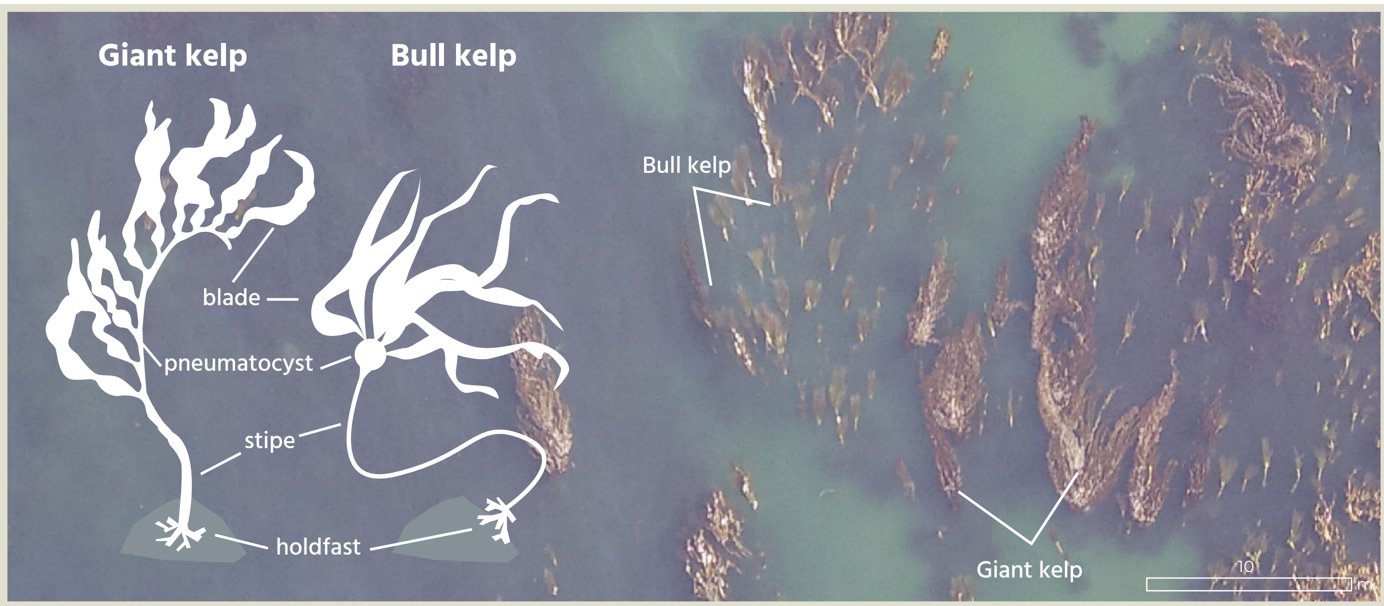
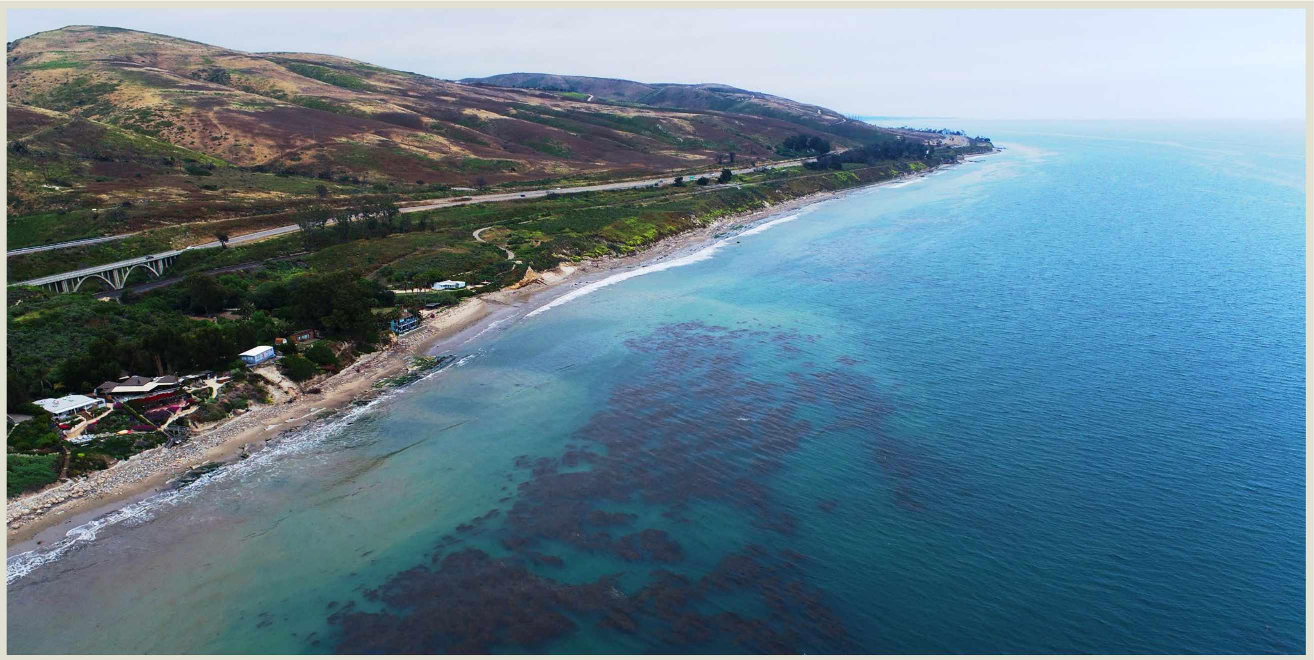


Figure 3. On a low tide, giant kelp fronds lie across the surface of the ocean and have the appearance of looking "feathery" from above. In the same scene, bull kelp look more like matchsticks from above - the long stipe and bulb floating on the sea surface and blades trailing in the water. Image: Hakai Institue

Kelps that form large floating canopies (such as bull kelp and giant kelp) are relatively easy to distinguish in remote sensing optical imagery since the floating canopy is typically visible and spectrally distinct from the surrounding sea water (read more in Overview of remote sensing tools for mapping kelp). The area, density, and physiological condition (i.e. health) of canopy-forming kelps can be quantified and characterized in optical remotely-sensed imagery collected from different remote sensing platforms. These platforms can broadly be separated into three categories for kelp monitoring: **satellites**, **occupied aircraft** (e.g. planes and helicopters), and **unoccupied aerial systems** (UAS, referred to as "drones"). A variety of image analysis methods have been used to characterize different kelp canopy attributes (see Appendices 2 - 4).

In this section you will find information on:



Drone imagery of a giant kelp bed near Santa Barbara, California. **Image**: Kyle Emery

What's the Difference Between a Kelp Bed and a Kelp Forest?

In the same way that stands of trees make up a grove and many groves make up a forest, individual kelp plants make a bed and many beds make a kelp forest. While "kelp forest" has been identified as the preferred term for the ecosystems these species create (Wernberg & Filbee-Dexter, 2019), within this document we refer to the detection and mapping of "kelp beds" (i.e., areas containing multiple kelp plants). We do so because often regions experiencing kelp loss only have patchy mosaics of kelp plants remaining. For the purposes of mapping and monitoring sparse patches of kelp, we use the term "kelp bed" and include the occurrence of small and fringing kelp (**Figure 4**). We intentionally refrain from prescribing an area-based threshold for the definition of a kelp bed versus a kelp forest given substantial variability between regions and the importance of historical context as the area of kelp fluctuates.

Note to reader: In this guidebook all remote sensing recommendations are based on mapping kelp canopy **present at the ocean's surface** (i.e., emergent) — a limitation when using optical remote sensing methods for mapping kelp. In other words, if the kelp is underwater all the time, the tools and methods presented here aren't the methods you're looking for.

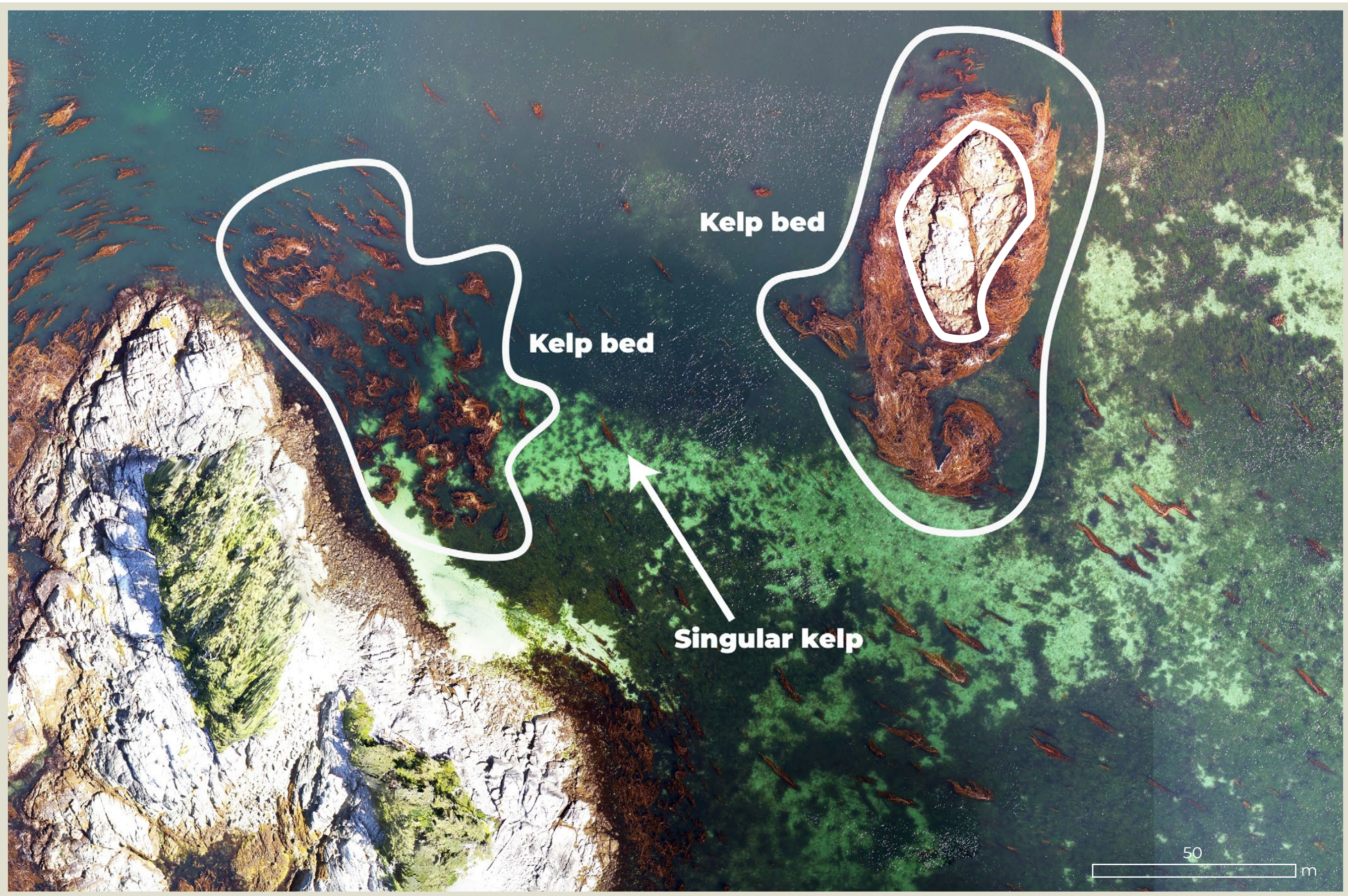


Figure 4. Drone imagery showing individual giant kelp plants and kelp beds. **Image**: Hakai Institute.

When looking at a kelp bed from above, what it looks like is determined by how the kelp plants are distributed in that place – **fringing**, **offshore**, **dense**, or **sparse** (**Figure 5**). **Fringing** kelp beds grow in a narrow band directly adjacent to the shoreline while **offshore** kelp beds are located tens of meters away from the shoreline. A kelp bed may be characterized as **dense** — where many kelp plants are growing very close together and may be overlying each other and tangled up together. In a **sparse** kelp bed, individual kelp plants are further apart. Therefore kelp bed distribution influences the selection of the best remote sensing tool for a given kelp bed, based on kelp bed size and distribution, where it is growing (Gendall et al., 2023), and your monitoring objective. We guide the user through this decision pathway and provide further detail in tables found in **Appendix 1.**

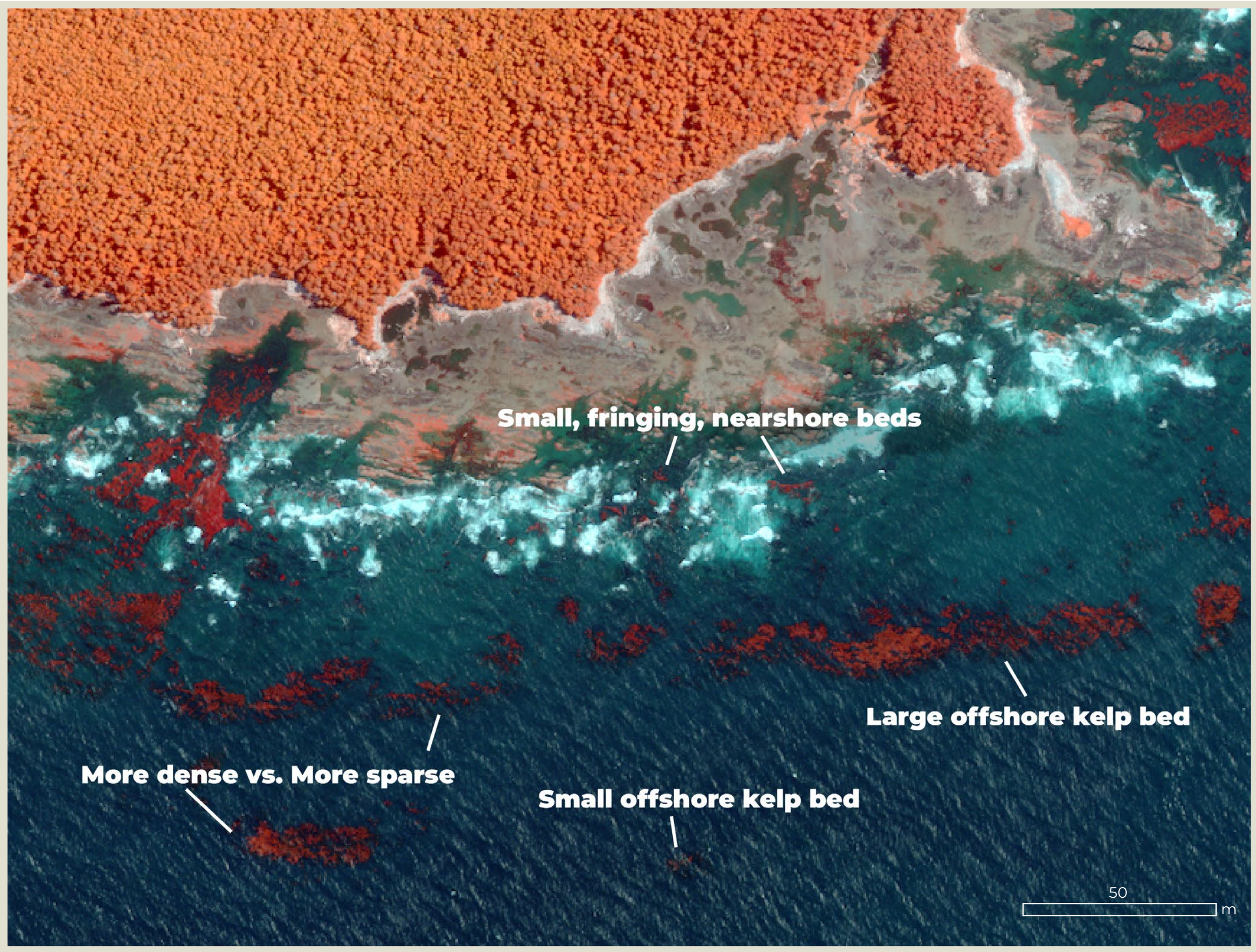


Figure 5. High-resolution WorldView-2 satellite image (2 m resolution shown in false color infrared) with different types of kelp beds imagery. **Image:** © DigitalGlobe, Inc. All Rights Reserved.

Remote Sensing 101

Remote sensing refers to when we obtain information about the surface of the Earth without making physical contact. In this guidebook, we refer to remote sensing **tools** as the combination of a **platform** (e.g., a drone or satellite) and a **sensor** (e.g., a RGB camera or a hyperspectral sensor). So, with the optical imagery we obtain from satellites, planes, and drones, we can "sense" and detect kelp canopy (and its attributes) remotely. We don't dive into describing the rigorous details of optical remote sensing (that's a whole course's worth of material) but throughout this guidebook, you will come across some key terms that are used to describe the properties of remote sensing imagery that you should be familiar with.

Optical remote sensing imagery is similar to the digital pictures we take with cameras—images made up of pixels collected as digital information based on how much light was detected in certain spectral bands (e.g., red, green, and blue [RGB] for the camera on your phone). In remote sensing, the properties of these pixels — **spatial resolution**, **spectral resolution** and **temporal resolution** — help us detect and make maps of kelp canopy (**Figure 6**). You can read more about each of those properties below.

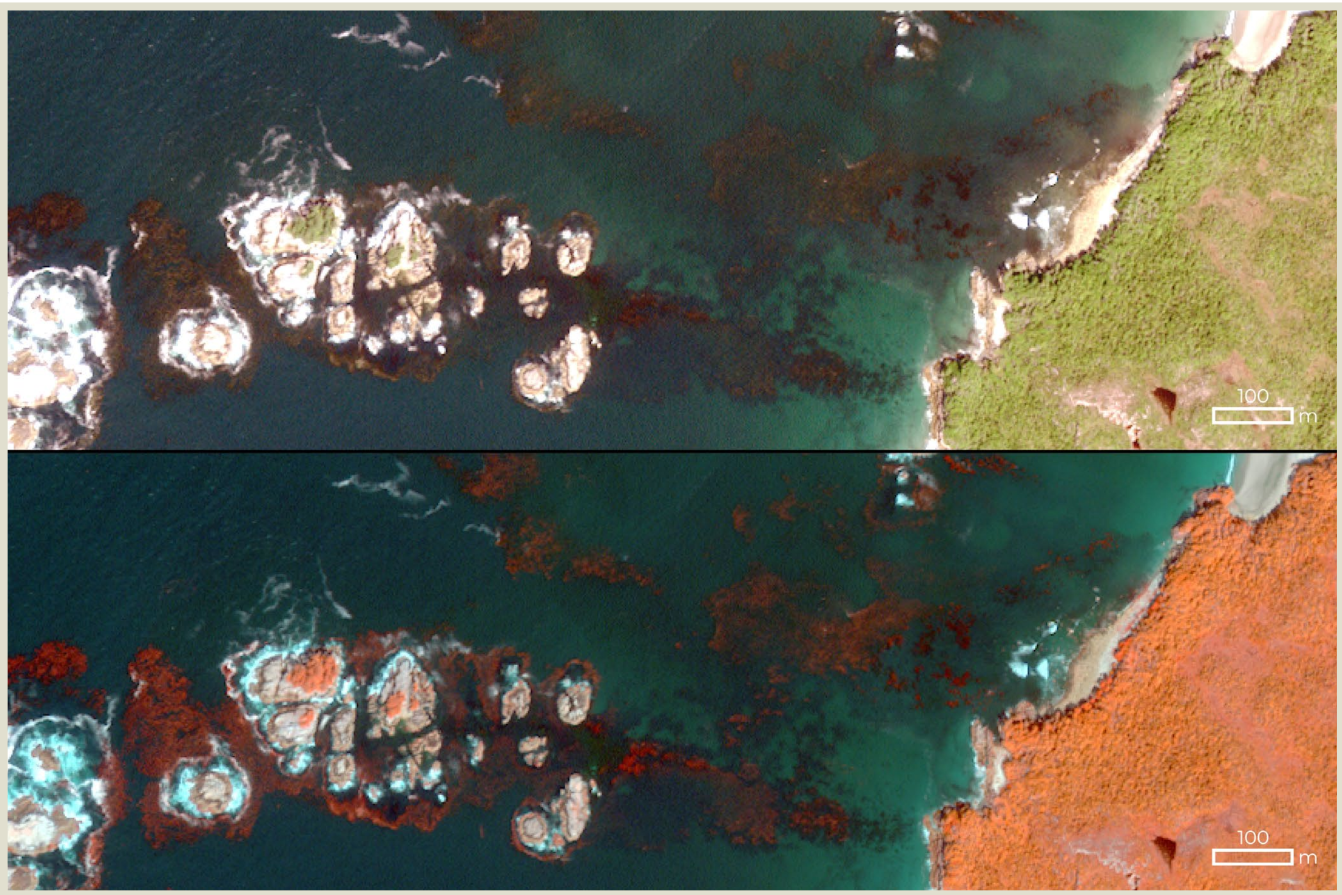


Figure 6. (Top panel) WorldView-2 imagery (2 m) shown with "true color" bands (red, green, and blue). (Bottom panel) WorldView-2 imagery (2 m) shown in false-color infrared (where the near-infrared band is shown in red) which makes vegetation (like kelp) look more red/orange. Image: WorldView-2 © 2014 Maxar Technologies.

Spatial Resolution

Spatial resolution (or ground sample distance) typically refers to the size of a pixel within an image, or more specifically the distance between the centre of neighboring pixels. The higher the spatial resolution, the smaller the pixel size (e.g., 3 cm-sized pixels in a drone image). The coarser or lower the spatial resolution, the larger the pixel (e.g., 30 m-sized pixels in Landsat imagery).

Take home message: There is a tradeoff between spatial resolution and spatial coverage — typically imagery with higher spatial resolution covers less area overall while imagery with lower spatial resolution will cover larger areas (**Figure 7**) and (**Figure 10**).

In this document we use the following definitions when describing the spatial resolution of data:

- **Coarse** resolution imagery: 10 m and greater (e.g., Sentinel 2 and Landsat imagery)
- **Medium** resolution imagery: 5 to <10 m (e.g., RapidEye, SPOT)
- **High** resolution imagery: 2 to <5 m (e.g., IKONOS, Planet Dove)
- **Very high** resolution imagery: pixels <0.5 m (e.g., drone imagery, Planet Skysat, WorldView-3)

Check out **Figure 7** below and **Figure 10** (later in the guidebook) to see a comparison of how kelp beds appear using different sensors.

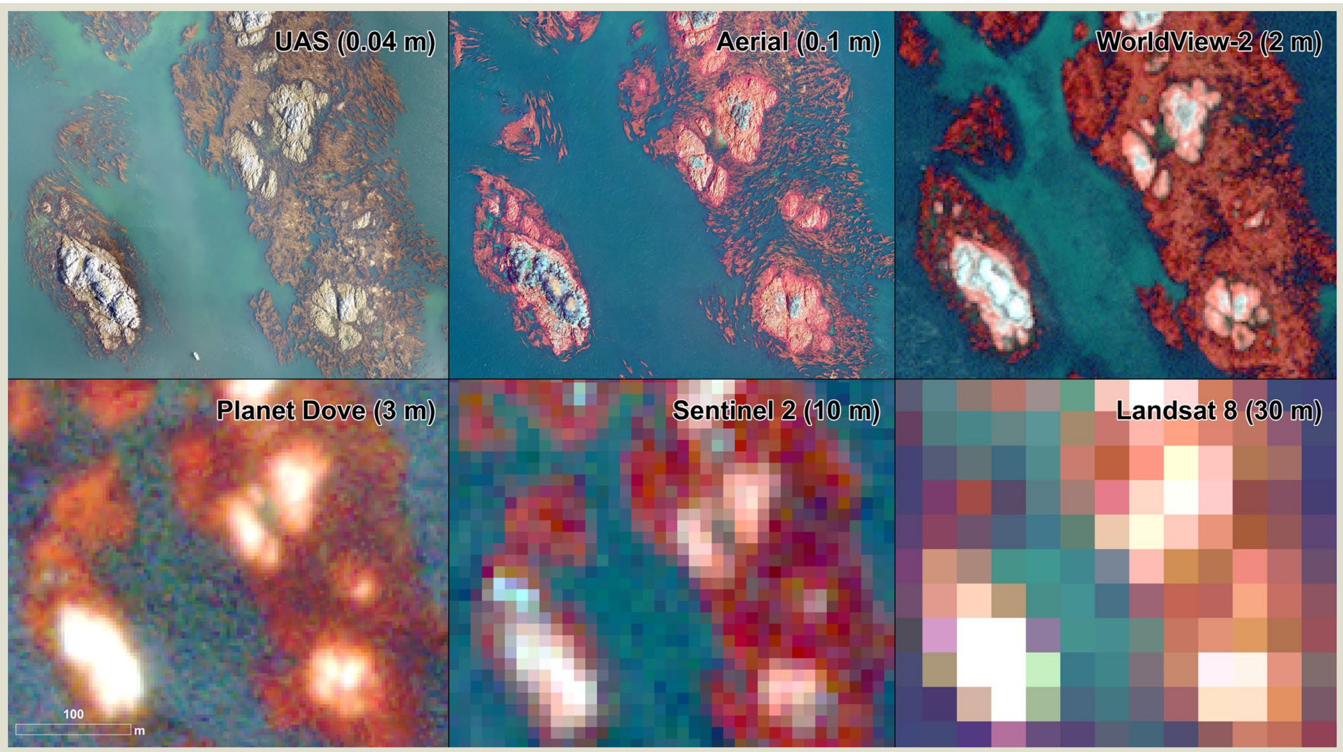


Figure 7. A comparison of emergent kelp canopy acquired from different sensors. (Top left) 0.04 m drone image. **Image:** Hakai Institute. (Top middle) 0.1 m aerial image. **Image:** Hakai Institute. (Top right) 2 m WorldView-2 image. **Image:** © DigitalGlobe, Inc. All Rights Reserved. (Bottom left) 3 m Planet Dove image. **Image:** © 2022 Planet Labs PBC. (Bottom middle) 10 m Sentinel 2 image. **Image:** Modified Copernicus Sentinel data 2021/Sentinel Hub. (Bottom right) 30 m Landsat 8 image. **Image:** 2021 Landsat 8 image courtesy of the U.S. Geological Survey. Note: imagery was not acquired on the same dates or tide height. All imagery is shown in false-colour near-infrared except for the drone imagery which is RGB.

Spectral Resolution

Spectral resolution refers to the number and narrowness of the spectral bands that a sensor is sensitive to (or "detects"). You can think of a band as a segment of the electromagnetic spectrum. For example, the camera in your mobile phone collects reflected light in three bands — (RGB). That is also true for many images collected with off-the-shelf drones. Other sensors, like those found on satellites, can detect light in other wavelengths. Most commonly you will see remote sensing imagery that has a near-infrared band (NIR), which is useful for mapping vegetation since vegetation, including kelp, largely reflects NIR light while seawater absorbs it (Timmer et al., 2022; Schroeder et al., 2019). As a result, NIR imagery is useful for distinguishing kelp that emerges at the ocean's surface, but not submerged kelp. Different pigments in kelp plants have different reflectance and absorption characteristics. Sensors with higher spectral resolution can capture nuanced spectral differences that can indicate health, age, or other characteristics.

In this document, we refer to three-band imagery specifically as **RGB** imagery. We refer to **multispectral** (**MS**) imagery as data collected with sensors that have four to ten bands (most commonly red, green, blue, and near-infrared). **Hyperspectral** imagery covers a continuous range of wavelengths with hundreds of bands that are contiguous (**Figure 8**). Note that for multispectral and hyperspectral sensors, spectral calibration and atmospheric correction of the imagery is required (an advanced topic not covered in this guidebook).

Take home message: The higher the spectral resolution, the more information (e.g., health status, canopy chlorophyll a to carbon ratios) can potentially be derived from the imagery.

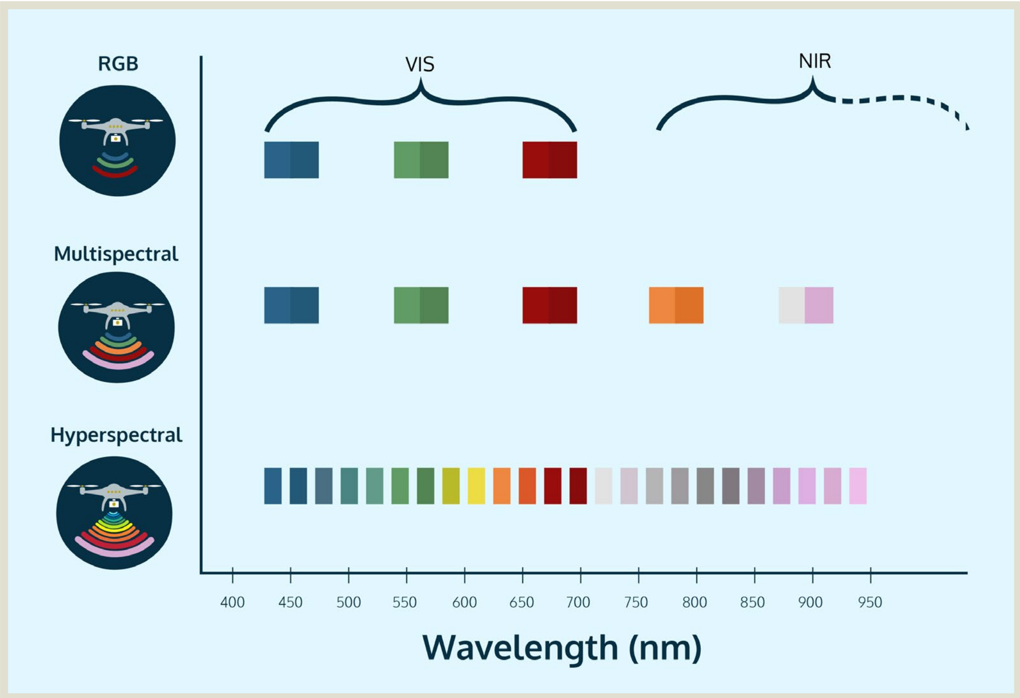


Figure 8. Visual diagram of RGB, multispectral, and hyperspectral sensor bands.

Temporal Resolution

Temporal resolution (also referred to as "revisit time") refers to how often a remote sensing platform returns to the exact same place on the planet and collects an image. Typically, temporal resolution applies to Earth observation satellite platforms which have consistent schedules and timing in imagery collection (e.g., a Landsat satellite collects an image over the exact same place on the planet every 16 days). Lower temporal resolution refers to imagery that is collected less frequently (e.g., 16 days for Landsat) compared to higher temporal resolution that is collected more frequently (e.g., 5 days for Sentinel 2). You control temporal resolution when you are collecting the imagery yourself, for example when using drones (**Figure 9**).

Note to reader: The infographics in this guidebook reflect recommendations based on **annual** monitoring efforts (i.e., surveys conducted once per year). Recommendations for surveys with higher temporal resolution needs are covered in our Kelp Infographic Tables for daily, monthly, and seasonal recommendations (see tables in **Appendix 1**).

Figure 9. Drone imagery collected at a long-term giant kelp monitoring site from March and July 2019. The imagery was collected to support work looking at seasonal dynamics in kelp forests. **Images:** Hakai Institute.

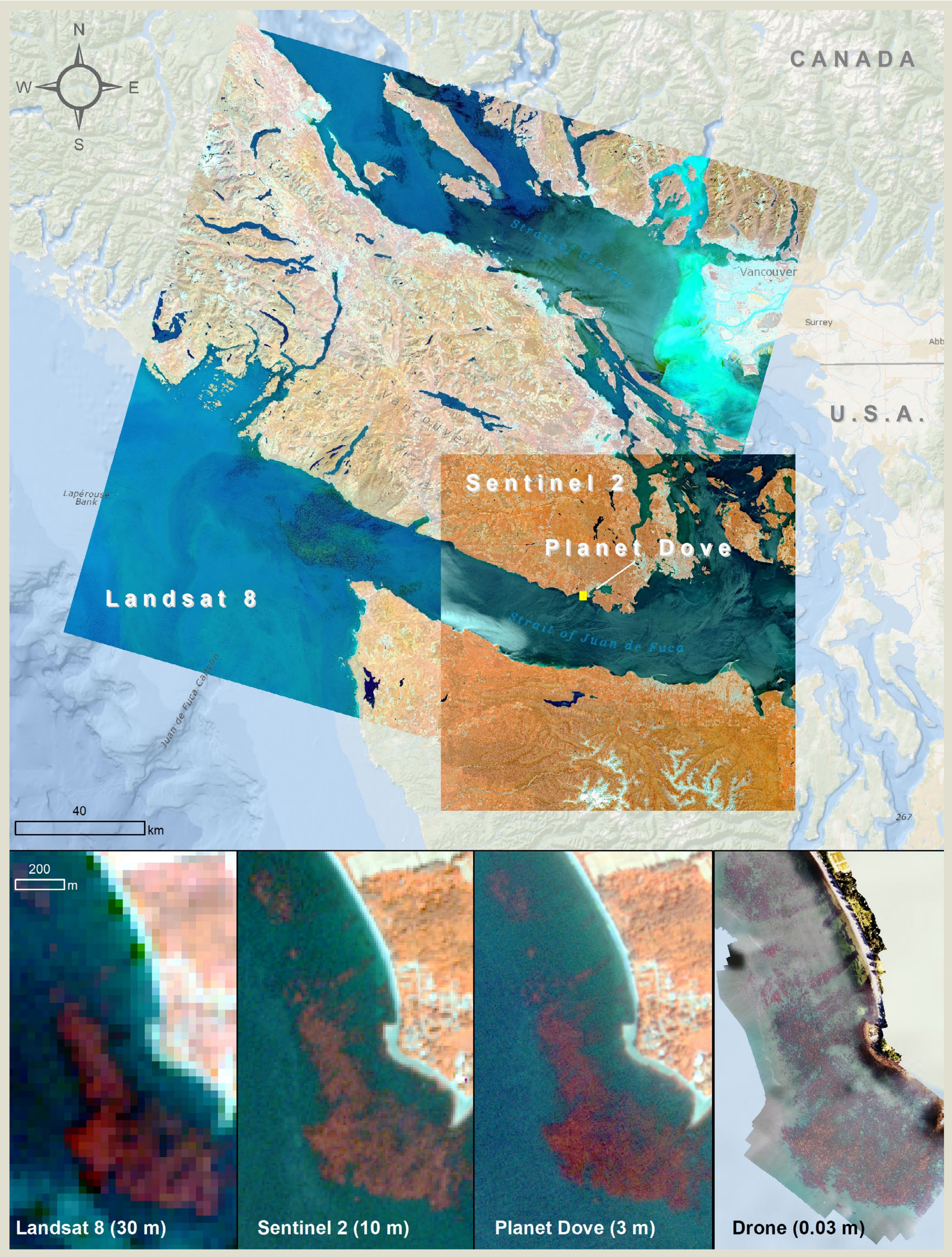


Figure 10. In general a trade-off between the spatial resolution and spatial coverage remote sensing imagery. The coarser the resolution (ie., the larger the pixel) the larger the spatial coverage. For example, 30 m Landsat imagery covers a larger spatial area than the 10 m Sentinel imagery and 3 m Planet Dove imagery. The 0.03 m resolution drone imagery has the smallest spatial footprint. Note: Images in this figures were not acquired on the same dates or tide height. All imagery is shown in false-color NIR except for the drone imagery which is RGB. **Images:** Landsat 8 image courtesy of the U.S. Geological Survey; Modified Copernicus Sentinel data 2022/Sentinel Hub; Planet Dove image © 2022 Planet Labs PBC; drone image Hakai Institute.

Overview of Optical Remote Sensing Tools for Kelp Mapping

Giant kelp and bull kelp are brown algae that look different from the surrounding sea water due to the pigments present in their blades, stipes, and fronds. With multispectral remote sensing imagery our ability to detect kelp is made possible by the high reflectance of the photosynthetic kelp biomass in the NIR and the low reflectance of the surrounding seawater in the NIR (**Figure 11**). Seawater strongly attenuates NIR light, therefore, submerged kelp is much more difficult to detect. This difference in NIR reflection by kelp versus seawater makes kelp "pop" in multispectral imagery (**Figure 12**).

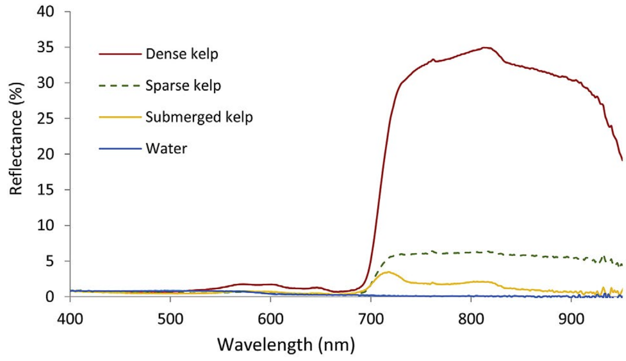


Figure 11. Reflectance of dense (>50% of 1 m^2 covered), sparse (<50% of 1 m^{2}covered), submerged kelp (all plants slightly below water surface) and ocean water measured with a spectroradiometer in the coastal waters of British Columbia, Canada. Figure from Schroeder et al., 2019.

Different remote sensing platforms and sensors have been applied to map various attributes of kelp beds (e.g., presence/absence, biomass) to address a variety of research and monitoring goals (see publications and reports in Appendices 2-5).

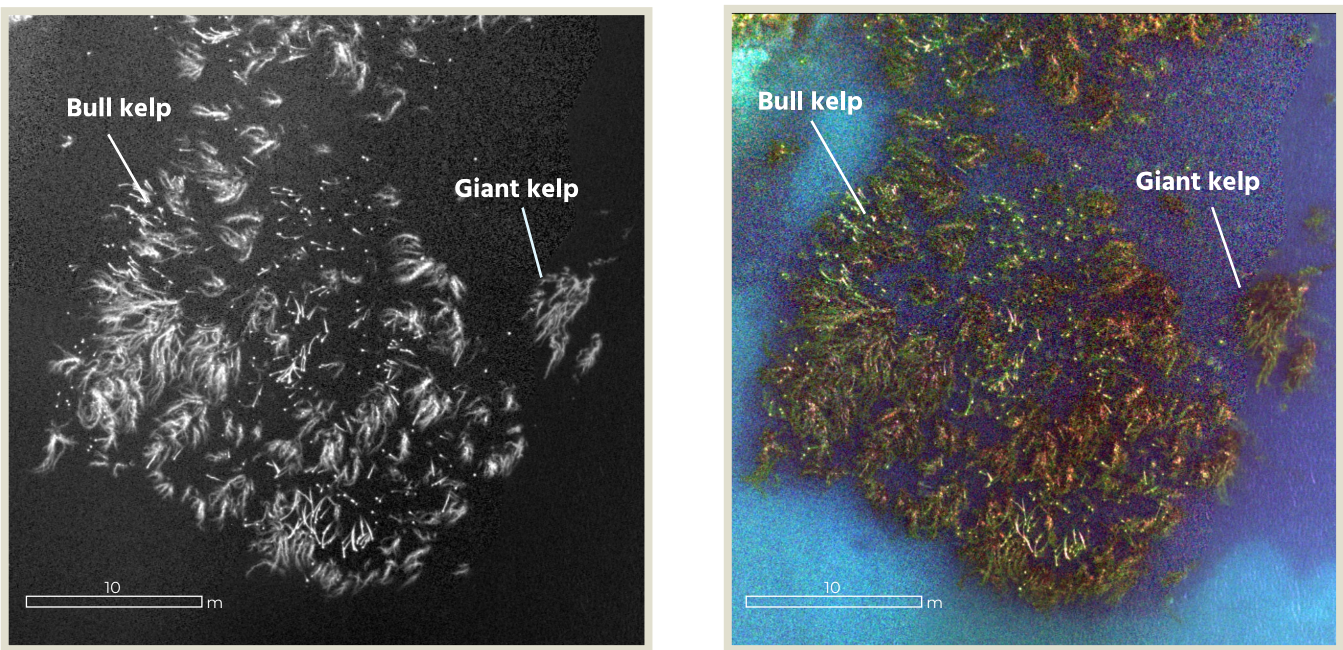


Figure 12. Multispectral drone imagery obtained over a kelp bed. (left panel) Grayscale image in NIR. (right panel) True colour RGB image. **Image:** Hakai Institute

In this section of the guidebook, we provide a cursory overview of the application of the most common optical remote sensing tools — drones, planes, and satellites — identified as useful by the International Kelp Mappers Community of Practice for mapping canopy kelp. Other resources have created more exhaustive lists and we refer to those where relevant.

Introduction to Using Drones for Kelp Canopy Mapping

Most people are familiar with **drones** — small flying robots with cameras that are controlled remotely by a pilot on the ground or on a boat. In the past few years, small drones have revolutionized monitoring habitats on local scales. Small drones give you the opportunity to map kelp canopy under the right conditions — i.e., when the tide is low, the sea is calm, and the kelp is at its peak growth. Many off-the-shelf drones are relatively affordable (approximately US $500 - $8,000), easy to operate, and lightweight for easy transportation.

When selecting a drone, it is important to **determine what sensor** you will require. For example, the spectral resolution of the sensor that comes with the drone may be RGB (standard for most commercially available drones), multispectral, or hyperspectral. What type of sensor you have which attributes of kelp you can discern. For example:

- Burt et al. (2018) used **RGB** drone imagery to document changes in kelp forests with changing ecosystem predators
- Cavanaugh et al. (2021) demonstrated the effects of tides and currents on kelp extent using **RGB** drone imagery
- McPherson et al. (2023) used **multispectral** drone imagery to examine the relationship between imagery and in situ kelp biomass

When selecting a drone, it is important to **consider the spatial scale of your monitoring objectives** relative to the weight of your gear. Larger, and often heavier drones, can fly at higher speeds, carry larger or more sensors, and withstand higher wind speeds and more difficult flight conditions. But as technology advances, smaller drones are becoming more and more common and have competitive flight times and sensor megapixel levels. The type and size of drone you choose may also depend on whether you will be operating your drone from a boat or from land. When working on boats, smaller drones are typically safer and more comfortable to operate.

Image of a drone over a kelp bed. **Image Credit.** Hakai Institute

Once drone imagery has been collected, a large and ever-increasing suite of softwares (e.g., Agisoft Metashape, DroneDeploy) exist to stitch the individual images together to **create an orthomosaic**—a complete scene of the area flown by the drone. New tools have been created specifically for kelp canopy mapping to address issues of sun glint in imagery (Denouden, Timmer & Reshitnyk, 2021) when creating orthomosaics.

After the creation and georeferencing of the orthomosaic, you are ready for **image analysis**. The analytical methods you use will depend on your kelp mapping objective. For example, for mapping the extent of kelp, a new open-source tool — the **KelpOMatic** — automates the detection of kelp in RGB drone imagery using advanced AI techniques (Denouden & Reshitnyk, 2021). This tool greatly reduces the processing time for extracting canopy extent and species data from RGB imagery. Other methods for extracting kelp canopy include index-based thresholds (Cavanaugh et al., 2021) and manual delineation (see Appendix 3.3).

While small drones are a nimble tool and provide data with exceptional spatial resolution (typically <5 cm), this tool is not yet cost- or time-effective when surveying large regions (e.g., coastwide (Saccomanno et al., 2022). Drones 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 quadcopter-style drones), reliance on batteries with finite charge, and other physical and technological limitations. Additionally, the need for an accessible launch site limits which areas can be surveyed, making it difficult to survey some areas if a viable launch site can't be used. Many aviation administrations require operators to obtain a license prior to operating for commercial or research purposes.

Check out Appendix 2 for more information and resources on how to map kelp with drones.

Note to reader: Drones may be referred to as Unmanned Aerial Vehicles (UAV), Unmanned Aerial Systems (UAS) or Remotely Piloted Aerial Systems (RPAS).

Aerial view of kelp forest in California taken with a drone. **Image.** Heidi Hirsch

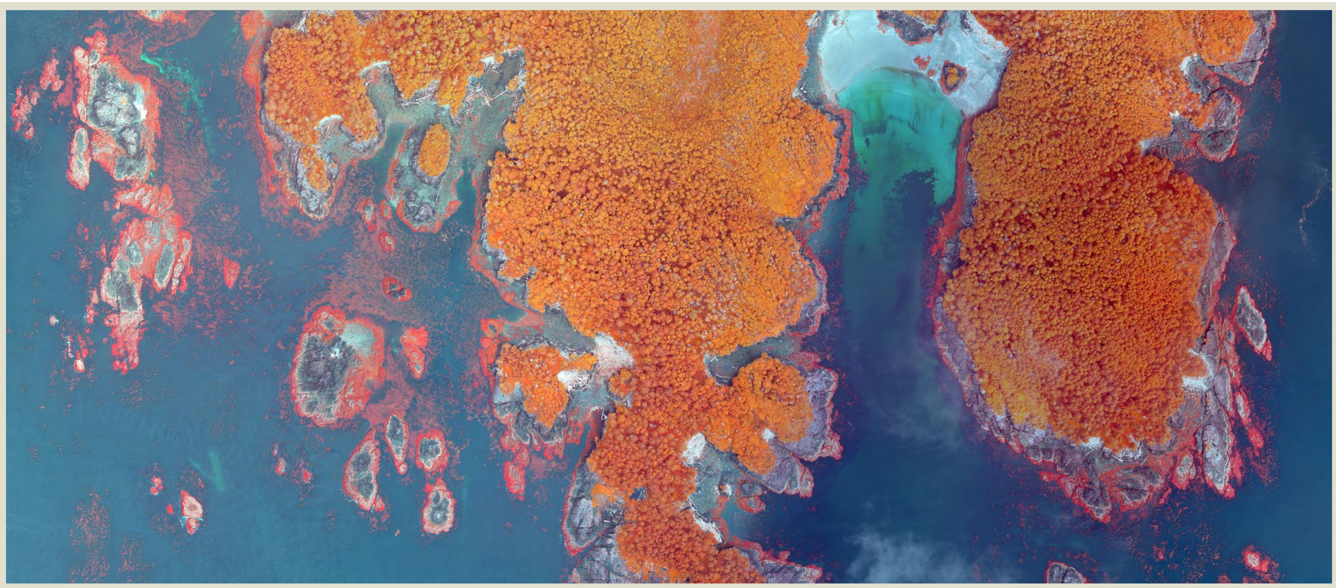
Introduction to Using Occupied Aircraft for Kelp Mapping

Photographic surveys in the 1950s from occupied aircraft (e.g., airplanes, helicopters) using film cameras were one of the first ways in which kelp canopy was mapped in the northeast Pacific. (Jensen et al., 1980). Modern aerial surveys are conducted from occupied aircraft mounted with digital RGB cameras or multispectral or hyperspectral sensors. Your type of sensor will determine the kelp canopy attribute you can capture.

Airplane surveys are **most advantageous** for capturing very high resolution imagery (0.1-2 m) across regional and coast-wide scales (10s to 100s of kilometers) or for mapping areas of interest that are too remote to map with drones. In addition to mapping canopy extent, the higher resolution imagery typically provides enough detail to discern between different species of canopy-forming kelp (depending on image resolution and quality). For example, imagery collected from aerial platforms has been used to study environmental drivers of kelp forest ecosystems (Pfister et al., 2019) as well as to create estimates of kelp biomass based on in situ and aerial mapping (Sutherland et al., 2008; Stekoll et al., 2006). Check out **Appendix 3** for more examples of research conducted with imagery collected from occupied aircraft.

Fun fact! The Washington Department of Natural Resources has the longest annual time series for canopy kelp mapped using aerial surveys — they began in 1989!

The **main considerations** for conducting aerial surveys are the higher cost of plane-based imagery collection (compared to drone surveys), the processing capacity (both in computer and people power), and storage needed to handle terabytes of data. Typically a geospatial survey company is contracted to conduct the plane surveys for imagery collection but classification may be conducted by another group or organization. Additionally, collecting high quality aerial imagery suitable for kelp mapping requires good planning (and some luck) to line up ideal environmental conditions during survey collection. These include ideal tide heights, sun angles, cloud ceilings, wave/wind conditions, and time of year.

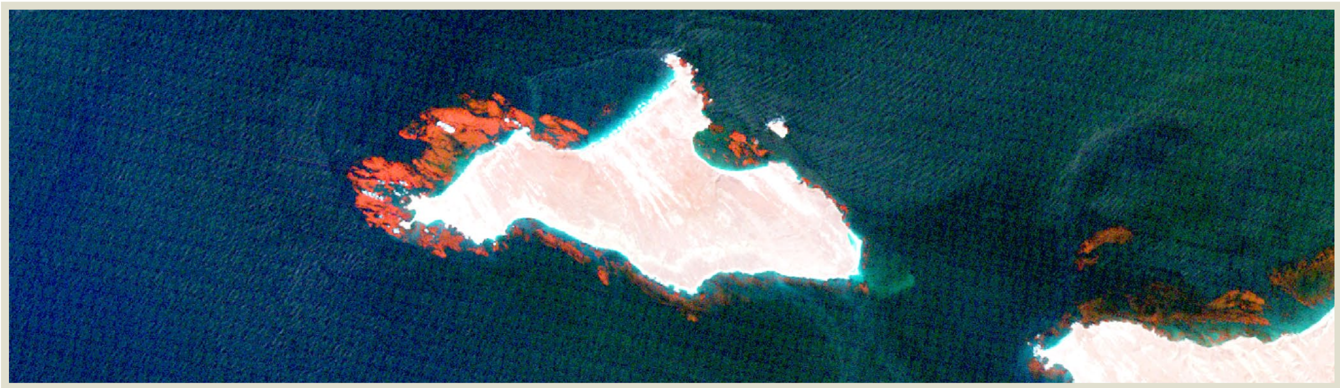


4-band imagery acquired from Phase-1 cameras mounted on a fixed-wing aircraft. Image shown in false-color NIR. **Image:** Hakai Institute.

Introduction to Using Satellites for Kelp Mapping

Over the past decade, **satellite remote sensing** has emerged as a method to map kelp canopies across **large scales** (100s to 1000s of kilometers). The use of spaceborne platforms to map the floating kelp canopy was first attempted in the early 1980s (Jensen et al., 1980). Over the next two decades, methods were improved with higher spatial resolution satellite imagery using common spectral band ratios and indices (Deysher et al., 1993; Augenstein et al., 1991). With the release of the entire Landsat imagery catalog into the public domain in 2008, Cavanaugh et al. (2011) developed the first-time series approach for canopy biomass which has since been developed into an automated method for estimating giant kelp biomass (Bell et al., 2019). Further advancements using very new hyperspectral satellite imagery are being used to estimate canopy biomass and kelp health conditions (ie., physiological) (Bell & Siegel, 2022; Bell et al., 2015).

The **choice of satellite sensor** used to determine canopy area, biomass, or other metric depends on the size of the study area; kelp bed size, density, and orientation to the coast; and the research question (e.g., Gendall et al., 2023). While there are several options for spaceborne imagery, each satellite sensor produces imagery of a specific **spatial**, **temporal**, and **spectral resolution** (**Figure 10, Table 1**), and each has a different temporal domain (start/end date of mission) and imagery cost (ranging from free to thousands of US dollars).



Landsat satellite image acquired over San Miguel Island, California **Image:** Courtesy of the U.S. Geological Survey.

For this guide, we separate satellite imagery into four broad categories based on the spatial resolution of the imagery:

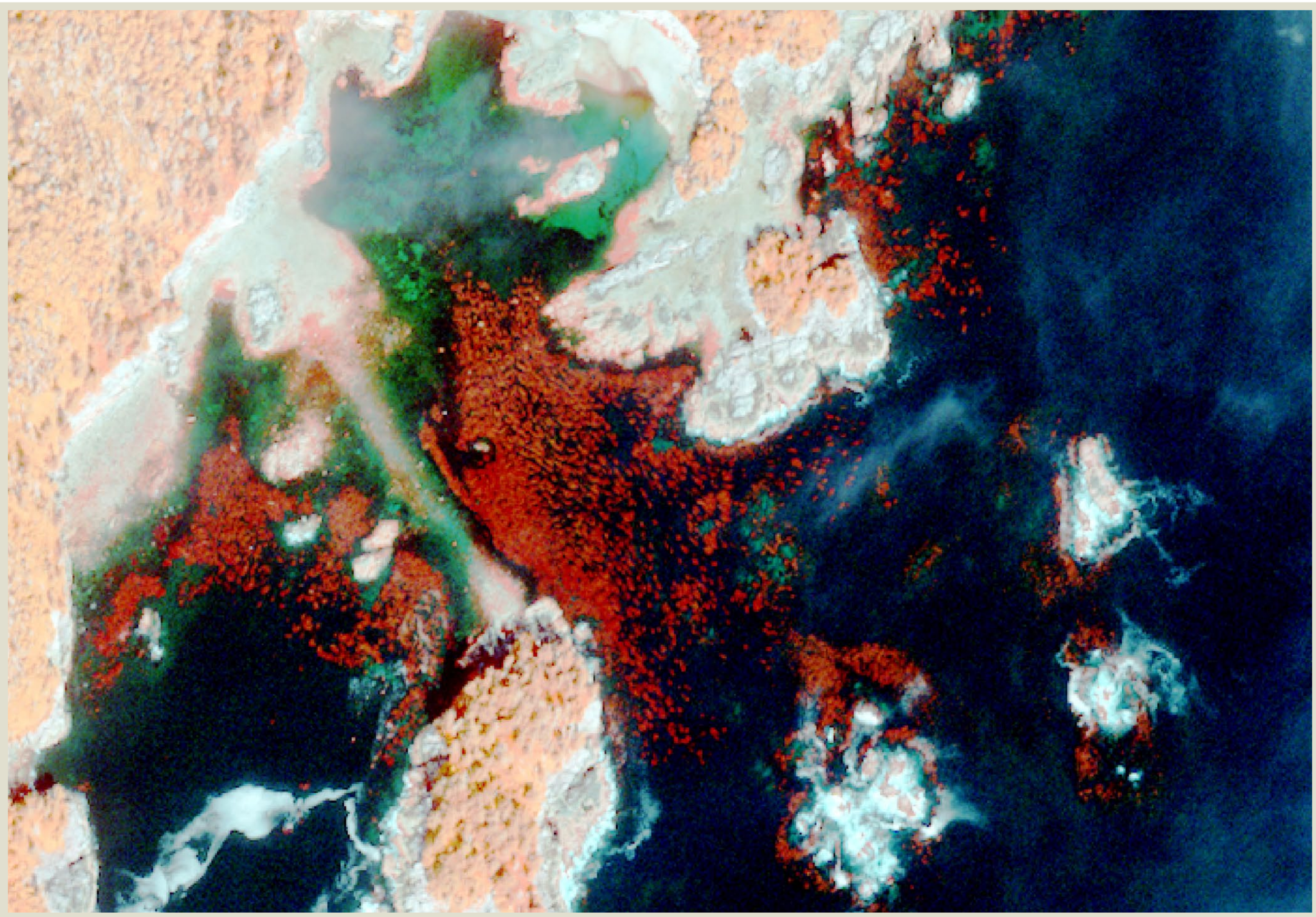
- **very high-resolution** (pixels <2 m)
- **high-resolution** (pixels 2-<5 m)
- **medium resolution** (pixels 5-<10 m)
- **coarse resolution** (pixels 10-30 m).

This is different from the terms used in the broader remote sensing community where there is an even wider range of spatial resolutions.

Very high-resolution RGB or multispectral imagery is usually acquired by tasked satellites (they collect imagery to order). High- and medium-resolution multispectral imagery may be acquired from both tasked satellites and constellations and may be either RGB or multispectral. One of the most exciting developments in the medium-resolution space is the multispectral imagery collected by the PlanetScope constellation, which aims to offer daily multispectral imagery at a 3 m resolution. Recent advancements in the classification of this imagery for canopy presence show their ability to monitor the dynamics of small to large forests over regional scales (Cavanaugh et al., 2023).

Coarse resolution satellites, such as Landsat (80 m; 1972 to 1981; 30 m; 1982 to present) and Sentinel 2 (10m; 2015 - present), offer publicly available imagery that is free to download (see Appendix 4). Imagery from these satellites typically have longer and more complete time series available than the other classes of satellites discussed above and have vetted imagery products, such as atmospheric or top-of-atmosphere correction imagery and multispectral bands.

Take home message: The larger and farther from shore your kelp beds are, the coarser the satellite imagery that you can use. Higher resolution imagery is more appropriate if your kelp beds are small and close to shore.



WorldView-3 image collected over giant kelp and bull kelp beds, Central Coast, British Columbia. **Image**: © DigitalGlobe, Inc. All Rights Reserved

Resolution	Sensor	Company	Dates	Spatial Resolution (m)	Number of Bands	Revist Time	Cost
Coarse (10-30m)	Landsat 9	NASA/USGS	2022- Present	30 multispectral	11	16 days	Free
	Landsat 8	NASA/USGS	2023- Present	30 multispectral	11	16 days	Free
	Landsat 7	NASA/USGS	1990- Present (2003 onwards Scan line correction Failure)	30 multispectral	8	16 days	Free
	Landsat 4/5	NASA/USGS	1984-2013	30 multispectral	7	16 days	Free
	Sentinel 2	ESA	2015- Present	10 multispectral	12	5 days	Free
	EnMAP	FMEACA	2023- Present	30 hyperspectral	230	4 days	Unknown
Medium (5-< 10m)	SPOT- 5	CNES	2002-2015	2.5 panchromatic, 10 multispectral, 20 SWIR	5	2–3 days	$
	SPOT- 6/7	Airbus	2012- Present	1.5 panchromatic, 6 multispectral	5	1–3 days	$
	RapidEye	Planet	2008-2020	6.5m GSD at nadir, resampled to fm pixel size on orthorectified products	5	5.5 days at nadir	$
High Resolution (2-< 5m)	Worldview-2/3	Maxar	2009- Present	0.46 panchromatic, 1.84 multispectral	9	1–3 days	$
	Quickbird	Maxar	2001-2015	0.65 panchromatic, 2.62 multispectral	5	1–3.5 days	$
	Planetscope Dove Classic (PS2)	Planet	2014-2022	3-4.1	4	daily at nadir	$
	Planetscope Dove-R(PS2.SD)	Planet	2019-2022	3-4.1	4	daily at nadir	$
	PlanetScope Super Dove (PSB-SD)	Planet	2020- Present	3.7-4.3	8	daily at nadir	$
Very High Resolution (< 2 m)	SkySat	Planet	2016- Present	panchromatic 0.58m, multispectral 0.72m	5	4-5 days	$
	Pleiades Neo	Airbus	2021- Present	0.3 panchromatic, 1.2 multispectral	7	2x/day	$
	GeoEye	Maxar	2008- Present	0.41 panchromatic, 1.64 multispectral	5	1.7 days at 1-m GSD resolution	$

A Note on Field-Based Methods

Depending on the monitoring objective and its scale, there are several non-remote sensing, **field-based options** available for documenting the presence, extent, species, and health of emergent canopy kelp. These include, but are not limited to, visual observations, SCUBA surveys, and boat-based surveys. Depending on your kelp mapping objective, field-based measurements are necessary for pairing with remote sensing data into order to estimate kelp bed density, biomass, and health (e.g., counting kelp plants in quadrats, collecting and weighing kelp plants, etc.). We refer to these methods in the infographics where these methods are relevant and applicable.

Check out Appendix 5 for more information and resources on how to map kelp with non-remote sensing methods.

(Top left panel) Quadrat and water quality measurements being taken in a kelp bed on the west coast of Vancouver Island. **Image:** Graham Owsianski

(Top right panel) Drone image over kelp quadrat measurements being taken in a kelp bed. **Image:** Markus Thompson

(Bottom left panel) Drone image over a kelp bed with kayak surveys in Washington State. **Image:** Tyler Cowdrey

(Bottom right panel) Quadrat measurements being taken in a kelp bed in Pacific Rim National Park Reserve. **Image:** Markus Thompson

A Note on Tides and Currents

Giant kelp and bull kelp are fixed to the seafloor by their root-like holdfasts, therefore, increases in tidal height and current velocity can submerge portions of the floating kelp canopy (**Figure 13**). This submergence negatively affects the ability of many of the optical remote sensing methods described here to detect kelp canopy presence, area, biomass, and health (Timmer et al., 2022). **In very simple terms — if the kelp is underwater, we are very limited in applying optical remote sensing methods for mapping kelp.**

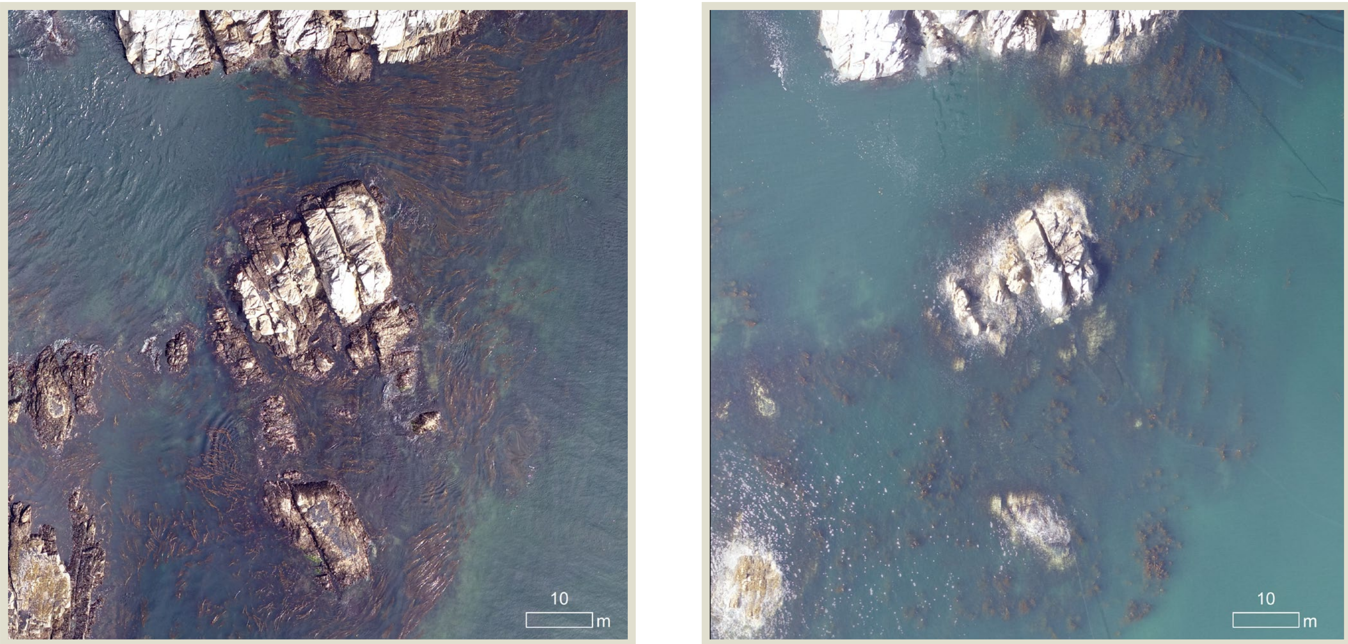


Figure 13. Drone imagery collected over a kelp bed at low tide (left panel) and high tide (right panel). **Image:** Hakai Institute

A lot of research has focused on studying the effects of tides and currents on kelp mapping. Bull kelp canopy was found to decrease in the presence of higher tides and currents across four kelp beds using high temporal resolution digital imagery collected from shore, although the magnitude of these effects varied by site (Britton-Simons et al., 2005). Cavanaugh et al. (2021) used a time series of multispectral drone imagery to show that increased tidal height reduced the area of floating giant kelp at two sites in southern California. There was also a significant negative effect of increased current velocity, however, tides and currents are strongly linked in this region. Tidal height effects can also be apparent in satellite estimates of kelp canopy metrics. Across sites in British Columbia, a 2 m increase in tidal height resulted in a 40% reduction in the classified canopy area of mixed beds observed with Landsat (Nijland et al., 2019). Bell et al. (2020) showed a similar effect for giant kelp beds across southern California and how the 8-day acquisition frequency of the Landsat sensors can often synchronize with tidal fluctuations leading to antagonistic kelp canopy dynamics when multiple Landsat sensors were compared. Furthermore, the kelp biomass density can dampen current velocity (Monismith et al., 2022), leading to greater canopy submergence across sparse beds and along the bed edges (McPherson et al., in prep).

Take home message: Tides and currents affect our ability to map kelp canopy therefore it is important to understand the local physical conditions at a monitoring site or region to fully understand the effect of tide and currents on kelp canopy dynamics.

Kelp Mapping Infographics

In this section you will find four infographics toto help you determine which optical remote sensing tool(s) are recommended for your given kelp monitoring objective.

The kelp monitoring objectives are:

Presence/absence/extent: Is kelp canopy present or absent, at a given place and time? If present, what is the area of canopy present at the ocean's surface (e.g., m^2 of canopy kelp)?

Species: What species of kelp are present (bull kelp and/or giant kelp) in a given place and time and what is the species' extent (e.g., m^2 of giant kelp)?

Density/biomass: How much kelp is present at a given place and time (e.g., kg/m^2, tonnes/ha)?

Health: What is the health of kelp at a given place and time? For example, quantitative health assessments such as carbon to nitrogen ratios and pigments, or qualitative assessments such as visual observations of kelp health (e.g., bryozoan cover).

For each monitoring objective you can then choose the spatial scale of your monitoring objective. At each of these spatial scales you may have kelp beds of different sizes and densities which also influence which remote sensing tools are appropriate.

The spatial scales are:

- **Local:** your area of interest is a few kilometers of coastline or smaller (e.g., a single bay or reef).
- **Regional:** your area of interest is 10s -100s kilometers of coastline (e.g., marine protected area or archipelago).
- **Coast-wide:** your area of interest is 100s - 1000s of kilometers of coastline (e.g., all of Washington State).

Following your selections you will see what remote sensing tools are available based on your objective and spatial scale. We created a series of icons to represent aspects of kelp remote sensing described in the infographics which are described in **Figure 14**. In these infographics, we focus on annual kelp canopy surveys for giant kelp and bull kelp. For annual surveys, kelp forests are typically mapped in the NE Pacific from mid- to late- summer (depending on the region) when the kelp is at its peak growth. Please see Appendix 1 if you have different temporal monitoring needs for surveys (e.g., daily, monthly, etc).

The infographics use colour (green, yellow and red) to highlight your "best option", a "maybe" option and the not recommended (or "nah") option for what remote sensing tool you should use.

Kelp Mapping Icon Legend

Field Observation


Boat-based observations.


Visual observations.


Underwater survey (e.g., SCUBA).

Drone Mapping


Drone with RGB sensor.


Drone with multispectral sensor (MS).


Drone with hyperspectral sensor.

Aerial Mapping


Plane with RGB sensor.


Plane with multispectral sensor (MS).


Plane with hyperspectral sensor.

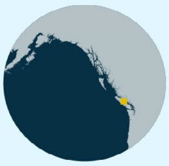
Satellite Mapping


Coarse resolution satellite imagery.


Medium resolution satellite imagery.


High resolution satellite imagery.

Spatial Scale


Local scale: your area of interest is a few km of coastline (e.g. < 10 km).


Regional scale: your area of interest is 10s to 100s of kms of coastline.


Coast wide scale: Your area of interest is 100s to 1000 kms of coastline.

Other Symbols


Needs lab data.


Is expensive.

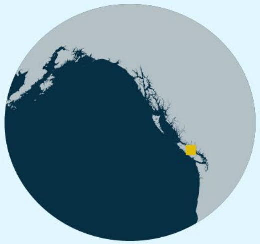
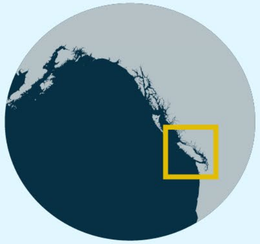
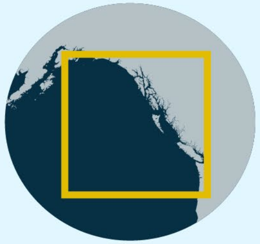

Ongoing area of research.

Figure 14. Icons and definitions used in the kelp infographics. You can read more about spectral resolution and spatial resolution in other sections of this guidebook.

Presence/Absence/Extent

Kelp Mapping Tools

Use this chart if you have only 1 species of kelp present in a given area, or if you are quantifying kelp canopy regardless of species.

Scale →	Local	Regional	Coastal
			
Best Option →	A drone (RGB or MS) is the best option to get kelp species & bed extent if the site is accessible. Use shore- or boat-based methods for kelp bed presence/absence observations.	High-res satellite or aerial imagery (RGB or MS) is best option in general & only option to map small, fringing kelp beds.	Medium or coarse resolution satellites are best for mapping dense, large, offshore kelp beds.
Maybe →	Aerial imagery or high-res satellites are OK options if site is unaccessible, but expensive at small scales. Medium & coarser resolution satellites are OK option if kelp beds are several pixels big*.	Medium & coarser resolution satellites are OK options if kelp beds are several pixels big*.	Medium & coarser resolution satellites are OK option if kelp beds are several pixels big*.
Nah →	Medium & coarser resolution satellites can't map small, fringing beds.	Would need small drone army to map area this large.	Aerial & high-res satellite imagery is very expensive at a large scale. Medium & coarser resolution satellites can't map small, fringing beds.

Footnotes : Hyperspectral sensors of anykind are overkill for presence/absence/extent.

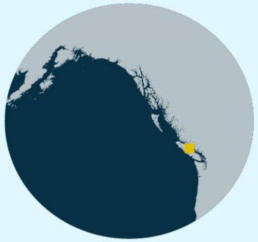
* In this context a pixel is 30 m.

Species

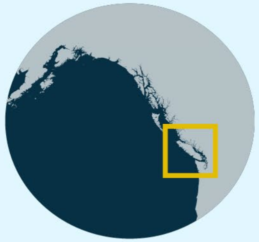
Kelp Mapping Tools

Use this chart if you have both species (giant kelp and bull kelp) present and are trying to determine the extent of each. If you only have one species present then use the presence/absence/extent chart.

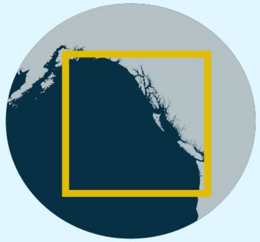
Scale →



Local



Regional



Coastal

Scale →	Local	Regional	Coastal
Best Option →	A drone (RGB or MS) is the best option to get kelp species & bed extent if the site is accessible. Can also use shore- or boat-based observations to identify species present.	Aerial imagery (RGB or MS) best option in general, and can obtain very high-res imagery (<0.1 m).	Aerial imagery best option in general (but becomes more expensive in larger areas). Only option to map small, fringing beds.
Maybe →	Aerial imagery or high-res satellites are OK options if site is inaccessible, but expensive at small scales.	High-res satellites feasible (need <0.5 m resolution).	High-res satellites (<0.5 m) feasible, but expensive & difficult to task for very large areas.
Nah →	Can't tell species apart with medium and coarse resolution satellite imagery.	You would need a small drone army to map an area this large.	Can't tell species apart with medium and coarse resolution satellite imagery.

Footnotes : Hyperspectral sensors of any kind are overkill for presence/absence, and spectral methods don't exist for telling bull and giant kelp apart.

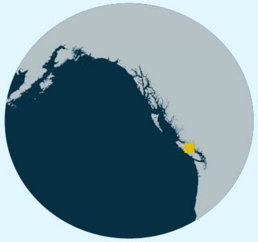
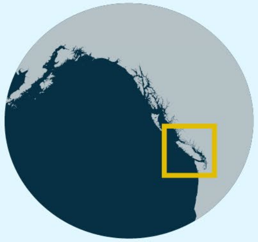
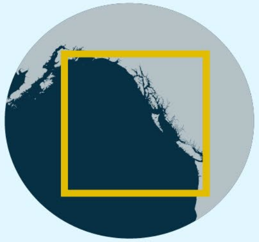
Health

Kelp Mapping Tools

The recommendations in this table are for areas with one kelp species present.

Quantitative kelp health: Research has shown that you can detect nitrogen content or carbon ratios from hyperspectral imagery. This requires lab processing and hyperspectral data.

Qualitative kelp health: Based on observations/estimates by visual observation (e.g., SCUBA, snorkel, boat surveys).

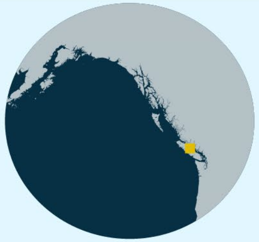
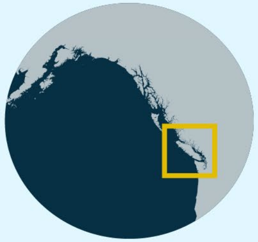
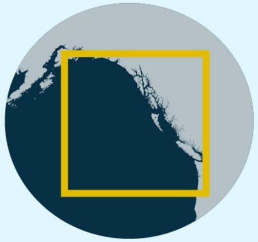
Scale →	Local	Regional	Coastal
			
Best Option →	Quantitative health: Use hyperspectral drone paired with field & lab data. Qualitative health: Use boat or visual observations for bed-level estimates.	Hyperspectral aerial imagery paired with field and lab data is best option in general & only option if you have fringing beds.	Currently no datasets or technologies exist that examine coast-wide kelp health.
Maybe →	Possibly feasible to use drone (RGB or MS) to detect kelp health status, but more research is needed.	Regional qualitative observations could be established by larger working groups or government organizations. Very new coarse satellite sensors (e.g., EnMAP) coming online, but more research is needed.	Hyperspectral aerial imagery is best option in general & only option if you have fringing beds. Expensive & difficult to task for very large areas.
Nah →	Deriving kelp bed health not possible with current medium & coarse resolution satellite imagery.	Deriving kelp bed health not possible with current medium & coarse resolution satellite imagery.	Drones and planes too expensive at such a large scale. Deriving kelp bed health not possible with current medium & coarse resolution satellite imagery.

Footnotes : Hyperspectral instruments and sensors are expensive

Biomass

Kelp Mapping Tools

In general, linking remote sensing imagery to biomass is an ongoing and active area of research for the kelp mapping community.
Currently the relationship between biomass and kelp detected from satellite imagery has only been established for giant kelp (*Macrocystis* sp.) in Landsat imagery (Cavanaugh et al. 2011 and Bell et al. 2020).
In theory, establishing the relationship between imagery and biomass is feasible with any multispectral sensor paired with in situ density and biomass data.

Scale →	Local 	Regional 	Coastal 
Best Option →	A drone (MS) paired with field data is feasible if site is accessible. Use Landsat imagery if site only has giant kelp beds that are several pixels big*.	Image-to-biomass relationship exist for Macrocystis using Landsat imagery. Use this if kelp beds are several pixels big* & only giant kelp present.	Image-to-biomass relationship exist for Macrocystis using Landsat imagery. Use this if kelp beds are several pixels big* & only giant kelp present.
Maybe →	Aerial imagery or high-res satellites paired with field data feasible. Both options expensive at small scales.	If only one species present: medium & coarser resolution satellites paired with field data feasible if kelp beds are several pixels big*. If multiple species present: aerial imagery or high-res satellites (<0.5 m) paired with field data feasible.	If only one species present: medium & coarser resolution satellites paired with field data feasible if kelp beds are several pixels big*. If multiple species present: aerial imagery or high-res satellites (<0.5 m) paired with field data feasible, but expensive & difficult to task for very large areas.
Nah →	Coarser resolution satellites can't differentiate small fringing beds or tell species apart.	You would need a small drone army to map an area this large.	Drones and planes too expensive at such a large scale. Can't tell species apart with medium and coarse resolution satellite imagery.

Footnotes :

Hyperspectral sensors are possibly feasible for determining biomass but are expensive and limited to local surveys. Currently, spectral methods don't exist for telling bull and giant kelp apart.

Making the link between imagery (drone, aerial, satellite) to in situ kelp bed biomass is an ongoing area of research.

* In this context a pixel is 30 m.

Conclusion

Optical remote sensing imagery — whether collected via **drones**, **planes,** or **satellites** — is a valuable and powerful tool for mapping and monitoring the presence/absence/extent, distribution, abundance, and health of kelp forests. With remote sensing, coastal communities, managers, researchers, and restoration practitioners can obtain vital data that can be used to inform conservation and management efforts, identify areas of potential restoration or protection, and assess the impact of environmental factors such as climate change on kelp ecosystems. With the continued development and improvement of remote sensing technology, it's likely that it will play an even more significant role in the future of kelp mapping and management.

Our **goal** with this **guidebook** and **infographics** was to synthesize the current state of kelp mapping in the northeast Pacific. We know that the methods and resources provided here will be relevant to kelp mapping efforts on other continents and coastlines. We've tried our best to create a succinct summary of the current state of kelp mapping and know this topic will continue to evolve and grow as more practitioners start mapping kelp and new technologies become available. We hope you find this guidebook useful!

We encourage users of this best practices guidebook to engage with other members of the global kelp mapping community to share their experiences (and challenges!), so that this community of practice can continue to grow and learn from each other.

Aerial view over Calvert Island, British Columbia. **Image:** Keith Holmes, Hakai Institute

References

Augenstein, E., Stow, D., & Hope, A. (1991). Evaluation of SPOT HRV-XS data for kelp resource inventories. Photogrammetric Engineering and Remote Sensing, 57(5), 501–509.

Bell, T.W., Cavanaugh, K.C., Siegel, D.A. (2015) Remote monitoring of giant kelp biomass and photosynthetic condition: An evaluation of the potential for the Hyperspectral Infrared Imager (HyspIRI) mission. Remote Sensing of Environment, 167, 218-228.

Bell, T.W., Allen, J.A., Cavanaugh, K.C., Siegel, D.A. (2020), Three decades of variability in California's giant kelp forests from the Landsat satellites. Remote Sensing of Environment. 238, 110811.

Bell, T.W., Siegel, D.A. (2022), Nutrient availability and senescence spatially structure the dynamics of a foundation species, Proceedings of the National Academy of Sciences, 119, 1, e2105135118.

Britton-Simmons, K., Eckman, J., & Duggins, D. (2008). Effect of tidal currents and tidal stage on estimates of bed size in the kelp Nereocystis luetkeana. In Marine Ecology Progress Series (Vol. 355, pp. 95–105). Inter-Research Science Center. https://doi.org/10.3354/meps07209

Cavanaugh, K. C., Cavanaugh, K. C., Bell, T. W., & Hockridge, E. G. (2021). An Automated Method for Mapping Giant Kelp Canopy Dynamics from UAV. In Frontiers in Environmental Science (Vol. 8). Frontiers Media SA. https://doi.org/10.3389/fenvs.2020.587354

Cavanaugh, K. C., Cavanaugh, K. C., Pawlak, C. C., Bell, T. W., & Saccomanno, V. R. (2023). CubeSats show persistence of bull kelp refugia amidst a regional collapse in California. In Remote Sensing of Environment (Vol. 290, p. 113521). Elsevier BV. https://doi.org/10.1016/j.rse.2023.113521

Cavanaugh, K.C., Siegel, D.A., Reed, D.C., & Dennison, P.E. (2011). Environmental controlsof giant-kelp biomass in the Santa Barbara Channel, California. Marine Ecology Progress Series, 429, 1–17.

Cavanaugh, K. C., Bell, T., Costa, M., Eddy, N. E., Gendall, L., Gleason, M. G., Hessing-Lewis, M., Martone, R., McPherson, M., Pontier, O., Reshitnyk, L., Beas-Luna, R., Carr, M., Caselle, J. E., Cavanaugh, K. C., Flores Miller, R., Hamilton, S., Heady, W. N., Hirsh, H. K., … Schroeder, S. B. (2021). A Review of the Opportunities and Challenges for Using Remote Sensing for Management of Surface-Canopy Forming Kelps. In Frontiers in Marine Science (Vol. 8). Frontiers Media SA. https://doi.org/10.3389/fmars.2021.753531

Dayton, P. K. (1972). Toward an understanding of community resilience and the potential effects of enrichments to the benthos at McMurdo Sound, Antarctica. pp. 81–96 in Proceedings of the Colloquium on Conservation Problems Allen Press, Lawrence, Kansas.

Denouden, T., Timmer, B., & Reshitnyk, L. (2021). GlintMaskGenerator (2.0.5) [Computer software]. https://doi.org/10.21966/3cpa-2e10

Denouden, T., & Reshitnyk, L. (2021). Kelp-O-Matic (Version 0.5.2) [Computer software]. https://doi.org/10.5281/zenodo.7672167

Deysher, L.E. (1993). Evaluation of remote sensing techniques for monitoring giant kelp populations. Hydrobiologia, 260–261(1), 307–312.

Filbee-Dexter, K., & Wernberg, T. (2020). Substantial blue carbon in overlooked Australian kelp forests. In Scientific Reports (Vol. 10, Issue 1). Springer Science and Business Media LLC. https://doi.org/10.1038/s41598-020-69258-7

Holbrook, S., Carr, M., Schmitt, R. & Coyer, J. (1990). Effect of Giant Kelp on Local Abundance of Reef Fishes: The Importance of Ontogenetic Resource Requirements. Bulletin of Marine Science. 47. 104-114.

Jensen, J. R., J. E. Estes, and L. Tinney. (1980). Remote sensing techniques for kelp surveys. Photogrammatic Engineering and Remote Sensing 46:743–755.

Kobluk, H. M., Gladstone, K., Reid, M., Brown, K., Krumhansl, K. A., & Salomon, A. K. (2021). Indigenous knowledge of key ecological processes confers resilience to a small-scale kelp fishery. In People and Nature (Vol. 3, Issue 3, pp. 723–739). Wiley. https://doi.org/10.1002/pan3.10211

Krumhansl, K. A., Okamoto, D. K., Rassweiler, A., Novak, M., Bolton, J. J., Cavanaugh, K. C., Connell, S. D., Johnson, C. R., Konar, B., Ling, S. D., Micheli, F., Norderhaug, K. M., Pérez-Matus, A., Sousa-Pinto, I., Reed, D. C., Salomon, A. K., Shears, N. T., Wernberg, T., Anderson, R. J., … Byrnes, J. E. K. (2016). Global patterns of kelp forest change over the past half-century. In Proceedings of the National Academy of Sciences (Vol. 113, Issue 48, pp. 13785–13790). Proceedings of the National Academy of Sciences. https://doi.org/10.1073/pnas.1606102113

Marquez, L., Fragkopoulou, E., Cavanaugh, K. C., Houskeeper, H. F., & Assis, J. (2022). Artificial intelligence convolutional neural networks map giant kelp forests from satellite imagery. In Scientific Reports (Vol. 12, Issue 1). Springer Science and Business Media LLC. https://doi.org/10.1038/s41598-022-26439-w

McPherson, M.L., Bell, T.W., Snyder, J.S., Cavanaugh, Ka.C., Siegel, D.A., Cavanaugh, K.C., Kudela, R.M. (in prep) Utilizing a Multiyear Dataset of Unoccupied Aircraft System Imagery to Validate Landsat Derived Giant Kelp Canopy. Remote Sensing of Environment.

Monismith, S. G., Alnajjar, M. W., Woodson, C. B., Boch, C. A., Hernandez, A., Vazquez Vera, L., Bell, T. W., & Micheli, F. (2022). Influence of Kelp Forest Biomass on Nearshore Currents. In Journal of Geophysical Research: Oceans (Vol. 127, Issue 7). American Geophysical Union (AGU). https://doi.org/10.1029/2021jc018333

Mora Soto, A., Capsey, A., Friedlander, A. M., Palacios, M., Brewin, P. E., Golding, N., Dayton, P., Van Tussenbroek, B., Montiel, A., Goodell, W., Velasco Charpentier, C., Hart, T., Macaya, E. C., Pérez Matus, A., & Macias Fauria, M. (2021). One of the least disturbed marine coastal ecosystems on Earth: Spatial and temporal persistence of Darwin's sub Antarctic giant kelp forests. In A. F. Palmeirim (Ed.), Journal of Biogeography (Vol. 48, Issue 10, pp. 2562–2577). Wiley. https://doi.org/10.1111/jbi.14221

Nijland, W., Reshitnyk, L., & Rubidge, E. (2019). Satellite remote sensing of canopy-forming kelp on a complex coastline: A novel procedure using the Landsat image archive. In Remote Sensing of Environment (Vol. 220, pp. 41–50). Elsevier BV. https://doi.org/10.1016/j.rse.2018.10.032

Roelfsema C.M., S.R. Phinn, D. Tracey, J. Speirs, M. Kamal, M. Hewson and K. Johansen, (2017), A Web Based Toolkit for Using Remote Sensing to Map and Monitor Terrestrial, Marine and Atmospheric Environments. https://www.rsrc.org.au/rstoolkit/

Saccomanno, V. R., Bell, T., Pawlak, C., Stanley, C. K., Cavanaugh, K. C., Hohman, R., Klausmeyer, K. R., Cavanaugh, K., Nickels, A., Hewerdine, W., Garza, C., Fleener, G., & Gleason, M. (2022). Using unoccupied aerial vehicles to map and monitor changes in emergent kelp canopy after an ecological regime shift. In Remote Sensing in Ecology and Conservation (Vol. 9, Issue 1, pp. 62–75). Wiley. https://doi.org/10.1002/rse2.295

Schroeder, S. B., Dupont, C., Boyer, L., Juanes, F., & Costa, M. (2019). Passive remote sensing technology for mapping bull kelp (Nereocystis luetkeana): A review of techniques and regional case study. In Global Ecology and Conservation (Vol. 19, p. e00683). Elsevier BV.

Stekoll, M.S., Deysher, L.E., & Hess, M. (2006). A remote sensing approach to estimating harvestable kelp biomass. Journal of Applied Phycology, 18(3–5), 323–334

Sutherland, I. R., Karpouzi, V., Mamoser, M., & Carswell, B. (2008). Kelp Inventory, 2007. Areas of the British Columbia central coast from Hakai Passage to the Bardswell Group. Oceans and Marine Fisheries Branch, BC Ministry of Environment Fisheries and Oceans Canada BC Ministry of Agriculture and Lands Heiltsuk Tribal Council.

Timmer, B., Reshitnyk, L. Y., Hessing-Lewis, M., Juanes, F., & Costa, M. (2022). Comparing the Use of Red-Edge and Near-Infrared Wavelength Ranges for Detecting Submerged Kelp Canopy. In Remote Sensing (Vol. 14, Issue 9, p. 2241). MDPI AG https://doi.org/10.3390/rs14092241

Wernberg, T., Krumhansl, K., Filbee-Dexter, K., & Pedersen, M. F. (2019). Status and Trends for the World's Kelp Forests. In World Seas: An Environmental Evaluation (pp. 57–78). Elsevier. https://doi.org/10.1016/B978-0-12-805052-1.00003-6

Appendices

Appendix 1 - Technical Infographic Tables

The infographics presented in this document highlight remote sensing tools recommended for mapping emergent kelp canopy on an **annual basis**. However, the Kelp Mappers Community of Practice produced tables containing recommendations for mapping kelp attributes (presence/absence/extent, species, biomass, health) based on (1) spatial scale (local, regional, and coast-wide), (2) site accessibility, (3) temporal scales (daily, monthly, etc.,) and (4) kelp distribution (e.g. sparse, dense, nearshore, offshore).

The structure of the infographic tables used to create the infographics in this document was based on the Marine Remote Sensing toolkit (Roelfsema et al., 2017) which highlights remote sensing tools and applications to a suite of different environmental features. We would like to thank Dr. Chris Roelfsema and Dr. Stuart Phinn for providing the rubric that was adapted for the work presented in this guidebook.

You will find all the technical tables here.

Appendix 2 - Resources on Kelp Mapping Using Unoccupied Aerial Systems (Drones) Infographic Tables

2.1 A Selection Of Peer-Reviewed Publications And Reports Of Kelp Mapping Using Drones (Listed Chronologically)

- **Denouden, T., & Reshitnyk, L.** (2023). Kelp-O-Matic (Version 0.5.2) [Computer software] Zenodo https://zenodo.org/record/7672167 Download tool here.
- **McPherson, M. L., & Kudela, R. M.** (2022). Kelp Patch-Specific Characteristics Limit Detection Capability of Rapid Survey Method for Determining Canopy Biomass Using an Unmanned Aerial Vehicle. In Frontiers in Environmental Science (Vol. 10). Frontiers Media SA. https://doi.org/10.3389/fenvs.2022.690963
- **Saccomanno, V. R., Bell, T., Pawlak, C., Stanley, C. K., Cavanaugh, K. C., Hohman, R., Klausmeyer, K. R., Cavanaugh, K., Nickels, A., Hewerdine, W., Garza, C., Fleener, G., & Gleason, M. (**2022). Using unoccupied aerial vehicles to map and monitor changes in emergent kelp canopy after an ecological regime shift. In Remote Sensing in Ecology and Conservation (Vol. 9, Issue 1, pp. 62–75). Wiley. https://doi.org/10.1002/rse2.295
- **Timmer, B.** (2022). The effects of kelp canopy submersion on the remote sensing of surface-canopy forming kelps. Master's of Geography Thesis. University of Victoria, Canada. http://hdl.handle.net/1828/14087
- **Timmer, B., Reshitnyk, L. Y., Hessing-Lewis, M., Juanes, F., & Costa, M**. (2022). Comparing the Use of Red-Edge and Near-Infrared Wavelength Ranges for Detecting Submerged Kelp Canopy. In Remote Sensing (Vol. 14, Issue 9, p. 2241). MDPI AG. https://doi.org/10.3390/rs14092241
- **Berry, H. & Cowdrey, T.** (2021) Kelp Forest Canopy Surveys with Unmanned Aerial Vehicles (UAVs) and Fixed-Wing Aircraft: a demonstration project at volunteer monitoring sites in northern Puget Sound. Final report to Northwest Straits Commission (IAA 93-102466). Washington State Department of Natural Resources, U.S.A.
- **Cavanaugh, K. C., Cavanaugh, K. C., Bell, T. W., & Hockridge, E. G.** (2021). An Automated Method for Mapping Giant Kelp Canopy Dynamics from UAV. In Frontiers in Environmental Science (Vol. 8). Frontiers Media SA. https://doi.org/10.3389/fenvs.2020.587354
- **Cowdrey, T.** (2021). Mapping bull kelp (Nereocystis luetkeana) forests in Puget Sound with a consumer-level unmanned aerial vehicle (UAV). [Masters of Environmental Studies Thesis]. The Evergreen State College, Washington, USA. http://collections.evergreen.edu/s/repository/item/10194

- **Lee, L. C., Daniel McNeill, G., Ridings, P., Featherstone, M., Okamoto, D. K., Spindel, N. B., Galloway, A. W. E., Saunders, G. W., Adamczyk, E. M., Reshitnyk, L., Pontier, O., Post, M., Irvine, R., Wilson, G. taa'a gaagii ng. aang N., & Bellis, S. K̲ung V.** (2021). Chiixuu Tll iinasdll: Indigenous Ethics and Values Lead to Ecological Restoration for People and Place in Gwaii Haanas. In Ecological Restoration (Vol. 39, Issues 1–2, pp. 45–51). University of Wisconsin Press. https://er.uwpress.org/content/39/1-2/45
- **Bell, T. W., Nidzieko, N. J., Siegel, D. A., Miller, R. J., Cavanaugh, K. C., Nelson, N. B., Reed, D. C., Fedorov, D., Moran, C., Snyder, J. N., Cavanaugh, K. C., Yorke, C. E., & Griffith, M.** (2020). The Utility of Satellites and Autonomous Remote Sensing Platforms for Monitoring Offshore Aquaculture Farms: A Case Study for Canopy Forming Kelps. In Frontiers in Marine Science (Vol. 7). Frontiers Media SA. https://doi.org/10.3389/fmars.2020.520223
- **Cavanaugh, K. C.** (2020). Effect of Tides and Currents on UAV-Based Detection of Giant Kelp Canopy. University of California Los Angeles. ProQuest ID: Cavanaugh_ucla_0031N_18976. Merritt ID: ark:/13030/m5m383vg. Retrieved from https://escholarship.org/uc/item/0tn1p1p6
- **Burt, J. M., Tinker, M. T., Okamoto, D. K., Demes, K. W., Holmes, K., & Salomon, A. K.** (2018). Sudden collapse of a mesopredator reveals its complementary role in mediating rocky reef regime shifts. In Proceedings of the Royal Society B: Biological Sciences (Vol. 285, Issue 1883, p. 20180553). The Royal Society. https://doi.org/10.1098/rspb.2018.0553
- **Timer, B. Reshitnyk, L. Y., Hessing-Lewis, M., Juanes, F., Gendall, L. & Costa, M.** Capturing Accurate Extent of Floating Kelp Canopy: The Role of Tides, Currents, and Species-level Morphology in Kelp Remote Sensing. [Manuscript in preparation]. Department of Geography, University of Victoria, Canada.

2.2 Resources on Methods And Guidelines for Mapping Kelp Using Drones

You may find many guides online for flying drones for any mapping application - doesn't matter if it's kelp or carrot crops. These guides can typically be applied for your specific mapping case and needs. However, in all cases, be sure that you are following the regulations for the country and air space you are flying in.

Some kelp-specific drone resources include:

- Thompson, Markus (2021) MaPP Kelp Monitoring Protocol. Marine Plan Partnership. Access link.
- Vitality Training Program on Indigenous stewardship data collection – kelp forests. Check out resources and links under "Data collection training material". Access link.
- Denouden, T., Timmer, B., & Reshitnyk, L. (2021). GlintMaskGenerator (Version 2.0.5) [Computer software]. https://doi.org/10.21966/3cpa-2e10

2.4 Additional Groups, Datasets, Web Maps or Media Focused on Mapping Kelp Using Drones

- Mapping Bull kelp forest canopies with aerial imagery (StoryMap). Tyler Cowdrey, Washington Department of Natural Resources Nearshore Habitat Program. Access link.
- Marine Plan Partnership (MaPP) (2021). Regional Kelp Monitoring on the North Pacific Coast: A Community-Based Monitoring Initiative to Inform Ecosystem-Based Management (Storymap). Access link.
- California BIOS dataset for kelp UAV surveys from Northern California. Access link.

Appendix 3 - Resources on Kelp Mapping Using Occupied Aircraft

3.1 A Selection of Peer-Reviewed Publications of Kelp Mapping Using Occupied Aircraft (Listed Chronologically)

Starko, S., Timmer, B., Reshitnyk, L., Csordas, M., McHenry, J., Schroeder, S., Hessing-Lewis, M., Costa, M., Zielinksi, A., Zielinksi, R., Cook, S., Underhill, R., Boyer, L., Fretwell, C., Yakimishyn, J., Heath, W. A., Gruman, C., Baum, J. K., & Neufeld, C. J. (2023). Temperature and food chain length, but not latitude, explain region-specific kelp forest responses to an unprecedented heatwave. Cold Spring Harbor Laboratory. https://doi.org/10.1101/2023.01.07.523109

Starko, S., Neufeld, C. J., Gendall, L., Timmer, B., Campbell, L., Yakimishyn, J., Druehl, L., & Baum, J. K. (2022). Microclimate predicts kelp forest extinction in the face of direct and indirect marine heatwave effects. In Ecological Applications (Vol. 32, Issue 7). Wiley. https://doi.org/10.1002/eap.2673

Bell, T. W., & Siegel, D. A. (2021). Nutrient availability and senescence spatially structure the dynamics of a foundation species. In Proceedings of the National Academy of Sciences (Vol. 119, Issue 1). Proceedings of the National Academy of Sciences. https://doi.org/10.1073/pnas.2105135118

Bell, T, D. Siegel. 2021. Kelp canopy chlorophyll to carbon ratio derived from aerial hyperspectral imagery ver 1. Environmental Data Initiative. https://doi.org/10.6073/pasta/c85974f3c0d11fb8cdb1ac2890698906.

Berry, H. D., Mumford, T. F., Christiaen, B., Dowty, P., Calloway, M., Ferrier, L., Grossman, E. E., & VanArendonk, N. R. (2021). Long-term changes in kelp forests in an inner basin of the Salish Sea. In M. (Gee) G. Chapman (Ed.), PLOS ONE (Vol. 16, Issue 2, p. e0229703). Public Library of Science (PLoS).https://doi.org/10.1371/journal.pone.0229703

Finger, D. J. I., McPherson, M. L., Houskeeper, H. F., & Kudela, R. M. (2021). Mapping bull kelp canopy in northern California using Landsat to enable long-term monitoring. In Remote Sensing of Environment (Vol. 254, p. 112243). Elsevier BV. https://doi.org/10.1016/j.rse.2020.112243

Pfister, C. A., Berry, H. D., & Mumford, T. (2017). The dynamics of Kelp Forests in the Northeast Pacific Ocean and the relationship with environmental drivers. In A. Randall Hughes (Ed.), Journal of Ecology (Vol. 106, Issue 4, pp. 1520–1533). Wiley. https://doi.org/10.1111/1365-2745.12908

Bell, T.W., Cavanaugh, K.C., Siegel, D.A. (2015) Remote monitoring of giant kelp biomass and photosynthetic condition: An evaluation of the potential for the Hyperspectral Infrared Imager (HyspIRI) mission. Remote Sensing of Environment, 167, 218-228.

Sutherland, I. R. (2008). Kelp Inventory, 2007. Areas of the British Columbia Central Coast from Hakai Passage to the Bardswell Group. In. British Columbia Ocean and Marine Fisheries Branch, Ministry of Environment, pp 1-63.

Stekoll, M. S., Deysher, L. E., & Hess, M. (2006). A remote sensing approach to estimating harvestable kelp biomass. In Journal of Applied Phycology (Vol. 18, Issues 3–5, pp. 323–334). Springer Science and Business Media LLC. https://doi.org/10.1007/s10811-006-9029-7

Foreman, R. E. (1975). KIM-1. A method for inventory of floating kelps and its application to selected areas of Kelp Licence Area 12. Benthic Ecological Research Program Report 75-1. Report to Federal Fisheries and marine Service and Provincial Marine Resources Branch. 81 pp.

3.2 Available or Existing Datasets

Available kelp datasets from aerial surveys (these datasets do not include imagery):

- Washington Department of Natural Resources: data are here.
- California Department of Fish and Wildlife: data are here.
- Province of British Columbia kelp surveys: data are housed on the BCMCA website (search for kelp).

3.3 Resources on Methods and Guidelines

- Washington State Department of Natural Resources has been collecting aerial imagery of the Washington coast annually since 1989. This report details the methods for delineation of canopy and kelp bed area. These methods are currently under review.
- The Province of British Columbia conducted kelp surveys at multiple sites across the province in the 1970s, 1990s, and 2000s using the KIM-1 method. Methods for kelp bed area delineation can be found in reports and are based on manual delineation of area and species classification.
- Washington State Department of Natural Resources floating kelp monitoring data viewer. Access link.

3.4 Specifications for Aerial Imagery Collections for Kelp Surveys

The Hakai Institute has been conducting aerial (plane-based) surveys for kelp since 2020 and uses the following table to determine priority conditions for image collection. These specifications were adapted from the Washington Department of Natural Resources Kelp Mapping program as well as other references listed below.

Parameter	Condition for image acquisition	Notes	Acquisition priority
Tide height during survey	< 1.5 m (chart datum) As low as possible means we also capture seagrass (if that is a priority)	Target lowest tides Ideally surveys are 2 hr either side of low for slack tide NOTE: slack tide and low tide are not coincident for all regions of the NE Pacific.	1
Sun Angle	> 30 degrees above horizon, < 152 from solar azimuth	Avoiding glint is important but the deglinting methods work well for aerial imagery.	2
Sea state	Surface winds < 10 kn, sea swell < 1.5 m	Calm sea state is ideal	3
Clouds	Ideal - cloud free or 100% overcast		4
Clouds Ceiling and visibility	> 8000 msl- Washington DNR standards 5 mile visibility		5
Time of year	Mid July - early September	Peak biomass for kelp (varies regionally)	6
Sidelap	20 - 30%		
Image resolution	10 cm	<15 cm recommended resolution to visually determine species.	

Note to reader:WADNR uses the following guidelines: a sun angle of >= 25 and <=45, a tide height Of <1 foot MLLW (+/- 1 hr) with 80% overlap and 40% sidelap.

Below are some additional references for planning the specifications of aerial surveys for kelp:

- Department of Natural Resources, Washington - Report here
- **Finkbeiner, M., B. Stevenson, and R. Seaman.** 2001. Guidance for Benthic Habitat Mapping: An Aerial Photographic Approach. NOAA Coastal Services Center. -Report here
- **Dobson, J. E., E. A. Bright, R. L. Ferguson, D. W. Field, L. L. Wood, K. D. Haddad, et al.** (1996). Monitoring Submerged Land Using Aerial Photography. NOAA Coastal Change Analysis Program (C-CAP). NOAA technical report NMFS 123. Report here

3.5 Additional Groups, Datasets, Webmaps or Media Focused on Mapping Kelp with Occupied Aircraft

- **Samish Indian Nation & Palmer-McGee, C** . A Decade of Disappearance: Bull Kelp in the San Juan Islands (Storymap). Access link.
- **Marine Plan Partnership** (MaPP) (2021). Regional Kelp Monitoring on the North Pacific Coast: A Community-Based Monitoring Initiative to Inform Ecosystem-Based Management (Storymap). Access link.
- **Kelp Forests Along Washington State's Strait Over a Century**. Washington Department of Natural Resources. Access link.
- **Washington state** (USA) floating kelp indicator program (some links):
  - Puget Sound Vital Signs web site
  - KelpForestsWA indicator hub site
  - Statewide Summary Report
  - Monitoring Program Design report
  - Interactive map
- Mapping bull kelp forest canopies with aerial imagery (StoryMap). Tyler Cowdrey, Washington Department of Natural Resources Nearshore Habitat Program. Access link.

Appendix 4 - Resources on Kelp Mapping Using Satellites

4.1 A Selection of Peer-Reviewed Publications of Kelp Mapping Using Satellites (Listed Chronologically) Aircraft

Bell, T. W., Cavanaugh, K. C., Saccomanno, V. R., Cavanaugh, K. C., Houskeeper, H. F., Eddy, N., Schuetzenmeister, F., Rindlaub, N., & Gleason, M. (2023). Kelpwatch: A new visualization and analysis tool to explore kelp canopy dynamics reveals variable response to and recovery from marine heatwaves. In A. Pérez-Matus (Ed.), PLOS ONE (Vol. 18, Issue 3, p. e0271477). Public Library of Science (PLoS). https://doi.org/10.1371/journal.pone.0271477

Cavanaugh, K. C., Cavanaugh, K. C., Pawlak, C. C., Bell, T. W., & Saccomanno, V. R. (2023). CubeSats show persistence of bull kelp refugia amidst a regional collapse in California. Remote Sensing of Environment, 290, 113521.

Gendall, L., Schroeder, S. B., Wills, P., Hessing-Lewis, M., & Costa, M. (2023). A Multi-Satellite Mapping Framework for Floating Kelp Forests. In Remote Sensing (Vol. 15, Issue 5, p. 1276). MDPI AG. https://doi.org/10.3390/rs15051276

Houskeeper, H. F., Rosenthal, I. S., Cavanaugh, K. C., Pawlak, C., Trouille, L., Byrnes, J. E. K., Bell, T. W., & Cavanaugh, K. C. (2022). Automated satellite remote sensing of giant kelp at the Falkland Islands (Islas Malvinas). In B. K. Veettil (Ed.), PLOS ONE (Vol. 17, Issue 1, p. e0257933). Public Library of Science (PLoS). https://doi.org/10.1371/journal.pone.0257933

Mantha, K. B., Sankar, R., Zheng, Y., Fortson, L., Pengo, T., Mashek, D., Sanders, M., Christensen, T., Salisbury, J., Trouille, L., Byrnes, J. E. K., Rosenthal, I., Houskeeper, H., & Cavanaugh, K. (2022). From fat droplets to floating forests: cross-domain transfer learning using a PatchGAN-based segmentation model (Version 1). arXiv. https://doi.org/10.48550/ARXIV.2211.03937

Marquez, L., Fragkopoulou, E., Cavanaugh, K. C., Houskeeper, H. F., & Assis, J. (2022). Artificial intelligence convolutional neural networks map giant kelp forests from satellite imagery. In Scientific Reports (Vol. 12, Issue 1). Springer Science and Business Media LLC. https://doi.org/10.1038/s41598-022-26439-w

Finger, D. J. I., McPherson, M. L., Houskeeper, H. F., & Kudela, R. M. (2021). Mapping bull kelp canopy in northern California using Landsat to enable long-term monitoring. In Remote Sensing of Environment (Vol. 254, p. 112243). Elsevier BV. https://doi.org/10.1016/j.rse.2020.112243

McPherson, M. L., Finger, D. J. I., Houskeeper, H. F., Bell, T. W., Carr, M. H., Rogers-Bennett, L., & Kudela, R. M. (2021). Large-scale shift in the structure of a kelp forest ecosystem co-occurs with an epizootic and marine heatwave. In Communications Biology (Vol. 4, Issue 1). Springer Science and Business Media LLC. https://doi.org/10.1038/s42003-021-01827-6

Tait, L. W., Thoral, F., Pinkerton, M. H., Thomsen, M. S., & Schiel, D. R. (2021). Loss of Giant Kelp, Macrocystis pyrifera, Driven by Marine Heatwaves and Exacerbated by Poor Water Clarity in New Zealand. In Frontiers in Marine Science (Vol. 8). Frontiers Media SA. https://doi.org/10.3389/fmars.2021.721087

Bell, T. W., Allen, J. G., Cavanaugh, K. C., & Siegel, D. A. (2020). Three decades of variability in California's giant kelp forests from the Landsat satellites. In Remote Sensing of Environment (Vol. 238, p. 110811). Elsevier BV. https://doi.org/10.1016/j.rse.2018.06.039

Bell, T. W., Nidzieko, N. J., Siegel, D. A., Miller, R. J., Cavanaugh, K. C., Nelson, N. B., Reed, D. C., Fedorov, D., Moran, C., Snyder, J. N., Cavanaugh, K. C., Yorke, C. E., & Griffith, M. (2020). The Utility of Satellites and Autonomous Remote Sensing Platforms for Monitoring Offshore Aquaculture Farms: A Case Study for Canopy Forming Kelps. In Frontiers in Marine Science (Vol. 7). Frontiers Media SA. https://doi.org/10.3389/fmars.2020.520223

Butler, C., Lucieer, V., Wotherspoon, S., & Johnson, C. (2020). Multi-decadal decline in cover of giant kelp Macrocystis pyrifera at the southern limit of its Australian range. In Marine Ecology Progress Series (Vol. 653, pp. 1–18). Inter-Research Science Center. https://doi.org/10.3354/meps13510

Friedlander, A. M., Ballesteros, E., Bell, T. W., Caselle, J. E., Campagna, C., Goodell, W., Hüne, M., Muñoz, A., Salinas-de-León, P., Sala, E., & Dayton, P. K. (2020). Kelp forests at the end of the earth: 45 years later. In M. (Gee) G. Chapman (Ed.), PLOS ONE (Vol. 15, Issue 3, p. e0229259). Public Library of Science (PLoS). https://doi.org/10.1371/journal.pone.0229259

Hamilton, S. L., Bell, T. W., Watson, J. R., GrorudK̲Colvert, K. A., & Menge, B. A. (2020). Remote sensing: generation of long- term kelp bed data sets for evaluation of impacts of climatic variation. In Ecology (Vol. 101, Issue 7). Wiley. https://doi.org/10.1002/ecy.3031

Mora-Soto, A., Palacios, M., Macaya, E., Gómez, I., Huovinen, P., Pérez-Matus, A., Young, M., Golding, N., Toro, M., Yaqub, M., & Macias-Fauria, M. (2020). A High-Resolution Global Map of Giant Kelp (Macrocystis pyrifera) Forests and Intertidal Green Algae (Ulvophyceae) with Sentinel-2 Imagery. In Remote Sensing (Vol. 12, Issue 4, p. 694). MDPI AG. https://doi.org/10.3390/rs12040694

Nijland, W., Reshitnyk, L., & Rubidge, E. (2019). Satellite remote sensing of canopy-forming kelp on a complex coastline: A novel procedure using the Landsat image archive. In Remote Sensing of Environment (Vol. 220, pp. 41–50). Elsevier BV. https://doi.org/10.1016/j.rse.2018.10.032

Schroeder, S. B., Boyer, L., Juanes, F., & Costa, M. (2019). Spatial and temporal persistence of nearshore kelp beds on the west coast of British Columbia, Canada using satellite remote sensing. In K. He & V. Lecours (Eds.), Remote Sensing in Ecology and Conservation (Vol. 6, Issue 3, pp. 327–343). Wiley. https://doi.org/10.1002/rse2.142

Schroeder, S. B., Dupont, C., Boyer, L., Juanes, F., & Costa, M. (2019). Passive remote sensing technology for mapping bull kelp (Nereocystis luetkeana): A review of techniques and regional case study. In Global Ecology and Conservation (Vol. 19, p. e00683). Elsevier BV. https://doi.org/10.1016/j.gecco.2019.e00683

Bell, T. W., Cavanaugh, K. C., Reed, D. C., & Siegel, D. A. (2015). Geographical variability in the controls of giant kelp biomass dynamics. In Journal of Biogeography (Vol. 42, Issue 10, pp. 2010–2021). Wiley. https://doi.org/10.1111/jbi.12550

Cavanaugh, K., Siegel, D., Reed, D., & Dennison, P. (2011). Environmental controls of giant-kelp biomass in the Santa Barbara Channel, California. In Marine Ecology Progress Series (Vol. 429, pp. 1–17). Inter-Research Science Center. https://doi.org/10.3354/meps09141

Cavanaugh, K., Siegel, D., Kinlan, B., & Reed, D. (2010). Scaling giant kelp field measurements to regional scales using satellite observations. In Marine Ecology Progress Series (Vol. 403, pp. 13–27). Inter-Research Science Center. https://doi.org/10.3354/meps08467

Anderson, R., Rand, A., Rothman, M., Share, A., & Bolton, J. (2007). Mapping and quantifying the South African kelp resource. In African Journal of Marine Science (Vol. 29, Issue 3, pp. 369–378). Informa UK Limited. https://doi.org/10.2989/ajms.2007.29.3.5.335

Silva, T. S. F., Costa, M. P. F., Melack, J. M., & Novo, E. M. L. M. (2007). Remote sensing of aquatic vegetation: theory and applications. In Environmental Monitoring and Assessment (Vol. 140, Issues 1–3, pp. 131–145). Springer Science and Business Media LLC. https://doi.org/10.1007/s10661-007-9855-3

Deysher, L.E. Evaluation of remote sensing techniques for monitoring giant kelp populations. Hydrobiologia 260, 307–312 (1993). https://doi.org/10.1007/BF00049033

Jensen, J. R., Estes, J. E., & Tinney, L. (1980). Remote sensing techniques for kelp surveys. Photogrammetric Engineering and Remote Sensing, 46(6), 743-755.

Mora-Soto, A., Schroeder, S., Gendall, L., Wachmann, A., Narayan, G., Pearsall, I., Rubidge. E, Lessard, J., Martell, K., Capdevilla, P. & Costa, M.. Persistence, resistance and resilience of floating kelp beds along a gradient in the Southern Salish Sea of British Columbia. [Manuscript in preparation] University of Victoria, Victoria, British Columbia, Canada.

Gendall, L., Hessing-Lewis, M., Lee, L.; Crawford, S., & Costa, M. A Century of Loss & Resilience: Understanding the Spatio-Temporal Drivers of Haida Gwaii Kelp Forests. [Manuscript in preparation] University of Victoria, Victoria, British Columbia, Canada.

4.2 Available or Existing Datasets

- Landsat-derived kelp canopy extent for parts of the Northeast Pacific - Kelpwatch
- **Bell, T, K. Cavanaugh, D. Siegel.** 2022. SBC LTER: Time series of quarterly NetCDF files of kelp biomass in the canopy from Landsat 5, 7 and 8, since 1984 (ongoing) ver 14. Environmental Data Initiative. https://sbclter.msi.ucsb.edu/data/catalog/package/?package=knb-lter-sbc.74.

4.3 Additional Groups, Datasets, Webmaps or Media Focused on Mapping Kelp with Satellites

- Marine Plan Partnership (MaPP) (2021). Regional Kelp Monitoring on the North Pacific Coast: A Community-Based Monitoring Initiative to Inform Ecosystem-Based Management (web map). Access link.
- Global map of giant kelp forests (web map). Access link. Mora-Soto, A.; Palacios, M.; Macaya, E.C.; Gómez, I.; Huovinen, P.; Pérez-Matus, A.; Young, M.; Golding, N.; Toro, M.; Yaqub, M.; Macias-Fauria, M. A High-Resolution Global Map of Giant Kelp (Macrocystis pyrifera) Forests and Intertidal Green Algae (Ulvophyceae) with Sentinel-2 Imagery. Remote Sens. 2020, 12, 694.
- Hakai Kelp Tool (web map). Access link. Hakai Institute.
- The Google Earth Engine Kelp Tool (StoryMap). Access link. Hakai Institute.

Appendix 5 - Resources On Kelp Mapping Using Non-Remote Sensing Methods

5.1 A Selection Of Peer-Reviewed Publications Of Kelp Mapping Using Non-Remote Sensing Methods (Listed Chronologically)

- **Berry, H. D., Mumford, T. F., Christiaen, B., Dowty, P., Calloway, M., Ferrier, L., Grossman, E. E., & VanArendonk, N. R.** (2021). Long-term changes in kelp forests in an inner basin of the Salish Sea. In M. (Gee) G. Chapman (Ed.), PLOS ONE (Vol. 16, Issue 2, p. e0229703). Public Library of Science (PLoS). https://doi.org/10.1371/journal.pone.0229703
- **Kenner, M. C., & Tomoleoni, J. A.** (2020). Kelp forest monitoring at Naval Base Ventura County, San Nicolas Island, California: Fall 2018 and Spring 2019, fifth annual report. In Open-File Report. US Geological Survey. https://doi.org/10.3133/ofr20201091
- **Britton-Simmons, K., Eckman, J., & Duggins, D.** (2008). Effect of tidal currents and tidal stage on estimates of bed size in the kelp Nereocystis luetkeana. In Marine Ecology Progress Series (Vol. 355, pp. 95–105). Inter-Research Science Center. https://doi.org/10.3354/meps07209

5.2 Resources On Methods And Guidelines

- **Thompson, Markus** (2021) MaPP Kelp Monitoring Protocol. Marine Plan Partnership. Access link.
- Vitality Training Program on Indigenous stewardship data collection – kelp forests. See link under "Data collection training material". Access link.
- Northwest Straits Kayak-based Survey Protocol for Floating Bull Kelp Beds. Access link.
- Guidelines and Methods for Mapping and Monitoring Kelp Forest Habitat in British Columbia. Acces link.
- Mayne Island Conservancy Kelp Bed Monitoring Program. Access link to program and to methodology.

5.3 Additional Groups, Datasets, Webmaps Or Media Focused On Mapping Kelp With Non-Remote Sensing Methods

- **Marine Plan Partnership (MaPP)** (2021). Regional Kelp Monitoring on the North Pacific Coast: A Community-Based Monitoring Initiative to Inform Ecosystem-Based Management (web map). Access link.