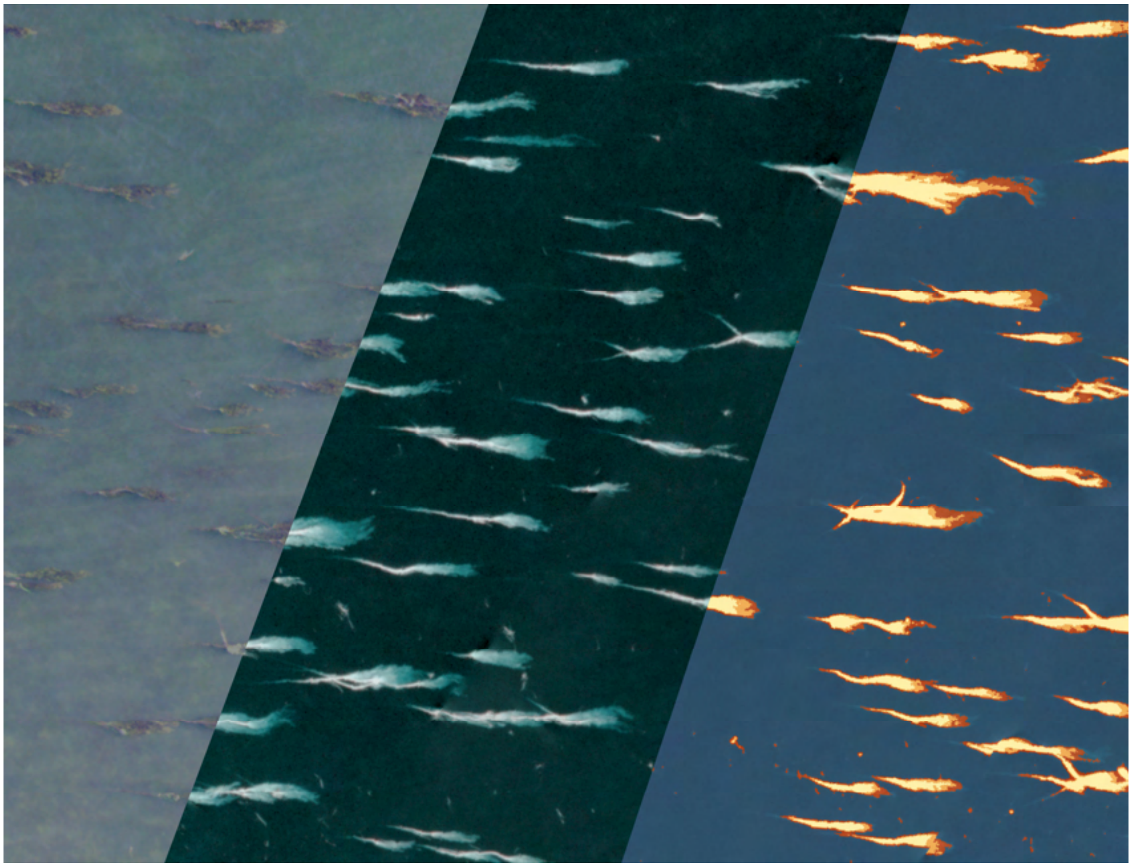
NATURAL RESOURCES

Monitoring Puget Sound Bull Kelp Forests with Multispectral UAS: An Index-Based Approach

Assessment of threshold classification methods and canopy change between 2021 and 2022

March 2024



WASHINGTON STATE DEPT OF NATURAL RESOURCES

The Nearshore Habitat Program is part of the Washington State Department of Natural Resources, and supports the agency's mandate to ensure environmental protection of state-owned aquatic lands. https://www.dnr.wa.gov/programs-and-services/aquatics/aquatic-science/nearshore-habitat-program

The Nearshore Habitat Program is also a component of the Puget Sound Ecosystem Monitoring Program (PSEMP). https://www.psp.wa.gov/PSEMP-overview.php

Cover photo: (Left) Multispectral UAS imagery collected at Vashon Island in 2022, shown in standard RGB band combination. (Middle) Same imagery visualized using only near-infrared and red edge bands. Bull kelp stipes, bulbs, and blades can be seen as bright features against a dark backdrop, showcasing the utility of multispectral data for vegetation classification. (Right) Same imagery with kelp canopy classified using three different spectral index thresholds.

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Aquatic Resources Division
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The Nearshore Habitat Program is part of the Aquatic Resources Division within the Washington State Department of Natural Resources (DNR), the steward for state-owned aquatic lands. The Nearshore Habitat Program monitors and evaluates the status and trends of marine vegetation for DNR, in association with the Puget Sound Partnership as a component of the Puget Sound Ecosystem Monitoring Program (PSEMP).

The Nearshore Habitat Program is grateful to the WA State Legislature for providing funding for DNR to continue developing remote-sensing capabilities for long-term monitoring of floating kelp, and for codifying into law our state's commitment to conserving and restoring kelp forests.

The primary author of this report is Tyler Cowdrey. Danielle Claar co-led development of the canopy area change assessment methodology and provided direct writing support. Pete Dowty, Helen Berry, and Julia Ledbetter were close collaborators throughout the project and were also the primary editors of this report.

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Contents

EXECUTIVE SUMMARY

The Washington State Department of Natural Resources (DNR) manages 2.6 million acres of state-owned aquatic lands for the benefit of current and future residents of Washington State. As part of this responsibility, DNR's Nearshore Habitat Program (NHP) monitors populations of nearshore marine vegetation including floating kelp forests along Washington's shorelines.

Within Puget Sound, bull kelp (*Nereocystis luetkeana*) is the primary species of brown algae to form conspicuous floating forests. Growing concerns about the potential decline of Washington's floating kelp forests have led to multiple large-scale collaborative initiatives to improve the understanding and protection of these critical habitats including a new Puget Sound Partnership Vital Sign Indicator, the statewide Kelp Forest and Eelgrass Meadow Health and Conservation Plan, and the Habitat Strategic Initiative Lead. To support these efforts, continuous long-term monitoring data and targeted site surveys using high spatial resolution methods are needed to inform our understanding of kelp forest variability and assess trends over time.

In recent years, the suitability of uncrewed aircraft systems (UAS; or "drones") for mapping floating kelp forest canopies has been demonstrated across many coastal regions, including projects conducted by NHP and partners within Puget Sound (e.g. Berry & Cowdrey, 2021; Cowdrey, 2021). This report builds on that foundation by expanding the spatial and temporal scope of NHP's UAS survey work, and by assessing the uncertainty associated with mapping our region's kelp forest canopies using spectral index threshold-based classification methods.

KEY FINDING

Overall, this project demonstrates that multispectral uncrewed aircraft systems (UAS) provide adaptable capabilities crucial to surveying floating kelp forests in Puget Sound. UAS complement DNR's kayak and conventional aerial survey platforms as part of a multitiered approach to long-term kelp forest monitoring.

Summary of Approach

We assessed the effectiveness of multispectral UAS for mapping the detailed spatial characteristics of floating kelp forest canopies across Puget Sound.

- A total of 18 multispectral UAS surveys were conducted at six kelp beds in 2021 and 2022. These surveys mapped an estimated 48 hectares of bull kelp "*bed extent" – including the overall perimeter of each kelp forest* – at image resolutions of 3.2 to 5.3 cm.
- Kelp "*canopy area" – or the area of only kelp stipes, bulbs, and blades floating at or near the surface* – across four sites was ~10,500 m^2 in 2021 and ~5,300 m^2 in 2022, signaling a large drop at North Beach. An additional ~5,200 m^2 of *canopy area* was mapped at two more sites in 2022.
- While user interpretation was still required for individual threshold value selections, a spectral index threshold classification approach enabled the development of a new semi-automated processing pipeline that greatly improves the efficiency of NHP's UAS processing and analysis workflow and scalability of the program as a whole.

Using same-day replicate ("paired") surveys, we evaluated uncertainty in two kelp area metrics associated with a key source of environmental variability: tides and currents.

- *Bed extent* estimates of paired surveys conducted within the same low-tide survey window differed by a median value of ~3%. Spatial overlap in bed extent between paired surveys ranged from 83-93% relative to mean bed extent.
- *Canopy area* estimates varied more with a median difference of ~17% between midpoint estimates, controlling for differences in bed extent. We identified several factors to consider when determining if surveys are suitable for use in multi-year change assessments, some universal and others site-specific.
- The paired surveys also provided an opportunity to assess our current ground control methods. Spatial precision, as measured by registration error between paired surveys, showed an average root mean square error of ~27 cm.

To characterize uncertainty in canopy area estimates generated by spectral index-based classification, we identified ranges of plausible thresholds for each survey.

- Visual assessments of a wide range of blue normalized difference vegetation index (BNDVI) threshold classification results for each survey were used to generate *canopy area* intervals. This approach yielded a mean difference of ~38% between low and high canopy area estimates across all surveys.
- An automated BNDVI threshold selection algorithm similar to those used in other UAS kelp mapping research (Otsu's Method) was also tested. It was found to be unreliable as it resulted in consistent overestimation of canopy area, possibly due to the low plant density common to bull kelp forests in Puget Sound.

We analyzed changes in canopy area between 2021 and 2022 at four sites, at both site-wide and sub-site levels.

- *Canopy area* decreased at North Beach from ~7,700 - 10,100 m^2 (inclusive of entire BNDVI range) in 2021, to ~1,800 - 4,200 m^2 in 2022. This magnitude of decrease exceeded the sources of uncertainty evaluated in this report.
- Lincoln Park showed an overall decrease in *canopy area* as well, but further inspection of the survey imagery revealed pervasive false positives in 2021 due to floating wrack. No changes in overall *canopy area* were observed at Vashon Island and Owen Beach.
- Dividing sites into quadrants revealed distinct sub-site changes between years. For example, there was a ~280% increase in *canopy area* in the deep west quadrant at Owen Beach, and also a ~90% increase in the shallow east quadrant at Vashon Island.

CONCLUSIONS

- **Multispectral UAS complement other monitoring methods through high-resolution detection of floating kelp canopies and quantification of changes between years.**
- **Additional years of UAS survey data will enable us to assess long-term trends in canopy distribution and abundance.**
- **UAS are uniquely able to provide flexible, high-resolution imagery that deepens our understanding of kelp forest dynamics in Washington.**

1 Introduction

1.1 Bull Kelp Forests in Puget Sound

Kelp forests occur around the world and serve as foundational biogenic habitats for the ecosystems in which they occur. Among the many critical functions they perform are supporting marine food webs through primary production and nutrient cycling, and the creation of three-dimensional habitat structure for other organisms to inhabit (Hurd et al., 2014; Klinger, 2015; Schiel & Foster, 2015; Von Biela et al., 2016; Teagle et al., 2017, Duarte et al., 2023, Shaffer et al., 2023). In addition, they provide a variety of ecosystem services to human societies, which have recently been valued at $500 billion globally (Eger et al., 2023). The Northeast Pacific, a biogeographic region stretching from Alaska to Baja California, has the highest species richness of kelps anywhere on earth (Bolton et al., 2010; Druehl & Clarkston, 2016; Fragkopoulou et al., 2021), with over 20 species being found in Washington State alone (Mumford, 2007).

Within Puget Sound, bull kelp (*Nereocystis luetkeana*) is a prominent species that forms conspicuous floating forests seen from Squaxin Island to the Strait of Juan de Fuca. While research on these forests is somewhat limited compared to other species and regions (Hollarsmith et al., 2021), there is growing concern that they are at risk of local extinction due to climate change and urbanization. This concern is informed by a growing body of evidence that kelp forests are at risk globally due to these forces (Harley et al., 2012; Krumhansl et al., 2016; Vergés et al., 2016; Wernberg et al., 2016; Filbee-Dexter & Wernberg, 2019; Rogers-Bennett & Catton, 2019; Smale, 2020, Starko et al., 2022), as well as work by DNR’s Nearshore Habitat Program (NHP) documenting that bull kelp forests in south Puget Sound are declining and currently occupy just a small percent of shorelines that historically supported bull kelp (Berry et al., 2019; Berry et al., 2021). Recent research has also shown that bull kelp populations within the Salish Sea are genetically distinct from those in Alaska, Oregon, and California (Gierke et al., 2023), and that reproduction and growth of these local populations are severely diminished at temperatures that are predicted to become more common in the region due to ocean warming (Schiltroth, 2021; Fales et al., 2023; Weigel et al., 2023).

1.2 Growing Management Linkages

Due to the growing awareness of the importance of bull kelp forests in Washington State, and concern of their continued decline, a number of recent initiatives have sought to develop a robust monitoring and management framework to track their status and trends, and inform conservation and restoration actions. A common thread running through them all is a stated need for expanded monitoring in order to generate a complete picture of how bull kelp forests in Washington are doing. To support these efforts, NHP conducts annual monitoring of bull kelp forests at a growing network of sites using a variety of methods including surveys conducted via kayak, piloted fixed-wing aircraft, and most recently uncrewed aircraft systems (UAS).

In 2020, a group of diverse partners including Northwest Straits Commission, NOAA's National Marine Fisheries Service, Puget Sound Restoration Fund, the Washington State Department of Natural Resources, and Marine Agronomics published the Puget Sound Kelp Conservation and Recovery Plan ("Kelp Plan"; Calloway et al., 2020). One of the primary strategic goals outlined in this plan was the expansion of monitoring of kelp forest distribution and trends, and to fill the many gaps in knowledge of kelp forest dynamics in Puget Sound.

Following this, in 2021 a similarly diverse group of partners came together to develop a statewide floating kelp forest indicator for the Puget Sound Partnership's Vital Signs project. This group includes many of the partners involved in the Kelp Plan, as well as Samish Indian Nation, the University of Washington, and WA Sea Grant. The inaugural "Floating Kelp Bed Area Vital Sign Indicator" was published in May of 2023 (Berry et al., 2023a), showing the geographically divergent state of bull and giant kelp forests in Washington, and the many areas where additional monitoring data is still needed.

Finally, in 2022 the Washington State Legislature passed SB 5619, directing DNR to create a statewide Kelp Forest and Eelgrass Meadow Health and Conservation Plan. The ultimate goal of this plan is to conserve and restore at least 10,000 acres of kelp forest and eelgrass meadow habitat by 2040, prioritizing areas based on an open and inclusive engagement process. As of the end of 2023, progress has been made on engaging the public through a series of public workshops and a number of important structuring documents have been published including: an Engagement Plan, a site selection Prioritization Plan, and a Monitoring Plan. There are many more significant actions planned for the near future including engaging the public at a regional level in order to begin prioritizing sites for conservation and restoration.

1.3 Kelp Canopy Mapping with Remote Sensing and UAS

Aerial image-based ecological monitoring is both a long-established and rapidly advancing field of research, with a wealth of historical lessons to be drawn on and ever-evolving technology to capture data with. For example, NHP has been monitoring kelp forest canopies along the Strait of Juan de Fuca and Pacific Coast of Washington with piloted fixed-wing aircraft imagery since 1989 (Van Wagenen, 2015), and a similar program existed in California from about 1989 to 2016 (Deysher, 1993; Saccomanno et al., 2022). Comparable efforts to map bull kelp forests with conventional aerial imagery have also been successful in Oregon (Merems, 2011) and Alaska (Stekoll et al., 2006). However, one limitation of these aerial surveys is that they typically do not capture the same level of spatial distribution and plant condition detail as in situ surveys, such as those conducted via kayak.

There is also a decade-plus-long body of research investigating the use of satellite imagery, particularly Landsat, to map kelp forests. These methods have been successful at capturing the extent and estimating the biomass of large giant kelp forests in places with favorable conditions (Cavanaugh et al., 2011; Bell et al., 2020; Finger et al., 2021; McPherson et al., 2021; Houskeeper et al., 2022) but often are not able to capture small and/or thin fringing kelp canopies

(Hamilton et al., 2020, Saccomanno et al., 2022), such as those commonly found in Puget Sound. While higher resolution satellites such as those in the ESP Copernicus Sentinels and Planet Labs CubeSats could perform better in these contexts, classification methods for these platforms is still in development (E. Nielsen, K.C. Cavanaugh, pers. comm.).

Uncrewed aircraft systems (UAS) offer a complementary platform to kayak surveys, conventional aerial surveys, and satellites. UAS provide many advantages including extremely high spatial resolution, flexible and rapid deployment during suitable environmental conditions, and lower personnel requirements than traditional field surveys of floating kelp forests. In recent years, UAS have successfully been used to map kelp forests in many places around the world, including Puget Sound (Berry & Cowdrey, 2021; Cowdrey, 2021). In particular, UAS that capture imagery not only in the visible range of the light spectrum but also in near-infrared have been shown to be highly effective at differentiating kelp tissue from the surrounding environment (Tait et al., 2019; Berry & Cowdrey, 2021; Cavanaugh et al., 2021b; McPherson & Kudela, 2022; Timmer et al., 2022).

On balance, existing research demonstrates that UAS are well suited to complement NHP's other kelp monitoring methods by providing rich spatial detail at the site to sub-regional level. For example, UAS surveys and *in situ* kayak-based data collection could be combined to generate a data rich and field-verified record of canopy distribution and plant condition at important monitoring sites. In addition, UAS surveys could be used as a form of ground truth for the four-band piloted fixed-wing aerial imagery that DNR began collecting annually in 2022 to support the Floating Kelp Bed Area Vital Sign Indicator, the Kelp Forest and Eelgrass Meadow Health and Conservation Plan, and the Habitat Strategic Initiative Lead's Marine Vegetation Implementation Strategy. The potential for complementary applications of different survey platforms and the need to continue developing region-specific methods of monitoring and data integration is a perspective shared by a growing community of practitioners that map floating kelp forests from Alaska to Baja California (Cavanaugh et al., 2021a, Reshitnyk et al., 2023).

Project Objectives

The primary goal of this project was to build on previous work demonstrating the potential for UAS to map floating kelp canopies in Puget Sound by developing efficient and repeatable analysis workflows and comparing data over multiple years to assess change. Specific research questions addressed in this report are:

- Is spectral index (e.g., BNDVI) threshold-based classification of multispectral UAS imagery a tractable method for mapping canopy distribution Puget Sound bull kelp forests? Can the method be standardized and scaled?
- How does the appearance of bull kelp canopies change over short timescales, as assessed using same-day replicate surveys conducted within a single low tide window? What implications does this result have for detecting temporal changes in floating kelp distribution and abundance?
- Have any of the sites where data was analyzed for both 2021 and 2022 changed significantly between those two years, and if so, in what ways?
- What can partitioning site-level classified canopy results into spatial subsets (quadrants) reveal about the temporal dynamics of kelp distribution? Do the changes detected within quadrants mirror the changes detected at the site scale, or are there intra-site differences in change over time?

2 Methods

2.1 Study Area

The study area for this project is Puget Sound, the southern portion of the Salish Sea defined here as the marine waters of Washington State bounded to the north and west by Admiralty Inlet and Deception Pass. The Salish Sea is a large fjordal estuarine system that includes Puget Sound, Hood Canal, the Strait of Georgia, the Strait of Juan de Fuca, and the myriad other small bodies of water connected to them.

Within the study area, surveys were conducted at six kelp forest monitoring sites in 2021 and 2022 (Figure **1**). Five of these sites are locations with ongoing annual kayak-based canopy monitoring conducted by DNR's Nearshore Habitat Program (NHP) (Owen Beach, Vashon Island, Lincoln Park, Hansville) and the Jefferson County Marine Resources Committee (MRC) (North Beach). The sixth site, Hat Island, is monitored annually by boat by the Snohomish County MRC, is included in DNR's first Kelp and Eelgrass Protection Zone at the mouth of the Snohomish River, and is also a site of interest for the Tulalip Tribes for their own kelp forest monitoring work (S. Kaiser, pers. comm.).

These sites represent a range of geographic and oceanographic conditions, and kelp forest characteristics. At the southernmost site in this report, Owen Beach, there is a thin fringing bed that is quickly pulled beneath the water's surface after low tide due to the extreme currents found in the Tacoma Narrows (pers. obs.). Lincoln Park and Vashon Island are two moderate size annual forests in Central Puget Sound that have remained relatively stable since NHP began monitoring them by kayak in 2020 (Ledbetter & Berry, in prep). Both these sites appear to experience more moderate tidal currents than at Owen Beach. Hansville is a moderate size but sparser forest that NHP began monitoring in 2021. This site has also been observed to have plants at the deep edge start getting pulled under by currents less than an hour after low tide (Ledbetter & Berry, in prep). North Beach is a section of an expansive, mostly continuous, forest that stretches from Point Wilson to McCurdy Point that has been monitored by the Jefferson County MRC since 2016 (Ledbetter & Berry, 2023) and by NHP annually since 2020. This site lies at the boundary between Admiralty Inlet and The Strait of Juan de Fuca, where it experiences large tidal fluxes and where slack tide occurs shortly before low tide (pers. obs.). Finally, Hat Island is an expansive bed that has been monitored by Snohomish County MRC by motorized boat since 2017. It also is a site where the MRS collaborates with the Tulalip Tribes on other marine research project. Its size is reported to have fluctuated quite a bit since 2017, but the appearance of kelp at the surface is observed to be "heavily influenced" by tidal currents as well (Ledbetter & Berry, 2023).

Figure 1. Map of the six bull kelp forest sites surveyed with UAS for this project. Sites are symbolized according to the number of years they were surveyed.

2.2 UAS Surveys

2.2.1 Field methods

The uncrewed aircraft system (UAS) used in this project was the DJI Phantom 4 Multispectral (P4M) quadcopter (DJI, Nanshan, Shenzhen, China) (Figure 2). This UAS is real-time kinematic (RTK) enabled and carries a five-band multispectral camera that collects imagery in the visible and near-infrared spectra (Figure 2, Table 1).

Surveys were flown at an altitude of 60-100 meters above-ground-level, yielding ground sampling distances between 3.4 and 5.3 cm (Table 2). Flight grids were planned in DJI GS Pro (DJI, Nanshan, Shenzhen, China), with 70-80% frontlap and sidelap. Before and after each survey, images of a MicaSense Calibrated Reflectance Panel (AgEagle Aerial Systems Inc., Wichita, Kansas, USA) were captured in order to calibrate the multispectral imagery during processing.

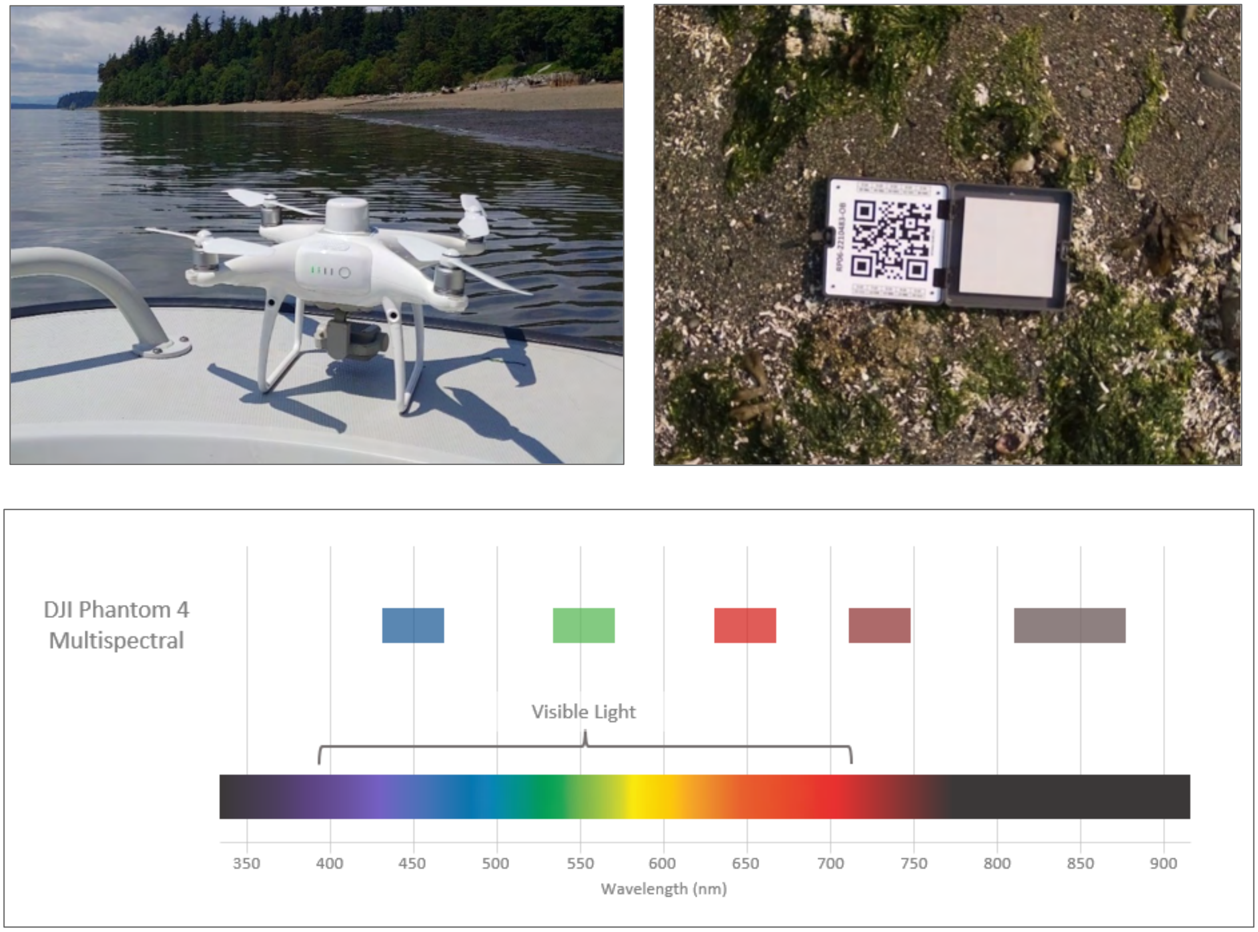


Figure 2. (Top left) DJI Phantom 4 Multispectral UAS used for the surveys included in this project. (Top right) MicaSense Calibrated Reflectance Panel. Images taken of this with the UAS before and after each survey in order to properly calibrate multispectral image products. (Bottom) Visual representation of the portion of the electromagnetic spectrum captured by each band of the P4M camera.

Table 1. Band numbers and spectral ranges for DJI Phantom 4 Multispectral UAS.

Name	P4M band number	Spectral range (nm)
Blue	1	434 – 466
Green	2	544 – 576
Red	3	634 – 666
Red edge	4	714 – 746
Near-infrared	5	814 – 886

Prior to each UAS survey, a series of at least five ground control points were marked and recorded within the survey area. This included deployed high contrast checkerboard panels and natural monuments on the landscape. The locations of these points were collected using a Trimble GeoExplorer 6000 Series GeoXH and post-processed in Trimble GPS Pathfinder Office (Trimble Inc., Sunnyvale, California, USA), using correction data provided by the Washington State Reference Network (Seattle Public Utilities and Washington State University, Washington, USA). This method consistently generates location data with 10 cm or better horizontal and vertical positional accuracy for each control point.

Surveys were conducted between July and September in 2021 and 2022, targeting specific environmental conditions that have been identified by NHP for consistent floating kelp monitoring in Washington State across multiple methodologies (Berry & Cowdrey, 2021; Berry et al., 2023b; Ledbetter & Berry, 2023). This field sampling protocol aims to mitigate variability in the area of kelp visible at the surface associated with variation in tidal stage and currents. The protocol calls for surveying within approximately one hour before and after predicted low tide using the nearest NOAA tide station, on days with predicted low tides of +1 ft or less mean lower low water (“MLLW”), and with forecast wind waves of 1 ft or less. In addition, sun angles of between 25 and 50 degrees above the horizon – measured using the public service SunCalc.org – were prioritized when possible in order to minimize the extent of glint on the water’s surface in survey imagery. Photographs of the sky were taken during each survey to document cloud cover. While clear or uniform overcast days are preferred for collecting imagery over water, surveys proceeded regardless of cloud conditions.

In total, 18 surveys conducted across six bull kelp forest sites in Puget Sound were included in this project (Table 2). Sixteen of eighteen were conducted as same-day replicate, or “paired,” surveys, within an hour of each other during the same low tide. Throughout this report these surveys will be referred to as either S1 or S2, representing the first and second paired survey respectively.

Additional details about the environmental conditions present during each survey can be found in Appendix A.

Table 2. List of the 18 UAS surveys conducted with the DJI Phantom 4 Multispectral platform at six bull kelp monitoring sites in 2021 and 2022 that are included in this project. Surveys are listed by date at each site in those two years. Rows that are listed as having two surveys were conducted as same-day replicates ("paired" surveys), which will be referred to individually as either "S1" or "S2" in this report. Additional details about the environmental conditions during each survey can also be found in Appendix A.

Site	Date	# of surveys	Areal coverage	Altitude	Ground sample distance	Approx. survey time (each)
Lincoln Park	7/21/2021	1	11 ha	80 m	4.2 cm	30 mins
	8/25/2022	2	10 ha	60 m	3.2 cm	45 mins
Owen Beach	8/18/2021	2	15 ha	80 m	4.2 cm	25 mins
	9/7/2022	2	12 ha	65 m	3.4 cm	35 mins
North Beach	8/20/2021	1	30 ha	85 m	4.5 cm	50 mins
	9/22/2022	2	23 ha	80 m	4.2 cm	45 mins
Vashon Island	8/21/2021	2	26 ha	100 m	5.3 cm	20 mins
	8/24/2022	2	14 ha	65 m	3.4 cm	40 mins
Hansville	8/26/2022	2	16 ha	70 m	3.7 cm	50 mins
Hat Island	9/9/2022	2	40 ha	80 m	4.2 cm	75 mins

2.2.2 *Survey processing*

All UAS surveys were processed in the photogrammetric software Agisoft Metashape (v2.0) (Agisoft LLC, St Petersburg, Russia) following the workflow described in Cowdrey (2021). Survey and calibration panel imagery were imported into a project and initial image alignment was run. Then, ground control point coordinates were imported and tagged in survey images. Finally, at least two iterations of manual cleaning of the sparse point cloud and re-running camera optimization were performed until the average control point error settled to less than one meter (typically less than 0.5 meters) and a surface without significant errant undulations could be observed in the data.

Following image alignment, georeferencing, and point cloud refinement, an extrapolated digital elevation model ("DEM") was generated onto which the corresponding survey orthomosaic was draped. This final orthomosaic was exported in the default geographic coordinate system WGS 1984, and finally projected onto NAD 1983 HARN StatePlane Washington South FIPS 4602 in ArcGIS Pro (ESRI, Redlands, California, USA) using a resampling resolution matching the orthomosaic resolution reported in Metashape.

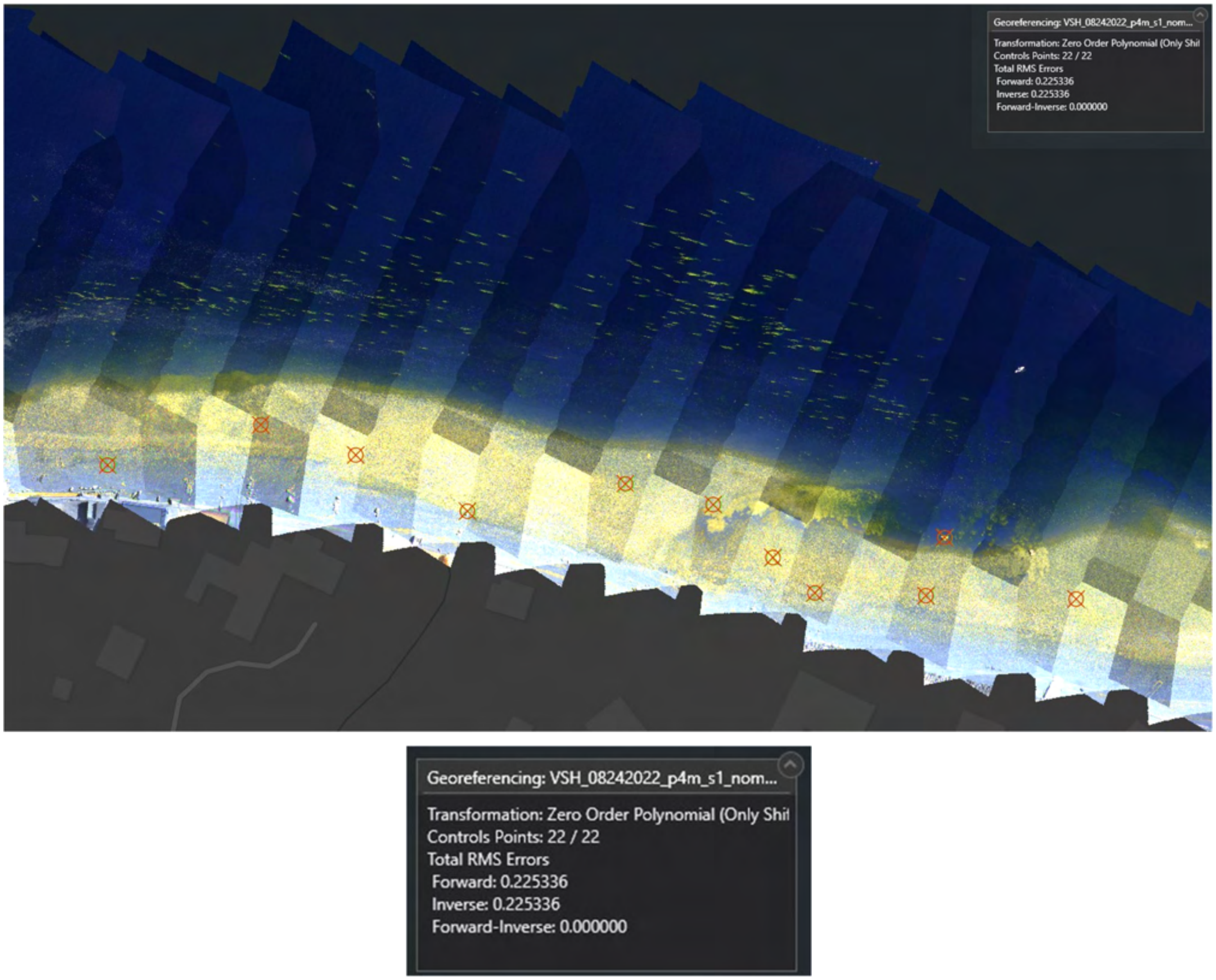
2.2.3 Georeferencing evaluation and refinement

In order to assess the spatial accuracy of image products, typically a large number of “check points” collected with very high accuracy GNSS equipment are required. The American Society for Photogrammetry and Remote Sensing (ASPRS) recommends at least 20 check points for areas less than 500 square kilometers (ASPRS, 2015). Lacking that many check points in the UAS surveys included in this project, a different approach was taken to evaluate differences in georeferencing between surveys conducted at the same site that will be referred to herein as “spatial precision.” This approach measures what is sometimes referred to as “registration error” between datasets.

The method developed for this project involves first identifying a survey orthomosaic to serve as a “reference” for the others conducted at the same site. This selection was based on the average root mean square projection error reported in Metashape for the control points of each survey following image alignment, panel georeferencing in individual images, image optimization, and mosaicking; the survey conducted in 2022 with the lowest average error was selected. All but one of the surveys included in this report had an average error of less than one meter (survey two at Hansville in 2022 had an average error of 1.05 m), and the mean of the average errors for surveys used as references was 0.66 meters (n = 6).

After a reference mosaic was selected, the spatial precision of the other surveys at each site were evaluated using the georeferencing toolset in ArcGIS Pro. This involved identifying at least 20 fixed visible features in each mosaic to serve as check points, such as large rocks, corners of structures, and ground control panels for same-day replicate (“paired”) surveys. The offset between surveys of these check points is reported by ArcGIS in terms of root mean square (RMS) errors (Figure 3). These values were recorded and are presented in Section 3.1, constituting the spatial precision results of all surveys included in this report.

The final step of georeferencing refinement prior to image classification was to apply a transformation to the non-reference survey mosaics, bringing each into closer alignment with the reference. This was done in order to minimize the impact of spatial offset in the evaluation of changes in canopy distribution and abundance between paired surveys and years. There are many types of transformations that were considered for this step, and for this project “affine” was chosen. This transformation allows for translation, rotation, scaling, and shearing of the raster, but does so only with first order polynomials and maintains the orientation of the plane on which the data rests. In this way, the georeferencing of surveys at the same site can be brought into better alignment, without the risk of distorting the distribution of kelp in the imagery.



Georeferencing: VSH_08242022_p4m_s1_nom...

Transformation: Zero Order Polynomial (Only Shi

Controls Points: 22 / 22

Total RMS Errors

Forward: 0.225336

Inverse: 0.225336

Forward-Inverse: 0.000000

Figure 3. (Top) Portion of a survey conducted at Vashon Island in 2022 displayed in the “NEG” band combination (see Sec. 2.3.1.) with a sample of the check points used for spatial precision evaluation visible as red circles with x’s through them. (Bottom) Zoomed in summary of the RMS Errors of the 2022 check points used for this survey prior to running a transformation.

2.3 Image Classification

2.3.1 *Delineation of bed extent*

The first step in the image classification workflow for this project was to delineate the boundary of visible floating kelp canopy in each survey orthomosaic. Polygons were created by manually tracing along the perimeter of the kelp canopy until the edge of the orthomosaic was reached or the starting point returned to. These polygons served two functions, first to estimate the "bed extent" metric of the kelp forest at each site (Section 3.2), and also to be used to mask (exclude) areas without floating kelp from subsequent canopy area classification.

When delineating the extent boundary of each kelp bed, a distance threshold guideline for grouping plants together was followed, similar to that used for NHP's kayak-based kelp surveys and imagery delineation in Cowdrey (2021). To facilitate this, a 25-meter grid was displayed over the imagery (Figure 4) to guide decisions on the fly whether to group plants together or treat as separate beds. The guideline was not a hard cutoff, and plants that were up to ~30 meters apart would sometimes be grouped, particularly in areas with sparse plants that would require the creation of many individual groupings rather than a single continuous bed. In this way, the bed extent mapping applied here is not directly analogous to the measurement of "bed area" used in NHP's kayak surveys, but is closely related to it.

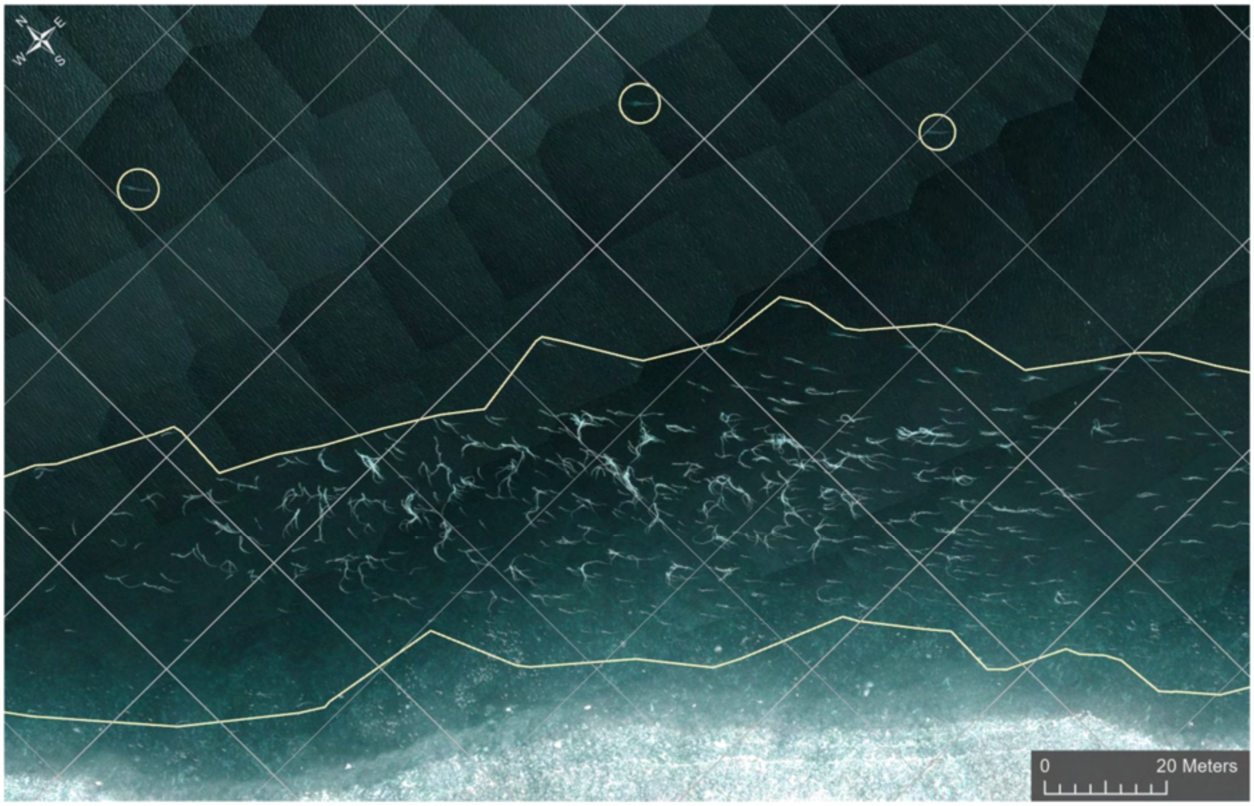


Figure 4. Section of a survey conducted at Vashon Island in 2021 displayed in the "NEE" band combination (Table 3), with a 25-meter grid displayed. The bed extent polygon is symbolized in yellow, showing individuals more than ~30 meters apart being treated as separate from the main bed.

Multispectral band combinations for visualization of kelp canopy

The DJI Phantom 4 Multispectral UAS (P4M) used for this project collects data in five spectral bands (Table 1), however only three can be rendered by a computer monitor at one time. To facilitate the delineation of kelp bed extent, a number of different multispectral band combinations were found to be particularly useful (Table 3, Figure 5). For example, by displaying the near-infrared, red edge, and green data in the red, green, and blue channels respectively, kelp tissue displays as bright yellow while the surrounding water shows as deep blue. These different band combinations were toggled between when delineating kelp bed extent in order to ensure complete coverage of all kelp canopy visible in each survey.

Table 3. List of multispectral band combinations found to be useful in creating contrast between floating kelp canopy and the surrounding environment.

	Visualization channel		
Name	**Red**	**Green**	**Blue**
RGB (reference)	Red	Green	Blue
False-color NIR	Near-infrared	Green	Blue
Color infrared (CIR)	Near-infrared	Red	Green
False-color NEG	Near-infrared	Red edge	Green
NEG inverted	Red edge	Green	Near-infrared
High-contrast NEE	Near-infrared	Red edge	Red edge

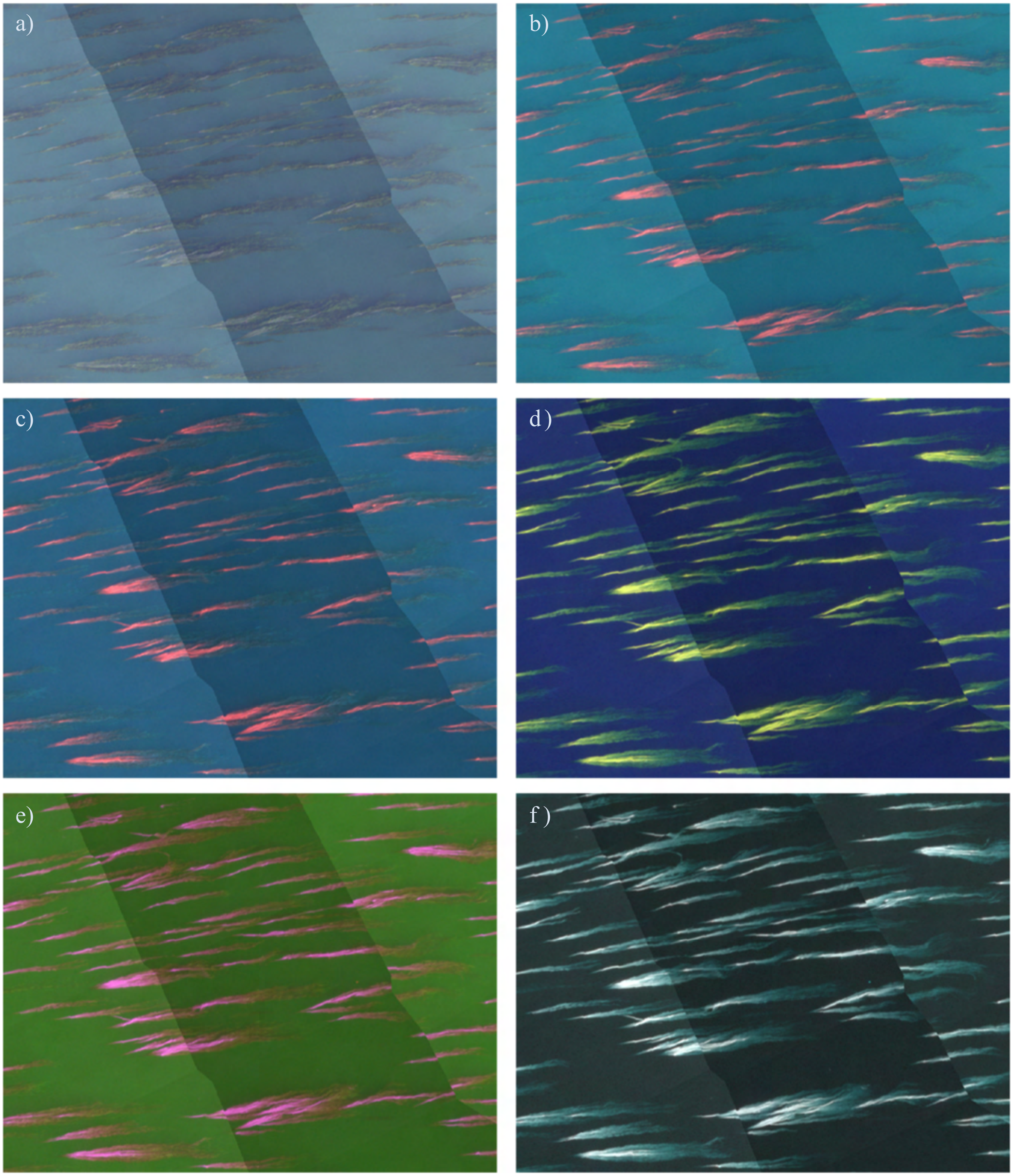


Figure 5. Panels showing the appearance of kelp canopy using different multispectral band combinations for display including: RGB (a), false-color NIR (b), CIR (c), NEG (d), NEG inverted (e), and high-contrast NEE (f). Note: the dark band running down the middle of each frame is an artifact of the mosaicking process.

2.3.2 Automated processing of spectral index thresholds

One of the primary goals of NHP's UAS-based kelp mapping work is to develop workflows that can generate spatial data products of plant distribution and abundance at a site in an efficient and repeatable manner. The program's prior work classifying floating kelp canopy in UAS orthomosaics relied on random forest supervised classifications (Berry & Cowdrey, 2021; Cowdrey, 2021), which also yielded accurate results but involved the laborious process of creating manual training data for every survey. Recent research highlighting the effectiveness of spectral indices for classifying floating kelp canopy in multispectral UAS imagery (Cavanaugh et al., 2021b; McPherson & Kudela, 2022; Timmer et al., 2022) served as the basis for creating an automated processing workflow that avoids this bottleneck.

The processing pipeline for this project was developed in Python 3.9 using primarily the *arcpy* (ArcPy, ESRI, 2023) and *numpy* (NumPy, 2023) packages. It was designed to ingest survey orthomosaics, delineated bed extent polygons (Section 2.3.1), and a user-defined range of threshold values for one or more spectral indices, and generate as outputs clipped spectral index and classified canopy rasters, as well as tables summarizing kelp pixel counts corresponding to different thresholds. In addition, modules using *rasterio* (Mapbox, 2023) and *matplotlib* (Matplotlib, 2023) can be toggled on to generate histograms of pixel counts of individual image bands in stacked, gridded, or 2-dimensional representations, and of spectral index products derived from the imagery. A description of each processing component is included below, and a summary diagram of the pipeline can be seen in (Figure 6).

Components of the core processing pipeline are:

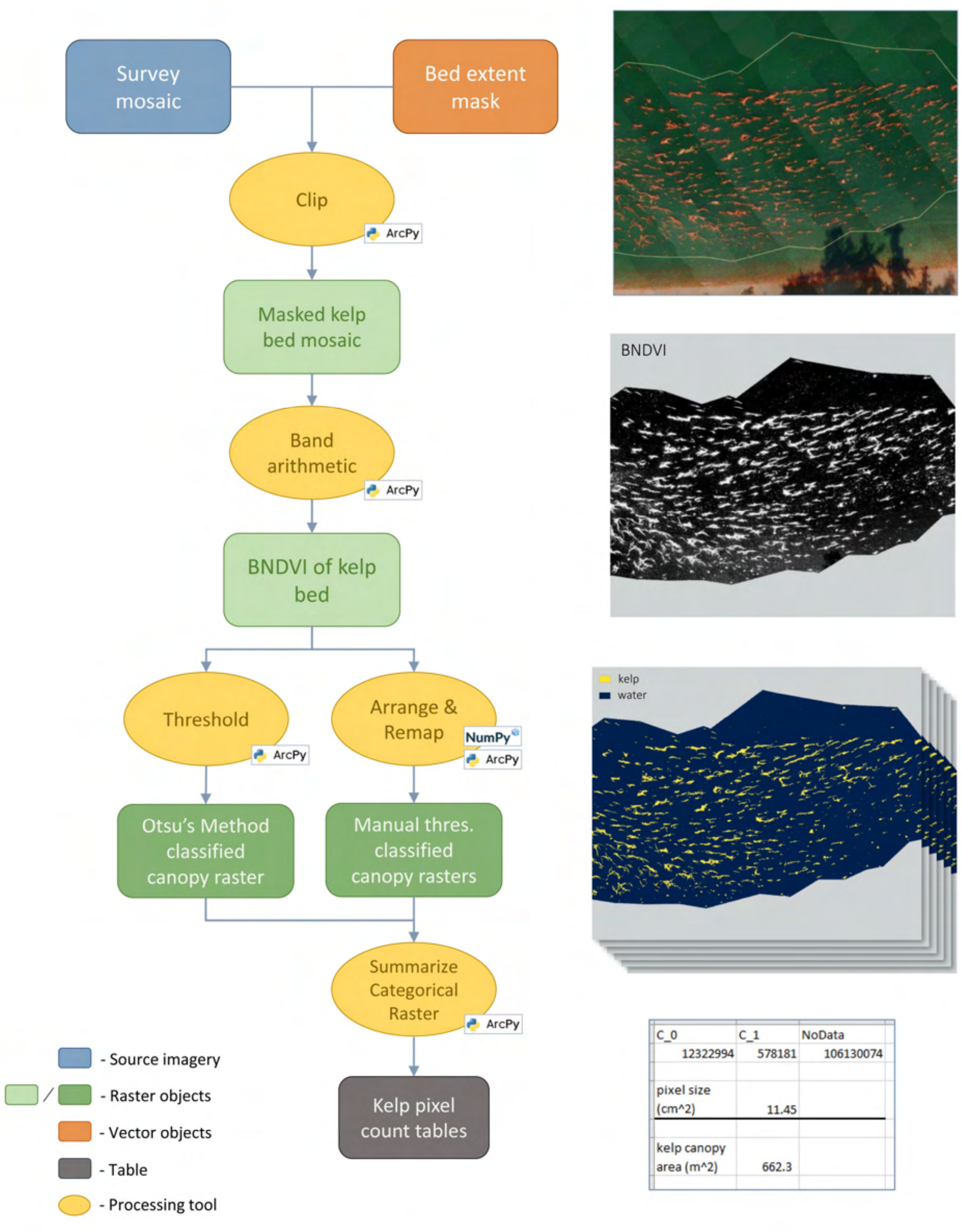
- *Clip (ArcPy, Image Analyst)* takes survey orthomosaics and bed extent polygons and generates raster data containing just areas that were delineated to contain visible floating kelp canopy. The pipeline allows this to be run on many of both types of input files (raster and vector) and parse which overlap each other.
- *Copy Raster (ArcPy, Data Management)* can be toggled on and off to choose whether to export the intermediate clipped imagery product as a standalone GeoTIFF. If not the temporary image object can still be carried forward and used as input in other processing tools. This functionality repeats many times below.
- *Band Arithmetic (ArcPy, Spatial Analyst)* takes the clipped survey orthomosaic and applies a specified index operation to produce a single-band raster result. This intermediate product can also be saved as a standalone raster file using *Copy Raster*, or carried forward as a temporary image object. The primary spectral index used in this project is blue normalized difference vegetation index (BNDVI; formula below), but the pipeline has functionality built in to generate a variety of vegetation indices using visible (RGB), red edge, and near-infrared bands.

$$BNDVI = \frac{NIR - Blue}{NIR + Blue}$$

- *Arrange (NumPy)* is used to rapidly generate lists of threshold values to apply to the spectral index raster based on the low and high ends of a range and the step interval between them. For BNDVI (and similar vegetation indices that swap red edge for NIR and/or other visible bands for blue) this range goes from -1.0 to 1.0, and in this project a 0.05 step between test values was used, for a total of 40 test thresholds.

- *Remap (ArcPy, Spatial Analyst)* takes the spectral index raster object and generates a binary categorical raster for each threshold value in the list generated using *arrange* (described above)*,* where everything below the threshold is set to 0 and everything equal to or above the threshold, to 1. These categorical rasters are saved as standalone outputs using *Copy Raster* to enable the summation of pixel counts for the kelp and non-kelp classes.
- *Threshold (ArcPy, Image Analyst)* is an additional automated threshold-based classification that is run on the single-band spectral index rasters. It classifies pixels into 1s and 0s using Otsu's Method (Otsu, 1979), which is an algorithm that minimized intra-class variance. Similar to other products above, the categorical rasters generated by this method are saved as standalone outputs using *Copy Raster* to enable the summation of pixel counts.
- *Build Raster Attribute Table (ArcPy, Data Management)* is run on each of the exported categorical rasters generated by the threshold-based classification methods above in order to ensure they have attribute tables that can be populated with pixel counts of each class.
- *Summarize Categorical Raster (ArcPy, Image Analyst)* is the final component of the core automated processing workflow. It takes the categorical classified raster results from *remap* and *threshold* and generates a table for each containing pixel counts per class. These pixel counts are combined with the pixel dimensions for each survey orthomosaic to arrive at an estimate of floating kelp canopy area.

Upon completion of the automated processing of each survey, classified canopy results were reviewed against the original imagery in ArcGIS in order to identify areas of false positives that persisted even at threshold values more restrictive than those that effectively isolated kelp canopy. Common examples where this occurs are large patches of floating wrack and very shallow subtidal to intertidal transition areas, which have been found to pose challenges to other methods of classifying Puget Sound bull kelp canopies as well (Berry & Cowdrey, 2021; Cowdrey, 2021). In order to generate canopy area estimates that were both accurate and conservative, these areas with persistent false positives were removed from bed extent masks, and the corresponding surveys would be run through the automated processing workflow again to generate revised results. In each such case, the percent of each bed extent that was excluded from canopy classification as part of this process was recorded and is presented in Section 3.2.



C_0	C_1	NoData
12322994	578181	106130074
pixel size (cm^2)	11.45	
kelp canopy area (m^2)	662.3	

Figure 6. Abridged flowchart showing the major components of the core image classification pipeline developed for this project, with corresponding examples of input and output products on the right.

2.3.3 Threshold range selection

In order to assess the impact of different BNDVI index threshold choices on canopy area, a method was developed to identify a range of potential threshold values that were observed to effectively separate kelp canopy from the surrounding environment in each survey. The low and high end of these threshold ranges represent rough "uncertainty" bounds associated with classifying bull kelp canopy area using the spectral index threshold technique utilized in this report. Any value within the interval defined by these bounds is considered plausible as a threshold value for kelp canopy classification. The low and high threshold range values were also used to identify a single "midpoint" threshold canopy area estimate for each survey, by estimating the canopy area associated with the average threshold value of the range. Importantly, this is not the same as taking the average canopy area of the high and low estimates, as the relationship between index threshold and canopy area is not strictly linear. Midpoint canopy area estimates were then used as the basis of comparison at four sites in 2021 and 2022 (Section 2.4).

The process of selecting low and high index threshold values that effectively separated floating kelp canopy from the surrounding environment involved the balancing of different sources of error. On the low end of each range, the dominant source of error was type I (false positives for kelp) while at the high end it was type II (false negatives for kelp) (Figure 7). These errors were also more concentrated in different portions of each survey. For example, a common place for false positives to occur at the low end of a range was in the water pixels immediately surrounding the stipes and bulbs of visible kelp plants, creating a subtle halo effect around them in the classification result. This may be due to the kelp's high reflectivity in the near-infrared portion of the electromagnetic spectrum causing more incident NIR light to reflect into the surrounding water. On the other hand, even at the low end of a threshold range there often was some of the tail end of bull kelp blades that would not get classified as kelp due to their diminished near-infrared signal. As higher threshold values were considered more of the blades would become false negatives. Finally, another common source of type I errors was the presence of floating debris or wrack in a kelp bed. In some surveys this source of error was easily mitigated with a slightly higher threshold selection, while in others it posed a more persistent challenge. A full list of the factors considered in choosing index threshold ranges for each survey can be found in Appendix B.

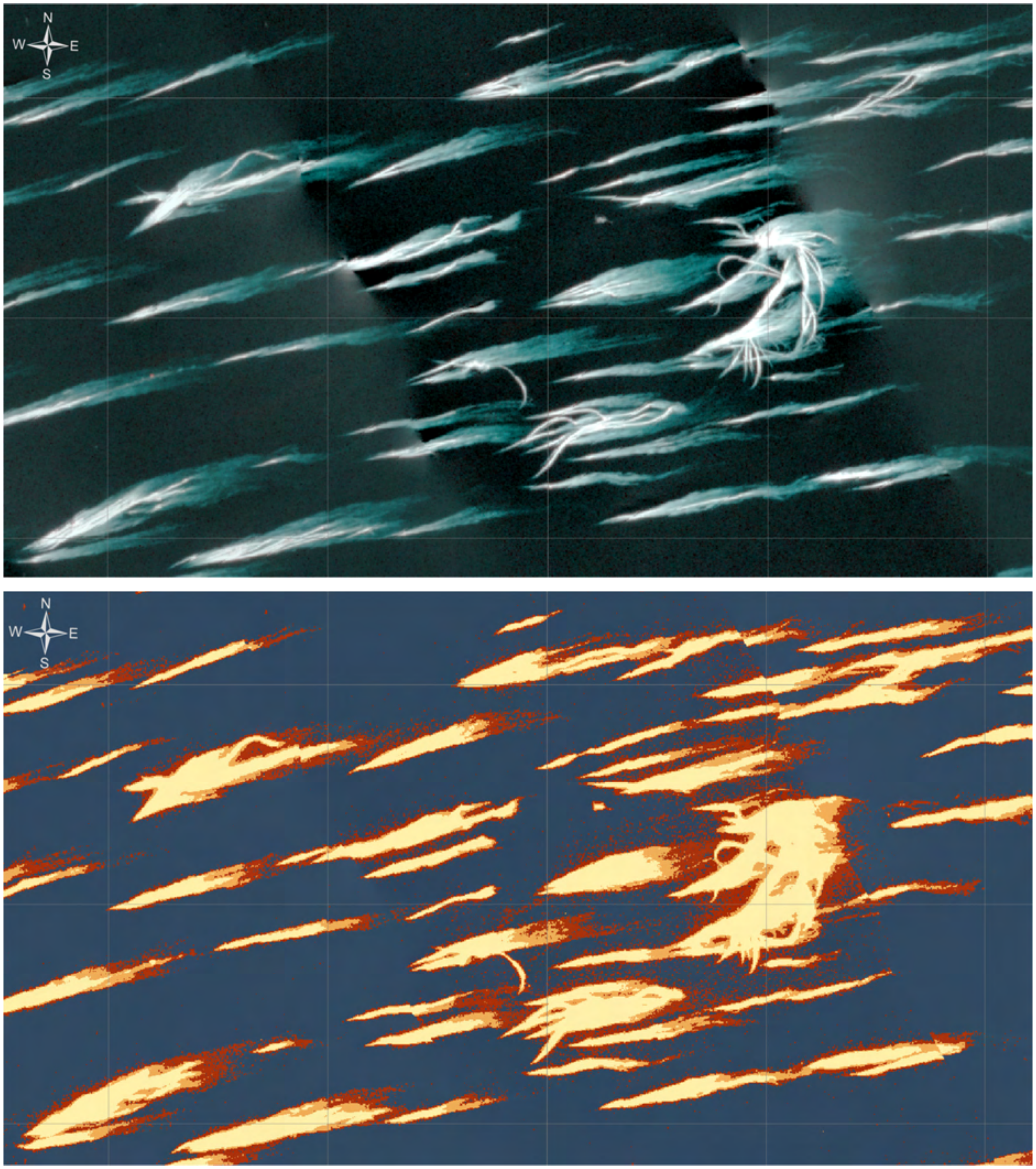


Figure 7. Two panels showing classification results of a survey at North Beach in 2022 using multiple BNDVI thresholds. A 10 m grid is also displayed in each panel to aid comparison. (Top) Original imagery with no classification result, displayed with “NEE” band combination. (Bottom) Classified canopy results corresponding to three BNDVI thresholds: below the identified range by 0.2 (dark red), midpoint of identified range (orange), and above the identified range by 0.2 (light yellow). Pixels classified as “water/other” in all three results are shown in dark blue.

2.3.4 Calculation of canopy area and percent cover

A simple arithmetic equation was used to calculate canopy area estimates in meters squared or hectares within the delineated bed extent of each survey (Equation 1). This equation combined the pixel count generated by the automated processing pipeline (tabular format, Figure 6) with the pixel dimension of the original survey orthomosaic, which is a common way to convert classified raster data into area estimates.

$$canopy\ area\ =\ \#\ of\ kelp\ pixels\ \ in\ classified\ result * pixel\ dimension\ of\ orthomosaic \qquad \text{(Equation 1)}$$

A second equation was used to calculate percent cover within the delineated bed extent from the pixel counts for kelp canopy and non-kelp canopy generated by the automated processing pipeline (Equation 2).

$$percent\ cover\ =\ \frac{\#\ of\ kelp\ pixels\ \ in\ classified\ result}{(\#\ of\ kelp\ pixels + \#\ of\ non\text{-}kelp\ pixels)} \qquad \text{(Equation 2)}$$

2.4 Interannual change assessment

2.4.1 Selection of surveys for comparison

To assess differences in kelp distribution and abundance at a site between years in cases with paired surveys, it was necessary to select which two surveys to compare. Despite following stringent survey parameters for floating kelp canopy monitoring (Section 2.2.1.) there can still be differences in the environmental conditions observed during surveys (Appendix A), so surveys that appeared to be most similar in terms of canopy visibility and were chosen (Table 4). Factors that were considered when selecting surveys for comparison were the presence of shadows and floating wrack or detritus within the survey area, the visibility of the kelp canopy, and the overall similarity in survey conditions. When possible, choosing the same of the paired surveys (both before or after low tide) was also prioritized in order to have consistent tidal flux conditions between years.

Table 4. List of surveys to be used in interannual change assessment, with selected surveys highlighted in green. "S1" and "S2" correspond to the first and second paired survey listed in Table 2. Notes on why each selection was made are included with each comparison set.

Site	Year	Paired survey selected		Selection notes
Lincoln Park	2021	S1		Some floating wrack/detritus present in all surveys. S1 in 2022 has shadows from trees on the bluff behind the site impacting canopy visibility in the southern portion.
	2022	S1	S2	
Vashon Island	2021	S1	S2	All four surveys appeared suitable for comparison. In 2022, S2 had somewhat more uniform blade orientation throughout the site so the second survey for both years was chosen for consistency.
	2022	S1	S2	
Owen Beach	2021	S1	S2	S2 in both years shows impacts from currents in that plants at the deep edge of the site are pulled under and no longer visible. Other conditions similar.
	2022	S1	S2	
North Beach	2021	S1		S2 was selected in 2022 because the orientation of the blades was more similar to that seen in 2021. Blades in S1 were visibly drooping, rather than trailing out.
	2022	S1	S2	

2.4.2 Site results summarized by quadrants

Floating bull kelp forests in Puget Sound are dynamic habitats, and exhibit variability in density and distribution from year to year. As such, it follows that changes in abundance at a site do not occur uniformly, and that there may be important population trends that are only observable at the sub-site level and would be missed by monitoring methods that just record total bed extent or canopy area.

For this project, a method of dividing each site into four quadrants was developed in order to test whether changes at a sub-site scale could be detected where an overall site-level trend would not. This involved dividing each site in both the across- and along-shore directions (Figure 8). To create the across-shore divisions, the length of shoreline containing bull kelp at each site was manually measured in ArcGIS. Then at the rough midpoint of each of these stretches of shoreline, a single line segment was drawn perpendicular to shore extending from the beach to twenty or more meters beyond the deepest edge of the bed extent. For the along-shore division, a negative three meter (-3 m) MLLW bathymetric contour was used as the dividing line. This contour was generated using the Washington State CoNED MLLW Bathymetric DEM published by the Nearshore Habitat Program (Cowdrey, 2024).

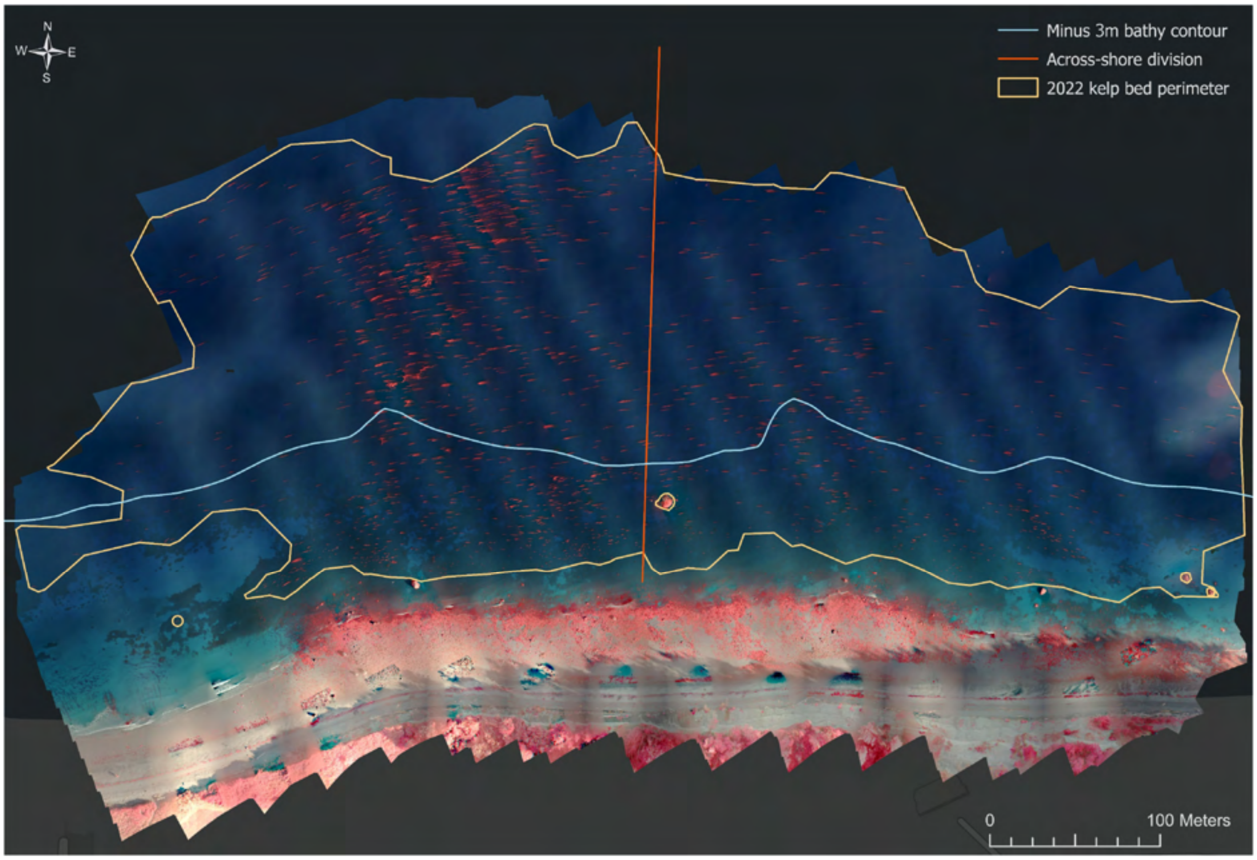


Figure 8. Survey conducted at North Beach in 2022 visualized in a CIR color band combination, showing the bed extent perimeter (yellow), across-shore divider (red), and -3 m bathymetric contour (light blue) used to divide the site into quadrants. Canopy area metrics were summarized in each of the four areas.

To summarize the canopy area and percent cover results by quadrants, the bed extent polygons were first split by the across-shore line segment and -3 m bathymetric contour in ArcGIS using feature editing tools and exported as a new feature class. *Calculate Geometry* was then run to get their respective proportion of bed extent area. Finally, *Summarize Categorical Raster* was run on the midpoint threshold classification result and the quadrants to get pixel counts of kelp and non-kelp coverage in each quadrant. The pixel counts were used to calculate canopy area and percent cover following the equations in Section 2.3.4.

3 Results

3.1 Spatial precision

3.1.1 Original orthomosaics

Spatial precision, or registration error (see Section 2.2.3 for definition), was measured across all sites and years where surveys were available (Table 5). Comparison of orthomosaics showed overall root mean square errors (RMSE) of approximately one meter or less in the majority of cases (mean = 48.4 cm, SD = 30.7 cm, n = 12). Measured RMSE for surveys conducted across multiple years was consistently higher than those captured on the same day. Between same-day replicate surveys in 2022 (due to selection of reference surveys) the median RMSE was ~27 cm (SD = 16.1 cm, n = 6).

Table 5. Root mean square error (centimeters) between specified orthomosaic and reference orthomosaic (marked "Reference") at each site prior to additional transformation. Survey 1 and Survey 2 correspond to the first and second paired survey listed in Table 2.

	RMSE (centimeters)			
	2021		2022	
Site	Survey 1 (S1)	Survey 2 (S2)	Survey 1 (S1)	Survey 2 (S2)
Lincoln Park	41.3*		19.3	Reference
Vashon Island	56.7	60.6	22.5	Reference
Owen Beach	102.9	57.4	33.3	Reference
Hansville			Reference	10.8
North Beach	102.3		17.8	Reference
Hat Island			55.7	Reference

*not enough visual cues on shoreline to meet ASPRS standard of 20 check points

3.1.2 *Following affine transformation*

After the refinement of survey georeferencing with affine transformations using the visually identified check points, RMSE values between surveys were consistently improved (Table 6). For all surveys, RMSE values were 37 centimeters or less, with those captured on the same day being 18 centimeters or less.

Table 6. Root mean square error (centimeters) of each orthomosaic relative to the reference orthomosaic at each site following affine transformation based on visually identified control points. Survey 1 and Survey 2 correspond to the first and second paired survey listed in Table 2.

	RMSE (centimeters)			
	2021		2022	
Site	Survey 1 (S1)	Survey 2 (S2)	Survey 1 (S1)	Survey 2 (S2)
Lincoln Park	9.2*		8.4	Reference
Vashon Island	21.4	13.2	12.7	Reference
Owen Beach	24.3	27.1	11.4	Reference
Hansville			Reference	6.0
North Beach	36.6		8.5	Reference
Hat Island			17.6	Reference

*not enough visual cues on shoreline to meet ASPRS standard of 20 check points

3.2 Bed extent

3.2.1 Bed extent estimates and paired survey comparison

Bed extent of bull kelp at the six study sites varied from approximately 1 to 20 hectares, following a general gradient of smaller to larger moving from South Puget Sound towards the Strait of Juan de Fuca (Table 7). Differences in bed extent among surveys captured on the same day ranged from 1% to 22% relative to mean extent area (mean = 9.6%, SD = 8.5%), though the high end of this range is reduced to 14% (median = 2.9%, n = 6) by excluding the four surveys at Hansville and Hat Island where incomplete image mosaicking at the deep edge in one or both paired surveys contributed in-part to the difference observed. At Lincoln Park, Vashon Island, and North Beach, differences in extent were ~3% or less (n = 4).

Bringing spatial overlap into this picture, some key differences emerge. At Lincoln Park, Vashon Island, and North Beach bed extent delineations were most consistent, with ~91-93% of the mean bed extent area being shared in both paired surveys. At Owen Beach, larger differences between paired survey bed extents were observed, with ~83% overlap relative to mean bed extent in 2021, and ~86% overlap in 2022. This site has the thinnest bed and experiences some of the strongest fluxes in tidal currents of any study site included in this project, and it is apparent in comparing paired surveys in both years that most of the difference in bed extent is concentrated at the deep edge (Figure 9). Due to differences in image mosaicking, Hansville and Hat Island also exhibited lower spatial overlap in bed extent between paired surveys (~88% and ~81% respectively), but the utility of these results is limited by this processing artifact.

Table 7. Bed extent corresponding to delineated kelp perimeters for each survey and approximate percent differences between same-day paired surveys where applicable. In addition, the spatial overlap of bed extent perimeters for same-day surveys expressed as both area and rough percent of the average extent area (between S1 & S2).

Site	Year	Survey 1 (S1) Bed Extent (ha)	Survey 2 (S2) Bed Extent (ha)	S1 & S2 ~Percent Difference	S1 & S2 Bed Extent Spatial Overlap (ha)	Spatial Overlap rough % of Mean Extent
Lincoln Park	2021	1.79				
	2022	1.73	1.70	1%	1.59	93%
Vashon Island	2021	3.89	3.77	3%	3.48	91%
	2022	4.05	4.16	3%	3.78	92%
Owen Beach	2021	1.26	1.09	14%	0.97	83%
	2022	1.64	1.45	13%	1.33	86%
Hansville	2022	5.55	4.60*	19%	4.45	88%
North Beach	2021	14.43				
	2022	13.77	14.02	2%	12.94	93%
Hat Island	2022	16.02*	20.08	22%	14.65	81%

*result lower than other paired survey partially due to incomplete mosaicking at deep edge

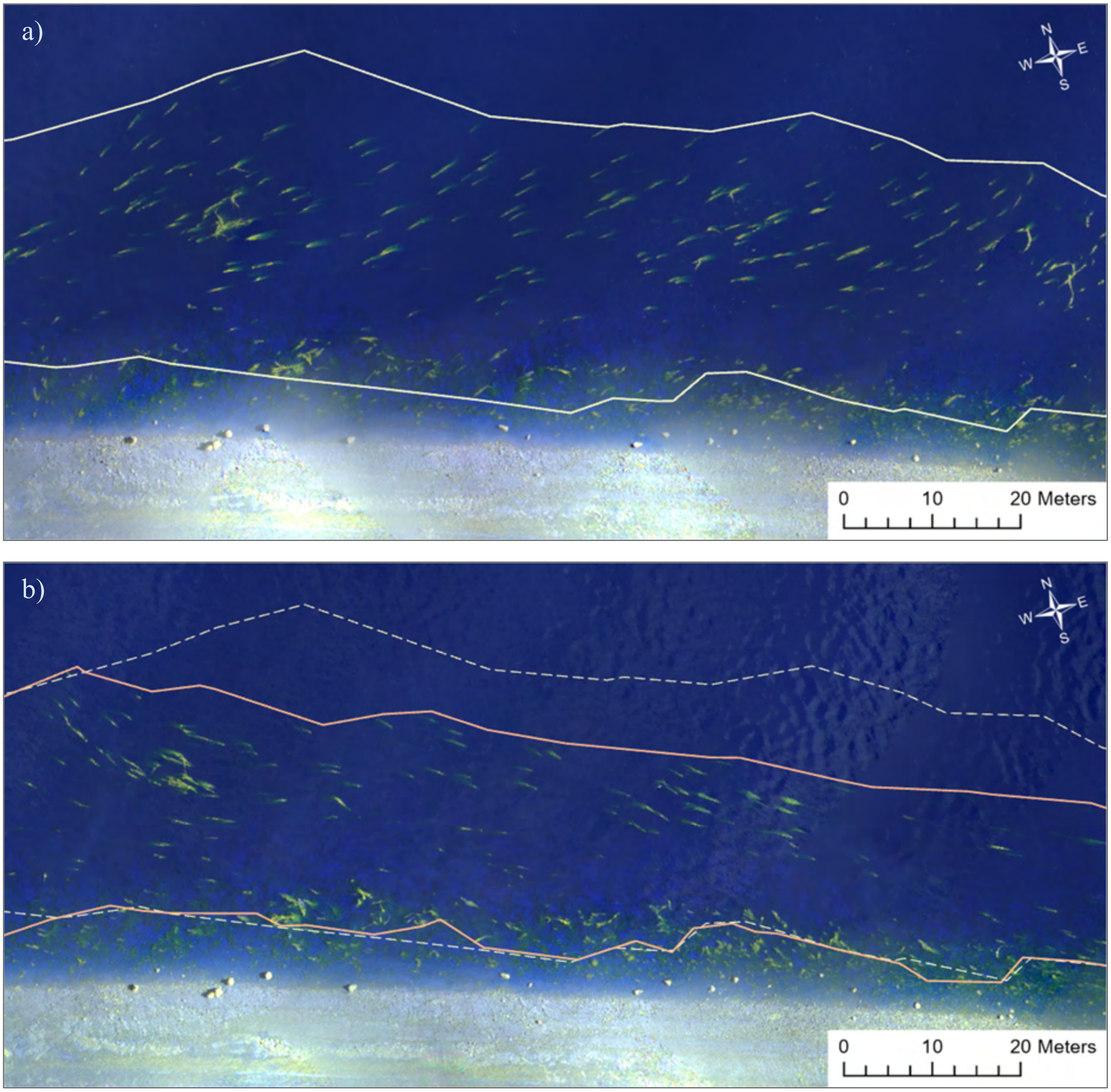


Figure 9. Subsection of same-day paired surveys from Owen Beach in 2022 taken in the hour before (a) and after (b) low tide. In the latter, the kelp canopy has shifted substantially and some individuals at the deep edge are no longer visible, resulting in a 13% difference in delineated bed extent. Both surveys are visualized using the "NEG" band combination (Table 3) and the bed extent perimeter from the first survey is replicated in figure (b) by a dashed line.

Revised bed extents used in canopy classification

Surveys varied in the percent of the original bed extent polygons that needed to be excluded prior to canopy classification due to false positives (Table 8). In some cases, there were minimal false positives due to floating material or misclassification of other submerged vegetation and shallow substrate. For example, the four surveys at Hansville and North Beach in 2022 all included ~99% or more of the original bed extent in canopy classification. By contrast, the two surveys at Vashon Island in 2021 both needed more than 10% of the original bed extent excluded from classification due to false positives in the shallow subtidal. Across all 18 surveys, the median percent of the original bed extent that needed to be excluded from canopy classification was 4.5%.

Table 8. Bed extent estimates following exclusion of areas with persistent false positives to facilitate accurate canopy classification results.

Site	Year	Survey	Bed extent (ha)	Bed extent post-revision (ha)	~Percent of area excluded
Lincoln Park	2021	S1	1.79	1.70	5%
	2022	S1	1.73	1.65	4%
		S2	1.70	1.65	3%
Vashon Island	2021	S1	3.89	3.43	12%
		S2	3.77	3.13	17%
	2022	S1	4.05	3.82	6%
		S2	4.16	3.86	7%
Owen Beach	2021	S1	1.26	1.23	2%
		S2	1.09	1.03	6%
	2022	S1	1.64	1.58	4%
		S2	1.45	1.40	3%
Hansville	2022	S1	5.55	5.51	1%
		S2*	4.60	4.55	1%
North Beach	2021	S1	14.43	13.51	6%
	2022	S1	13.77	13.71	< 1%
		S2	14.02	13.98	< 1%
Hat Island	2022	S1*	16.02	14.78	8%
		S2	20.08	18.35	9%

*results lower than other paired survey partially due to incomplete mosaicking at deep edge

3.2.2 Interannual changes

Overall, kelp bed extent at the four sites with data in both 2021 and 2022 appeared to remain stable or increase between years. At Lincoln Park and North Beach, only one survey was conducted in 2021, and the estimates generated that year are comparable to either of the paired surveys conducted in 2022 (Figure 10). At Lincoln Park, bed extent was estimated at 1.79 hectares in 2021 and 1.70-1.73 hectares in 2022. At North Beach, bed extent was estimated at 14.43 hectares in 2021 and 13.78-14.02 hectares in 2022.

At Vashon Island, there was a slight increase in bed extent estimates between years, but this increase was comparable to the difference in overlap among respective bed extent polygons of paired surveys. For example, the lower of the two estimates in 2021 was 3.77 hectares and the higher in 2022 was 4.16 hectares, which would yield a maximum estimated increase of ~10% between years. The incongruity in bed area between the two paired surveys in 2021 expressed as a percent of the average area between them was ~9%, and in 2022 it was ~8%.

Owen Beach showed a similar pattern but with a greater signal of bed extent increase than Vashon Island. Here there was an increase in bed extent from 1.09-1.26 hectares in 2021 to 1.45-1.64 hectares in 2022, a 15-50% increase. However, this site showed the greatest degree of disagreement between paired surveys, with 14-17% of bed extent differing between paired surveys in both years.

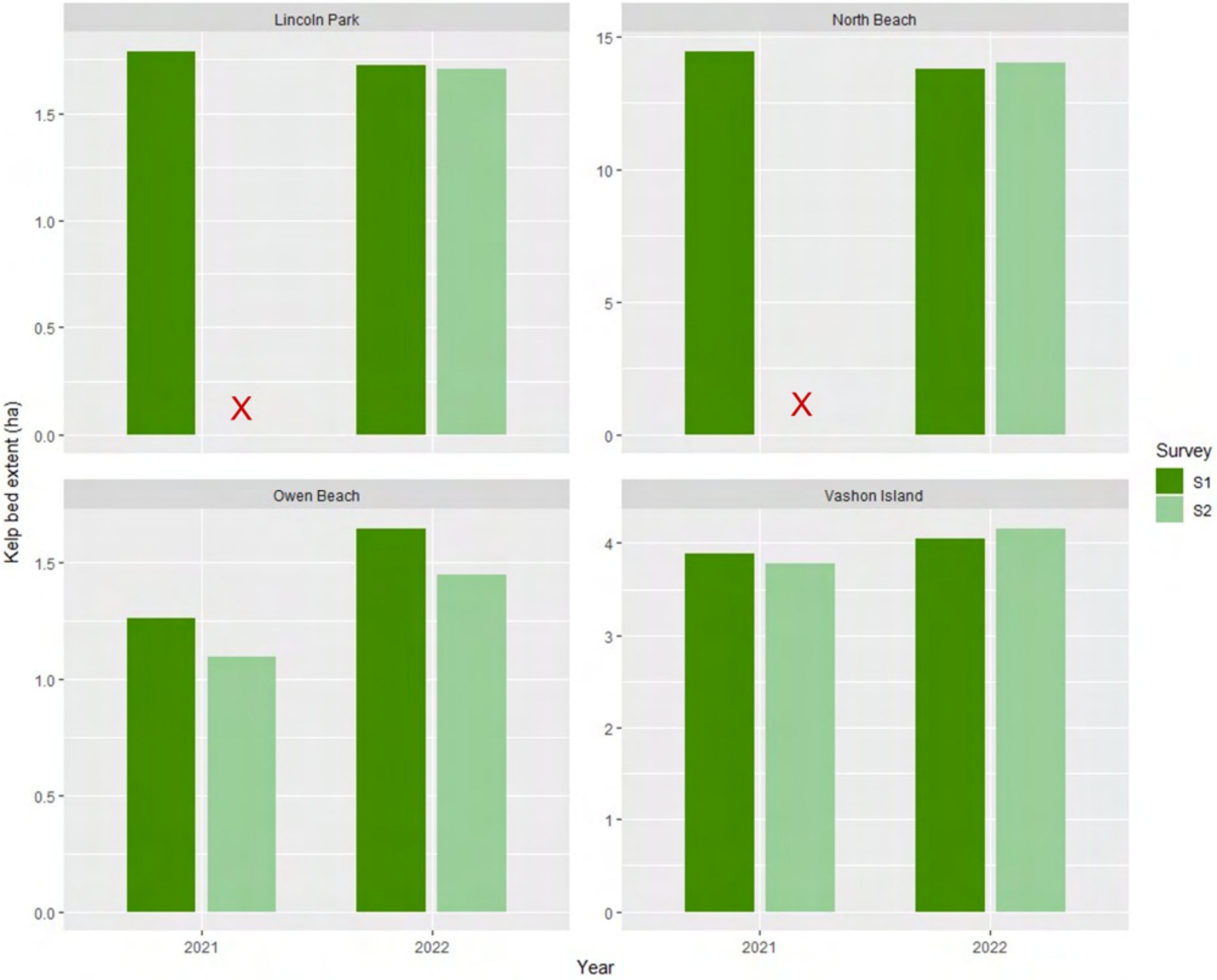


Figure 10. Kelp bed extent results for the four sites with surveys in both 2021 and 2022. Surveys 1 and 2 are indicated by two shades of green, and the red x's denote years where only one survey was conducted.

3.3 Canopy area

3.3.1 BNDVI thresholds

A wide range of BNDVI threshold values were observed to be plausible for distinguishing bull kelp canopy from the surrounding water across all sites and surveys (Table 9). These values ranged from -0.10 to 0.80, but low and high end values selected for a given survey were typically within 0.2 BNVDI of each other. The one exception to this was the pair of surveys at Vashon Island in 2022 with low-high spreads of 0.3 and 0.25 for the first and second surveys, respectively.

Table 9. Low and high end of the range of BNDVI values selected for each survey that best separated bull kelp canopy from the surrounding water, as well as the automated threshold identified by Otsu's method for the same surveys. Cells are colored to indicate positive values in green tones and negative values in orange tones.

		Determined by Visual Inspection				Automated	
		Survey 1 (S1)		Survey 2 (S2)		Otsu's	
Site	Year	Low	High	Low	High	S1	S2
Lincoln Park	2021	0.05	0.15			0.09	
	2022	0.40	0.55	0.70	0.80	-0.01	0.22
Vashon Island	2021	0.00	0.20	0.15	0.30	0.03	0.18
	2022	0.10	0.40	0.45	0.70	-0.18	0.12
Owen Beach	2021	0.00	0.10	0.45	0.55	-0.27	0.30
	2022	0.40	0.50	0.30	0.45	-0.09	-0.32
Hansville	2022	-0.10	0.00	0.20	0.30	-0.01	0.25
North Beach	2021	0.05	0.20			0.12	
	2022	0.30	0.50	0.10	0.25	-0.05	0.11
Hat Island	2022	-0.05	0.10	0.10	0.30	-0.02	-0.21

There was an observed positive drift of BNDVI threshold values between same-day replicate ("paired") surveys. The magnitude of this drift varied greatly among sites and years, and in two instances (Owen Beach and North Beach in 2022) the drift was negative. In all cases, the relative magnitude of drifts for both low and high thresholds between the same paired surveys were comparable (within 0.05 of each other), suggesting there may be an environmental condition that changes in a consistent way such as increasing light angles resulting in greater near-infrared penetration and reflectance off of submerged blades.

In 10 of the 18 surveys, the automated threshold identified by Otsu’s Method on the masked kelp extent BNDVI histogram fell outside the range selected by visual inspection (Table 9, Figure 11). In each of these cases Otsu’s Method selected a threshold that was lower than the range identified by visual inspection, thereby producing inflated kelp canopy area estimates. In multiple cases this difference neared or exceeded 0.5 on the BNDVI scale. In all but one of the eight cases where the Otsu threshold fell within the range identified visually, it was closer to the low threshold than the high one.

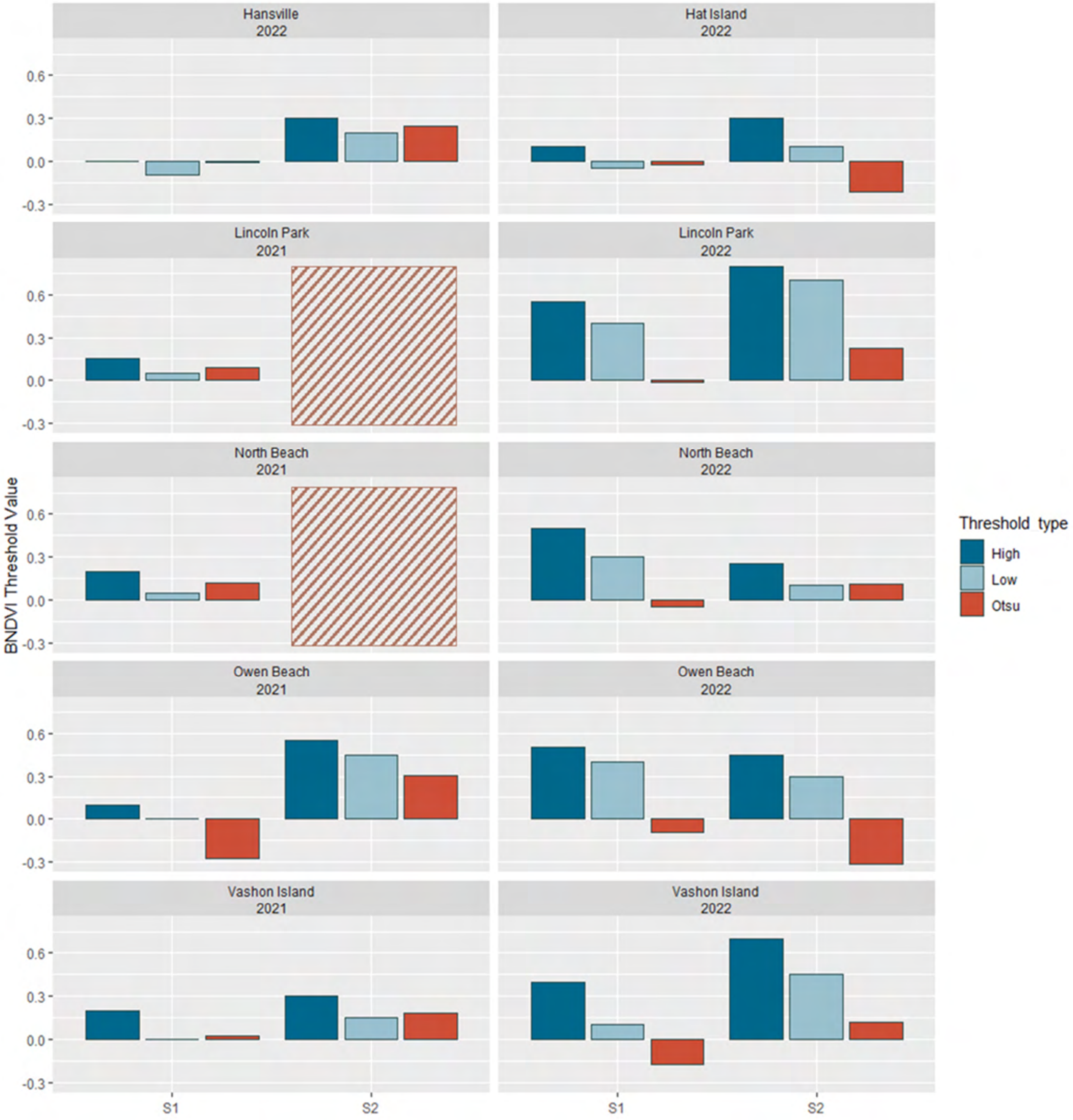


Figure 11. BNDVI threshold values identified in each survey that effectively separated kelp canopy from the surrounding environment, as well as the corresponding threshold generated by Otsu's Method. Results are faceted into paired surveys by site and year. Crosshatches represent that only one survey was flown at that site and year.

3.3.2 Canopy area estimates

Bull kelp canopy area and percent cover estimates corresponding to selected low and high BNDVI thresholds for each survey varied across multiple dimensions (Table 10). Canopy area estimates ranged from as little as ~100-250 m^2 at Owen Beach to over 5,000 m^2 at Hat Island and North Beach (Figure 12). Percent cover values at most sites ranged from roughly 1% to 3%, highlighting the low density of bull kelp individuals observed at many sites throughout Puget Sound. The exceptions to this were the relatively compact beds at Lincoln Park, with percent covers ranging from 3.4% to 6.8% in both years, as well at North Beach, where it ranged from 5.8% to 7.6% in 2022.

Table 10. Canopy area (CA) estimates based on low and high BNDVI thresholds within the revised bed extents (see Section 2.3.2 for description) of each survey.

Site	Year	Survey	Canopy area low estimate (m^2)	Percent cover low estimate	Canopy area high estimate (m^2)	Percent cover high estimate
Lincoln Park	2021	S1	863	5.1%	1,156	6.8%
	2022	S1	650	3.9%	842	5.1%
		S2	555	3.4%	777	4.7%
Vashon Island	2021	S1	433	1.3%	762	2.2%
		S2	441	1.4%	715	2.3%
	2022	S1	409	1.1%	676	1.8%
		S2	498	1.3%	844	2.2%
Owen Beach	2021	S1	121	1.0%	192	1.6%
		S2	124	1.2%	212	2.1%
	2022	S1	187	1.2%	232	1.5%
		S2	177	1.3%	242	1.7%
Hansville	2022	S1	619	1.1%	994	1.8%
		S2*	420	0.9%	637	1.4%
North Beach	2021	S1	7,727	5.8%	10,146	7.6%
	2022	S1	1,795	1.3%	2,510	1.8%
		S2	3,417	2.5%	4,191	3.0%
Hat Island	2022	S1*	3,835	2.6%	5,379	3.7%
		S2	2,360	1.3%	5,437	3.0%

*results impacted by incomplete mosaicking at deep edge

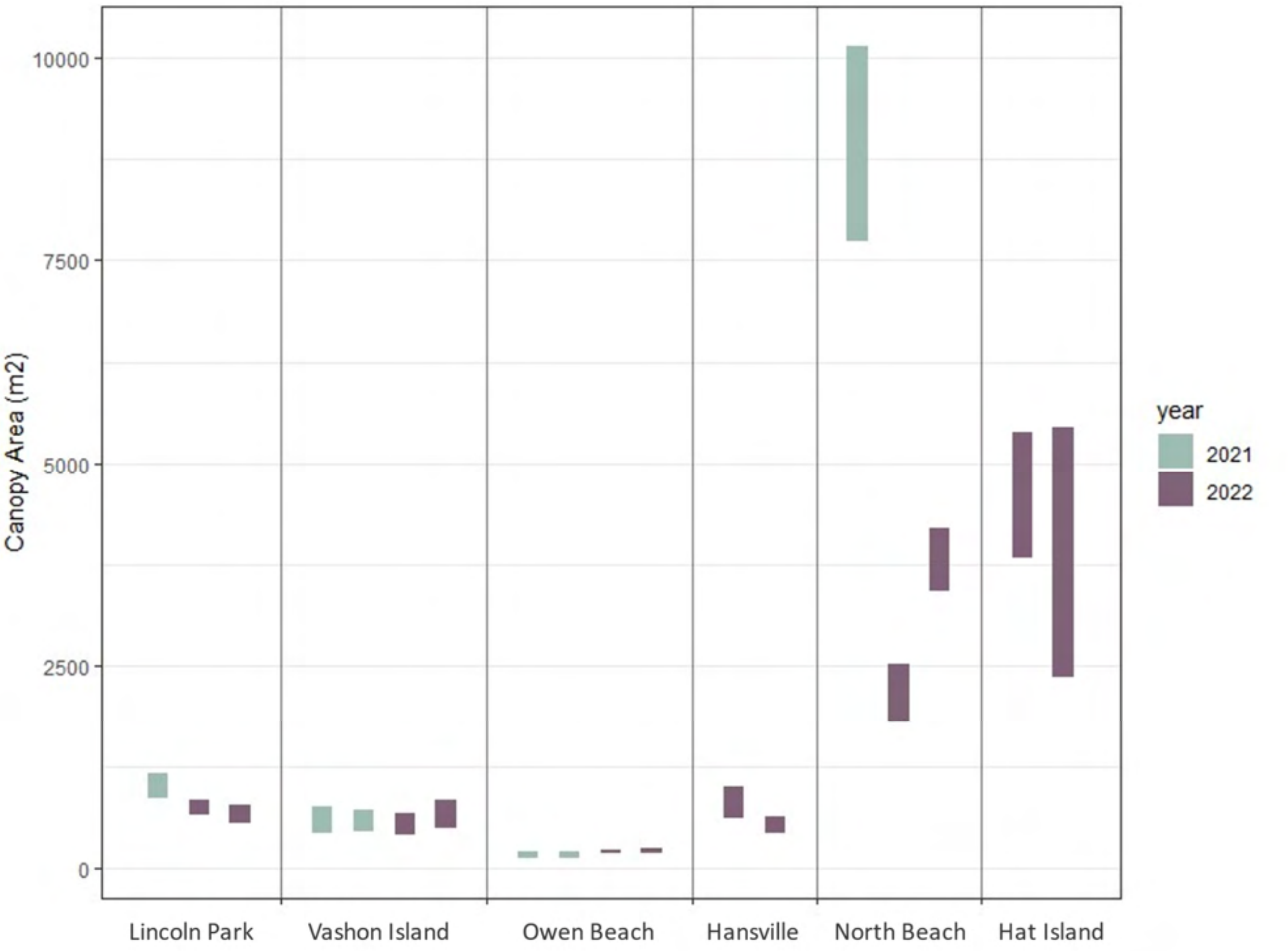


Figure 12. Canopy area estimate ranges within revised bed extents for each survey based on low and high BNDVI thresholds selections. Surveys are grouped by site and symbolized by year.

Midpoint canopy area estimates

Following the identification of the low and high BNDVI threshold values (Section 3.3.1), the midpoints of these two values were calculated for each survey as well (Table 11). These midpoint canopy area estimates served as the basis of comparison between paired surveys (Section 3.3.4) and for interannual change assessments (Section 3.3.5 and 3.4).

Table 11. Midpoint BNDVI threshold values of the ranges identified for each survey, and the canopy area (CA) estimate corresponding those thresholds. In addition, the percent difference from that midpoint canopy area estimate to both the low and high canopy area estimate for each range.

Site	Year	Survey	Midpoint BNDVI value	Midpoint canopy area estimate (m^2)	% difference in CA to low	% difference in CA to high
Lincoln Park	2021	S1	0.100	995	13.3%	16.2%
	2022	S1	0.475	747	12.9%	12.8%
		S2	0.750	673	17.6%	15.4%
Vashon Island	2021	S1	0.100	568	23.8%	34.2%
		S2	0.225	561	21.4%	27.5%
	2022	S1	0.250	535	23.6%	26.4%
		S2	0.575	678	26.6%	24.4%
Owen Beach	2021	S1	0.050	151	20.0%	27.3%
		S2	0.500	162	23.7%	30.5%
	2022	S1	0.450	209	10.6%	10.7%
		S2	0.375	209	15.0%	15.8%
Hansville	2022	S1	-0.050	761	18.7%	30.6%
		S2	0.250	512	18.1%	24.3%
North Beach	2021	S1	0.125	8,817	12.4%	15.1%
	2022	S1	0.400	2,104	14.7%	19.3%
		S2	0.175	3,768	9.3%	11.2%
Hat Island	2022	S1	0.025	4,522	15.2%	19.0%
		S2*	0.200	3,636	36.1%	49.6%

*removed from summary statistics as outlier

Percent differences between midpoint canopy area estimates and corresponding low and high CA estimates for each survey ranged from ~9 to 27% (mean = 17.5%, SD = 5.1%) in comparison to low, and ~11 to 34% (mean = 21.2%, SD = 7.4%) to high. BNDVI midpoint CA estimates were closer on average to the low CA estimates than high, indicating that the relationship of canopy area to BNDVI is typically non-linear. The second survey conducted at Hat Island in 2022 was removed from summary statistics due to percent differences being almost three standard deviations away from the mean with all surveys included.

3.3.3 Classification uncertainty relative to BNDVI range

Overall, percent differences between low and high canopy area estimates ranged from 20% to 55%, before normalization, with a mean of 37.8% (SD = 11.5%, n = 17) (Table 12). The second survey conducted at Hat Island in 2022 was removed from summary statistics due to the percent difference between low and high canopy area values being almost three standard deviations away from the mean with all surveys included.

By normalizing this range to a common BNDVI increment of 0.1 [percent difference / (BNDVI range * 10)] key differences among sites and years were revealed (Figure 13). Following normalization, percent differences between low and high canopy area estimates ranged from 14% and 52% per 0.10 BNDVI, with a mean difference of 27.9% (SD = 12.1%). BNDVI deltas ranged from 0.10 to 0.30 (mean = 0.15, SD = 0.06, n = 18).

Table 12. Percent differences between the low and high canopy area (CA) estimate of each survey. In addition, the BNDVI difference (Δ) between the low and high threshold values alongside the percent difference in canopy area when normalized to a common BNDVI increment scale of 0.1. Hat Island 2022 S2 was removed from summary statistics, it is more than two standard deviations away from the mean.

Site	Year	Survey	% difference in canopy area between low and high estimate	Δ BNDVI low to high	% difference in CA per 0.1 BNDVI
Lincoln Park	2021	S1	29.1%	0.10	29.1%
	2022	S1	25.7%	0.15	17.1%
		S2	33.4%	0.10	33.4%
Vashon Island	2021	S1	55.1%	0.20	27.6%
		S2	47.4%	0.15	31.6%
	2022	S1	49.2%	0.30	16.4%
		S2	51.6%	0.25	20.6%
Owen Beach	2021	S1	45.6%	0.10	45.6%
		S2	52.4%	0.10	52.4%
	2022	S1	21.2%	0.10	21.2%
		S2	30.7%	0.15	20.5%
Hansville	2022	S1	46.5%	0.10	46.5%
		S2	41.1%	0.10	41.1%
North Beach	2021	S1	27.1%	0.15	18.0%
	2022	S1	33.2%	0.20	16.6%
		S2	20.4%	0.15	13.6%
Hat Island	2022	S1	33.5%	0.15	22.3%
		S2*	78.9%	0.20	39.5%

*removed from summary statistics as outlier

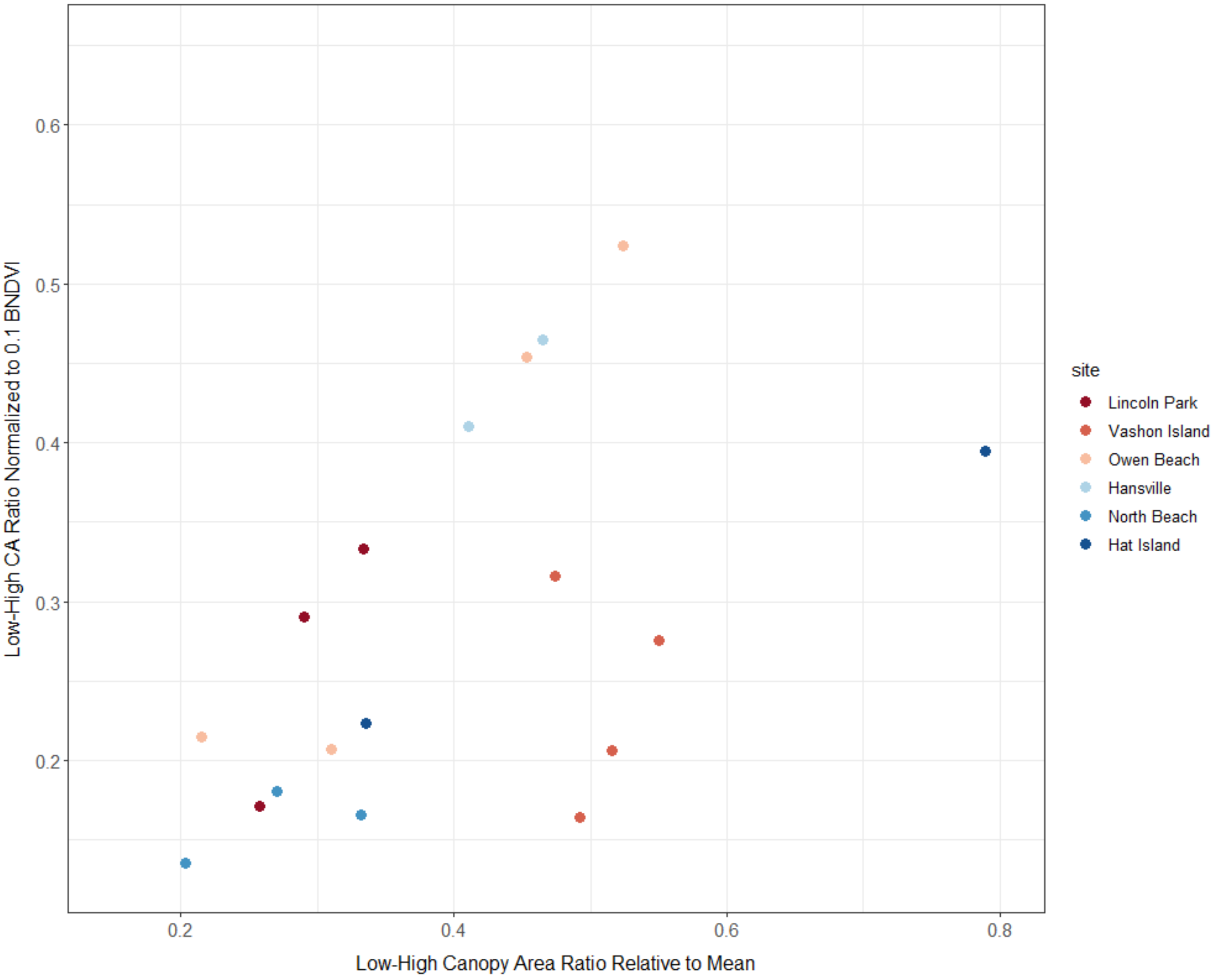


Figure 13. The percent difference between low and high canopy area estimates relative to mean canopy area (shown here as a ratio rather than percent), plotted before normalization to a common 0.1 BNDVI increment (x axis) and after normalization (y axis).

Some surveys showed relatively small differences in canopy area both before and after normalizing to a 0.1 BNDVI scale, such as those at Owen Beach in 2022. There, percent differences were 21.2% and 30.7% prior to normalization, and 21.2% and 20.5% after. There also were surveys with larger differences both before and after normalization. For example, Hansville in 2022 had percent differences of 46.5% and 41.1% both before and after standardization. In both cases, BNDVI deltas were low (0.10-0.15).

The third group of surveys were those where BNDVI differences were 0.20 or greater. Most notable among these is Vashon Island in 2022 where differences were 49.2% and 51.6% before normalization, but only 16.4% and 20.6% after. The latter represent two of the smaller percent differences in canopy area when normalized to the same BNDVI increment. These different cases show that the relationship of canopy area to BNDVI threshold is not uniform across all surveys.

3.3.4 Paired survey comparisons and survey timing uncertainty

For six of the eight sites and years with same-day replicates, the midpoint estimates of those paired surveys were in better agreement than the low-to-high spread of both surveys individually, as measured by percent difference in canopy area (Table 13, Figure 14). In these cases, percent differences between paired survey midpoint canopy area estimates ranged from 1.2% to 30.9% (median = 11.4%), while percent differences between low and high canopy area estimates ranged from 20.9% to 52.5% (median = 44.8%). Inclusive of all eight survey pairs, the median difference between midpoint estimates was ~17% (SD = 20.1, n = 8).

Table 13. Percent differences between midpoint canopy area estimates of same-day paired surveys, as well as the percent difference between low and high canopy area estimates of each survey individually. For these comparisons, only the bed extent in common of the paired surveys was considered, hence low-to-high values differing slightly from Table 11.

Site	Year	Survey	% difference between paired midpoint estimates	% difference in canopy area between low and high estimate (w/in extent in common)
Lincoln Park	2022	S1	9.9%	25.4%
		S2		33.0%
Vashon Island	2021	S1	6.0%	52.5%
		S2		46.7%
	2022	S1	21.0%	48.2%
		S2		50.9%
Owen Beach	2021	S1	12.9%	44.0%
		S2		51.7%
	2022	S1	1.2%	20.9%
		S2		30.0%
Hansville	2022	S1	30.9%	45.6%
		S2		40.8%
North Beach	2022	S1	58.4%	33.1%
		S2		20.0%
Hat Island	2022	S1	44.6%	33.4%
		S2		74.0%

The two sites where this did not hold were North Beach and Hat Island, both surveyed in 2022. At North Beach, the difference between the midpoint canopy area estimates of the paired surveys was 58.4%, which was higher than the low-to-high differences of each individually (33.1% and 20.0%). This is likely because of the disparity in how the kelp canopy at that site presented in the two surveys, appearing to be due to a change in currents (Figure 15). The percent difference between paired midpoint estimates at Hat Island was 44.6%, which fell between the individual low-to-high percent differences for each survey individually (33.4% and 74.0%). The large low-to-high percent difference for the second paired survey is notable, and led to that number being removed from summary statistics in Sections 3.3.2 and 3.3.3.

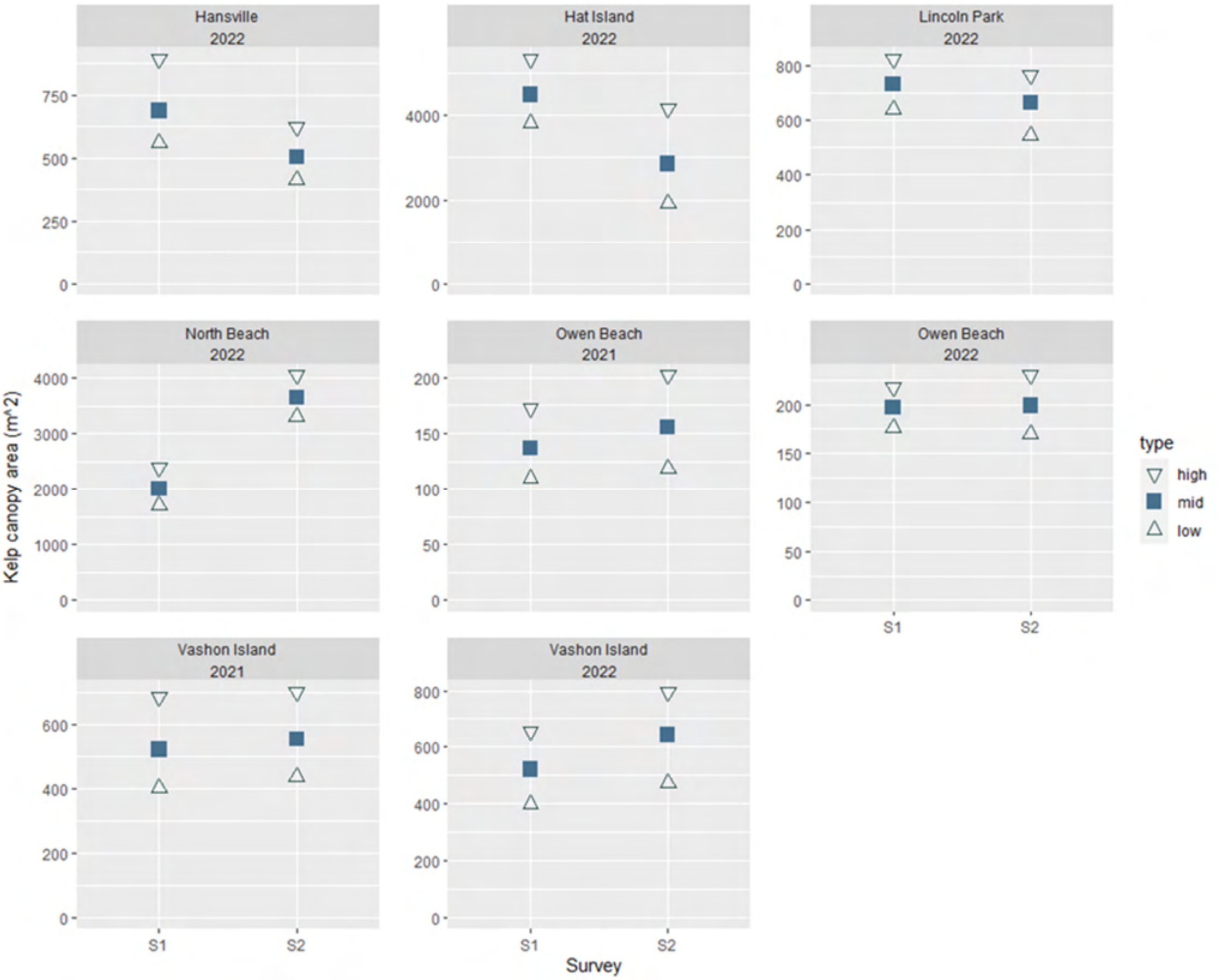


Figure 14. The paired surveys conducted in 2021 and 2022 included in this report. Low, midpoint, and high canopy area estimates are presented for each individual survey based on the BNDVI range identified in Section 3.3.1.

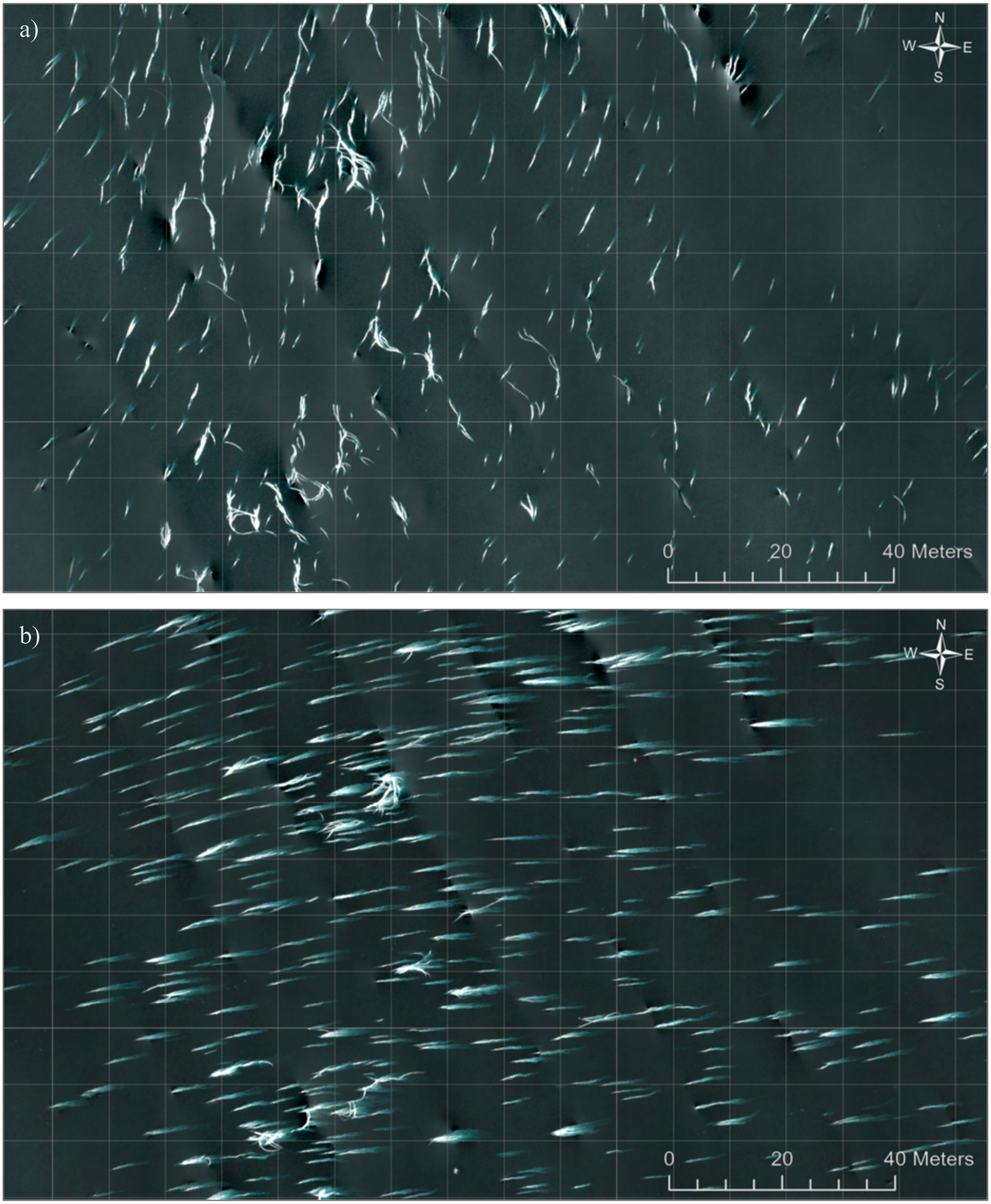


Figure 15. Subsection of paired surveys from 2022 at North Beach taken in the hour before (a) and after (b) low tide showing the shift in the kelp canopy. These surveys are visualized in the "NEE" band combination (Table 3), with a 10-meter grid displayed over top of the imagery.

3.3.5 Interannual changes

Sites with surveys conducted in both 2021 and 2022 showed divergent trends in canopy area estimates between years (Figure 16). At Vashon Island and Owen Beach, estimates of canopy area were overlapping between years. Vashon Island had canopy area estimates between 433-762 m^2 in 2021 and between 409-844 m^2 in 2022. Owen Beach had canopy area estimates between 121-212 m^2 in 2021 and 177-242 m^2 in 2022. However, at Owen Beach in particular, the midpoint estimates from both surveys in 2022 were higher than both surveys in 2021. This gives a stronger signal of a potential increase in canopy area than at Vashon Island where midpoint estimates in 2022 straddled those from 2021.

Lincoln Park had canopy area estimates that diverged more than Vashon or Owen, with 863-1,156 m^2 of canopy in 2021 and 555-842 m^2 in 2022. The lack of overlap among canopy area ranges between years is strong evidence for a potential decrease in kelp canopy area there. However, the survey at this site in 2021 had more false positives from floating wrack than other surveys (Appendix B), prompting a need for closer examination (Section 3.4.3). North Beach had the greatest difference between years with 7,727-10,146 m^2 in 2021, and 1,795-4,191 m^2 in 2022. This represents a minimum estimated decrease in canopy area of ~46% between 2021 and 2022.

These changes in canopy area are described in greater detail on a site-by-site basis in Section 3.4.

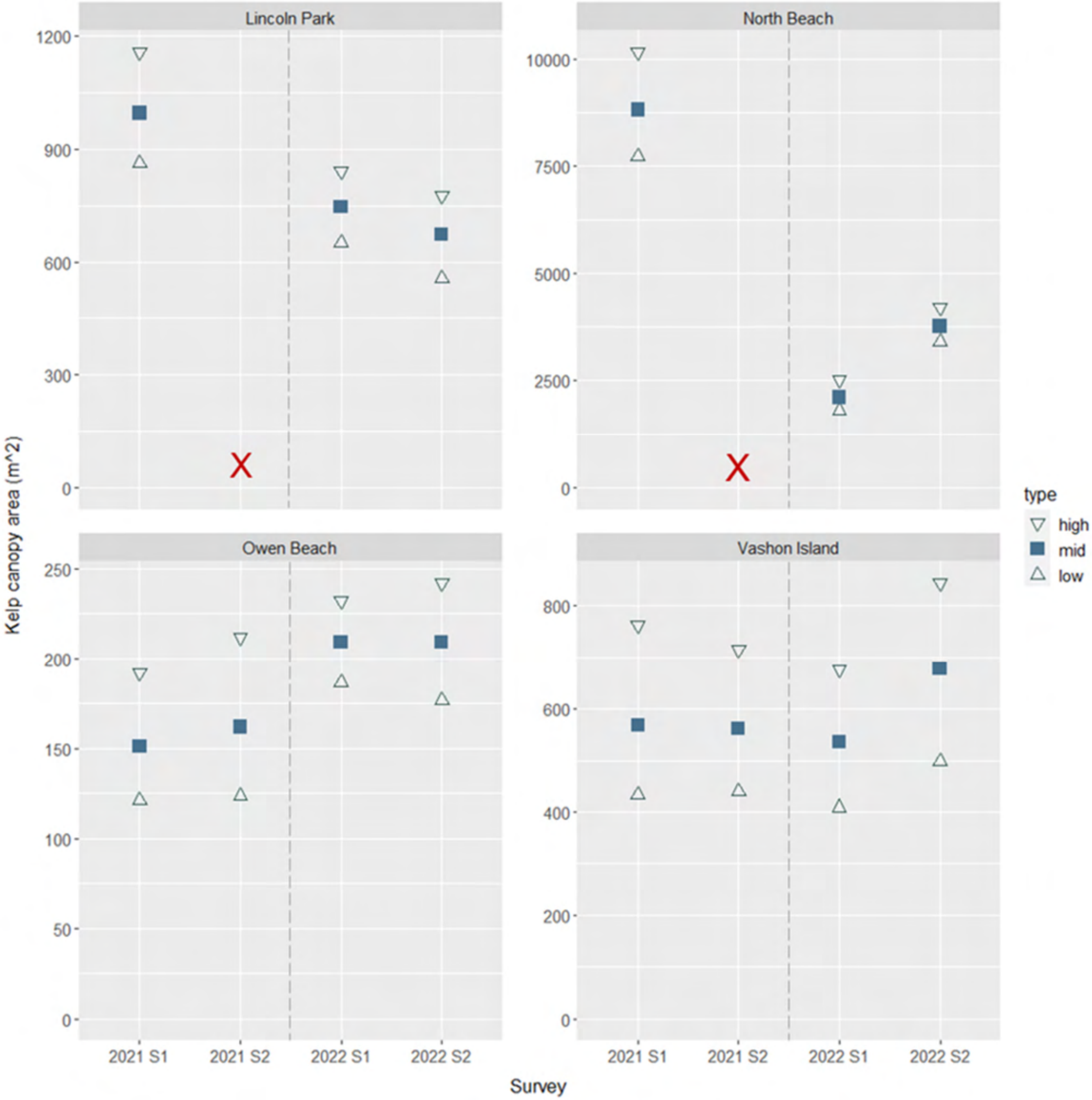


Figure 16. The four sites with surveys in both 2021 and 2022. Low, midpoint, and high canopy area estimates are presented for each individual survey based on the BNDVI range identified in Section 3.3.1. S1 and S2 correspond to the first and second same-day survey at a site in a given year respectively. Red x's denote years where only one survey was conducted at a given site.

3.4 Site-level 2021-2022 detailed change assessments

3.4.1 Vashon Island

The bull kelp bed at Vashon Island appeared to remain stable across most of the site between 2021 and 2022 based on midpoint canopy area estimates. For this comparison the second of the paired surveys from both years were judged to be most comparable (Section 2.4.1). The total canopy area in the three combined deep and west quadrants was ~460 m^2 in 2021 and ~492 m^2 in 2022. However, there was a marked increase in classified canopy area that almost entirely exceeded classification uncertainty estimations in the shallow east quadrant between years, with ~100 m^2 in 2021 and ~186 m^2 in 2022.

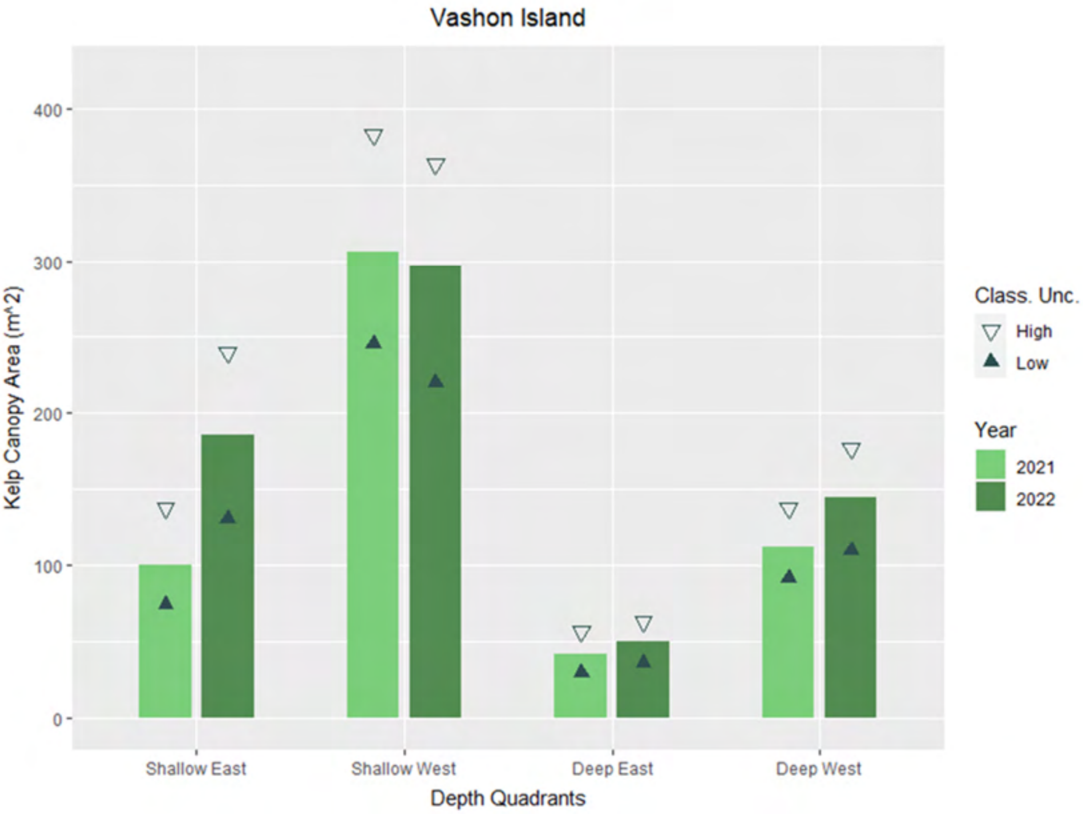


Figure 17. Bar plot showing the midpoint canopy area estimates for the four kelp bed quadrants at Vashon Island in 2021 and 2022, both representing the second of the paired annual surveys. Corresponding low and high CA estimates associated with classification uncertainty are also included for each midpoint estimate. An increase in canopy area was observed in the shallow east quadrant that largely exceeded uncertainty expectations, while the other three appeared to remain stable.

The kelp bed at this site is predominantly distributed shallower than the -3 m MLLW bathymetric contour (Figure 18). The survey results show that the overall distribution of bull kelp was mostly consistent between years, especially in the two west quadrants and the deep east quadrant. In the imagery, it appears there may have been a slight contraction in bed extent in the western half of the bed, but the patch there also is a bit denser in 2022 than 2021. The increase in canopy in the shallow east quadrant appears to be concentrated in a patch near the shoreline midpoint division. The deep east quadrant has very little canopy in both years.

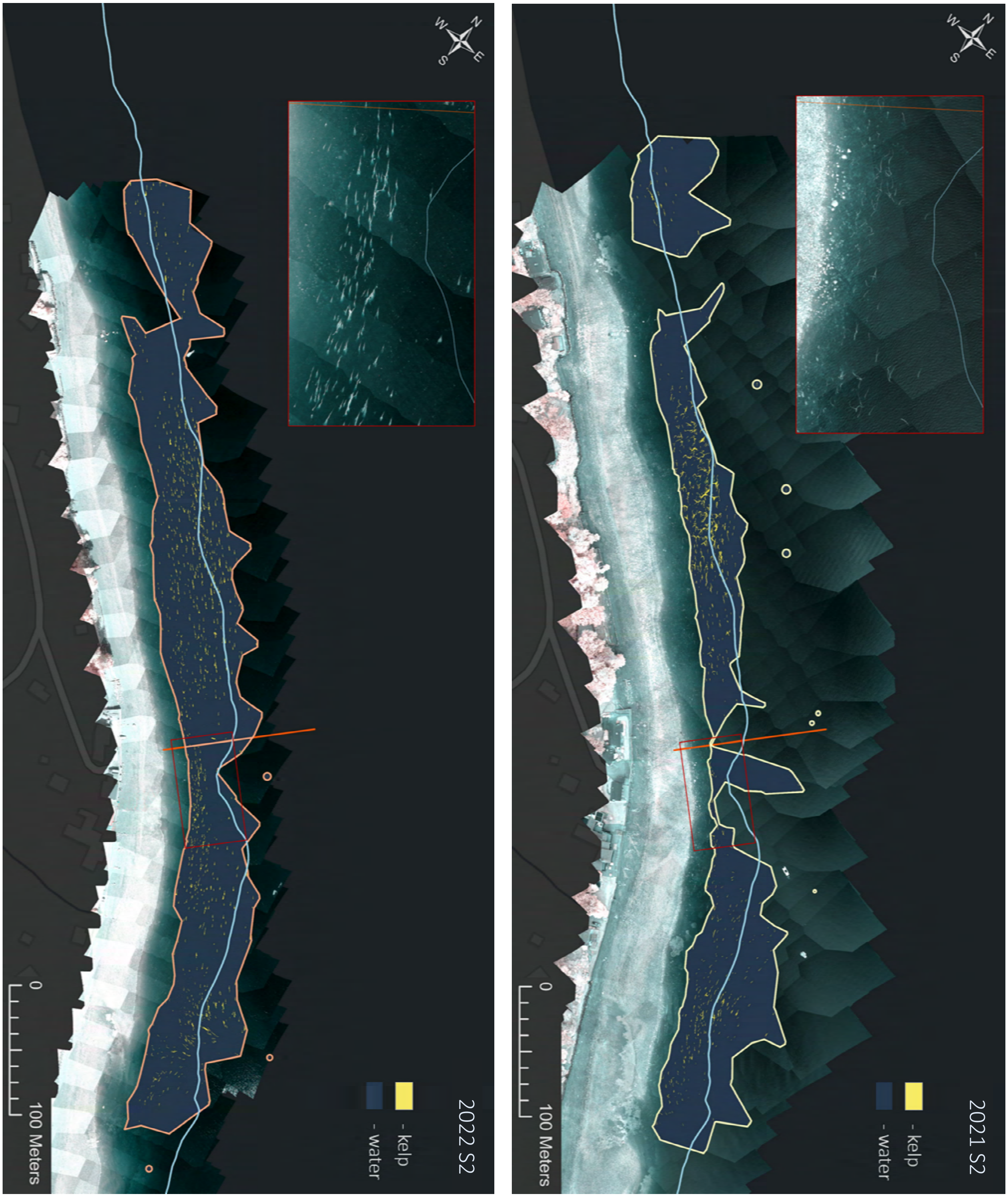


Figure 18. Surveys at Vashon Island from 2021 (right) and 2022 (left) displayed in "NEE" band combination showing their respective bed extent perimeters, and classified canopy results shown in yellow. The -3 m bathymetric contour and shoreline midpoint quadrant dividers are shown in blue and red respectively.

3.4.2 Owen Beach

Owen Beach has the thinnest fringing bull kelp bed of the six sites included in this project, ranging from ~10-40 m wide over a one kilometer stretch of shoreline (Figure 20). For this comparison the first of the paired surveys from both years were judged to be most comparable (Section 2.4.1). Combined canopy area in the two east quadrants appears stable between 2021 and 2022 (~107 m^2 and ~112 m^2 in combined shallow east and deep east respectively), but with more canopy in the shallow quadrant in 2022 (Figure 19). The deep west quadrant saw a substantial increase in canopy area between years, with ~22 m^2 in 2021 and ~84 m^2 in 2022. This was slightly offset by a decrease in the shallow west quadrant, but of much smaller magnitude with ~22 m^2 in 2021 and ~13 m^2 in 2022.

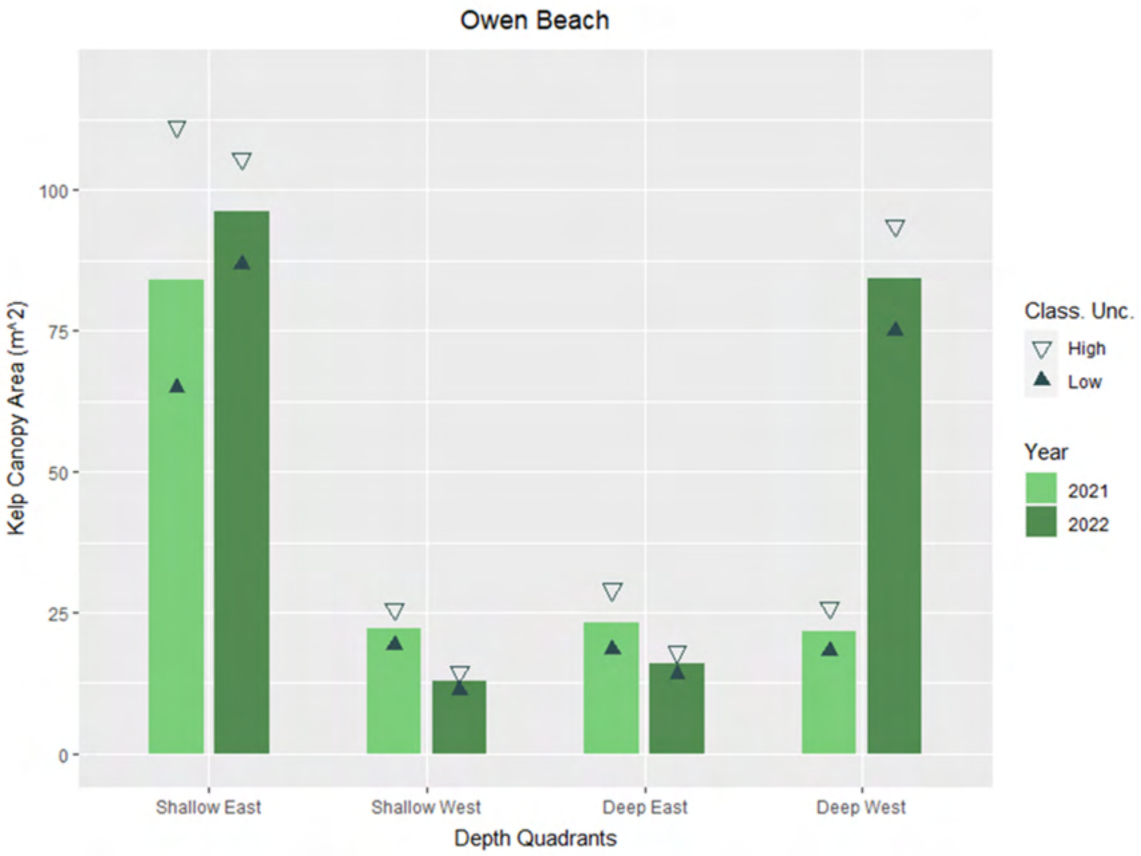


Figure 19. Bar plot showing the midpoint canopy area estimates for the four kelp bed quadrants at Owen Beach in 2021 and 2022, both represented by the first of the paired annual surveys. Corresponding low and high CA estimates associated with classification uncertainty are also included for each midpoint estimate. A marked increase in canopy area between years was observed in the deep west quadrant, while the other three appeared more stable.

In the two survey results it appears there was a bed expansion in the deep west quadrant in addition to the increase in canopy area (Figure 20). This accounts for most of the increase seen in Figure 10 as well. Examination of the imagery and comparison with the second paired survey in 2021 eliminates the possibility that this is caused simply by currents pulling plants at the deep edge under. Overall, there doesn't appear to be any prominent overall changes in the rest of the site.

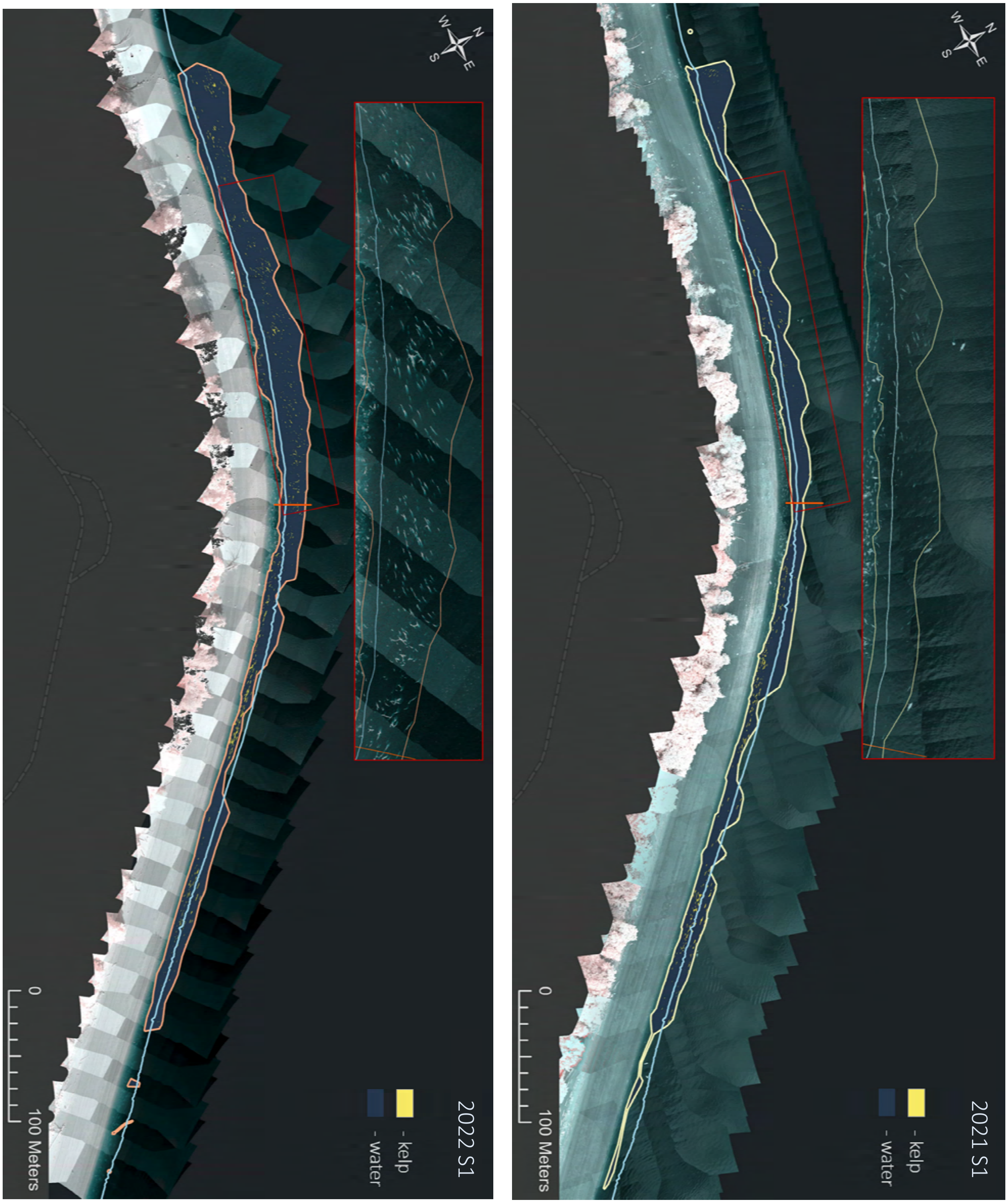


Figure 20. Surveys at Owen Beach from 2021 (right) and 2022 (left) displayed in "NEE" band combination showing their respective bed extent perimeters, and classified canopy results shown in yellow. The -3 meter bathymetric contour and shoreline midpoint quadrant dividers are shown in blue and red respectively.

3.4.3 Lincoln Park

Canopy area at Lincoln Park appeared to remain stable in the east half of the site between 2021 and 2022 (Figure 21). This site is characterized by two discontinuous "lobes" of the kelp bed, with the east half being the smaller of the two, distributed almost entirely above the -3 meter bathymetric contour (Figure 22). For this comparison the second of the paired surveys from 2022 was judged to be most comparable to the survey conducted in 2021 (Section 2.4.1). The west half of the site shows a marked decrease in canopy area between years (~735 m^2 in the shallow and deep west combined in 2021, and ~407 m^2 in 2022), particularly in the deep west quadrant (~396 m^2 and ~182 m^2 respectively).

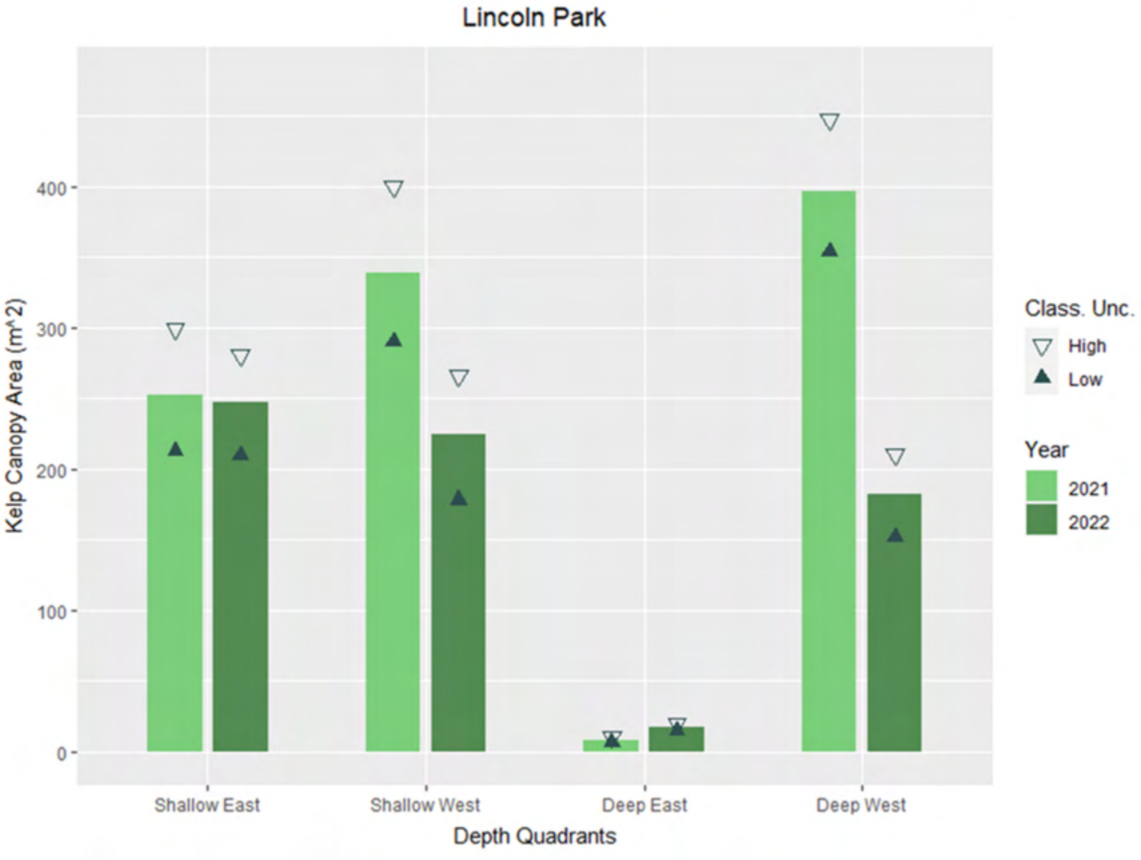


Figure 21. Bar plot showing the midpoint canopy area estimates for the four kelp bed quadrants at Lincoln Park in 2021 and 2022; the latter is represented by the second of the paired surveys. Corresponding low and high CA estimates associated with classification uncertainty are also included for each midpoint estimate. A marked decrease in classified canopy area between years was observed in the two west quadrants, while the other three appeared more stable. However, false positives in the 2021 result raise questions about the size of the change.

Further examination of the classified imagery shows that the spatial distribution of the west half of the bed remains largely consistent between 2021 and 2022 (Figure 22). In 2022, kelp canopy was spread throughout the bed extent and didn't appear to have any areas of a clear decrease. However, in 2021 there is a notable accumulation of floating wrack intermingled in the kelp canopy that is mis-classified as kelp, even in the high threshold result. This is particularly the case in the west half of the site, which is likely inflating the canopy area estimate for 2021.

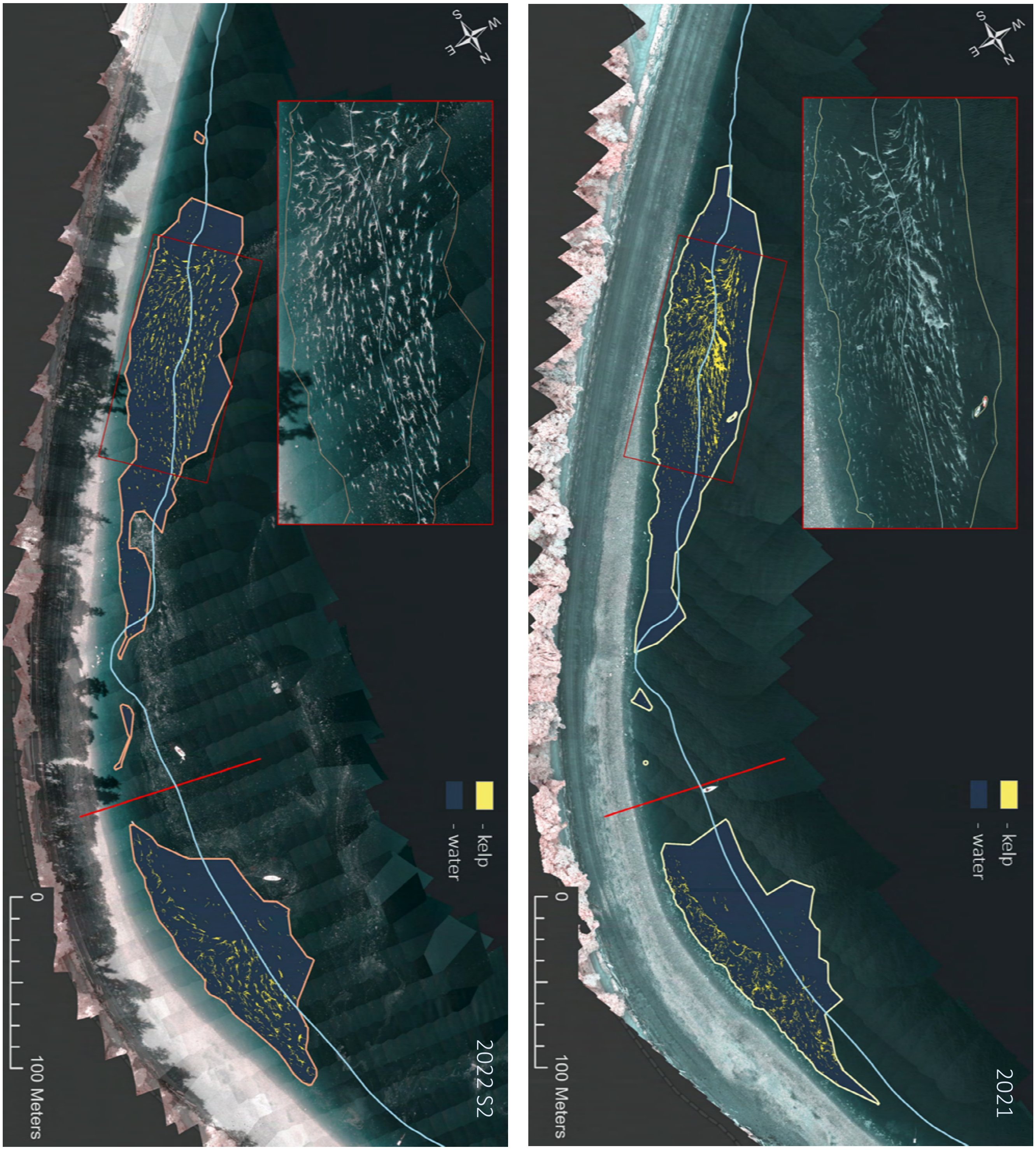


Figure 22. Surveys at Lincoln Park from 2021 (right) and 2022 (left) displayed in "NEE" band combination showing their respective bed extent perimeters, and classified canopy results shown in yellow. The -3 meter bathymetric contour and shoreline midpoint quadrant dividers are shown in blue and red respectively.

3.4.4 North Beach

The kelp forest at North Beach is the largest in terms of bed extent of the four sites with multiyear data (Table 7). The site is characterized by variable density kelp spread over a large area that, unlike the other sites presented in this report, is only a small portion of a much longer stretch of shoreline containing kelp forests that has been monitored by DNR for more than 30 years (Van Wagenen, 2015). For this comparison, the second of the paired surveys from 2022 was judged to be most comparable to the survey from 2021 (Section 2.4.1). In 2021, there was more classified canopy in the shallow half of the site than deep (~6,255 m^2 combined and ~2,542 m^2 combined respectively) (Figure 23). By contrast, in 2022 there was dramatically less visible canopy in the shallows, inverting this relationship (~1,054 m^2 and ~2,592 m^2 in the shallow and deep halves of the site respectively). Overall, the deep west quadrant was the only that did not show a decrease in canopy area that exceeded classification uncertainty estimates between years.

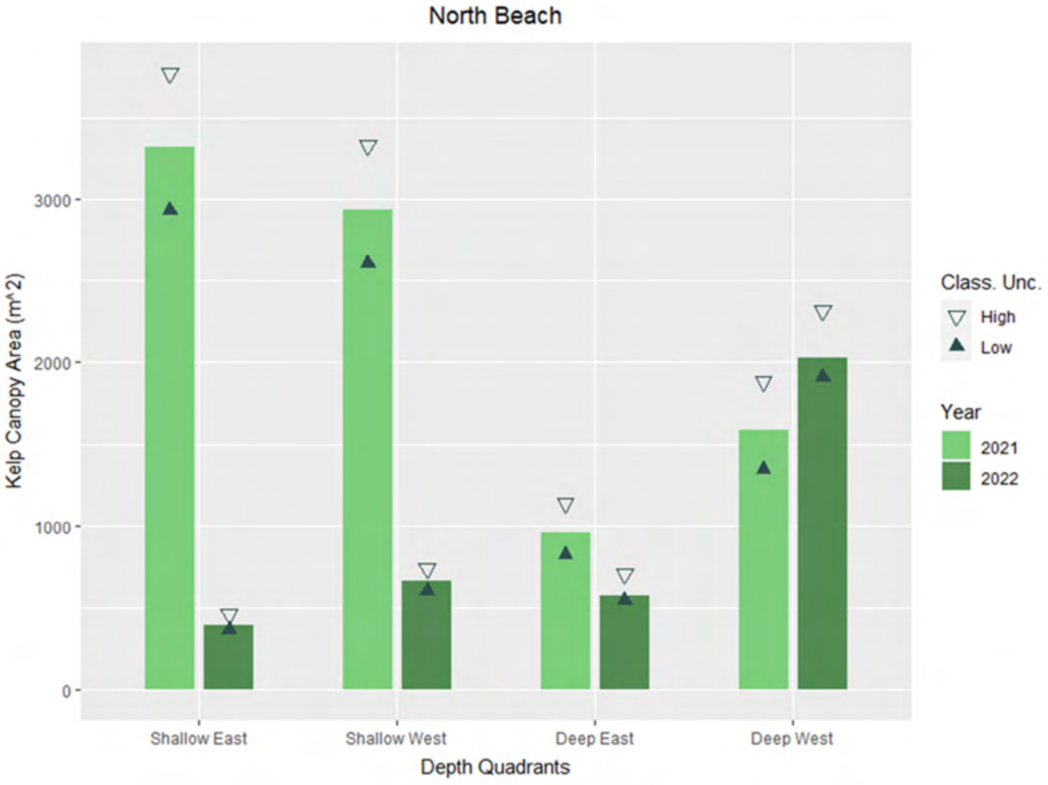


Figure 23. Midpoint canopy area estimates for the four quadrants of the kelp bed at North Beach in 2021 and 2022; the latter is represented by the second of the paired surveys. Corresponding low and high CA estimates associated with classification uncertainty are also included for each midpoint estimate. A striking decrease in classified canopy area between years was observed in the shallow half of the site, while the deep half appeared to be more stable overall. In particular, the deep west quadrant was the only to not show a decrease.

The decrease in canopy area throughout the shallow half of the site is apparent in the classified imagery (Figure 24). The thick mat of intertwined bull kelp stipes seen in 2021 has been replaced by a sparse low-density forest more similar to the rest of the sites in 2022. This change extends into the shallow edge of the deep east quadrant as well, likely accounting for the decrease there. The deep west quadrant appears similar in terms of canopy area between years.

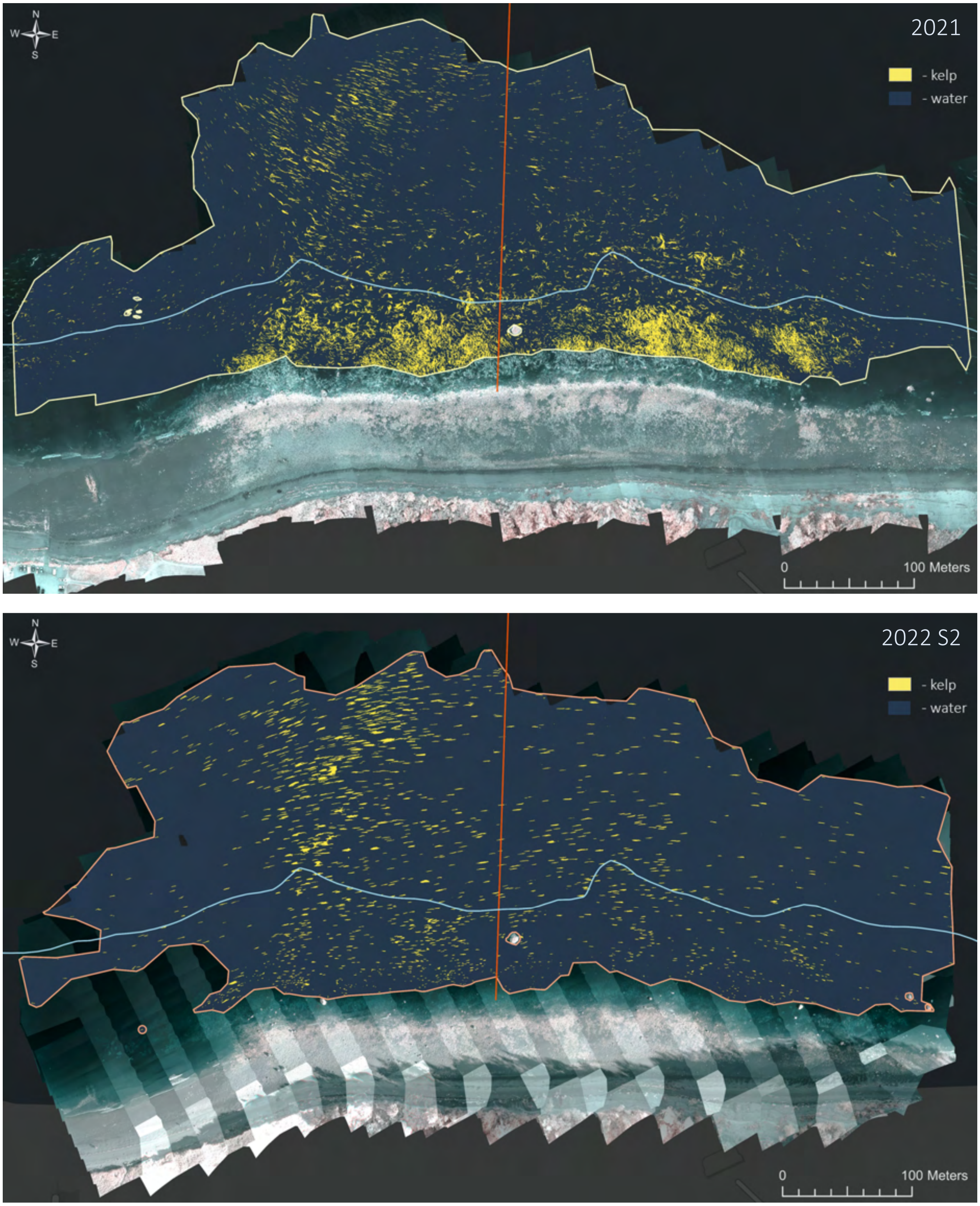


Figure 24. Surveys at North Beach from 2021 (top) and 2022 (bottom) displayed in "NEE" band combination showing their respective bed extent perimeters, and classified canopy results for both shown in yellow. The -3 meter bathymetric contour and shoreline midpoint quadrant dividers are shown in blue and red respectively.

4 Discussion

4.1 Multispectral UAS for bull kelp forest mapping

This project expanded on previous work mapping bull kelp forests in Puget Sound with uncrewed aircraft systems (UAS) (Berry & Cowdrey, 2021; Cowdrey, 2021), and assessed the applicability of recent research supporting the use of spectral index thresholds and multispectral imagery to classify kelp canopies (Cavanaugh et al., 2021b; Timmer et al., 2022). We conducted 18 multispectral UAS surveys across six kelp forest sites in Puget Sound in 2021 and 2022 and classified kelp canopy using a blue normalized difference vegetation index (BNDVI) binary threshold approach. Sixteen of these surveys were conducted in pairs in the hour before and after low tide to assess environmental sources of uncertainty in kelp forest canopy mapping.

In total, an estimated 48 hectares of kelp forest bed extent were mapped in these surveys with individual beds ranging from as small as 1 hectare to more than 20 hectares in size. The same-day replicate ("paired") surveys showed a high degree of spatial precision, with a median registration root mean square error of ~21 cm, confirming the effectiveness of the Nearshore Habitat Program's (NHP) current ground control workflow. Analysis of kelp forest extent in the paired surveys based on bed perimeter delineations produced an estimated median difference of ~3% in bed extent when mosaicking was consistent. Cases where differences in bed extent were more pronounced appear to be due to the impact of currents on plants at the deep edge, or were attributable to artifacts in image mosaicking.

To assess the uncertainty in spectral index-based classification, a novel method was developed based on identifying ranges of plausible BNDVI values for each survey. This method produced canopy area estimate ranges with a mean difference of ~38% between the low and high estimates. In addition, the midpoint canopy area estimates of paired surveys were compared and produced a median difference of ~17% across all eight pairs. Work remains to quantify these sources of uncertainty across more sites in Puget Sound and to determine how they fit together in a comprehensive model of overall uncertainty, but these results represent an important step forward in our aim to confidently assess temporal changes in kelp forest canopies.

Overall, these findings validate the utility of multispectral UAS imagery and spectral index-based classification for kelp forest monitoring in Puget Sound. While other survey methods such as diver, kayak, and conventional aerial imagery have a longer history of use for kelp monitoring, UAS surveys have the ability to efficiently provide detailed information about the abundance and distribution of canopy-forming kelps at a site level. Through the continued use of UAS surveys and integration of results across many survey methods, NHP will continue advancing our knowledge of the distribution, abundance and temporal trends of bull kelp forests in Puget Sound.

4.2 Benefits of paired surveys

Bull kelp forests can be challenging to map using remote-sensing methods due to the impact their annual lifecycle and environmental conditions such as tides and currents, water clarity, and incident light can all have on canopy visibility (Britton-Simmons et al., 2008; Cavanaugh et al., 2021b; Reshitnyk et al., 2023). In addition, accurately distinguishing kelp canopy from the surrounding environment can be challenging for the same reasons above, as well as confusion caused by other marine vegetation and shallow water benthic light reflection. By conducting UAS surveys at the study sites in same-day pairs, the impacts of some of these sources of uncertainty were estimated for the method of kelp forest mapping in this project.

4.2.1 Spatial precision assessment

The first benefit of pairing surveys was the ability to evaluate the spatial precision of surveys processed independently in Metashape using the same ground control points (GCPs). Previous efforts to compare surveys to georeferenced aerial imagery found that accuracy was roughly one meter or less (Berry & Cowdrey, 2021), and this project builds on that finding by referencing two high resolution data sets with a root mean square error (RMSE) approach. An average RMSE of ~27 cm was found among paired surveys from 2022, and verifies the efficacy of the GCP workflow currently employed for NHP's UAS surveys.

4.2.2 Temporal uncertainty in bed extent and canopy area estimates

Pairing bull kelp UAS surveys on the ebb and flood tides at multiple sites also provided insights into the variability of spatial metrics derived from them, and how canopy visibility can change depending on currents. The impacts of tides and currents on canopy visibility have previously been described for bull kelp in the San Juan Islands, WA (Britton-Simmons et al., 2008), and for giant kelp in southern California (Cavanaugh et al., 2021b), but the applicability of these results to bull kelp forests across Washington State broadly has not been fully evaluated. This project found a median difference in bed extent among same-day paired surveys of ~3% (Table 7), when mosaicking was consistent. However, Owen Beach showed a difference of 12-14% in bed extent between paired surveys in both 2021 and 2022, which appears to be due to plants at the deep edge of the site being pulled under by currents (Figure 9).

Similar analysis of the midpoint canopy area results among paired surveys in the cases where the paired estimates were more consistent than the low to high spread each survey individually (six of eight) yielded a median difference of 11.4% (Table 13). However, at North Beach this difference was 58.4%, which appears to be due to disparities in the orientation of the kelp canopy from a change in currents (Figure 15).

These results indicate that future efforts are needed to gain a better understanding of current dynamics at specific study sites in order to ensure consistent survey conditions from year to year. Work is currently being conducted by the Nearshore Habitat Program to identify the most reliable windows for kayak surveys at kelp forest monitoring sites in Puget Sound (Ledbetter and Berry, in prep). The combination of this report's findings and those of the kayak survey work will further inform the timing of and uncertainty associated with monitoring efforts across methodologies.

4.3 Multispectral index-based classification

4.3.1 Advantages of index-based methods

The spectral index-based classification approach had the advantage of enabling automation of many portions of the orthomosaic processing and analysis pipeline. This stands in contrast to the time-consuming process of manually identifying and iterating training data on a survey-by-survey basis that was necessary for the supervised classification used in previous NHP projects (Berry & Cowdrey, 2021; Cowdrey, 2021). The Python and R code written for this project replace much of the manual work of executing geoprocessing, data analysis, and visualization tasks with tools that only require specifying input raster and vector files, as well as the desired spectral index and threshold values for classification. This freed up significant time that it would have taken to manually execute all of the tasks individually to generate ranges of classification results, and enabled more focus to be applied to analysis and interpretation of the results.

In addition, using spectral index thresholds that produce classification results within a single normalized range enables comparisons of results across surveys, sites, and years. For instance, the results in Sections 3.3.1 and 3.3.2 summarizing many classifications using a sequence of threshold values would not be possible with unsupervised or supervised classification methods. The ability to describe subtle differences in the spectral properties of diverse bed characteristics and environmental conditions using specific index values was critical to contextualizing sources of uncertainty in the spatial metrics used to track kelp forest distribution and trends.

4.3.2 Threshold selection uncertainty

While the spectral index threshold approach has many advantages, there were a number of challenges identified in this project as well. First among these was the tendency for the method to produce type I errors (false positive) from floating wrack, and in high-subtidal to low-intertidal regions due to benthic reflection and other species of marine vegetation. The impact of this type of error on canopy area results can be mitigated by excluding areas of high confusion from classification (Section 2.3.2, Table 8), however this means that final canopy metrics may not capture the full amount of the bull kelp canopy in very shallow areas.

Moreover, the Otsu's automated global threshold method tested in this project – which is analogous to algorithms used in other research classifying kelp canopies (Cavanaugh et al., 2021b; Timmer, 2022) – consistently resulted in classified canopy maps that overestimated the amount of canopy area. The reason for this appears to be that the percent canopy cover values of bull kelp beds in Puget Sound are so low that they disrupt the generation of the clean bimodal histograms of index values (Figure 25) that are required for a suitable threshold to be identified. This indicates that global binary threshold algorithms are likely to be unsuitable for delineating kelp canopy at beds in Puget Sound, and methods that consider localized spatial contexts may perform better.

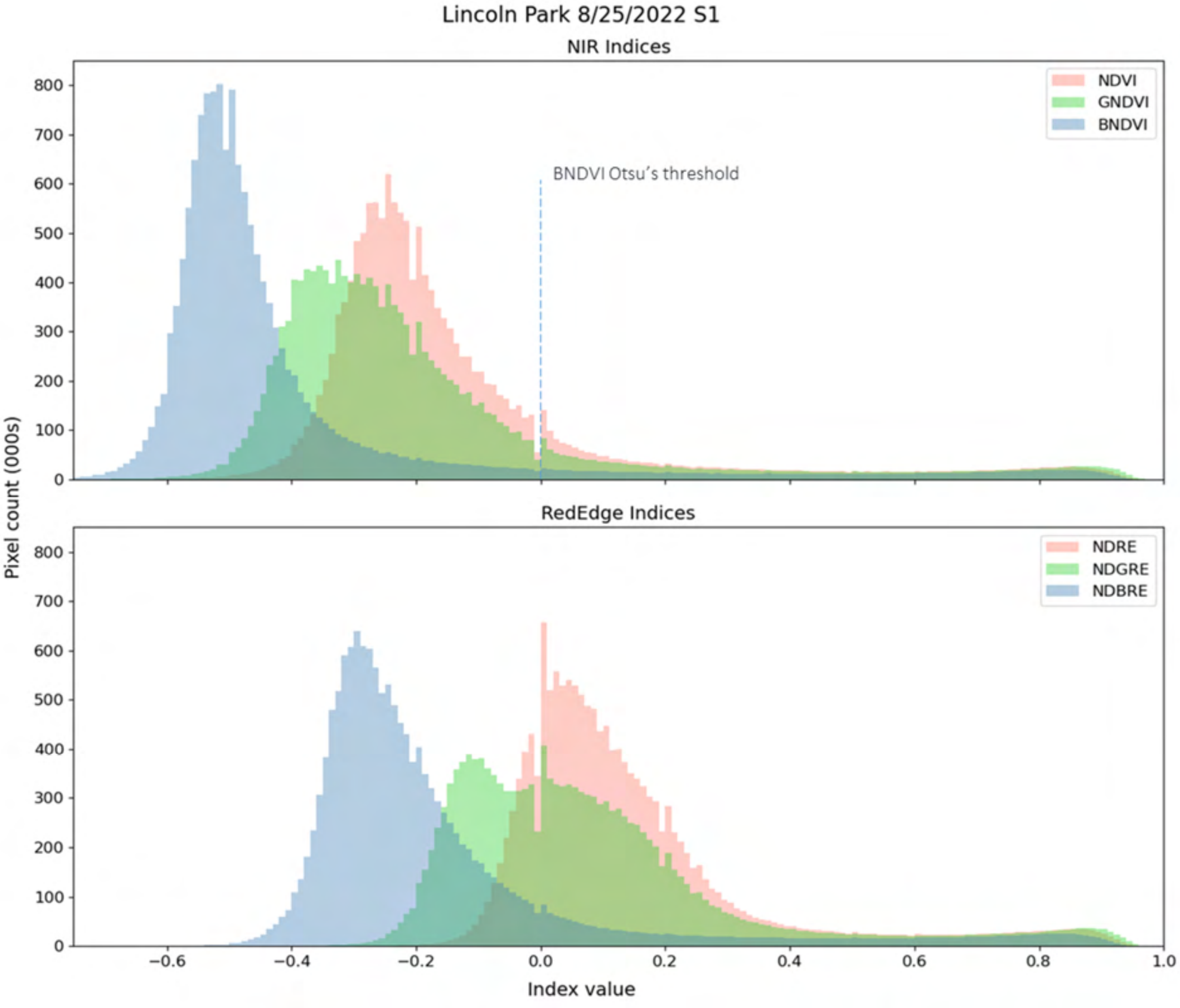


Figure 25. Histograms of index values for six NIR and red edge NDVI variant indices for a survey at Lincoln Park in 2022. Despite this being the site with the second highest percent cover of those included in this report, there is not a clear bimodal distribution in any of the six indices representing kelp pixels necessary for an automated binary threshold algorithm such as Otsu's method.

The selection of suitable BNDVI thresholds to differentiate kelp canopy from the surrounding environment used to generate final canopy metric estimates revealed the inherent tradeoff between type I (false positive) and type II (false negative) errors common in remote sensing. For each survey, the plausible BNDVI range represented values where increasing or decreasing the threshold value would overestimate kelp canopy in one way (e.g., around stipes) or underestimate it another (e.g., submerged blades). This made it necessary to weigh those impacts against each other as objectively as possible (Appendix B). Furthermore, because of the pronounced sensitivity of classification results around the edges of kelp plants in the low-density beds found in Puget Sound, differences between canopy areas estimates were often larger than expected (Figure 26). This resulted in an average difference of ~38% between the low and high plausible canopy area estimates across 17 of the 18 surveys in this project.

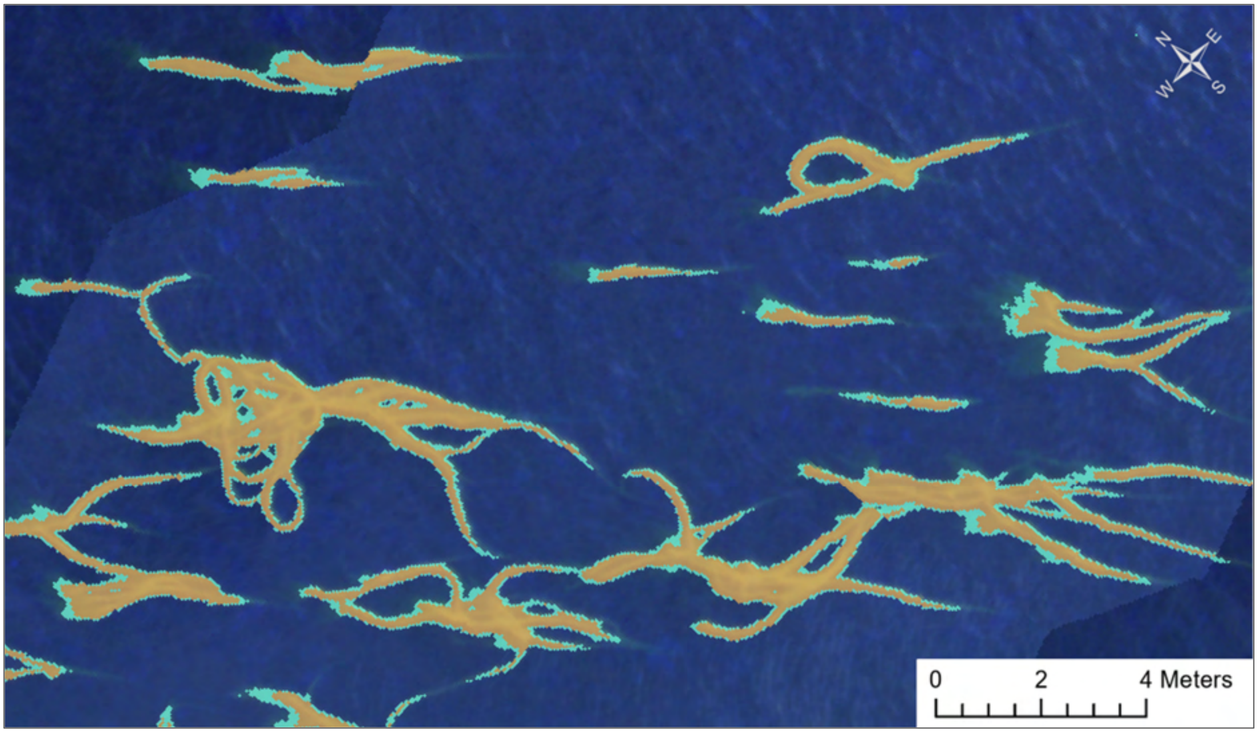


Figure 26. Patch of bull kelp canopy at Vashon Island in 2021 showing the canopy map resulting from low (light blue) and high (orange) plausible BNDVI thresholds. The canopy area estimates associated with the two thresholds are ~55% apart at 777 m^2 and 554 m^2 respectively.

Despite the challenges with selecting appropriate index thresholds, determining a range of plausible BNDVI threshold values allowed for the uncertainty associated with kelp forest canopy area metrics generated by NHP to be directly quantified for the first time. The sites surveyed for this project represent some of the smallest and lowest density kelp forests in Washington and therefore offer a theoretical worst case for the sensitivity of canopy area estimates to threshold selection. Furthermore, having a range of potential estimates for each survey offers insight into our power to detect change over time at a given monitoring site and will inform other canopy mapping efforts, such as those using kayaks and the piloted fixed-wing four-band nearshore imagery collected by DNR beginning in 2022.

4.4 Interannual canopy change assessments

The primary advantage the Nearshore Habitat Program sees in adding UAS surveys to its suite of survey methods of bull kelp forests is to provide a richer spatial picture of how kelp canopies are distributed over time. In particular, metrics calculated on classified UAS imagery like canopy area and comprehensive percent canopy cover are meaningful inclusions for annual survey records that are not as easily captured using other survey methods, particularly for the small and sparse beds common in Puget Sound. To evaluate the utility of these metrics, it was critical to not only generate estimates for individual surveys, but also to compare UAS-based canopy maps between years inclusive of the uncertainty associated with selecting BNDVI thresholds and timing surveys within a low tide window. This project provides a framework to conduct these comparisons at a site and sub-site level, with variable results detecting change between 2021 and 2022 at the four sites with multiyear data.

4.4.1 Vashon Island and Owen Beach

The analyses at Vashon Island and Owen Beach followed a similar theme. In terms of bed extent, Vashon Island appears to have remained fairly consistent, with a difference of only ~10% between 2021 and 2022, which was of the same magnitude as the disagreement between paired surveys there (Table 7). At Owen Beach, the signal of change was stronger with an estimated 15-50% increase in bed area between years. However, this site also had the highest degree of disagreement among paired surveys, with 13-14% difference in both years, introducing uncertainty into the magnitude of this increase. Still, even with that offset included, the potential increase in bed extent at Owen Beach between 2021 and 2022 is noteworthy.

At the site level, neither Vashon Island nor Owen Beach showed strong signals of changes in canopy area (Figure 16). At Vashon, canopy area was estimated to be 433-762 m^2 in 2021 and 409-844 m^2 in 2022. At Owen, the canopy area estimates were 121-212 m^2 in 2021 and 177-242 m^2 in 2022, although both the midpoint estimates at this site in 2022 were higher than both the midpoint estimates in 2021, a potential indication of increase. Sub-dividing each site into quadrants, some additional change indicators were revealed. In particular, canopy area in the shallow east quadrant at Vashon Island is estimated to have increased from ~100 m^2 in 2021 to ~186 m^2 in 2022 (Figure 17), far exceeding the estimated ~38% uncertainty associated with BNDVI selection found in this project. Similarly, the canopy area in the deep west quadrant at Owen Beach is estimated to have increased from ~22 m^2 in 2021 to ~84 m^2 in 2022 (Figure 19). These potential sub-site level changes are important and could serve as motivation to examine those portions of each site in greater detail to see what environmental conditions are present allowing for canopy expansion.

4.4.2 Lincoln Park

The bed extent mapped at Lincoln Park was among the most consistent of any of the sites included in this project (Table 7), with 1.79 ha in 2021 and 1.70-1.73 ha in 2022, as well as a ~93% spatial overlap among the paired surveys in 2022. However, canopy area estimates at this site diverged between years (Figure 16), with 863-1,156 m^2 in 2021 and 555-842 m^2 in 2022. Breaking down this canopy area result by quadrants, it became clear that the decrease was concentrated in the west half of the site, particularly the deep west quadrant (Figure 21). Midpoint canopy area estimates for the deep west quadrant were ~396 m^2 in 2021 and ~182 m^2 in 2022 (~74% difference relative to average), and ~735 m^2 and ~407 m^2 for west half of the site combined (~57% difference relative to average).

One confounding factor in this analysis is that the survey in 2021 showed persistent false positives in the classification result due to floating wrack intermingled in the kelp canopy, particularly in the west half of the site (Appendix A). Based on visual inspection alone it was difficult to assess how much this may have inflated the canopy area estimates for Lincoln Park in 2021, but it does challenge interpretation of the magnitude of the estimated decrease. A potential method for disentangling the false positives would be to run another classification on the multispectral imagery specifically targeting the area of wrack. This could provide additional context as to the likelihood of a canopy area decrease at the site between years. The accumulation of drifting wrack is common at this site, especially on flood tides (pers. obs.). Therefore, it may be necessary to conduct multiple surveys per season in future years in order to ensure that the monitoring record is less impacted by false positives in the canopy area result.

4.4.3 North Beach

Of the four sites surveyed in both 2021 and 2022, estimates at North Beach showed the largest signal of change in canopy area (Table 10). The lowest estimate for canopy area in 2021 was 7,727 m^2, while the highest estimate in 2022 was 4,191 m^2, conservatively representing a decrease of at least 46% between years. In the sub-site analysis, the majority of this decrease was detected in the two shallow quadrants, where canopy area dropped from ~6,255 m^2 to ~1,054 m^2 between 2021 and 2022 (Figure 23). A decrease in the deep east quadrant and increase in the deep west quadrant roughly cancelled each other out, resulting in a difference of just 50 m^2 between years in the deep half of the site. Given that bed extent at this site did not substantially change between 2021 and 2022 (Figure 10) the decrease appears to be mostly due to a drop in plant density, which would corroborate accounts from volunteers with the Jefferson County Marine Resources Committee who monitor the site by kayak (J. Ledbetter, pers. comm.).

However, there are two confounding variables that complicate this assessment. First, the UAS surveys in 2022 were conducted at a higher low tide (+0.2 m MLLW) than the one conducted in 2021 (-0.6 m MLLW) (Appendix A). This difference in tidal height could account for some of the difference in visible canopy, particularly in the shallows where density was the highest in 2021. Furthermore, the survey in 2021 was conducted on August 20th while the two in 2022 were conducted on September 22nd. While not far beyond NHP’s established window for kelp surveys (ends September 15th), this one month offset could mean that some of the bull kelp had already begun to senesce by the time the 2022 surveys were conducted. Conducting a survey at North Beach in August of 2024, or potentially multiple times throughout the summer, would be a meaningful first step towards continuing to assess change at this site.

4.4.4 Utility of quadrant analyses

Overall, comparing canopy area results at the quadrant level generate important additional findings. At Vashon Island and Owen Beach, the signals of change in canopy area between years were not particularly strong when looking at the sites as a whole, but both sites had one quadrant with a large increase in canopy area between years. At Lincoln Park, there was a weak signal of canopy area decrease between years at the site level, and a clearer one in the west half of the site following the partitioning of results into quadrants. This prompted closer investigation of the classification results and revealed a potentially significant source of error (i.e., classification confusion with floating wrack). Finally at North Beach, a large change between years site-wide was parsed such that the change detection was focused to the shallow half of the site. This type of information could be critical in studies of potential stressors or drivers of change in bull kelp forest distribution at sites where UAS surveys are conducted. In addition, with more years of data a richer picture of the interannual variability of bull kelp forest canopies can be constructed, including whether some sections of beds change more from year to year than others. In the future, these methods of sub-dividing canopy area results could be augmented to account for differences in bed size and site geography, but the benefits of examining canopy distribution in a more detailed way are clear.

4.5 Future work

This report marks a significant step forward in DNR's kelp monitoring capabilities by demonstrating methods to efficiently analyze multispectral UAS surveys and detect temporal change in bull kelp distribution and abundance at study sites, while also evaluating the strengths and weaknesses of index threshold-based canopy classification. There are many ways this work can continue to evolve from here.

First, a myriad of other classification techniques exist that could be tested against the method used in this project. In particular, other algorithms could be better at selecting thresholds in an automated fashion and accounting for differences in local contexts within a survey, rather than the global index value distributions. Eventually, there is a high likelihood that the type of UAS surveys in this project could be classified using machine learning segmentation tools trained to identify floating kelp in high resolution multispectral imagery. There already exists one such tool trained for RGB UAS imagery called Kelp-O-Matic (Denouden et al., 2021) and researchers at the Hakai Institute who created it are currently developing a similar tool for multispectral imagery (Reshitnyk, pers. comm.).

Another future undertaking that will be critical for long-term monitoring of bull kelp forests in Puget Sound with remote-sensing platforms is to assess all the disparate sources of uncertainty that can impact kelp canopy measurements and combine them into a comprehensive model. These include environmental factors included in this report such as tide height and currents, but also wind waves, incident light conditions, site characteristics such as the depth distribution and density of individual plants, and changes to the canopy area of bull kelp that result from its annual life cycle. Efforts to assess each of these could rely on repeat surveys of the same site many times within a season and in a variety of conditions. From there, relative impacts could be weighted and fit to ranges of canopy area results such as those generated in this report, in order to assign confidence levels to kelp forest metrics and evaluate temporal changes.

The Nearshore Habitat Program plans to continue surveying bull kelp forests in Puget Sound and beyond with multispectral UAS as one component of its statewide monitoring program, and foresees that a multifaceted approach will be needed to effectively monitor floating kelp throughout the state and address different research questions. For example, while fixed-wing aerial imagery is more efficient at gathering data at a regional scale, UAS are better suited to surveying small low-density beds common in Puget Sound. In addition, UAS surveys can be combined with *in situ* kayak-based surveys to produce annual survey records with greater data richness including not only bed extent and canopy area, but also plant condition, morphology, and species identification. Overall, through the integration of UAS surveys within its broader kelp monitoring program, NHP aims to efficiently and accurately detect changes in the distribution and abundance of bull kelp forests throughout Washington State. The results of this multi-tiered monitoring will inform responsible stewardship of public lands and environmental policy development, and support the conservation of these vital ecosystems.

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Appendix A: Survey conditions record

The following table includes the environmental conditions under which each of the 18 surveys included in this report were conducted. These include date, time, predicted tides, and sun altitude angle. Other conditions that are recorded during each survey but not included here are photos of cloud cover and general weather observations.

Table A1. Environmental conditions present during UAS surveys.

Site	Year	Survey	Date	Time start	Time end	Tide start (m)	Tide end (m)	Low tide time	Low tide (m)	Sun angle start (deg)	Sun angle end (deg)
Lincoln Park	2021	S1	7/21/2021	8:46	9:15	-0.7	-0.7	9:18	-0.7	29.9	34.8
	2022	S1	8/25/2022	9:42	10:25	0.0	-0.1	10:34	-0.2	32.7	39.2
		S2		10:44	11:27	-0.1	0.0			41.8	47.0
Owen Beach	2021	S1	8/18/2021	7:43	8:18	-0.4	-0.4	8:06	-0.4	14.4	20.3
		S2		8:25	8:43	-0.4	-0.3			21.5	24.5
	2022	S1	9/7/2022	8:27	9:03	-0.4	-0.5	8:58	-0.5	17.7	23.6
		S2		9:13	9:49	-0.5	-0.3			25.2	30.8
North Beach	2021	S1	8/20/2021	8:42	9:33	-0.6	-0.5	8:56	-0.6	23.7	31.9
	2022	S1	9/22/2022	8:02	8:45	0.2	0.2	8:36	0.2	9.9	16.7
		S2		8:54	9:37	0.2	0.3			18.1	24.6
Vashon Island	2021	S1	8/21/2021	9:58	10:41	-0.5	-0.6	10:43	-0.6	36.0	42.3
		S2		10:47	11:06	-0.6	-0.6			43.1	45.6
	2022	S1	8/24/2022	9:17	9:56	0.0	-0.1	9:55	-0.1	29.0	35.1
		S2		10:06	10:45	-0.1	0.0			36.6	42.2
Hansville	2022	S1	8/26/2022	10:08	10:59	0.0	-0.2	11:00	-0.2	36.2	43.1
		S2		11:03	11:54	-0.2	0.0			43.6	48.9
Hat Island	2022	S1	9/9/2022	10:01	11:18	-0.4	-0.4	10:38	-0.5	31.8	41.3
		S2		11:22	11:58	-0.4	-0.1			41.7	44.7

Appendix B: BNDVI threshold range values

The following tables contain lists of BNDVI threshold values that were selected as suitable to separate floating kelp canopy from the surrounding environment in all 18 UAS surveys included in this project. Each list contains the low and high end of a survey's identified BNDVI range and the step value just outside that range on both ends, as well as detailed observations with regard to the balancing of type I and type II errors in classification that led to the selections. Rows marked "Out – low" and "Out – high" represent the step values just outside the identified range.

Table B1. BNDVI threshold range values for surveys conducted at Lincoln Park.

Site	Year	Survey	Index range condition	BNDVI value	Observations
Lincoln Park	2021	S1	Out – low	0.00	Overestimates around stipes, particularly where tangled, many false positives throughout survey
			Low	0.05	Tight around most stipes, some false positives from floating material, missing small amount of stipes in north bed, few blades visible in general throughout survey
			High	0.15	Tight around all stipes, missing some submerged stipes throughout survey, still some false positive from floating detritus in south bed
			Out - high	0.20	Starting to underestimate stipes throughout survey, very few false positives other than piled up detritus in bed
	2022	S1	Out – low	0.35	Significant overestimation around kelp stipes, many false positives throughout survey
			Low	0.40	Missing small amount of blades, tighter around kelp plants, some false positive floating debris
			High	0.55	Very little overestimation, removal of most false positives, more of blades beginning to be missed
			Out - high	0.60	Beginning to lose large portions of visible canopy

2022	S2	Out – low	0.65	Overestimation around kelp, lots of false positives
		Low	0.70	Tight around kelp, some false positives from flotsam, minimal missing blade tissue
		High	0.80	Tight around kelp, minimal false positives, more blades starting to be lost
		Out - high	0.85	Beginning to lose large portions of visible kelp canopy

Table B2. BNDVI threshold range values for surveys conducted at Vashon Island.

Site	Year	Survey	Index range condition	BNDVI value	Observations
Vashon Island	2021	S1	Out – low	-0.05	Significant overestimation around stipes, many false positives
			Low	0.00	Missing very small amount of blades, some false positive around stipes
			High	0.20	Very little overestimation, removal of most false positives, more blades missing
			Out - high	0.25	Beginning of noticeable false negatives of blades and stipes
	2021	S2	Out – low	0.10	Significant overestimation around kelp stipes, some false positives
			Low	0.15	Generous around stipes, little bit of ends of blades missing
			High	0.30	Slight overestimation around stipes still, many missing blades
			Out - high	0.35	Beginning to lose many stipes and blades throughout survey
	2022	S1	Out – low	0.05	Generous around stipes, prominent false positives from floating debris
			Low	0.10	Tight around stipes, minimal blade loss, some false positives from floating debris
			High	0.40	Starting to lose some blades, less false positives
			Out - high	0.45	False positives minimized but losing much more of visible blades
	2022	S2	Out – low	0.40	Generous around stipes, many false positives throughout survey
			Low	0.45	Some overestimation around stipes but less false positives
			High	0.70	Tight around stipes, losing some visible blades in places
			Out - high	0.75	Losing lots of blades and even some stipes in many places throughout survey

Table B3. BNDVI threshold range values for surveys conducted at Owen Beach.

Site	Year	Survey	Index range condition	BNDVI value	Observations
Owen Beach	2021	S1	Out – low	-0.05	Overestimates around stipes in more than half of the survey
			Low	0.00	Conservative on west side of survey, generous on east side
			High	0.10	Conservative throughout survey, missing some blades
			Out - high	0.15	Misses most blades throughout survey and some stipes as well
	2021	S2	Out – low	0.40	Significant overestimate around stipes, some false positives
			Low	0.45	Generous around stipes throughout survey area
			High	0.55	Tight around stipes, missing blades in many places
			Out - high	0.60	Misses blades throughout survey and some stipes as well
	2022	S1	Out – low	0.35	Overestimate stipes throughout, missing some visible but very submerged blades
			Low	0.40	Overestimate around stipes on east side of survey, missing some blades
			High	0.50	Tight around most stipes, starting to lose more blades
			Out - high	0.55	Missing many more blades, some stipes are being lost too
	2022	S2	Out – low	0.25	Overestimation around most stipes, no missing blades
			Low	0.30	Tight around most stipes, minimal missing blades
			High	0.45	Tight around all stipes, missing some blades on east side of survey
			Out - high	0.50	Significant blade loss, particularly east side of survey

Table B4. BNDVI threshold range values for surveys conducted at Hansville.

Site	Year	Survey	Index range condition	BNDVI value	Observations
Hansville	2022	S1	Out – low	-0.15	Overestimation throughout survey, significant false positives
			Low	-0.10	Slight overestimation on east side of survey, missing some blades on west, much less false positives
			High	0.00	Tight around all stipes, missing ends of blades throughout though
			Out - high	0.05	Missing blades throughout, some submerged stipes in deep extent as well
	2022	S2	Out – low	0.15	Overestimation in most of survey, significant false positives
			Low	0.20	Tight around stipes, missing some blades, minimal false positives
			High	0.30	Missing more blades throughout and some deep edge submerged plants
			Out - high	0.35	Missing more blades and some stipes, more deep edge submerged too

Table B5. BNDVI threshold range values for surveys conducted at North Beach.

Site	Year	Survey	Index range condition	BNDVI value	Observations
North Beach	2021	S1	Out – low	0.00	Overestimates around stipes, particularly in shallows, missing many blade ends throughout survey, some minor false positives in shallows
			Low	0.05	Slightly generous around some stipes, missing more blade ends, minimal false positives
			High	0.20	Tight around stipes, missing more blades and some submerged stipes
			Out - high	0.25	Missing majority of blades for scattered plants, missing some submerged individuals altogether in deep water
	2022	S1	Out – low	0.25	Slight buffer around deeper stipes in places, scattered false positives, decent blade coverage, though some ends still missing
			Low	0.30	Tight around most stipes, false positives largely minimized, very ends of blades missed in many places
			High	0.50	Tight around stipes, moderate blade loss throughout survey
			Out - high	0.55	Still capturing most stipes but blade loss apparent throughout survey
	2022	S2	Out – low	0.05	Generous around stipes, particularly deeper, scattered false positives, minimal blade loss at ends in some places
			Low	0.10	Minimal buffer around most stipes, less false positives, some blade ends missing in places
			High	0.25	Tight around almost all stipes, false positives gone, more blades missing throughout survey
			Out - high	0.30	Tight around stipes, but blade loss apparent throughout survey

Table B6. BNDVI threshold range values for surveys conducted at Hat Island.

Site	Year	Survey	Index range condition	BNDVI value	Observations
Hat Island	2022	S1	Out – low	-0.10	Generous around surface stipes and blades, missing some submerged plants but also false positives spread throughout
			Low	-0.05	Tighter around most surface kelp, missing slightly more submerged blades and plants, significantly less false positives
			High	0.10	Tight around all surface tissue, minimal false positives, missing more blades
			Out - high	0.15	Missing much of visible surface canopy throughout survey
	2022	S2	Out – low	0.05	Generous around some surface kelp, significant false positives, missing some submerged blades and plants
			Low	0.10	Tight on surface kelp, less false positives, missing more submerged blades
			High	0.30	Conservative on surface kelp, minimal false positives, missing many more submerged blades and plants
			Out - high	0.35	Virtually no false positives, missing significant portion of canopy across survey