NATURAL RESOURCES

Kelp Forest Canopy Surveys with Unmanned Aerial Vehicles (UAVs) and Fixed-Wing Aircraft:

a demonstration project at volunteer monitoring sites in northern Puget Sound

Final report to the Northwest Straits Commission

IAA 93-102466

December 31, 2021

WASHINGTON STATE DEPT OF NATURAL RESOURCES

Northwest Straits Commission

partners in marine conservation

The Nearshore Habitat Program is part of the Washington State Department of Natural Resources – Aquatic Resources Division, and supports the agency's work to ensure environmental protection of Washington's 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 photos: Imagery collected by multispectral UAV at the Edmonds volunteer kelp monitoring site, with the kelp canopy visible in red and various bed perimeter delineation polygons overlaid (top). Imagery collected by fixed-wing aircraft along the shoreline from McCurdy Point to Point Wilson, near Port Townsend, with the kelp forest canopy visible in light red in the shallow subtidal zone (bottom).

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Aquatic Resources Division
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http://www.dnr.wa.gov/programs-and-services/aquatics/aquatic-science/nearshore-habitat-publications

Contents

Executive summary

Kelp is a type of marine algae that is a foundation of nearshore ecosystems and has experienced declines in portions of Puget Sound. This report summarizes a kelp canopy monitoring demonstration project conducted by two agencies with stewardship responsibilities for kelp in Washington State marine waters. The Washington Department of Natural Resources (DNR) manages state-owned aquatic lands for the benefit of current and future residents of Washington State. DNR's stewardship work includes long-term monitoring of kelp forests. The Northwest Straits Commission (NW Straits) coordinates local ecosystem focused activities in northern Puget Sound, which includes supporting volunteer-based kelp canopy monitoring through Marine Resource Committees (MRCs) in seven counties.

This demonstration project investigated how aerial imaging platforms could potentially enhance the existing kayak-based bull kelp canopy monitoring program conducted by MRC volunteers. Airplanes and Unmanned Aerial Vehicles (UAVs or drones) have been used successfully to survey kelp and other vegetation in the past. We explored aerial imagery collection and processing in the context of field and office resources available to project partners and the region where they work. We compared imagery-derived estimates of kelp canopy and kelp bed area from multiple platforms to bed perimeter surveys by MRC volunteers and to DNR's quadrat-based estimates of canopy area, bed area, and percent cover.

Key findings:

The demonstration project successfully acquired and processed imagery from a variety of aerial platforms at MRC kelp canopy monitoring sites in northern Puget Sound. While exploratory, the results illustrate the strong potential benefits of using UAV and fixed-wing platforms to monitor bull kelp canopies. The results also highlight priorities for further methodological development. Key findings are reported in terms of research questions:

1. **Can the project partners effectively collect and process kelp canopy imagery in the MRC study areas using aerial platforms and processing tools accessible to them?**

   We collected imagery at 9 MRC sites which represent a range of conditions for aerial imagery collection: North Beach, Edmonds, Ebey's Landing, Possession Point, Point Partridge, Alden Bank, Point Whitehorn, Cherry Point, and Polnell Point.

   We tested multiple aerial platforms and spectral band combinations. A DJI Phantom 4 Multispectral UAV collected 5-band multispectral imagery, and we simulated red, green, blue (RGB) imagery from this data as an additional comparison. A low-cost MAPIR Survey3W camera affixed to the underside of a volunteer's aircraft collected near-infrared, green and blue (NGB) imagery. A DJI Matrice 200 UAV carrying a MicaSense RedEdge MX camera collected 5-band multispectral imagery (these data were not processed for this project due to funding limitations).

We produced orthomosaics, classified kelp canopies, and compared imagery results at two diverse kelp forest sites (Edmonds and North Beach) using imagery from multiple platforms.

2. **What are the relative strengths of UAVs and fixed-wing platforms for kelp surveys?**

   The primary tradeoff between UAV and fixed-wing platforms was pixel resolution and areal coverage. The higher resolution of UAVs (6.1-8.5 cm pixels) brought higher confidence in kelp detection. Fixed-wing imagery offered lower resolution (~21-30 cm pixels), but the ability to collect and process data more efficiently over larger areas. We identified a general size threshold for UAV surveys at ~100 hectares for a single low tide survey and less than 300 m in width for successful orthomosaic stitching.

   Fixed-wing platforms are more expensive in terms of upfront capital expenses, making volunteer pilots an important resource to minimize aircraft costs.

   The lightweight, compact Phantom 4 UAV proved to be more versatile than the larger and heavier Matrice 200 UAV, and could be easily deployed from a small boat or carried to 'walk-in' sites.

3. **How do estimates of kelp surface canopy area generated from aerial imagery compare among platforms and to ground-based methods?**

   We first ranked the accuracy of three platforms at two sites in terms of how well supervised classification of kelp canopy matched human interpretation. Classification performed better in open water than in shallow areas, where confusion with other vegetation occurred. Overall accuracy of kelp canopy classification of each platform at the two analysis sites were:

Platform	Edmonds	North Beach
Phantom 4 multispectral	91%	89%
Fixed-wing NGB	88%	89%
Phantom 4 RGB	67%	77%

   Estimates of kelp canopy area varied by a factor of two among the aerial platforms, relative magnitudes were not consistent between sites. Ground-based estimates from quadrat samples were as much as three times larger:

	Surface Canopy Area	
Platform	Edmonds (ha)	North Beach (ha)
Phantom 4 multispectral	0.25	1.78
Fixed-wing NGB	0.29	2.16
Phantom 4 RGB	0.47	1.08
DNR quadrat samples	0.93	3.04

4. **How do imagery and boat-based estimates of kelp bed location and area compare? (Term *kelp bed* encompasses the floating canopy and space between adjacent plants)**

   There was general agreement among methods in the overall spatial extent of the kelp bed. Semi-automated and hand-delineated bed area estimates derived from the imagery ranged widely though, from 50% to 100% of MRC kayak survey estimates. Generalized estimates of bed extent derived from DNR transects were consistently the largest:

	Bed Area (canopy and gaps)	
Platform	Edmonds (ha)	North Beach (ha)
Phantom 4 RGB hand delineated	3.32	9.22
Phantom 4 RGB automated	3.45	7.37
Phantom 4 Multi automated	3.33	7.94
Fixed-wing NGB hand delineated	1.65	9.14
Fixed-wing NGB automated	1.57	5.24
MRC kayak perimeters	3.27	10.27
DNR generalized bed extent	8.25	13.95

   The imagery identified that potential refinements could be made to MRC kayak-based bed delineations. The MRC kayak perimeter agreed more closely with the imagery and the DNR quadrat samples at Edmonds than at North Beach. Bed characteristics may be driving the difference: Edmonds is a small and narrow fringing kelp bed with pronounced boundaries. North Beach is an extensive bed with low density areas and kayak volunteers have reported that perimeter mapping there is challenging.

   Ground-based delineation is more successful at differentiating kelp canopy from other vegetation. In the intertidal and shallow subtidal areas, DNR quadrat samples and MRC kayak perimeters more reliably differentiated kelp from other vegetation.

   Discrepancies between results were sometimes associated with non-optimal field conditions. Further refinement of data collection windows, especially for currents, could decrease uncertainty.

5. **What opportunities and challenges exist related to further development of UAV or fixed-wing imagery to enhance MRC volunteer kelp canopy monitoring?**

   Further methodological development is needed. This project demonstrated the strength of aerial imagery to describe canopies spatially. It also found that imagery-based canopy area estimates varied widely with equipment, field conditions, and processing techniques.

   Compared to kayak-based monitoring, aerial imaging techniques require substantially more equipment, technical expertise and data processing. Kayak-based surveys are likely to remain preferable for most volunteers.

   Opportunities exist for NW Straits and MRCs to augment kayak surveys using information about canopy abundance and spatial structure from aerial imagery. Specific projects will depend on the programs' strategic direction and available resources:

   - Aerial imagery can provide insights for refining kayak-based surveys by comparing imagery to field survey results.

- Imagery could be collected at MRC sites on a prioritized or rotating basis to augment annual kayak surveys.
- Fixed-wing surveys could provide larger areal context for the kayak sites, if volunteer pilot are available.
- Analysis of existing photography could fill knowledge gaps. For example, approximately 10 years of low tide overflight imagery exist for Island County, collected by volunteer pilot Gregg Ridder.

There is an interactive ESRI ArcGIS StoryMap that serves as a companion to this report. Here, users can interact with imagery and data products generated during the course of this project. The link to that can be found at: https://storymaps.arcgis.com/stories/9daebbe14134440290e87bb77d2feb75

1 Introduction

1.1 Bull Kelp in Puget Sound: Ecosystem Role and Trends

Kelp refers to large brown seaweeds in the order Laminariales. More than 20 species of kelp occur in Washington State (Mumford, 2007), and while most of these are understory species a couple form forests of floating canopies ten meters or more in height. Kelp forests provide critical habitat to a wide range of species and perform many foundational ecosystem functions including primary production and the cycling of nitrogen (Klinger, 2015; Schiel & Foster, 2015; Teagle et al., 2017). Kelp also are sensitive to a variety of environmental conditions such as water temperature, pH, currents, and nutrient availability that can impact their growth and reproduction (Bolton et al., 2010; Krumhansl et al., 2016; Hollarsmith et al., 2020).

In Puget Sound, bull kelp (*Nereocystis luetkeana*) is the primary kelp species that forms floating canopies. Bull kelp has experienced major declines compared to historical extents within portions of the southern Salish Sea (Berry et al., 2021), while little is known about trends in other kelp species. Projected future impacts of climate change and population growth pose profound current and future threats to kelp populations (Harley et al., 2012; Verges et al., 2016; Wernberg et al., 2016; Rogers-Bennett & Catton, 2019; Smale et al., 2019). In 2020, a diverse partnership of organizations, communities, tribal nations and individuals defined actions to protect and restore kelp in the Puget Sound Kelp Conservation and Recovery Plan (Calloway et al., 2020). Among its strategic goals, the Kelp Plan calls for expansion of monitoring efforts in order to meet management and research needs for greater understanding of kelp status and trends.

1.2 DNR and NW Straits Commission

This report describes a kelp canopy monitoring demonstration project conducted by two agencies with stewardship responsibilities for kelp in Washington State marine waters. The Washington Department of Natural Resources (DNR) is the state steward of 2.6 million acres of state-owned aquatic land. DNR manages aquatic lands for the benefit of current and future residents of Washington State. As part of this responsibility, DNR's Nearshore Habitat Program monitors the health of nearshore marine vegetation and other indicators of habitat health along Puget Sound's shorelines.

The Northwest Straits Commission (NW Straits) coordinates ecosystem-focused activities in northern Puget Sound using a unique approach that bridges local governments through the Northwest Straits Marine Conservation Initiative. As part of its regional actions, the NW Straits coordinates volunteer-based kelp canopy monitoring through Marine Resource

Committees (MRCs) in seven counties in Washington State. This citizen monitoring project has the potential to increase community engagement and to improve understanding of trends in canopy-forming kelp in the region.

1.3 Kelp Canopy Surveys with Aerial Imagery

Aerial photography is an established tool for aquatic vegetation mapping. This is due to the ability of camera sensors to distinguish photosynthetic pigments spectrally from the surrounding environment, and because imagery enables detailed examination of canopy abundance and structure (Deysher, 1993; Fox et al., 1996; Stekoll et al., 2006; Van Wagenen, 2015). Satellite platforms have also proven effective for detecting large floating kelp canopies that are not intermixed with other vegetation in areas such as southern California where environmental conditions regularly provide limited cloud cover, consistent tidal heights and low currents (Cavanaugh et al., 2011; Bell et al., 2020; Finger et al., 2021; McPherson et al., 2021).

In areas that regularly have unfavorable conditions for image collection such as Washington State, fixed wing platforms have advantages because they can be deployed during narrow time windows when environmental conditions are suitable (Pfister et al., 2018). In recent years, UAV platforms have shown great potential to efficiently map kelp canopies at very high resolutions (Thomsen et al., 2019; Rossiter et al., 2020; Cavanaugh et al., 2021). Like fixed-wing aircraft, UAVs can be deployed rapidly during limited sampling windows. UAVs have lower upfront cost than fixed-wing platforms, although fixed-wing platforms can achieve economies of scale by covering larger areas (Manfreda et al., 2018). The availability of off-the-shelf sensor technology with bands in the infrared spectrum suited to identifying and assessing vegetation has also increased dramatically in recent years.

While modern technological advances in aerial platforms, sensors, and processing tools have improved the ability to detect kelp in aerial imagery, challenges posed to image classification by environmental conditions such as sun glint and waves still remain (Schroeder et al., 2019; Cavanaugh et al., 2021). The interpretation of image-based survey results of marine habitats in particular is also challenging due to environmental sources of classification uncertainty such as tidal height, currents, sea state, water penetration depth, and co-occurrence with other algal species.

Project Objectives

The overall goal of this demonstration project was to explore the potential of applying new aerial imaging technologies for kelp monitoring in the specific context of the project partners' existing work (e.g. regional environmental conditions and accessible equipment and data processing tools). Puget Sound has distinct challenges for imagery collection and the project partners have different institutional goals and resources compared to academic environments where similar research often takes place. Specific research questions that were explored:

- Can the project partners effectively develop the capacity to collect and process kelp canopy imagery in the MRC study areas, using aerial platforms and processing tools that are accessible to them?
- What are the relative strengths of UAVs and fixed-wing platforms for kelp surveys?
- How do semi-automated kelp canopy classification results compare between platforms and spectral band combinations?
- How do imagery-based and ground-based estimates of kelp bed location and area compare?
- What opportunities and challenges exist related to further development of UAV or fixed-wing imagery to enhance MRC volunteer kelp canopy monitoring?

2 Methods

2.1 Study Area

Our study area for this project was northern Puget Sound, a sub-region of the Salish Sea (Figure 1). The Salish Sea is a large estuarine ecosystem that encompasses Puget Sound, the Strait of Georgia, and the Strait of Juan de Fuca, and is characterized by strong circulation and relatively rapid water renewal and flushing, particularly nearest to the latter of these three sub-regions (Sutherland et al., 2011; MacCready et al., 2021). This exchange is important to the circulation of fresh nutrients and colder deep-ocean water that feed nearshore ecosystems and support species such as bull kelp.

Aerial imagery collection locations were selected from the pool of kayak-based kelp canopy monitoring sites established by the NW Straits volunteer kayak monitoring program. The primary goal was to select sites in the MRC's areas of interest that represent a wide range of bed characteristics and physical conditions in order to explore how field logistics and collected imagery varied.

Two sites with relatively long data records were chosen for detailed analysis: Edmonds and North Beach. At these sites, the precise locations of site boundaries have varied from year to year. The site polygons used in this report were jointly delineated by DNR and the MRC volunteers in Fall 2021 to encompass the spatial extent that was consistently surveyed in multiple years.

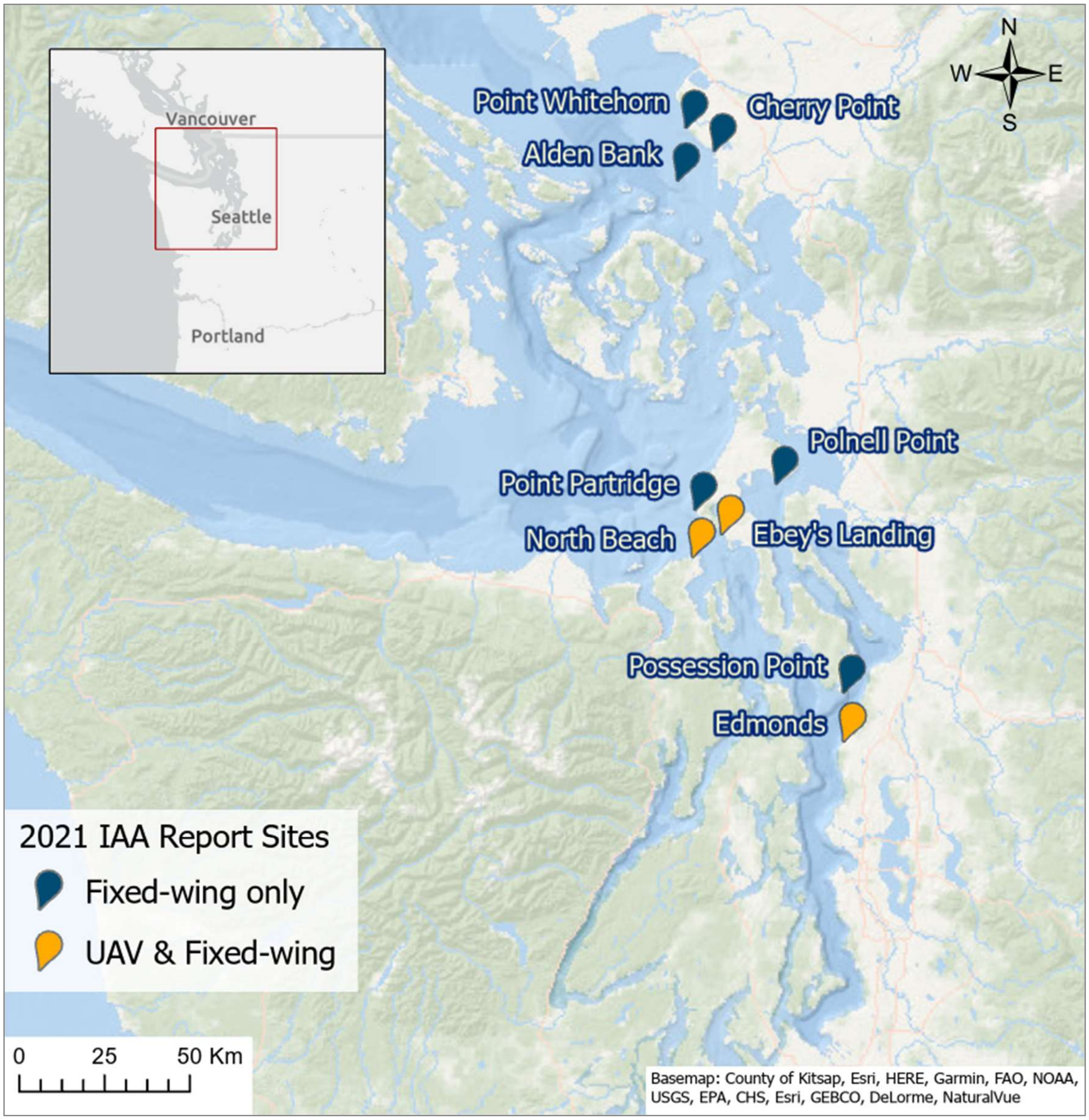


Figure 1. Map of the northern Puget Sound study region showing kelp forest sites that were surveyed using aerial imaging platforms. Dark blue markers represent sites surveyed only by fixed-wing aircraft, and lighter orange markers ones that were surveyed with both fixed-wing aircraft and UAV.

2.2 Aerial Image Collection

2.2.1 Survey window planning

UAV and fixed-wing aircraft surveys were conducted between July and September of 2021 within one hour of low tide, on days where low tides were lower than or equal to 0.0 m mean lower low water (MLLW). This general temporal window has been defined by DNR for boat-based surveys as the period of maximum kelp canopy visibility and to minimize the impact of tidal currents (Britton-Simmons et al., 2008). Sun angles of less than 45 degrees were also targeted in order to minimize sun glint (Nahirnick et al., 2018). The narrow confluence of both suitable low tides and sun conditions considerably limited the number of potential survey days.

Other environmental considerations when planning surveys included wind and general weather conditions. On days with moderate to heavy rain or wind speeds higher than 5 m/s forecasted, surveys were postponed.

2.2.2 UAV surveys

UAV equipment and flight control

The primary unmanned aerial vehicle (UAV) used for this project was a DJI Phantom 4 Multispectral (P4M) quadcopter (DJI, Nanshan, Shenzhen, China) carrying the stock DJI multispectral camera that collects imagery in five spectral bands (Table 1). Flight plans for the P4M were planned and executed using the application DJI GS Pro (DJI, Nanshan, Shenzhen, China). Survey grids of parallel lines were flown at an altitude of 85-120 m above ground level (AGL), with 75% overlap in ground coverage both along (frontlap) and across (sidelap) survey track lines, resulting in a pixel resolution of 4.5-6.4 cm.

The second UAV deployed for one of the two surveys at North Beach was the DJI Matrice 200 quadcopter (DJI, Nanshan, Shenzhen, China) carrying a MicaSense RedEdge MX multispectral camera (MicaSense, Seattle, Washington, USA), which also captures imagery in five spectral bands (Table 1). The Matrice 200 was deployed using the software DroneDeploy (DroneDeploy, Santa Clara, California, USA). This flight was conducted at an altitude of 50 m, with 75% frontlap and 70% sidelap, resulting in a pixel resolution of 2.8 cm.

Table 1. Specifications of the sensors for three cameras used in this project.

Camera	Spectral Bands (nm)						
	Blue	Green	Red	Red edge	Near-infrared	sensor megapixels	Field-of-view
Phantom 4 Multispectral	434-466	544-576	634-666	714-746	814-866	2.08	62.7°
MicaSense RedEdge MX	459-491	547-574	661-675	711-723	814-871	1.23	47.2°
MAPIR Survey3W NGB*	475	550	N/A	N/A	850	12.19	84.6°

*MAPIR does not specify band width information for its cameras

The parameters above were chosen based on comparable UAV mapping efforts in nearshore marine environments found in the peer-reviewed literature (Nahirnick et al., 2018; Doughty & Cavanaugh, 2019; Taddia et al., 2019), as well as from experience gained during survey efforts with a similar UAV platform the prior year (Cowdrey, 2021). In order to ensure complete coverage of each kelp bed area of interest in the imagery, kelp canopy perimeters generated from kayak surveys conducted in previous years by NW Straits MRC volunteers and DNR scientists were referenced to determine the extent of the survey grid patterns.

In total, five surveys of floating kelp canopies using UAVs were conducted at three NW Straits MRC volunteer monitoring sites in July and August 2021 (Table 2). One survey at Edmonds on July 20, 2021 had to be cut short due to rain. The first survey attempted at North Beach on July 7, 2021 had to be cancelled due to persistent low cloud cover and heavy misting conditions that made it impossible to fly in compliance with FAA guidelines that require the maintaining line-of-site of the UAV during flight.

Table 2. List of the six attempted UAV surveys at three MRC sites. Four surveys were successfully completed.

Site	Date	Platform	Areal coverage	Flight time	Altitude
Edmonds	7/20/2021	P4 Multispectral	45.8 ha*	37 mins	120 m
	8/5/2021	P4 Multispectral	45.8 ha	41 mins	120 m
North Beach	7/7/2021	P4 Multispectral	N/A**	N/A	N/A
	7/21/2021	Micasense RedEdge MX	26.1 ha	61 mins	50 m
	8/20/2021	P4 Multispectral	30.2 ha	51 mins	85 m
Ebey's Landing	8/6/2021	P4 Multispectral	35.4 ha	32 mins	120 m

*flight aborted before completion due to inclement weather
**flight cancelled due to low cloud ceiling and heavy misting rain

Ground control points

Before UAV surveys, five to six ground control points (GCP) were distributed along the shoreline as georeferencing markers. These consisted of 40x40 cm high-contrast black and white checkerboard panels that were clearly visible in imagery captured with the UAVs used for this project at altitudes of up to 120 m AGL. The position of each GCP was recorded with a Trimble GeoExplorer 6000 Series GeoXH (Trimble Inc., Sunnyvale, California, USA), which was left in place to record observations for a minimum of two minutes.

Field-collected GPS positions were post-processed in Trimble GPS Pathfinder Office (Trimble Inc., Sunnyvale, California, USA) using continuously operating reference stations (CORS) data from the Washington State Reference Network, hosted by Seattle Public Utilities and Washington State University. This method provided approximately 10-50 cm horizontal and ~0.5 m vertical positional accuracy for panel.

2.2.3 Fixed-wing aircraft surveys

Manned fixed-wing aircraft surveys were conducted by the NW Straits volunteer pilot Gregg Ridder, using a Cessna 177 Cardinal. For each survey, a pair of cameras were affixed to the underside of the aircraft's wings: the port wing carried a MAPIR Survey3W NGB (MAPIR, Inc., San Diego, California, USA) and the starboard wing carried a Canon PowerShot G10 (Canon Inc., Ota City, Tokyo, Japan). The MAPIR Survey3W NGB is a compact GoPro-sized camera that captures imagery in blue, green, and near-infrared bands (Table 1). An automatic trigger speed of 2 seconds was chosen based on a target flight speed of 100 knots to provide

80% overlap between images. The Canon imagery was not processed for this project due to time and resource limitations.

Flights were planned ahead of time by the pilot using the application ForeFlight (ForeFlight, LLC, Houston, Texas, USA). These plans consisted of parallel flight-lines running parallel to shore, with a sidelap of at least 50% based on a projected flight altitude of 1,500'. The target tide and sun conditions in Section 2.2.1 were prioritized, however greater logistical planning necessary for these flights meant that wasn't always possible.

The quick rate of data acquisition from the fixed-wing platform meant that multiple sites could be surveyed in a single day. Over the course of three flights between July and September 2021, a series of ten kelp forest canopy sites were surveyed with overlapping flight lines or a single pass "flyover" (Table 3). Flight lines were the preferred method, but flyovers were performed when greater efficiency was needed to cover many sites. In total, approximately 40 km of shoreline in areas of interest were surveyed with the fixed-wing survey method, not including repeat coverage.

Table 3. List of eleven attempted fixed-wing surveys at nine MRC sites. Nine surveys were successfully completed.

Date	Site	Aerial survey type	Linear shoreline coverage (approx)	Flight time	Altitude (approx.)
July 27, 2021	North Beach*	Overlapping flight lines	N/A	N/A	1,500 ft
	Ebey's Landing*	Overlapping flight lines	N/A	N/A	1,500 ft
	Possession Point	Overlapping flight lines	1.6 km	8 mins	1,500 ft
	Edmonds	Overlapping flight lines	3.2 km	7 mins	1,500 ft
August 24, 2021	North Beach	Overlapping flight lines	6.5 km	10 mins	1,500 ft
	Ebey's Landing	Overlapping flight lines	5.2 km	7 mins	1,500 ft
	Point Partridge	Flyover	4.2 km	N/A	1,500 ft
September 21, 2021	Alden Bank	Overlapping flight lines	2.5 km **	4 mins	2,000 ft
	Point Whitehorn	Flyover	14.3 km (combined)	6 mins	2,000 ft
	Cherry Point	Flyover			2,000 ft
	Polnell Point	Flyover	1.2 km **	N/A	2,000 ft

*camera malfunction prevented image collection
**not a linear stretch of shoreline so estimate is for width of kelp bed

2.3 Image Processing

From the full database of survey imagery collected during the surveys listed above (Table 2 and Table 3), a subset of 8 surveys were processed to produce large continuous image products known as "orthomosaics" using the methods described in this section. For a complete list of which surveys were processed in this way please see Table 7 in Section 3.1.

2.3.1 Glint masking

Survey imagery was pre-processed with an open-source tool called "GlintMaskGenerator" (Denouden et al., 2021), which generates masks of pixels that are impacted by sun glint and crashing surf (Figure 2). These pixels have been shown to disrupt the mosaicking process for imagery taken over water in nearshore environments (Cavanaugh et al., 2021). The tool selects these pixels based on user-defined percent thresholds of irradiance, and for this project values between 0.80 and 0.95 (representing a mask of the highest 20% and 5% of values respectively) on the blue band were found to be most effective at isolating patches of glare in the imagery.

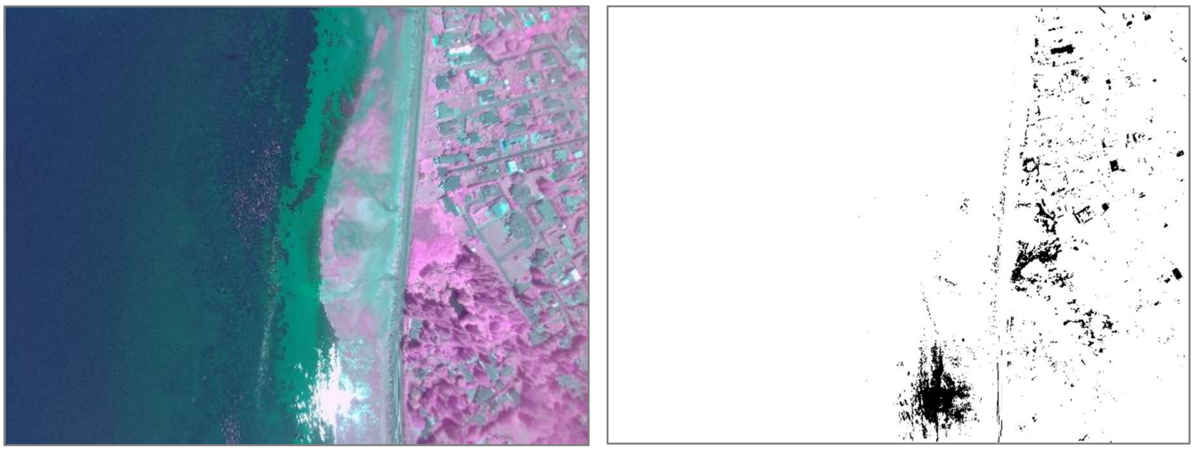


Figure 2. A fixed-wing NGB survey image taken at Edmonds on July 27, 2021 showing considerable sun glare in the bottom center (left), and the resulting pixel mask generated by GlintMaskGenerator tool on this image at a 0.95 threshold on the blue channel (right).

2.3.2 Photogrammetry

Following glint masking, survey imagery was imported with the accompanying pixel masks into Agisoft Metashape (v1.7) (Agisoft LLC, St Petersburg, Russia) for photogrammetric processing. Ground control point coordinates were then imported and the panels' locations were manually tagged within the imagery to improve georeferencing accuracy.

Image alignment was initially conducted using the "medium" quality setting such that photos were analyzed at one-quarter of full resolution, which significantly reduced processing time while still aligning the majority of imagery in most cases. If initial results were unsatisfactory, the alignment was run on higher quality settings until doing so did not result in more photos being successfully aligned. The result of this process was a grid of spatially aligned imagery (Figure 3).

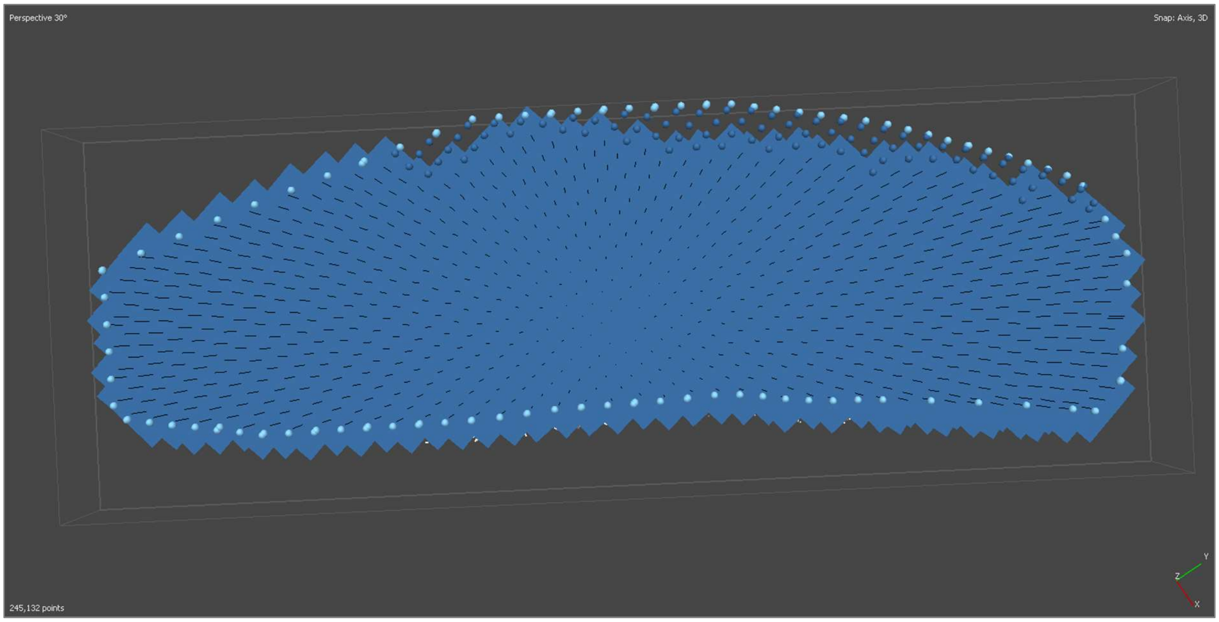


Figure 3. The result of image alignment of a UAV survey at Edmonds from August 5, 2021. Black lines represent the position and orientation of each image (shown as blue rectangles). Dark blue points are images that failed to align. Light blue points are images that were disabled at the border.

Image alignment produces "sparse point clouds" of pixels that were triangulated into 3D space (called "tie points") from overlapping imagery. These initial point clouds contain a significant amount of noise that don't accurately reflect the topography of the survey area. In order to refine the sparse cloud, a combination of manual selection (by cursor) and automated selection based on accuracy values calculated in the software were used to select and remove errant tie points. Following a series of cleaning iterations, the sparse point clouds more accurately match the expected topography of the sites.

Finally, once the point clouds were sufficiently refined they were used to generate digital elevation models (DEM) and imagery orthomosaics. The DEMs are produced by interpolating a continuous surface based on the positions of each tie point. The latter is produced as a function of the software identifying portions of images that represent surfaces on the DEM and stitching them together. Both of these final products were exported from Metashape as individual TIFF files, archived, and used in the analyses below.

2.3.3 Final orthomosaic projection

The native geographic coordinate system for image products generated in Agisoft Metashape is WGS 1984. Prior to analysis and classification, each orthomosaic was transformed to NAD 1983 HARN and projected onto StatePlane Washington South FIPS 4602 within the software ArcGIS Pro (ESRI, Redlands, California, USA) in order to minimize potential impacts of spatial distortion.

2.4 Image Analysis

Of the orthomosaics generated in Section 2.3, a subset consisting of four surveys performed at Edmonds and North Beach using the Phantom 4 Multispectral and fixed-wing NGB platforms was analyzed using ArcGIS Pro (Table 4). This set was limited due to the scope of this project, but the methods in this section could be applied to any other aerial kelp monitoring orthomosaics generated from this project or others in the future.

Table 4. The set of four surveys used to test the image analysis workflow developed for this project.

	P4M UAV	Fixed-wing NGB
Edmonds	8/5/2021	7/27/2021
North Beach	8/20/2021	8/24/2021

A strength of the Phantom 4 Multispectral UAV is that it collects imagery in five bands including blue, green, red, red edge, and near-infrared. By reducing the number of bands in the P4M orthomosaic to just the three in the visible spectrum, we were able to generate a separate set of analysis results to approximate those that would be produced from a survey conducted with a standard RGB sensor. This additional set of results will be referred to as "UAV RGB" or "P4 RGB" in this report.

2.4.1 Hand delineation of kelp bed perimeter

In order to compare imagery to kayak-based surveys in the most direct way possible, bed perimeters were hand delineated on orthomosaics using a digitizing process that mirrored the NW Straits kayak survey protocol (Bishop, 2016). UAV and fixed-wing orthomosaics were first imported into ArcGIS Pro and the display settings, or "stretch", of each was adjusted to maximize the visibility of the kelp canopy in the imagery. P4M UAV orthomosaics were displayed using just the visible bands (RGB) as this was determined to be the most likely band combination accessible to a broad audience.

The manual hand delineation method consisted of creating polygons by placing vertices around the visible canopy, with the following rules taken from the NW Straits volunteer kayak survey protocol (Bishop, 2016): 1) there must be multiple plants within a 5 meter radius to be considered a bed, 2) individual plants must be within 8 meters of the bed to be included, 3) the surveyor progresses along in either a clockwise or counter-clockwise fashion following these rules until they arrive back at the beginning (Figure 4). In order to aid in the determination of whether to include kelp plants in the same bed, an 8 meter grid was displayed in ArcGIS Pro while delineating. This grid was not used to analyze each and every instance that appeared close to the threshold, but rather was a guide for making on-the-fly decisions whether to include kelp plants or not, much the same as a kayak surveyor would experience. Following hand delineation of the kelp canopy, bed area was calculated within the perimeter to have an estimate to compare directly to the area measured by MRC kayak survey.

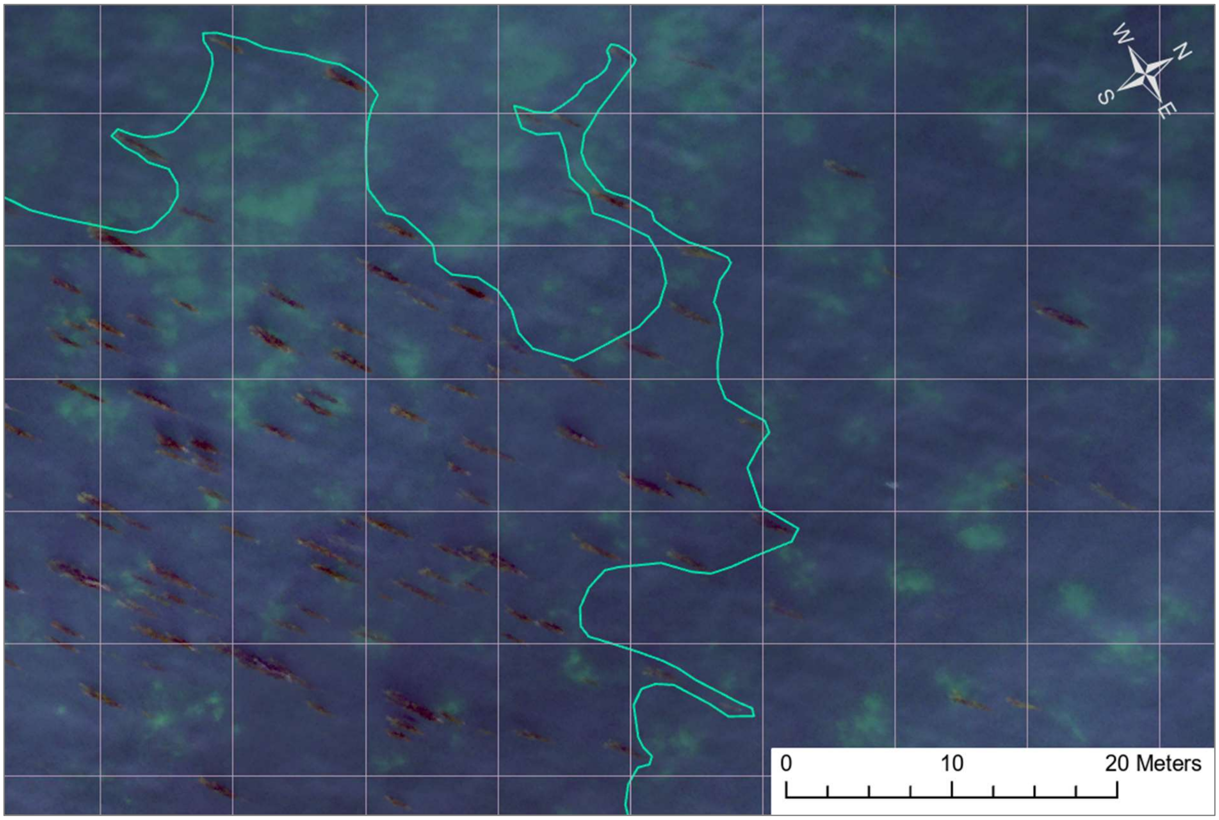


Figure 4. Hand delineation track (light blue) of the northeast patch of kelp canopy at Edmonds captured by P4M survey on August 5, 2021, visualized as RGB. The 8 meter grid shown was used to guide inclusion, and multiple plants considered outside the bed can be seen on the right.

2.4.2 Area of interest masking

The first step in the image classification workflow developed for this project was to create masks of each orthomosaic isolating the "area of interest" (AOI) of kelp canopy within the survey area. It was within these AOIs that the kelp classification methods in Section 2.4.3 onward took place.

The boundaries of each AOI were drawn using a minimum five meter buffer around the edge of any kelp visible in the imagery, except in the shallowest extent where kelp was sometimes found right up to the low tide line visible in the survey, in which case the boundary was drawn there. At North Beach, where bull kelp canopy continues to the east and west of the surveyed bed, the AOI was clipped to the linear guide-post features used by the Jefferson County MRC in order to directly compare to their kayak data.

These AOIs were further divided into two sub-regions based on differences in bottom characteristics and the visibility of other vegetation in the survey area (Figure 5). During the development of this and a prior UAV kelp canopy mapping project (Cowdrey, 2021), it was found that substantial differences in the accuracy of image classification results can occur based on these two conditions. Therefore, the creation of these two sub-regions – called "open water” and “shallow subtidal” in this project – was designed to facilitate more robust accuracy analysis.

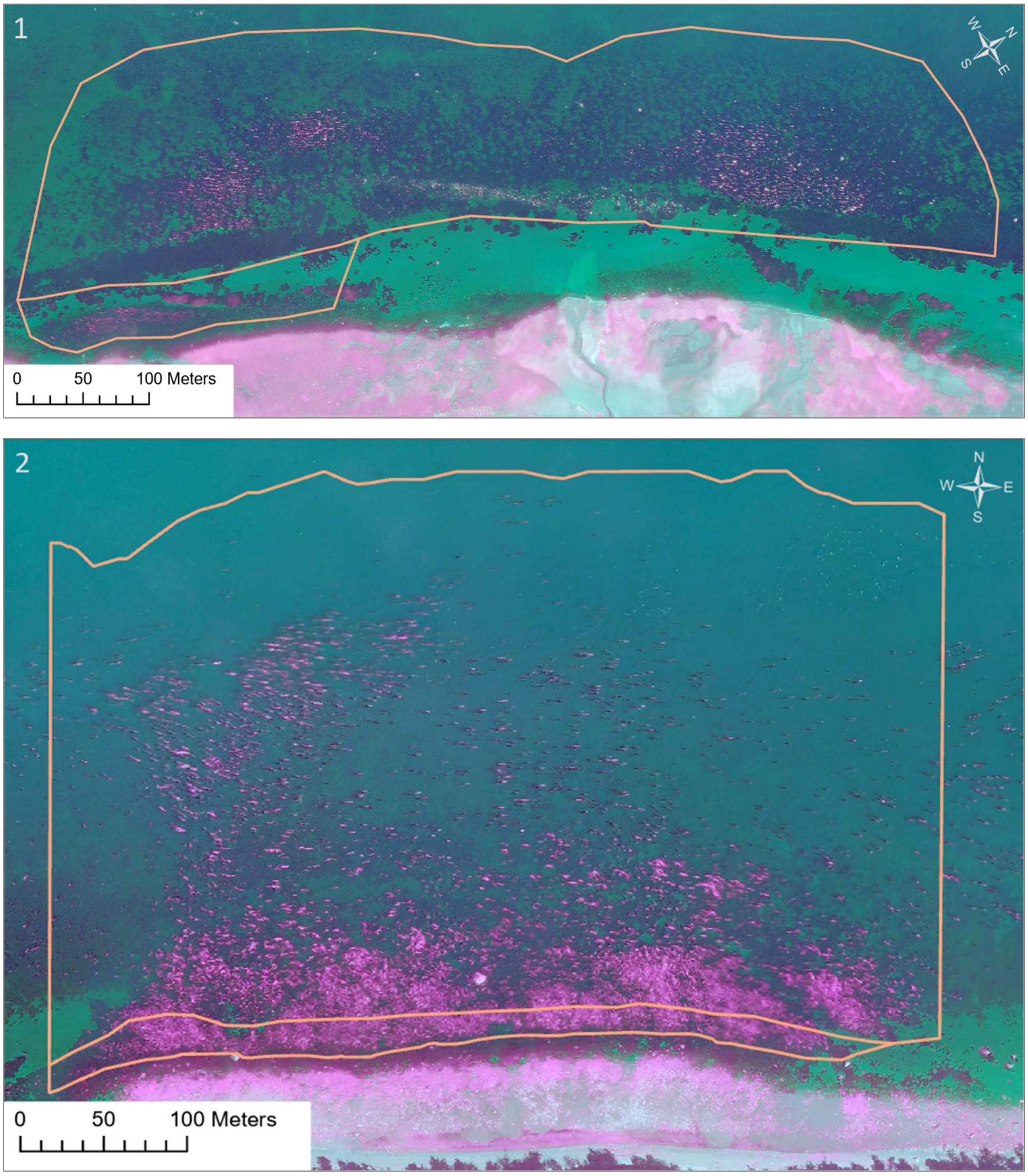


Figure 5. Area of interest sub-regions (orange) at Edmonds (1) and North Beach (2) displayed over the fixed-wing NGB orthomosaic for each. In each display the larger open water sub-region is on top and the smaller shallow subtidal region is on the bottom. At North Beach, the east and west extents of the AOI were set using Jefferson County MRC’s kayak survey guide lines.

2.4.3 Object segmentation

Prior to supervised classification, pixels in each orthomosaic were grouped into objects or "segments" of similar spectral and spatial quality. Object-based image analysis (OBIA) has been found to be particularly useful at distinguishing different species of aquatic vegetation in a variety of habitat types (Nahirnick et al., 2018; Ventura et al., 2018; Visser et al., 2018), including floating kelp canopies (Schroeder et al., 2019).

For this project, OBIA was conducted using the *Segmentation*/*Segment Mean Shift* tool in ArcGIS Pro. The settings that best differentiated kelp from the surrounding water for "Spectral detail" and "Spatial detail" were both found to be nearly maximum (19 and 17 out of 20 respectively). However, the "Minimum segment size in pixels" parameter – representing the minimum number of pixels necessary to create an object – varied between fixed-wing and UAV platforms due to their difference in spatial resolution. The average minimum pixel size that grouped kelp canopy most effectively for the P4M UAV was found to be ~27 pixels, and for the fixed-wing NGB ~4 pixels.

2.4.4 Image classification

Image classification was conducted in ArcGIS Pro within the *Classify* toolset using the "Random Trees" model (this is ESRI's name for their random forest classifier). Random forests are machine learning algorithms that deploy a series of random decision trees to produce a diverse array of modeled results based on an input data set (on the order of 1000s of iterations) (Belgiu & Drăguţ, 2016). A consensus mechanism is then used to weight the results of the model and generate a final decision. In the context of image classification the purpose of a random forest classifier is to determine which class pixels fall into, given a variety of spectral and spatial properties of the input data set, and any object segmentation performed thereon.

In order to run the random forest classifier, training data samples were identified in each orthomosaic for two classes: "kelp canopy" and "water." These consisted of hand drawn polygons for each class, with water features typically containing more pixels due to the small size of kelp objects (Table 5). These samples were drawn to include a variety of spectral expressions of each class present in the imagery. The water class also served as a catch-all for everything in the survey AOIs other than bull kelp (e.g. bottom algae, visible substrate, exposed rocks).

Table 5. Summary of manually drawn training data sample polygons used to train the random forest classifier on each survey orthomosaic.

		# of sample polygons		Mean pixel count per sample	
		kelp canopy	water/other	kelp canopy	water/other
P4 Multispectral	Edmonds	11	6	213	3,431
	North Beach	13	9	303	227
P4 RGB	Edmonds	11	6	214	3,431
	North Beach	9	12	156	1,184
Fixed-wing NGB	Edmonds	10	6	97	762
	North Beach	11	8	528	1,068

Following the creation of training data, the random forest classifier was run on the AOI of each orthomosaic using default settings in ArcGIS Pro: maximum number of trees = 50, maximum tree depth = 30, and maximum number of samples per class = 1000. This resulted in a raster containing pixels designated as either kelp canopy or water/other (Figure 6). Classified results were compared against the original orthomosaic via visual inspection for areas of strong agreement and disagreement, and training data was then added and removed in an iterative fashion to improve results. After 3-5 iterations results were typically found to be stable, and final classified rasters were exported as a TIFF file to be used in accuracy assessment.

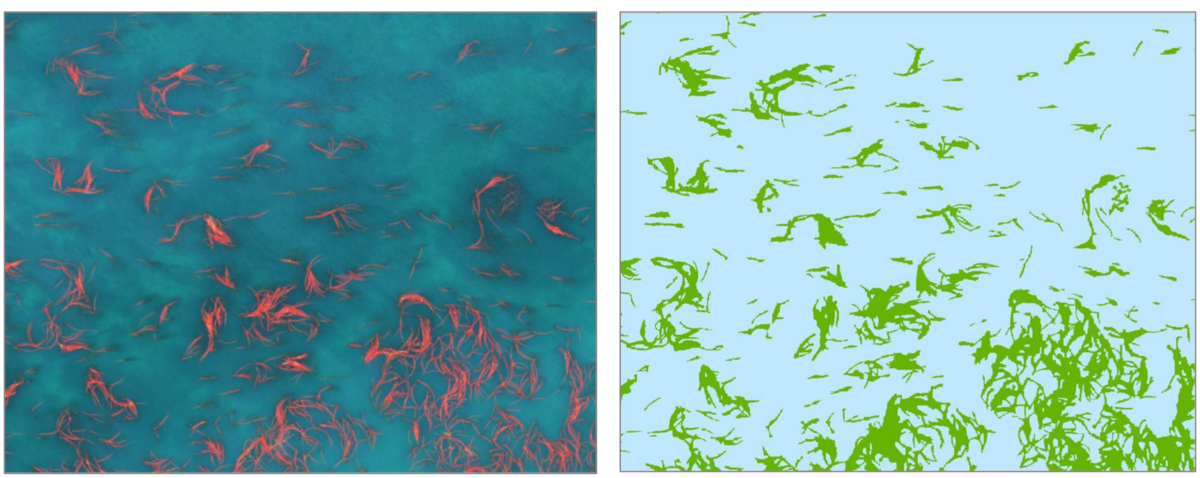


Figure 6. A small subsection of the P4 Multispectral orthomosaic (left; displayed as red edge, blue, green) at North Beach from the August 20, 2021 survey, and the results generated by the random forest classifier (right) of the same region. In the classified result, kelp canopy is symbolized as dark green and water/other as light blue.

2.4.5 *Accuracy assessment*

Accuracy assessment of the classified outputs generated by the random forest classifier was conducted using a random point verification method. This method relied upon a technician with field experience at the sites to examine the imagery and determine which pixels were correctly classified as part of the kelp canopy, and which were not.

Assessment points

To determine the number of accuracy assessment points to generate for each class, the percent of kelp canopy and water pixels contained within the AOI were first calculated. The equation in Congalton & Green (2019) (Equation 2.1) was then used to calculate the point quota required in order for the accuracy results generated to meet a predetermined confidence level (95% was used for this project). In general, this equation requires more accuracy assessment points with more classes and the closer to equal distribution those classes are.

$$n = B * \rho(1-\rho)/\beta^2 \qquad \text{(Equation 2.1)}$$

$$B = 1 - \alpha/k \qquad \text{(Equation 2.2)}$$

where:

- *B* is equal to upper tail critical value for the chi-square distribution with one degree of freedom for the desired confidence level or α (type 1 error) value *divided by* the number of classes in the schema (k) (Equation 2.2)
- ρ is equal to the percent cover (as a decimal) of the area of the smallest cover class in the schema
- β is the desired type 2 error, which also specifies desired power (1-β).

Assessment points were generated with the *Create Accuracy Assessment Points* tool in ArcGIS Pro. A combination of stratified (proportional based on size of class) and equalized stratified (equal number in each class) random point generation was used to ensure that a minimum of 20 points for each class were generated and the rest were proportionally distributed in the AOI.

Technician verification

The next step in accuracy assessment was to populate the “ground truth” value in the attribute table for the accuracy assessment point feature class in ArcGIS Pro. This value was called “technician verification” for this project, as the traditional meaning of the term ground truth in remote-sensing research does not fit here. This process involved examining each point overlayed on the initial orthomosaic without the classified result visible, and determining visually whether it was kelp canopy or water. For any points the technician was unable to determine which class should be applied, this value was marked as “other.”

Once the technician verification attribute for each point had been populated, an error matrix was generated (Table 6) with the ArcGIS Pro *Compute Confusion Matrix* tool. These error matrices include multiple metrics:

- User's accuracy for each class: the percent of classified pixels that match ground truth data. The complement of user's accuracy is a measure of Type I error, or false positives.
- Producer's accuracy for each class: the percent of ground truth pixels that were correctly classified. The complement of producer's accuracy is a measure of Type II error, or false negatives.
- Overall accuracy: the percent correctly classified pixels in both classes
- Cohen's kappa value: this compares the classification result to the rate of agreement one would expect given random chance and is expressed on a scale of 0-1

An accuracy result of 85% is considered the standard threshold for a reliable classification. Kappa values above 0.60 are considered to represent substantial accuracy, and those above 0.80 to represent excellent accuracy (Sim & Wright, 2005; Congalton & Green, 2019).

Table 6. Example of one error matrix generated for a random forest classified result of the orthomosaic from a P4 Multispectral survey.

	Technician verification					
	Water	Kelp Canopy	Other	Total	User Accuracy	
Water	127	2	0	129	98.4	
Kelp Canopy	13	55	7	75	73.3	
Total	140	57	7	204		
Producer Accuracy	90.7	96.5			Overall accuracy	89.2
					Kappa	0.767

Error matrices were primarily used to assess the efficacy of the image classification method developed for this project in terms of its ability to detect and characterize bull kelp canopy. They also served as indicators of where further research is needed to determine which kelp forest characteristics and environmental conditions have the greatest impact on producing accurate image classification results.

2.4.6 Estimation of canopy area, bed area and percent cover

The final phase of analysis was to trial various metrics that could be generated from the classified imagery results and compare them to ground-based counterparts collected by MRC and DNR kayak surveys. As with the hand delineation of the bed perimeter, these metrics were confined to the site AOIs for consistency.

Classified imagery-based metrics

The first metric generated from each classified result was kelp canopy area, which represents the total areal coverage of bull kelp floating at or near the surface. This was calculated as the product of the total number of pixels classified as kelp canopy within the AOI and the pixel dimension (Equation 2.3).

$$canopy\ area = \#\ of\ kelp\ pixels\ in\ AOI * pixel\ area\ of\ classified\ ortho \qquad \text{(Equation 2.3)}$$

The second metric generated was an aggregated kelp "bed area", which estimates the broader footprint of the kelp bed including the spaces between plants. This is generated with the *Aggregate Polygon* tool in ArcGIS Pro, which combines polygons within a predefined distance of each other together into larger overall polygons. For this project, an aggregation distance of 8 meters was used, in order to mirror the standard used by NW Straits in MRC volunteer kayak surveys (Bishop 2016).

From the canopy area and bed area metrics, percent cover was then calculated. This characterizes the relative abundance of kelp canopy within the bed, and is calculated by the canopy area divided by the overall aggregated bed area (Equation 2.4).

$$percent\ cover = \frac{(\#\ of\ kelp\ pixels) * (pixel\ resolution\ of\ classified\ ortho)}{aggregated\ bed\ area} \qquad \text{(Equation 2.4)}$$

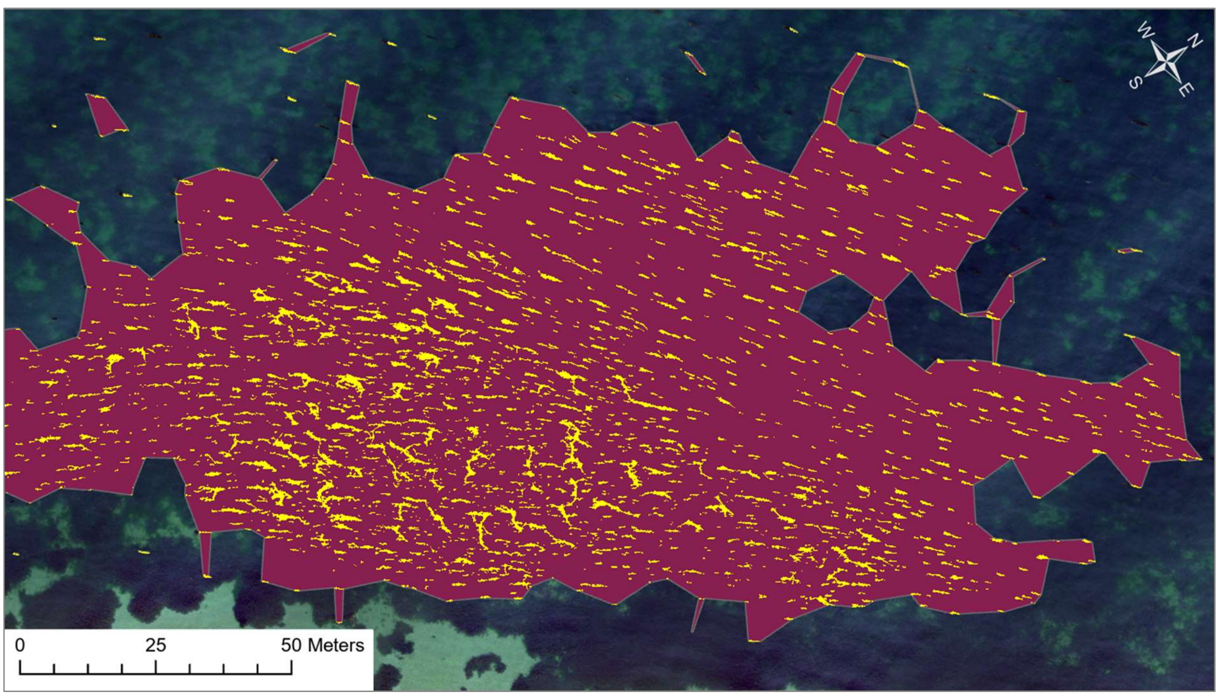


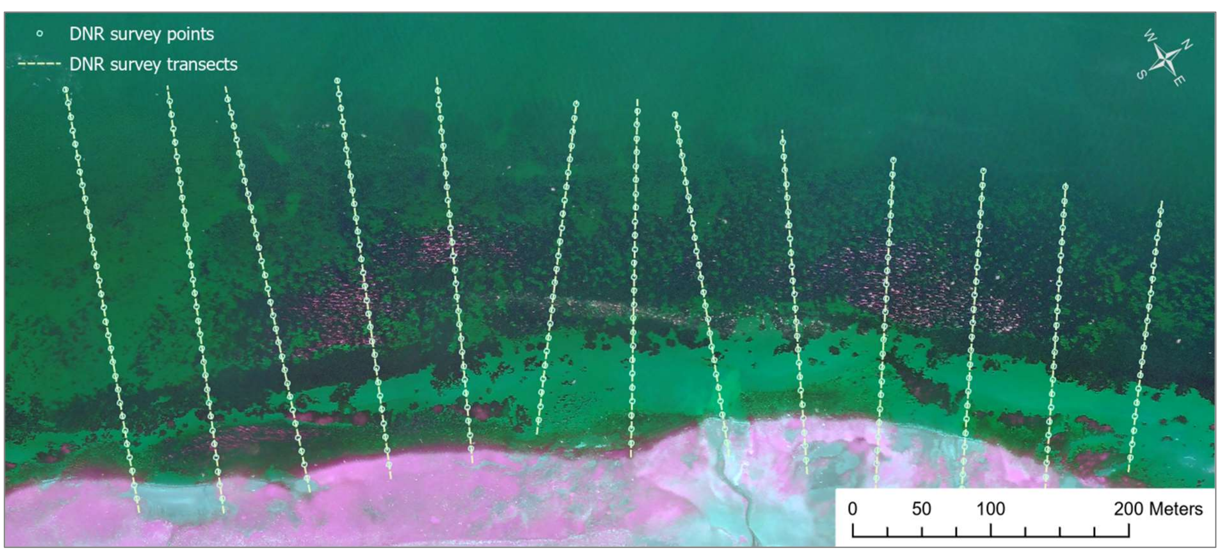
Figure 7. Example of semi-automated bed area estimation. Pixels classified as kelp canopy by the random forest classifier are shown in yellow. Canopy area equals the total area in yellow, bed area as generated using an 8 meter distance threshold is symbolized in maroon, and percent cover equals the area in yellow divided by the area in maroon.

DNR's ground-based canopy surveys

For comparison to aerial methods, DNR staff surveyed canopy extent and percent cover at the Edmonds and North Beach sites at grid points along systematically placed across-shore transects via kayak (Figure 8). Transects spanned potential bull kelp habitat by extending beyond the known depth range of bull kelp in Puget Sound, and were defined in ArcMap and downloaded to handheld Garmin GPS units for navigation. At regularly spaced grid points along each transect, staff measured percent cover of bull kelp canopy in 1 m^2 quadrats. Staff also recorded the bed boundaries along each transect by collecting GPS points where the shallowest and deepest bull kelp individuals occurred within 5 m of the transect. At these points, minimum and maximum depth measurements were collected with a handheld depth sounder.

Thirteen across-shore transects were surveyed at each site. At Edmonds, 122 points were assessed for density and cover. At North Beach, more points were assessed (341) because the bed was substantially larger. For comparison to the other datasets, the DNR data at North Beach were further constrained to the AOI used in this project, which was smaller. As a result, the western 4 transects were excluded from analysis.

We estimated mean site canopy percent cover by calculating the mean of all quadrat samples at grid points within the shallow and deep boundaries of bed, as defined by the GPS-located minimum and maximum depth points recorded along each transect. We estimated canopy area at each site by multiplying mean site cover by a simplified delineation of bed area. The simplified delineation of bed area was created by clipping the shallow and deep edges of the pre-defined site polygon at the minimum and maximum depth points that were surveyed on each transect.



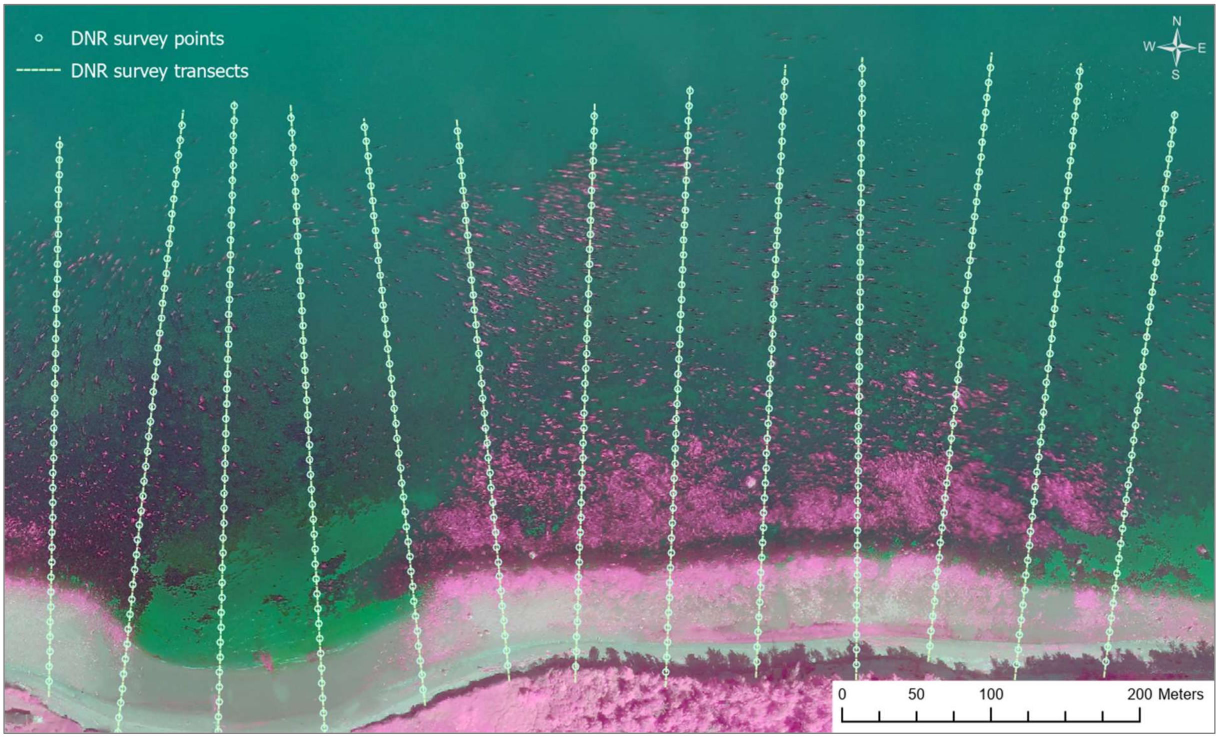


Figure 8. DNR grid points and transects that were used to assess percent cover and bed extent via kayak surveys at Edmonds (top) and North Beach (bottom). The underlying imagery is the fixed-wing NGB survey at each site from this project.

3 Results

3.1 Summary of Imagery Collected

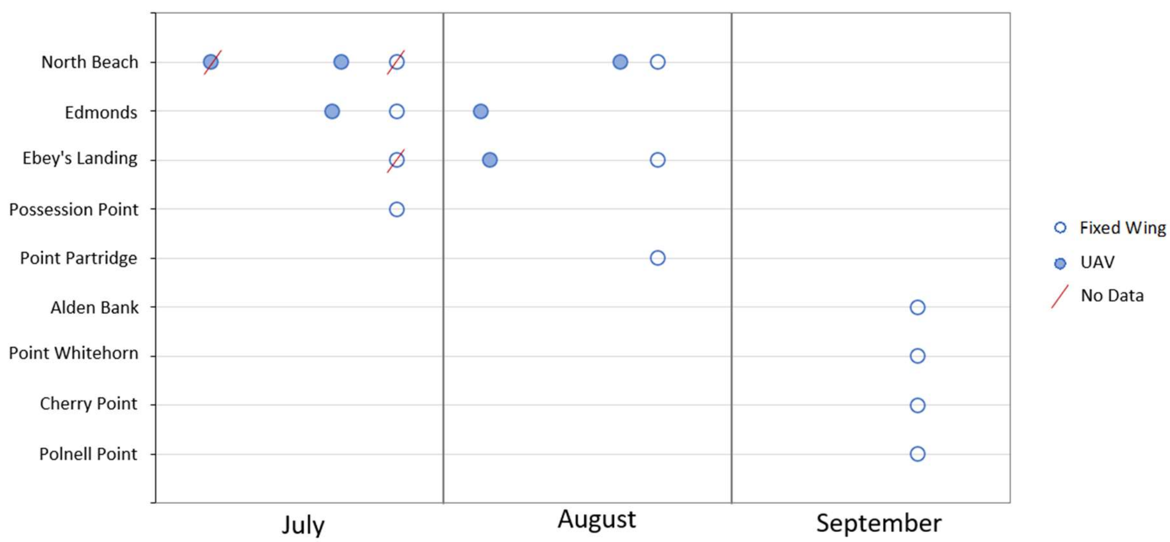


Figure 9. Summary of UAV and fixed-wing aerial surveys conducted at MRC sites in 2021.

Fourteen out of seventeen attempted surveys were successful (Figure 9). Appendix 1 lists all files generated from these surveys. Of the fourteen successful surveys, half were judged to be high quality (Table 7). Factors that compromised quality included spatial gaps in coverage, inclement weather, and imagery exposure levels (light/dark).

Five UAV surveys generated a total of 6,492 5-band multispectral images with a total survey area of 111.4 hectares, not including repeat coverage. Inclement weather prevented a planned survey at North Beach on July 7, 2021.

Nine fixed-wing surveys generated a total of 1,316 three-band NGB images covering approximately 38 km of shoreline in areas of interest, not including repeat coverage. A camera malfunction on July 27, 2021 prevented imagery from being collected at the two sites (North Beach and Ebey’s Landing).

Table 7. Dates, locations, platforms, final delivered product, and image quality of successful aerial surveys. Surveys in bold were further processed and assessed for photogrammetry and kelp classification performance.

Method	Site	Date	Image platform	Delivery final product stage	Product quality	Notes
UAV	Edmonds	7/20/2021	P4 Multispectral	Orthomosaic	Mid	Inclement weather led to orthomosaic with low contrast
		8/5/2021	**P4 Multispectral**	**Orthomosaic, classified**	**High**	
	North Beach	7/21/2021	MicaSense RedEdge MX	Raw imagery	Mid	Imagery is good quality but orthomosaic showed difficulty stitching due to low flight altitude
		8/20/2021	**P4 Multispectral**	**Orthomosaic, classified**	**High**	
	Ebey's Landing	8/6/2021	P4 Multispectral	Orthomosaic	High	
Fixed-wing	Possession Point	**7/27/2021**	MAPIR Survey3W - Flight lines	Raw imagery	Low	Bright signal from south facing shore leads to underexposed kelp forest
	Edmonds		**MAPIR Survey3W - Flight lines**	**Orthomosaic, classified**	**High**	
	North Beach	**8/24/2021**	**MAPIR Survey3W - Flight lines**	**Orthomosaic, classified**	**High**	
	Ebey's Landing		MAPIR Survey3W - Flight lines	Orthomosaic	High	
	Point Partridge		MAPIR Survey3W - Flyover	Raw imagery	Mid	Great imagery captured in multiple passes, however a portion of the bed was been missed
	Alden Bank	9/21/2021	MAPIR Survey3W - Flight lines	Orthomosaic	Mid	Orthomosaic creation was successful, but w/o ground points to tie to the spatial accuracy of the survey cannot be confirmed
	Point Whitehorn		MAPIR Survey3W - Flyover	Raw imagery	Low	Not centered over kelp forest, it appears rather dark
	Cherry Point		MAPIR Survey3W - Flyover	Raw imagery	High	Hard banking turn at beginning of path, otherwise captured the kelp forest perfectly
	Polnell Point		MAPIR Survey3W - Flyover	Raw imagery	High	Bed captured well/centered in flyover; some low density extent on western edge was missed

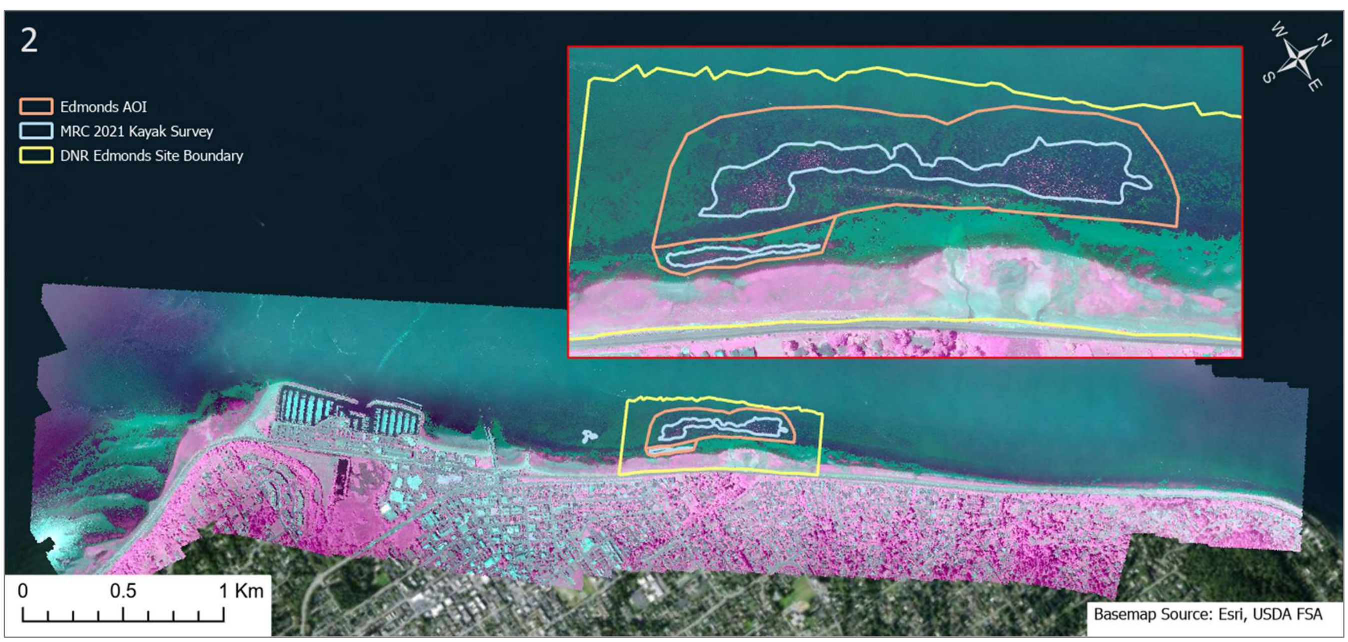
3.2 Photogrammetry

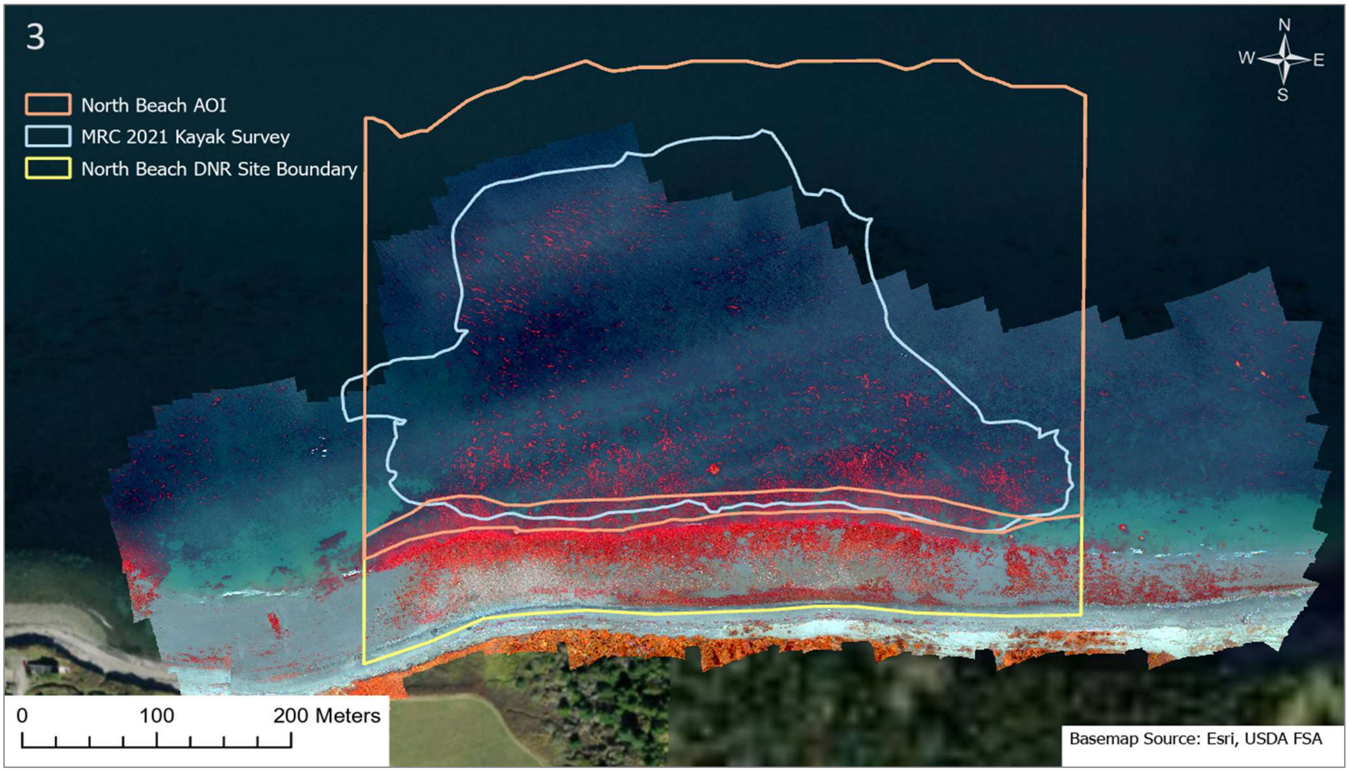
3.2.1 Orthomosaic creation

A single photogrammetric workflow successfully produced orthomosaics from UAV and fixed-wing platforms, which increased processing efficiency. Photo alignment success ranged from 60-100% of all photos for an individual platform and site (Table 8). Photo alignment success was higher on the fixed-wing platform and at the Edmonds site, possibly due to more alignment features being visible in photos with larger areal coverage, and the narrower nearshore zone at the Edmonds site (Figure 10). Alignment failures most often occurred along the deep edge of the survey area, where water predominated.

Table 8. Number of images that successfully aligned in Metashape for the analysis orthomosaics.

	P4M UAV		Fixed-wing NGB	
Edmonds	813/900	90%	117/117	100%
North Beach	748/1,247	60%	142/162	88%





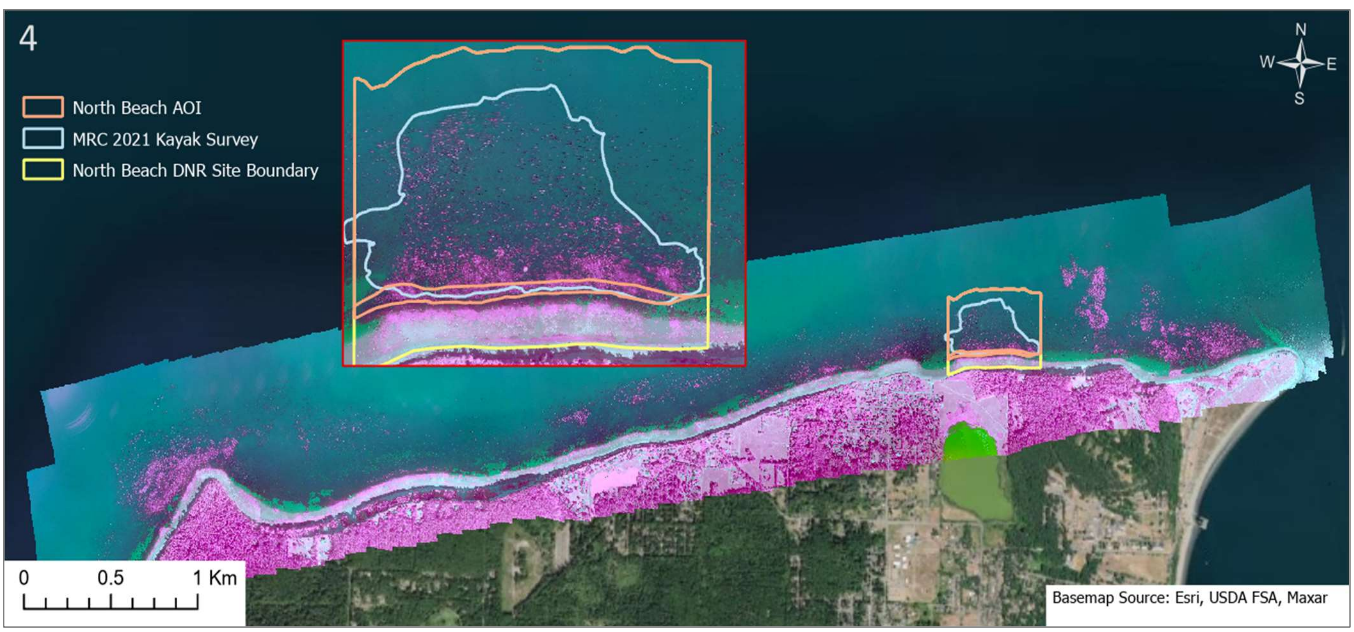


Figure 10. Final orthomosaics used to evaluate the photogrammetry processing: (1) P4 Multispectral UAV survey at Edmonds on 8/5. (2) Fixed-wing NGB survey at Edmonds on 7/27. (3) P4 Multispectral UAV survey at North Beach on 8/20. (4) Fixed-wing NGB survey at North Beach on 8/24. These orthomosaics are shown with near-infrared visualized in the red channel, and green and blue channels visualized as normal, giving them a false color appearance. The UAV orthomosaics show some evidence of banding, which occurs when lighting conditions change during surveys.

3.2.2 Positional accuracy

Comparison of features in the UAV orthomosaics and WA Statewide 1-ft NAIP Imagery showed ~1-2 m of horizontal uncertainty. This level of positional accuracy was attributed to the use of in situ ground control points (GCPs) with approximately 10 cm horizontal accuracy. The same comparison using the fixed-wing surveys showed horizontal position agreement on the order of < 10 m. To further refine the positional accuracy of the fixed-wing aircraft surveys, large objects in the final UAV orthomosaics were used as tie points for subsequent georeferencing. Following this, a similar visual comparison between the WA Statewide 1-ft and fixed-wing orthomosaics showed < 3 m of uncertainty.

It is important to note that this analysis of spatial accuracy was only performed on land or on very large boulders protruding from the intertidal zone. GCPs and recognizable features were generally lacking in the open water at the deep edge of these kelp forests. The only visible deep water features were generally the floating bulbs and blades of bull kelp, and these features change in shape and can move a meter or more with tides, currents and waves. Despite this uncertainty, visual comparison of repeated surveys suggested the improvement in spatial accuracy along shore translated to higher accuracy across shore as well.

3.3 Platform Resolution and Areal Coverage

The pixel resolution of imagery from the Phantom 4 Multispectral UAV was approximately four times greater than the resolution of the MAPIR imagery captured by fixed-wing aircraft (Table 9). In the higher resolution UAV imagery, edges of kelp canopies were distinctly sharper (Figure 11).

Table 9. Summary of the orthomosaics generated from UAV and fixed-wing surveys at three sites with overlapping methods.

Method	Site	Date	Spatial coverage	Survey time	Resolution
UAV	Edmonds	7/20/2021	46.2 ha	37 mins	8.3 cm
		8/5/2021	56.4 ha	41 mins	8.3 cm
	North Beach	8/20/2021	25.6 ha	51 mins	6.1 cm
	Ebey's Landing	8/6/2021	37.4 ha	32 mins	8.4 cm
Fixed-wing	Edmonds	7/27/2021	766 ha	7 mins	30.1 cm
	North Beach	8/24/2021	868 ha	10 mins	29.7 cm
	Ebey's Landing	8/24/2021	692 ha	7 mins	28.7 cm

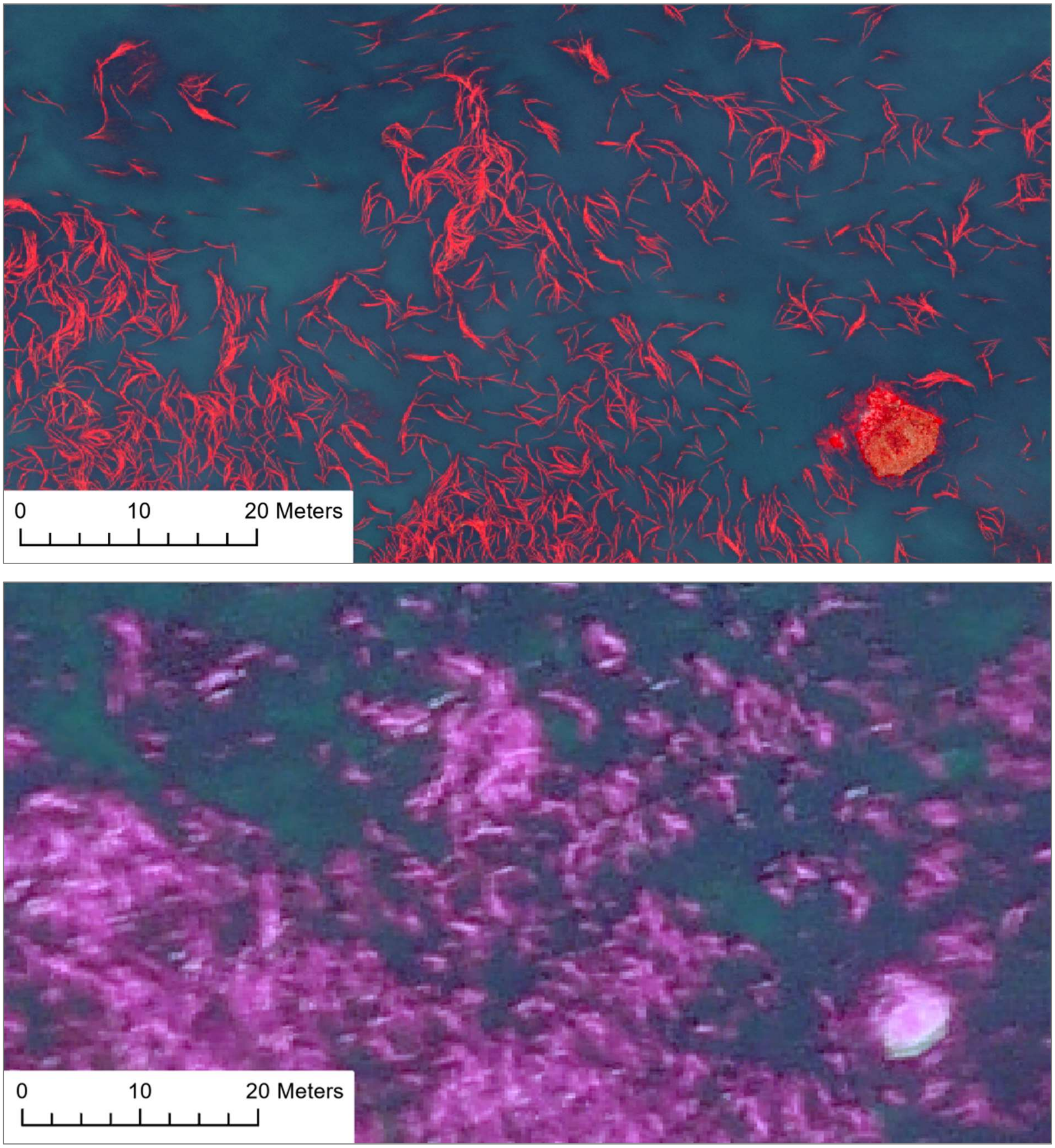


Figure 11. Subsection of the kelp canopy at North Beach as captured by the P4M UAV on 8/20/2021 (top) and fixed-wing NGB on 8/24/2021 (bottom). The former has substantially higher pixel resolution than the latter: 6.1 cm/pixel and 29.7 cm/pixel respectively.

In contrast, the fixed-wing aircraft platform covered much larger areas in a fraction of the time required by the UAV to survey (Figure 12). With the platforms used in this project, the fixed-wing NGB captured two orders of magnitude more area per unit time than the P4M UAV (98.4 and 1.1 hectares per minute, respectively).

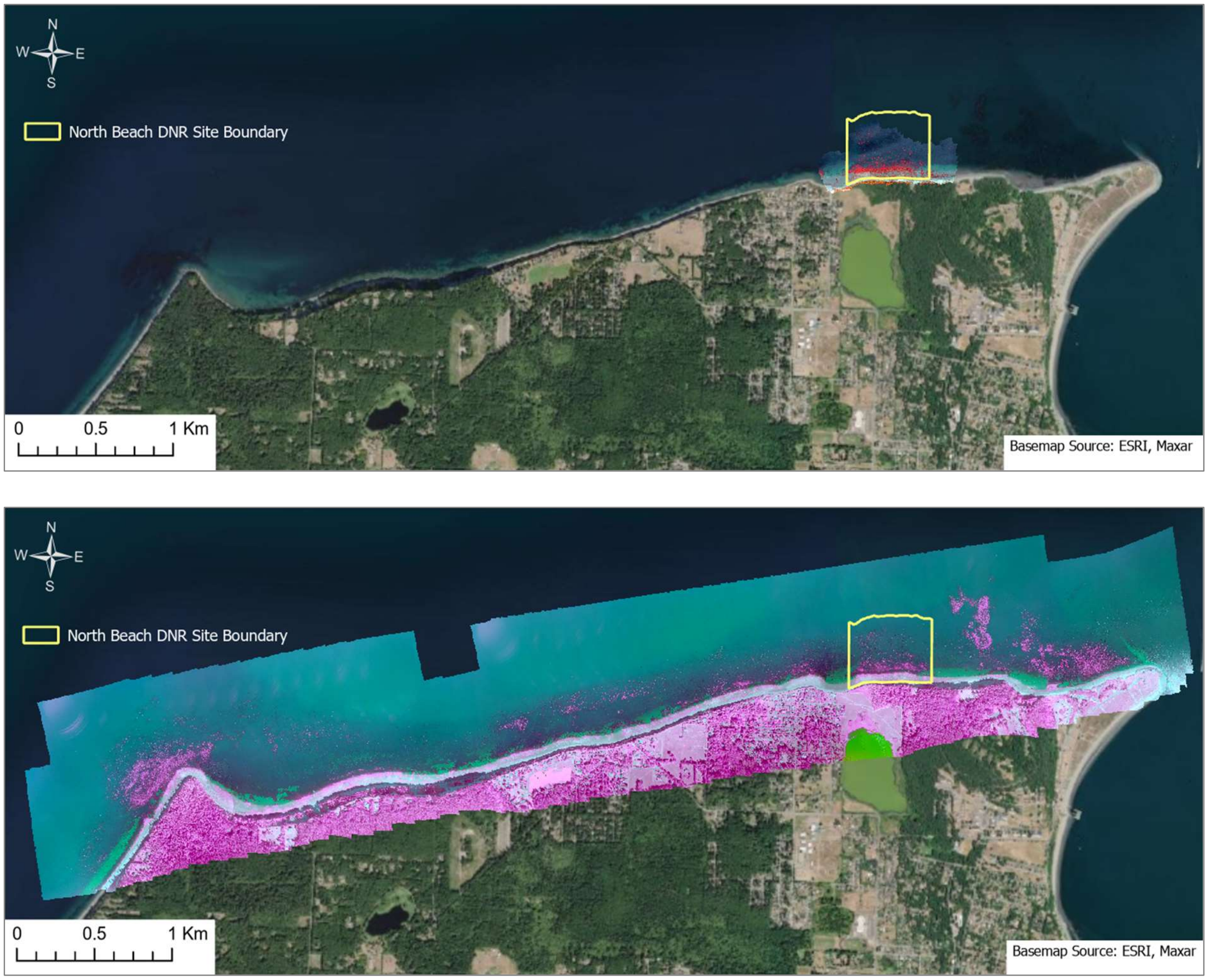


Figure 12. Shoreline from McCurdy Point to Fort Worden, which contains the North Beach site. It took the Phantom 4 Multispectral UAV 51 minutes to survey the site (top), whereas the fixed-wing NGB platform captured the entire shoreline (bottom) in approximately 10 minutes.

3.4 Image Classification

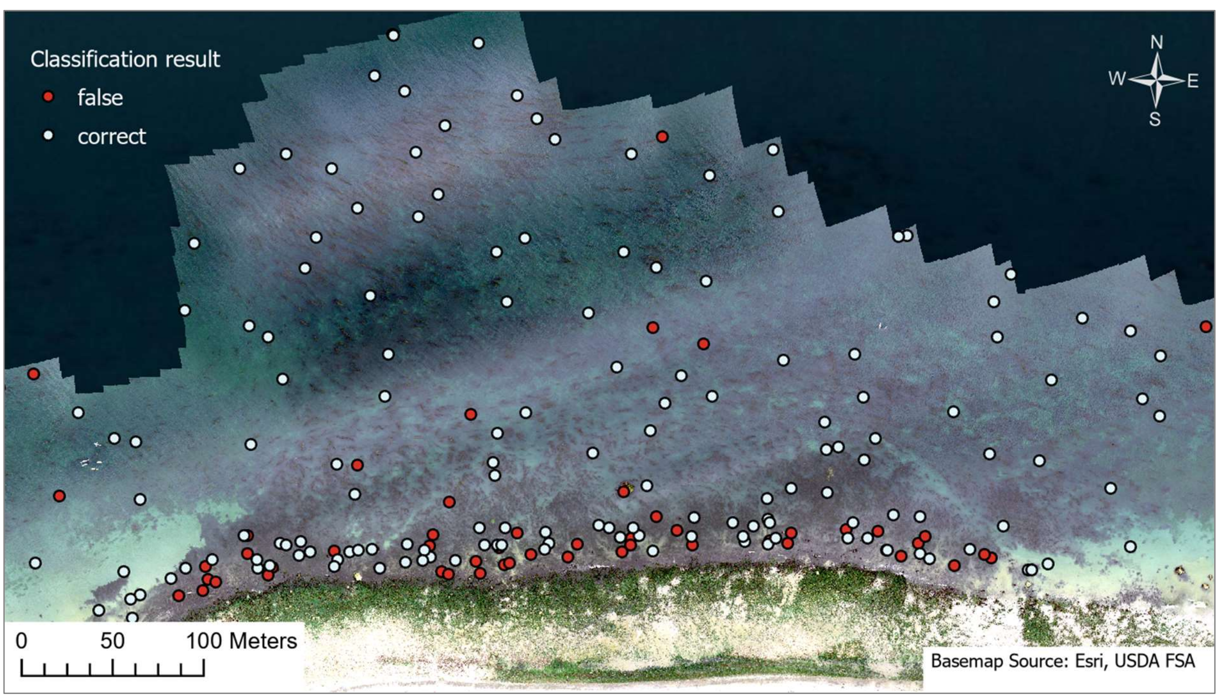
3.4.1 Accuracy assessment

Accuracy assessment of the six classified results found that four of them fell within the target range for kelp classification quality (over 85%) (Table 10). The results for Cohen's kappa were similar, with four out of six achieving values over 0.60 (substantial), but only one over 0.80 (excellent). The P4 RGB accuracy was the platform that fell below target ranges most often.

Table 10. Accuracy assessment of kelp classification results for 3 input data sets at the two analysis sites within the: 1) entire AOI; 2) open water subtidal sub-area; and 3) lower intertidal/shallow subtidal sub-area.

		entire AOI		open water		shallow subtidal	
Site	**Platform**	**overall accuracy**	**kappa**	**overall accuracy**	**kappa**	**overall accuracy**	**kappa**
Edmonds	P4 Multispectral	91%	0.81	99%	0.97	83%	0.64
	P4 RBG	67%	0.26	83%	0.55	48%	0.09
	Fixed-wing NGB	88%	0.76	91%	0.83	84%	0.70
North Beach	P4 Multispectral	89%	0.77	96%	0.89	77%	0.59
	P4 RGB	77%	0.55	91%	0.75	60%	0.32
	Fixed-wing NGB	89%	0.78	91%	0.75	87%	0.73

In the open water subtidal sub-area, all overall accuracy scores were near or above the target range (over 85%). Cohen's kappa values were also higher, all but one had values over 0.60 (substantial), and three were over 0.80 (excellent). Classification errors for kelp canopy most often occurred in the shallow subtidal to intertidal fringe for all surveys (Figure 13). In this zone, kelp canopies were confused with other vegetation or substrate that co-occurred there. These features were harder to distinguish spectrally from kelp canopies.



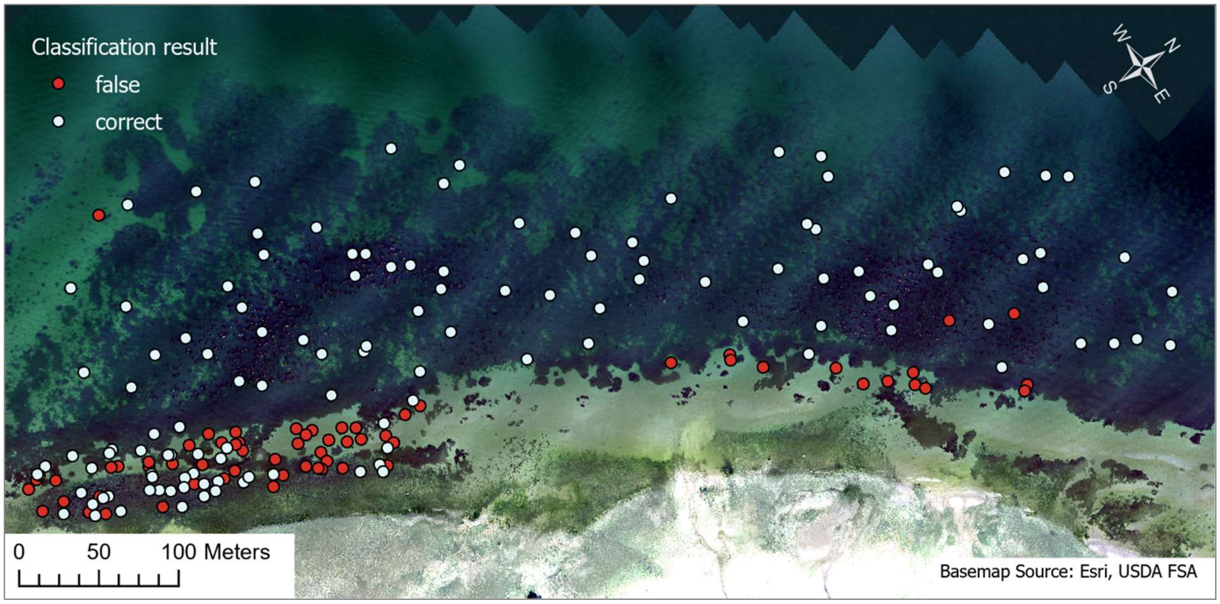


Figure 13. Examples of the distribution of correct (light blue) and false (red) classification results as assessed by stratified random point verification at North Beach (top) and Edmonds (bottom) for the P4 RGB orthomosaics at each site.

3.5 Estimated Kelp Area Metrics

3.5.1 Kelp canopy area

Imagery-based canopy area estimates ranged from 0.25-0.47 ha at Edmonds and 1.08-2.16 ha at North Beach (Figure 14). At both sites, the highest estimate was close to two times larger than the lowest estimate. The relative magnitude of the estimates produced by each platform was not consistent between sites.

The P4 RGB produced the most distinct estimates - the highest estimate at Edmonds and lowest estimate at North Beach. The P4 RGB estimates also had a much greater magnitude of difference from the other estimates at both sites (162% of the fixed-wing NGB estimate at Edmonds and 50% at North Beach). The P4 RGB estimate for the shallow subtidal sub-area at Edmonds represented the most striking difference in both the absolute and relative magnitude of areal estimates. This area had particularly low classification accuracy across platforms, and P4 RGB had the lowest classification accuracy of the three methods at both sites (Table 10).

The P4 Multispectral and fixed-wing NGB estimates for the sites were similar, with the latter estimates consistently being higher (Figure 14). The P4M gave estimates that were 86% and 82% of the fixed-wing NGB total canopy area estimates at Edmonds and North Beach, respectively. The relative similarity in the magnitude of these area estimates were echoed in the accuracy results. Both platforms had 89% overall at North Beach. At Edmonds, the P4M had 91% overall accuracy compared to 88% for the fixed-wing NGB (Table 10).

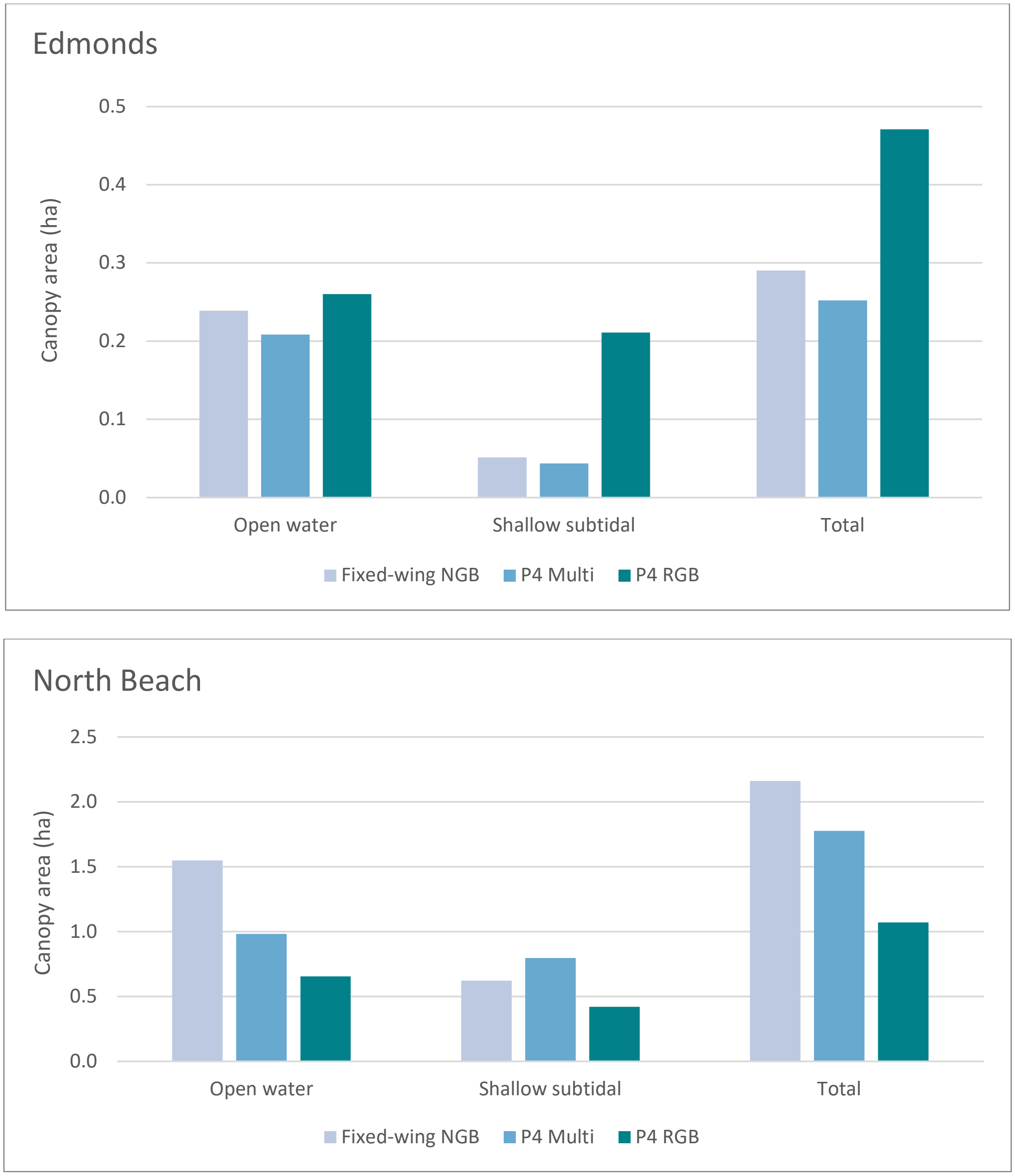


Figure 14. Kelp canopy area estimates calculated from the classified results of the three imagery sources at Edmonds (top) and North Beach (bottom).

Ground-based estimates of canopy area based on quadrat samples by DNR were larger than all of the imagery-based estimates at both sites. Total estimated area was 3.04 ha at North Beach (n=229) and 0.93 ha at Edmonds (n=122). Quadrat-based estimates of area were anticipated to be larger because they included slightly submerged plants, which can sometimes go undetected in imagery.

3.5.2 Kelp bed area

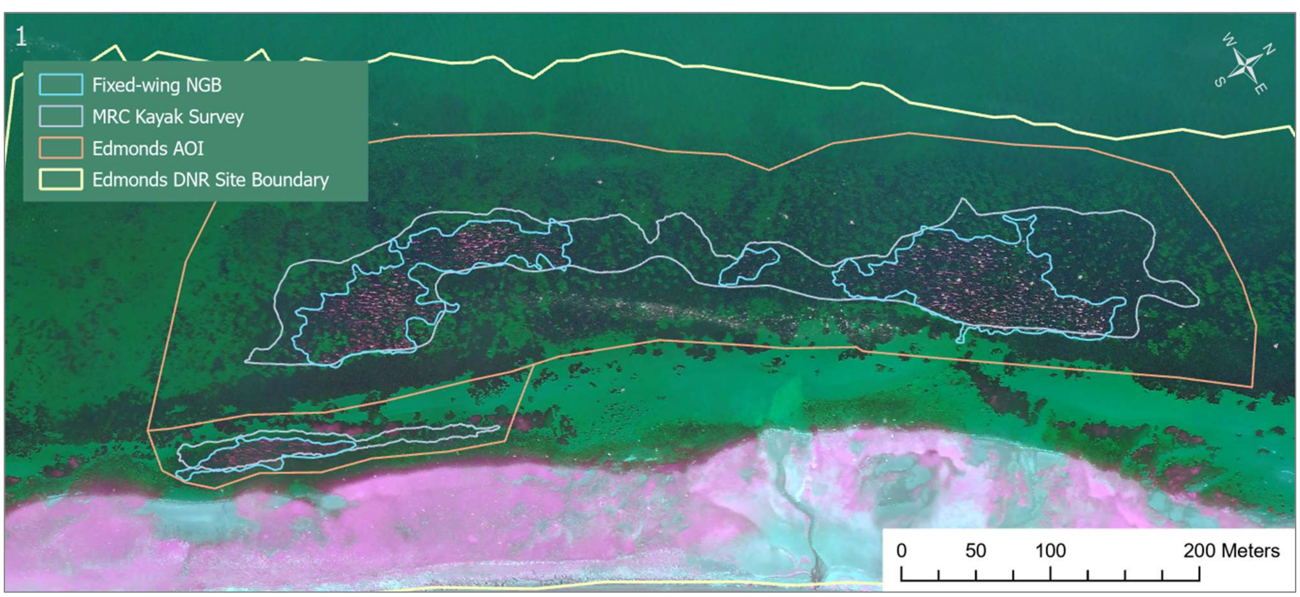
Kelp bed distribution and spatial extent were characterized with five imagery methods and two ground-based methods. The ground-based methods consistently produced at or very near the greatest estimates (Table 11). Results for each method are presented and compared in subsequent sections, with a primary focus on comparison to the area estimates from the MRC kayak perimeters.

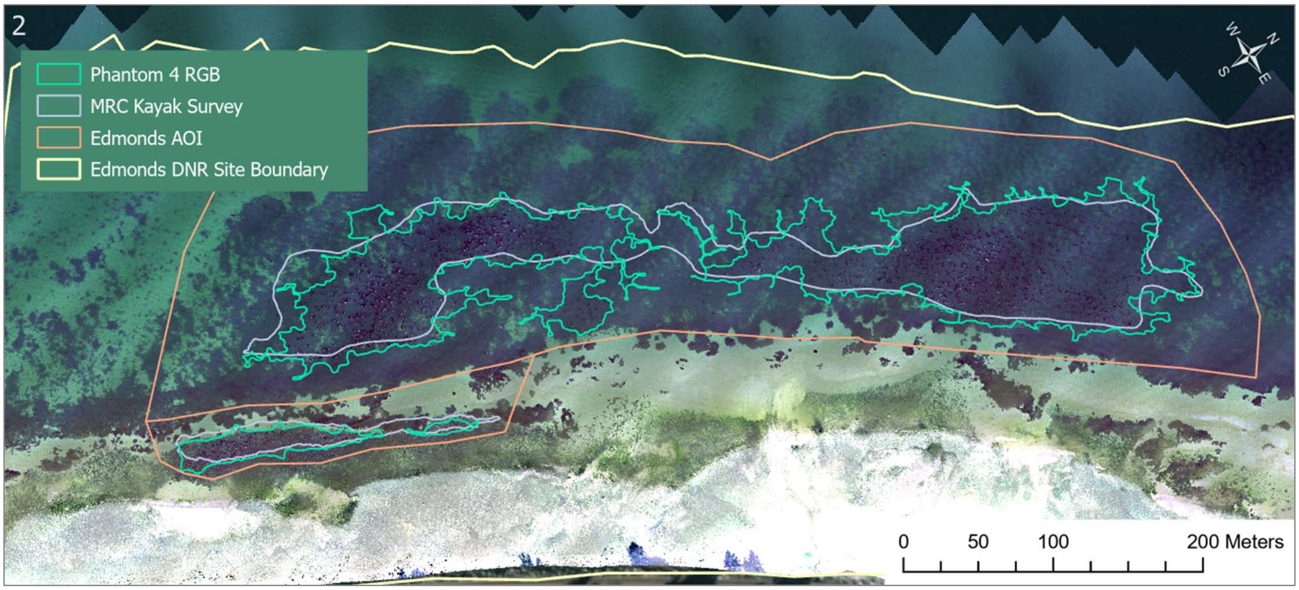
Table 11. Kelp bed area estimates generated by both imagery-based and ground based-methods at each site.

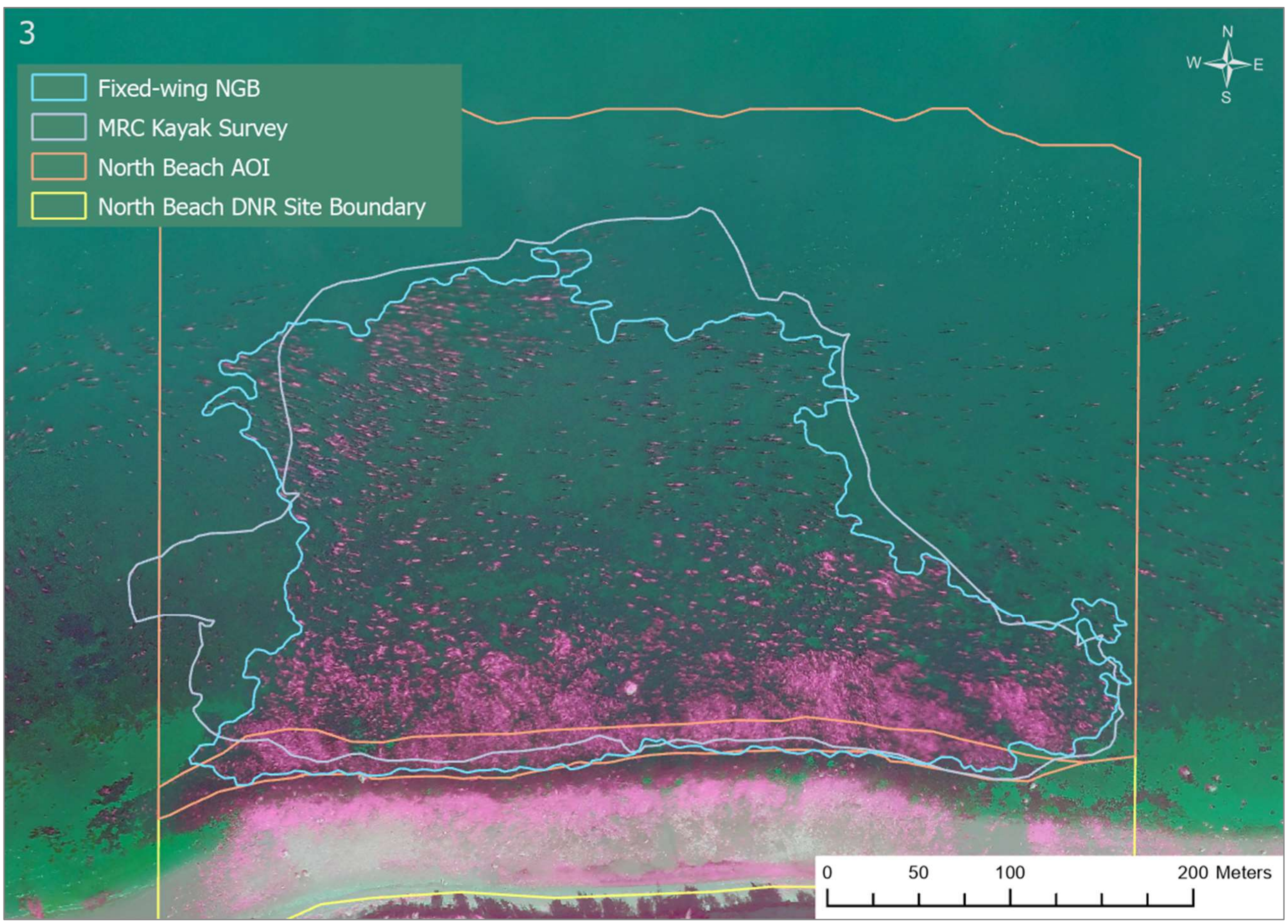
Platform	Edmonds (ha)	North Beach (ha)
Phantom 4 RGB hand delineated	3.32	9.22
Phantom 4 RGB automated	3.45	7.37
Phantom 4 Multi automated	3.33	7.94
Fixed-wing NGB hand delineated	1.65	9.14
Fixed-wing NGB automated	1.57	5.24
MRC kayak perimeters	3.27	10.27
DNR generalized bed extent	8.25	13.95

Manual delineation of bed area from imagery

The kelp bed perimeters manually delineated in the survey orthomosaics showed general agreement with the perimeters mapped by MRC volunteer kayakers (Figure 15). Areas of disagreement occurred in low density canopy locations: 1) patches of canopy, especially around the perimeter, were sometimes excluded by kayakers and included in the imagery delineation, or 2) kayakers sometimes included areas where the canopy that was visible in the imagery did meet the 8 meter distance threshold as applied to the imagery.




2
Phantom 4 RGB
MRC Kayak Survey
Edmonds AOI
Edmonds DNR Site Boundary
W
N
S
E
0
50
100
200 Meters


3
Fixed-wing NGB
MRC Kayak Survey
North Beach AOI
North Beach DNR Site Boundary
N
W
E
S
0
50
100
200 Meters

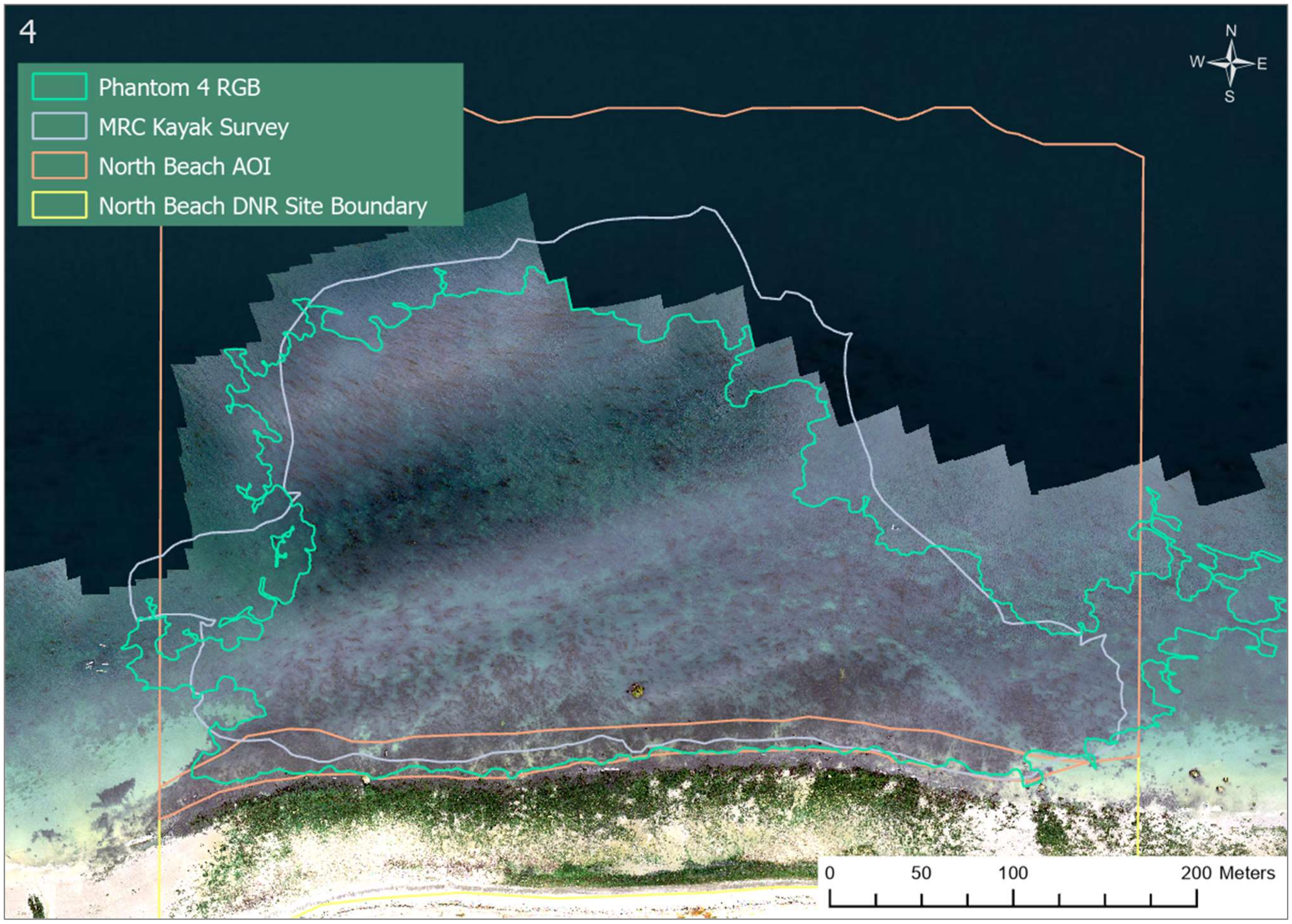


Figure 15. Kayak and imagery-based kelp bed perimeter methods using fixed-wing NGB and P4 RGB surveys at Edmonds (1 and 2 respectively) and North Beach (3 and 4 respectively). Imagery-based delineation relied on an 8 meter distance requirement to include kelp in the bed perimeter. At North Beach, perimeters were clipped at the AOI boundary for the sake of comparison.

The MRC kayak estimates of bed area were similar to, or larger than, estimates derived from hand delineated imagery (Figure 16). At Edmonds, the fixed-wing NGB estimate was lowest at 50% of the kayak area, while P4 RGB imagery produced results that were much more similar to the kayak area estimations at 102% of the kayak area. At North Beach, both sets of imagery were comparable relative to the kayak area estimation at 89% for fixed-wing NGB, and 88% for P4 RGB.

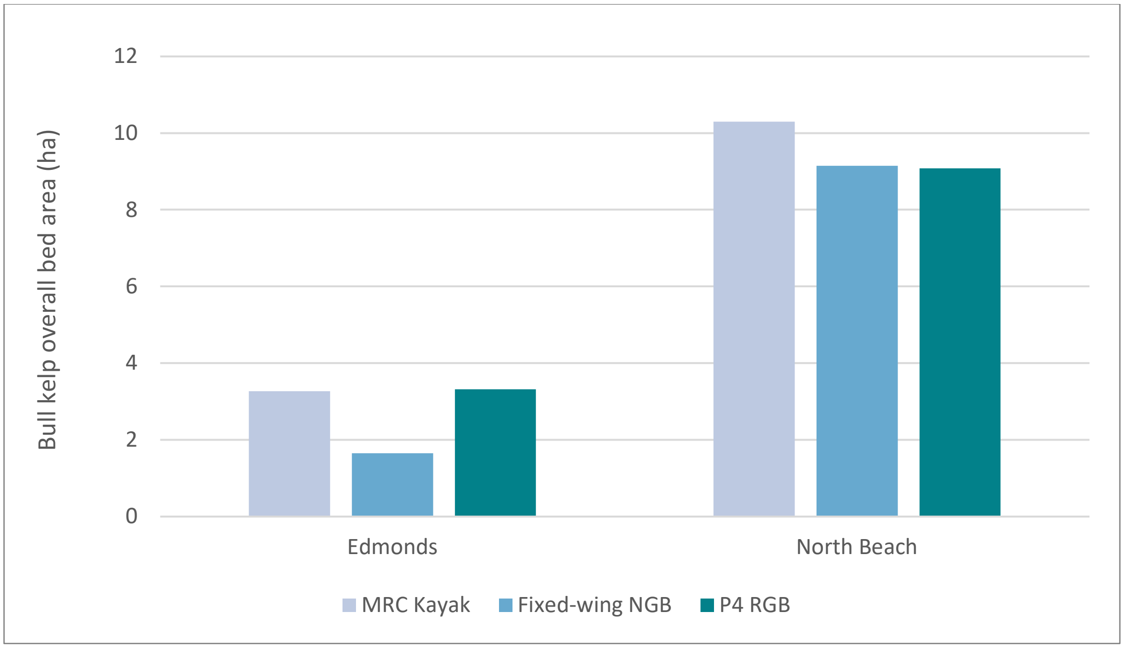


Figure 16. Kelp bed area calculated for the kayak perimeters and hand delineated imagery-based equivalent at each site.

Semi-automated estimate of bed-area from imagery

Estimates of bed area generated by the ArcGIS Pro *Aggregate Polygons* tool from the P4 Multispectral and P4 RGB imagery were similar (Figure 17), with P4 RGB equaling 93% of the P4M at North Beach and 104% at Edmonds. Fixed-wing NGB area estimates were lower and showed the greatest magnitude of difference from the other estimates (66% of the P4M estimate at North Beach and 47% at Edmonds). This pattern differs from the canopy results, in which the P4M and fixed-wing NGB were found to be similar and the P4 RGB was distinct.

The MRC volunteer kayak estimates were similar to, or higher than, automated image classification estimates (Figure 17). Agreement was closer with the UAV platforms (P4M and P4 RGB) than the fixed-wing platform. At Edmonds, the P4M equaled 102% of the kayak area, P4 RGB was 105%, and fixed-wing NGB was 48%. At North Beach, these values were 77%, 72%, and 51% respectively.

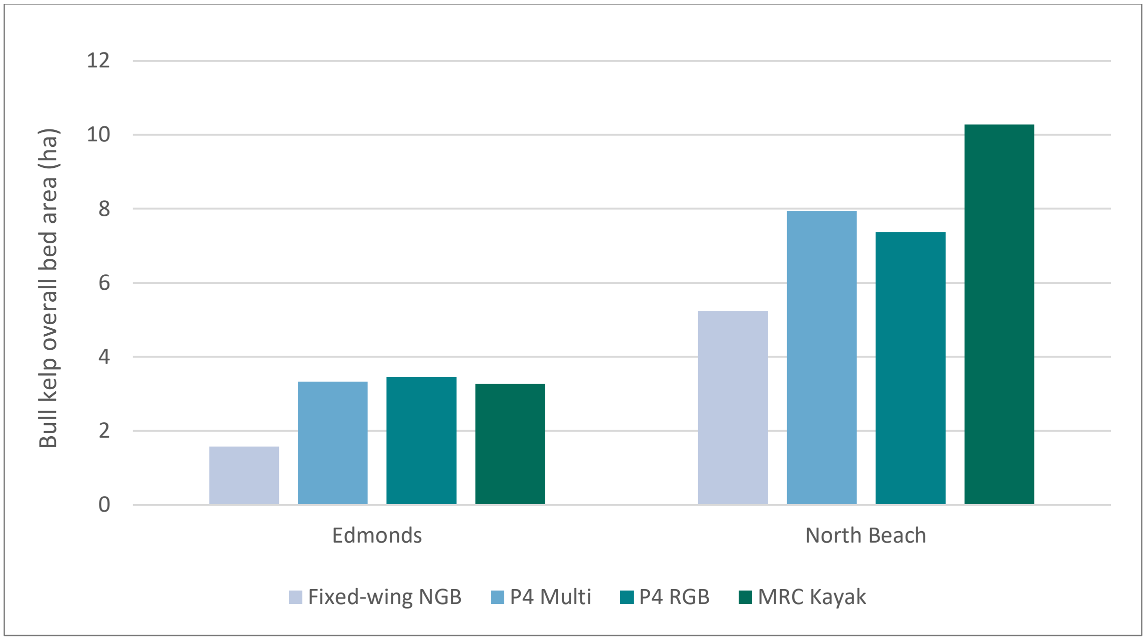


Figure 17. Estimates of overall bed area at each site generated by aggregating the classified kelp canopy from each imagery platform as compared to the area calculated from MRC kayak perimeters.

DNR ground-based estimates of canopy area based on quadrat samples

Ground-based quadrat and transect samples collected by DNR showed general agreement with the bed perimeters delineated by MRC volunteers (Figure 18). MRC kayak-delineated perimeters fell within the transect-based observations of the shallowest and deepest plants along all DNR transects at Edmonds and the majority of transects at North Beach. The transect data was expected to cover a larger footprint because it had a lower threshold for kelp detection (a single individual within 5 m of the transect). A notable exception to this general pattern occurred at two transects in the center of the North Beach site, where maximum depth delineated along the transects was shoreward of visible kelp canopy in the imagery and shoreward of one out of three MRC kayak-based perimeters. The apparent error in the location of the deepest plant along these two transects could be attributed to tides and currents; these points were assessed outside of the target window for data collection (up to 30 minutes later).

Transect-based measures of percent cover showed general agreement with the location of kayak bed perimeters; quadrats with higher cover generally fell within the MRC kayak bed boundaries. Differences between the two datasets were expected due to the distinct data collection methods, detection capabilities and spatial scales.

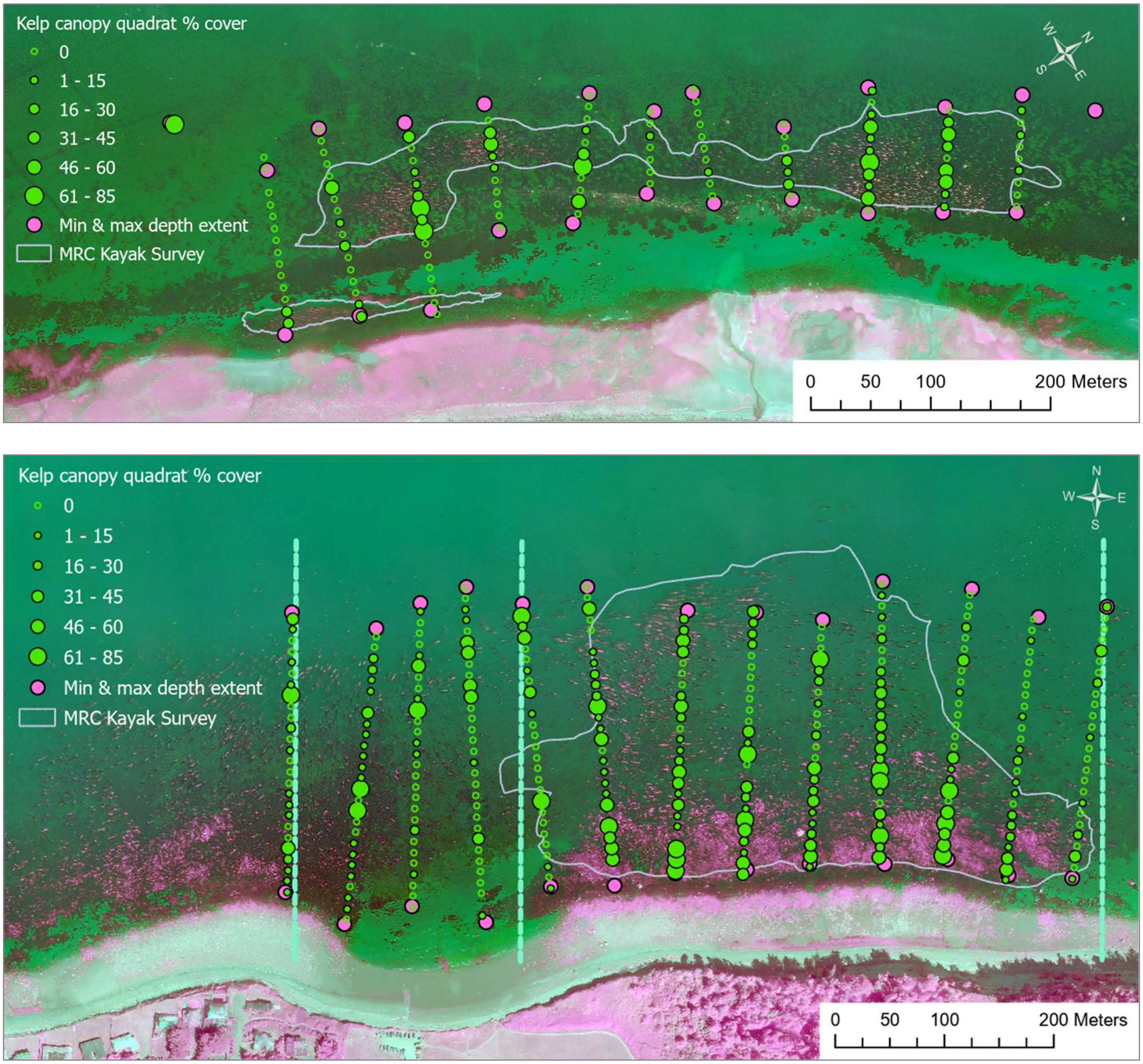


Figure 18. MRC kayak perimeters and DNR transect data overlaid on the fixed-wing NGB survey performed at Edmonds (top) and North Beach (bottom). The pink dots represent the minimum and maximum depth that bull kelp was found along each transect, and the green circles symbolize percent cover within 1 m^2 quadrats

3.5.3 *Percent cover*

Imagery-derived estimates of percent cover of kelp canopy within the bed ranged from 8-18% at Edmonds and 15-41% at North Beach (Table 12). The fixed-wing NGB estimates were the largest at both sites, and the P4 Multispectral were approximately half as large (ranging from 1.8-2.5 times smaller). The P4 RGB percent cover varied in magnitude relative to the other two platforms at each site.

Quadrat-based estimates of percent cover by DNR fell within the range of imagery-derived estimates at both sites. At Edmonds, estimated cover was 11% ± 1.9% (SE), compared to a range of 8-18% in the imagery. At North beach estimated cover was 22% ± 1.4% (SE), compared to a range of 15-41% in the imagery.

Table 12. Estimated percent canopy cover within the overall kelp bed areas generated from each classified result.

	Edmonds	North Beach
P4 Multispectral	8%	22%
P4 RGB	14%	15%
Fixed-wing NGB	18%	41%
Transect-based estimate	11%	22%

4 Discussion

4.1 Assessment of the Platforms and Methods Tested

This demonstration project successfully collected UAV and fixed-wing imagery at nine sites that represent a range of kelp canopies and environmental conditions in northern Puget Sound. From this imagery, large continuous orthomosaics were successfully generated using the same photogrammetric workflow for eight out of fourteen surveys using both platforms. These orthomosaics served as the basis for a variety of analyses that quantified kelp canopy characteristics, and compared them to ground-based observations. In this way, the project provided ‘proof of concept’ for a tractable work flow of data collection and processing. The results of this project demonstrated strong potential for aerial imagery-based data to complement kayak-based monitoring programs by further describing canopy abundance and spatial structure.

While the demonstration project showed ‘proof of concept’, we consider both the methods and results to be exploratory. Further methodological refinements are needed so that the results can be interpreted with confidence. A high priority for future processing will be to compare supervised classification results with those generated using various spectral indices, such as those explored in Cavanaugh et al. (2021). This work will allow us to understand how classification results relate to spectral characteristics and to findings from other studies. Staff at DNR’s Nearshore Habitat Program will explore these questions as part of related aerial imaging projects. The ultimate goal of this work is to develop standard, repeatable methods for surveying small and low density kelp canopies.

Ultimately, the goal of aerial imaging work in the applied management context of this project is to inform our understanding of kelp distribution and the dynamics and trends in kelp canopies. This is challenging because this and other studies show that small differences in processing methods, such as training site selection or spectral thresholds for classifying ‘kelp canopy’, often have major impacts on results. Additionally, many studies have shown that imagery analysis results are highly sensitive to known and common environmental conditions such as tides and currents, and the magnitude and timing of these individual effects are often specific to location. For example, Cavanaugh et al. (2021) estimated a 32% decrease in canopy area associated with a 0.1 m/s increase in current velocity at one site, and did not find a consistent relationship between tidal height and current speed. These results, and those from related studies such as Britton-Simmons et al. (2008) suggest that there is substantial uncertainty associated with areal extent estimates of kelp canopies, even with aerial technologies that capture extremely high resolution imagery.

Among the many questions that were raised during the course of this project, topics that most merit further research in the specific context of kelp canopy mapping in Puget Sound include:

- To what extent canopy area estimates vary between platforms as a direct result of the larger pixel size associated with fixed-wing platforms, and whether this offers further guidance on the optimal altitude for mapping bull kelp forest canopies. Furthermore, is this variance different for kelp forests with different sizes and densities?
- Whether the placing of unstable ground control objects in the open water region of kelp canopy surveys, such as buoys, substantially improves the orthomosaicking process over open water. If so, to what degree and is the effort associated with placing them an efficient use of resources.
- To what extent bed area estimates generated from hand delineation of aerial imagery of kelp bed perimeters in Puget Sound vary when the distance threshold for including plants in the bed increases. What implications does this have for use in kayak-based perimeter survey methods?
- Whether methodological improvements could be made to the image collection, processing, and analysis workflows to produce better estimates of the abundance of kelp in the shallow subtidal and intertidal fringe zone. If these areas prove to be difficult to assess using image-based techniques, how can survey results from a subset of the bed be used to draw conclusions about status and trends.

4.2 Future Opportunities for Aerial Imagery Surveys for NW Straits

Aerial imaging techniques differ profoundly from kayak-based monitoring; they require substantially more equipment, technological expertise and data processing effort. These factors likely make kayak-based monitoring more appropriate for most volunteers, especially considering the value of engagement for volunteers by spending time in the natural environment. In addition, community engagement has been found to be a significant factor in predicting whether science-based conservation efforts will be successful (LeFlore et al., 2021), and the volunteer kayak monitoring program is an exceptional example of community engagement. While volunteer opportunities for aerial imaging may be more limited, clear examples exist of volunteers with related skills and resources.

Future uses of aerial imagery will likely be driven by the NW Straits Commission and county MRC's strategic priorities and program resources. As input for future considerations, we identified some near-term opportunities for aerial imagery techniques to complement kayak-based monitoring:

- **Aerial imagery can provide insights into refining and/or augmenting kayak-based survey methods**. Work is ongoing with volunteers to compare their 2021 field data to the imagery products generated at the two primary sites that were mosaicked and classified for this project. Similar analysis would be possible at additional sites where imagery was collected during this project but project resources limited imagery processing.

- **Aerial imagery captures more detailed information on canopy abundance and bed spatial structure than ground-based efforts, albeit with greater resource requirements.** Aerial surveys could be completed at a subset of MRC sites on a prioritized or rotating basis to enrich annual kayak monitoring data.
- **Volunteers with special expertise and interest could collaborate on aerial surveys**. A potential opportunity exists to work with volunteers who have tools and expertise in aerial imagery collection. Gregg Ridder, a volunteer pilot with the Island County MRC, collected imagery for the fixed-wing portion of this project. The fixed-wing platform is optimized to survey 10s to 100s of km of shoreline, which could provide larger areal context for the intensive volunteer kayak monitoring sites. Additional resources are needed to refine imagery collection methods and to process the imagery. For example, we recommend collection of spectral bands in addition to RGB, which can be achieved with affordable cameras, such as the MAPIR Survey3W NGB camera used in this demonstration project. Other volunteers have expressed interest in working with UAVs.
- **Analysis of existing photography could fill knowledge gaps**. An ideal starting point would be to work with volunteer Gregg Ridder to analyze approximately 10 years of overflights that he collected around Island County. Kelp canopies could be hand delineated or classified using automated methods, depending on available expertise.

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Appendix 1: List of Delivered Files

The following pages contain lists of files delivered to the NW Straits Commission pursuant to IAA 93-102466. Tables are broken down into raw imagery files, orthomosaics, and classified raster results of random forest classification.

Raw Imagery

Method	Site	Date	Image platform	# of images	Image format	Total file size	Calibration panel images	Ground control panels GPS pts
UAV	Edmonds	7/20/2021	P4 Multispectral	4,908	JPG & TIFF	16.7 GB	yes	yes
		8/5/2021	P4 Multispectral	6,096	JPG & TIFF	20.9 GB	yes	yes
	North Beach	7/21/2021	MicaSense RedEdge MX	13,106	TIFF	30.4 GB	no	no
		8/20/2021	P4 Multispectral	10,482	JPG & TIFF	25.6 GB	yes	yes
	Ebey's Landing	8/6/2021	P4 Multispectral	4,734	JPG & TIFF	16.2 GB	yes	yes
Fixed-wing	Possession Point	7/27/2021	MAPIR Survey3W - Flight lines	187	JPG	627 MB		
	Edmonds		MAPIR Survey3W - Flight lines	167	JPG	592 MB		
	North Beach	8/24/2021	MAPIR Survey3W - Flight lines	251	JPG	875 MB		
	Ebey's Landing		MAPIR Survey3W - Flight lines	185	JPG	663 MB		
	Point Partridge		MAPIR Survey3W - Flyover	125	JPG	426 MB		
	Alden Bank	9/21/2021	MAPIR Survey3W - Flight lines	105	JPG	366 MB		
	Point Whitehorn				JPG			
	Cherry Point		MAPIR Survey3W - Flyover	134	JPG	482 MB		
	Polnell Point		MAPIR Survey3W - Flyover	15	JPG	52 MB		

Orthomosaics

Method	Site	Date	Image platform	File format	File size	File name
UAV	Edmonds	7/20/2021	P4 Multispectral	GeoTIFF	954 MB	ED_07202021_p4m_ortho_final_WGS84
		8/5/2021	P4 Multispectral	GeoTIFF	1,007 MB	ED_08052021_p4m_ortho_final_WGS84
	North Beach	8/20/2021	P4 Multispectral	GeoTIFF	1,031 MB	NB_08202021_p4m_ortho_final_WGS84
	Ebey's Landing	8/6/2021	P4 Multispectral	GeoTIFF	915 MB	EB_08062021_p4m_ortho_final_WGS84
Fixed-wing	Edmonds	7/27/2021	MAPIR Survey3W	GeoTIFF	314 MB	ED_07272021_mapir_ortho_final_WGS84
	North Beach	8/24/2021	MAPIR Survey3W	GeoTIFF	333 MB	NB_08242021_mapir_ortho_final_WGS84
	Ebey's Landing		MAPIR Survey3W	GeoTIFF	294 MB	EB_08242021_mapir_ortho_final_WGS84
	Alden Bank	9/21/2021	MAPIR Survey3W	GeoTIFF	14 MB	AB_09212021_mapir_ortho_final_WGS84

Classified orthomosaics raster

Method	Site	Date	Image platform	File format	File size	File name
UAV	Edmonds	8/5/2021	P4 Multispectral	GeoTIFF	1.6 MB	ED_08052021_p4m_multispec_classified_result_final_WGS84
			P4 RGB	GeoTIFF	1.8 MB	ED_08052021_p4m_rgb_classified_result_final_WGS84
	North Beach	8/20/2021	P4 Multispectral	GeoTIFF	2.8 MB	NB_08202021_p4m_multispec_classified_result_final_WGS84
			P4 RGB	GeoTIFF	3.0 MB	NB_08202021_p4m_rgb_classified_result_final_WGS84
Fixed-wing	Edmonds	7/27/2021	MAPIR Survey3W	GeoTIFF	152 KB	ED_07272021_mapir_classified_result_final_WGS84
	North Beach	8/24/2021	MAPIR Survey3W	GeoTIFF	127 KB	NB_08242021_mapir_classified_result_final_WGS84