MAPPING BULL KELP (*NEREOCYSTIS LUETKEANA*) FORESTS IN PUGET SOUND WITH A CONSUMER-LEVEL UNMANNED AERIAL VEHICLE (UAV)

by

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A Thesis
Submitted in partial fulfillment
of the requirements for the degree
Master of Environmental Studies
The Evergreen State College
December 2021

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ABSTRACT

Mapping Bull Kelp (*Nereocystis luetkeana*) Forests in Puget Sound
with a Consumer-Level Unmanned Aerial Vehicle (UAV)

Tyler Cowdrey

Bull kelp (Nereocystis luetkeana) is a species of large brown macroalgae endemic to the Northeast Pacific region that forms conspicuous floating forests throughout Puget Sound. These forests play a foundational role in nearshore ecosystems by fixing carbon, cycling nitrogen and other nutrients, and providing critical habitat for a diverse range of marine life. Mounting evidence of bull kelp population decline in Puget Sound has prompted urgent calls for widespread long-term monitoring of this vital species, however comprehensive data on the distribution and trends of kelp forests in this region are currently lacking. This project assessed the potential for imagery captured with consumer-level unmanned aerial vehicles (UAVs) to be used to effectively map and characterize bull kelp forests in Puget Sound. A total of thirteen aerial surveys were conducted with a DJI Mavic 2 Pro UAV at five sites from July to September 2020, which resulted in the creation of large continuous image products known as orthomosaics. These products were then analyzed via supervised classification of the floating surface canopy and manual delineation of the forest perimeter to characterize the kelp forests found at each site. Accuracy analysis of the classification results showed that the object-based random forest classifier was able to achieve an overall accuracy of 94% and Cohen's kappa of 0.86 on average (n = 9) when applied to subtidal areas with good contrast between kelp canopy and the surrounding environment. However, when shallow subtidal areas with other marine vegetation present were included in the accuracy analysis at each site, overall accuracy and Cohen's kappa values decreased to 84% and 0.47 respectively on average (n = 9). A comparison of image-based delineations of kelp forest boundaries and kayak-based perimeter surveys showed that UAV surveys were a viable method to map the overall extent of the kelp forests at each site, but that refinement of both methods may be necessary to bring them into better alignment. The percent difference between UAV and kayak-based kelp forest area estimates was 26.4% on average (n = 5). Overall, this study found that aerial surveys conducted with a consumer-level UAV were an effective platform for mapping bull kelp forests in Puget Sound, and that utilizing the methods developed in this project for the purpose of regional long-term monitoring holds significant promise.

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ACKNOWLEDGEMENTS

First and foremost I would like to acknowledge and thank my advisor Dr. Erin Martin, who helped me navigate what turned out to be a much larger and more challenging project than I initially envisioned. Her support over the past two years has been essential to me seeing it through to completion, and I am deeply appreciative of her patience in offering me thoughtful feedback and guidance along the way.

I'd also like to extend a thank you to Mike Ruth, whose instruction and mentorship set me on my career path using geographic information systems to conduct environmental research. His passionate teaching and unwavering enthusiasm for all forms of geospatial data analysis were a source of constant inspiration for me, and I'm grateful to have had the chance to serve as his teaching assistant for the GIS Certificate Program.

Acknowledgements are also owed to members of the Washington State Department of Natural Resources who collaborated with me in developing and executing this project, and who provided data from their kayak-based kelp canopy monitoring research for my analysis. In particular I would like to thank Helen Berry, Jeff Gaeckle, Andrew Ryan, Miles Micheletti, Julia Ledbetter, and the Nearshore Habitat Program team for their encouragement and support.

Finally, I'd like to thank my friends and family for always having my back. In particular I want to recognize my loving and patient partner Katrina, who stuck by me every time this project extended into another quarter and was always there to discuss the latest development with me over a glass of wine and a home-cooked meal. You all have kept me going and I could not be more appreciative.

1. Introduction

Kelps are primary producing seaweeds that inhabit rocky coastal ecosystems around the world. The term kelp refers specifically to species of large brown macroalgae in the order Laminariales, though it originally applied to the industrial soda ash precursor that was produced by burning these seaweeds on the shores of Scotland in the 18th century (Dyni & Jones, 1998). Kelp populations thrive in cooler water, and therefore are primarily found in the temperate and Arctic regions of the Northern and Southern Hemispheres (Bolton, 2010). A subset of kelp species form large floating canopies commonly referred to as "kelp forests," a term which has been found to carry the appropriate weight of associations to convey the scale and important nature of these habitats (Wernberg & Filbee-Dexter, 2019). In addition to having some of the highest primary productivity rates of any habitat on earth (Mann, 1973), kelp forests perform many critical functions including the creation of biogenic habitat, the cycling of nitrogen, and the dampening of current and wave energy in nearshore environments (Eckman et al., 1989; Schiel & Foster, 2015; Druehl & Clarkston, 2016).

Bull kelp (*Nereocystis luetkeana*) is one such large canopy-forming species that is endemic to the Northeast Pacific region from the Aleutian Islands, Alaska to the California Central Coast (Mondragon & Mondragon, 2003; Druehl & Clarkston, 2016). This macroalgae attaches to rocky substrates and can grow up to 30 meters in length to reach the surface with their distinct gas-filled bulbs and long trailing blades (Mumford, 2007; Druehl & Clarkston, 2016). It also is an annual species, uncommon among kelps, meaning that bull kelp forests die off and regrow every year. Bull kelp is the primary species comprising kelp forests in Washington State, and can be found throughout Puget Sound, the Strait of Juan de Fuca, and along the Pacific Coast from Cape Flattery to Destruction Island (Nearshore Habitat Program, 2001; Berry et al., 2005;

Mumford, 2007). Another species known as giant kelp (*Macrocystis pyrifera*) also grows in Washington, but is only found west of the Elwha River (Nearshore Habitat Program, 2019).

Kelp forests in this region and the broader Salish Sea – the inland sea including the connected waterways of Puget Sound, the Strait of Juan de Fuca, and the Strait of Georgia – have been vital resources for not only the marine life in those ecosystems, but also the people that called these places home since time immemorial. Because kelp forests serve as habitat for a such rich diversity of marine life, they served first and foremost as important hunting and fishing grounds that supported large communities (Rick et al., 2005; Erlandson et al., 2015; Rector & Karsen, 2015) and held important spiritual value in those communities (Swanton, 1909; Rector & Karsen, 2015). In addition, bull kelp itself had a myriad of uses including as food and medicine (Rick et al., 2005; Turner, 1979), as containers for storage and trade (Turner, 2001), and as vessels in which other materials such as wood and bark could be steamed to make hooks, bows, baskets, harpoon lines, etc. (Turner, 1979; Turner, 2005; Kirk, 2015). So abundant and supportive of human communities were these kelp forests, that many anthropologists now hypothesize that the first human migration to North America and South America actually occurred by sea along coastal kelp forests a full 1,000 years prior to the crossing of Beringia by land (Erlandson et al., 2007; Pitblado, 2011; Jones, 2014).

In modern times, the bull kelp forests of Puget Sound are in a much more precarious position. Recent research has found that bull kelp populations in South Puget Sound have declined by more than half from their historic extents 150 years ago (Berry et al., 2021), with some beds having dramatic declines and complete losses in just the last decade (Berry et al., 2019). Similar losses of entire kelp beds have been reported in Central Puget Sound (Calloway et al., 2020), and in North Puget Sound, the Samish Indian Nation has documented almost 40%

canopy area loss in the San Juan Islands since 2006. The exact cause of the declines is not known, but research both in the lab and field has shown kelp populations are sensitive to changes in water temperature and chemistry, available nutrient levels, and grazer populations (Steneck et al., 2002; Schiel et al., 2004; Harley et al., 2012; Falkenberg et al., 2013; Schiel & Foster, 2015; Verges et al., 2016; Pfister & Betcher, 2018; Hollarsmith et al., 2020), among others. The resilience of bull kelp forests therefore becomes even more concerning in light of the potential impacts on water quality due to continued population growth in the Puget Sound region (Khangaonkar et al., 2018), changes in ocean temperature and chemistry due to climate change (IPCC, 2021) and recent high-profile mass mortality events of kelp forests in places like northern California (Rogers-Bennett & Catton, 2019) and southwest Australia (Wernberg et al., 2016).

Based on that body of evidence, there is growing concern among scientists, resource managers, conservationists, and the public at large that the bull kelp forests in Puget Sound are at risk of further significant declines in the near future. This has led to calls for more action to be taken to preserve and restore these critical habitats through coordinated research and management of our impact on the regional environment, which culminated in the creation of the Puget Sound Kelp Conservation and Recovery Plan (Calloway et al., 2020). This Plan laid the groundwork for a system of effective management of Puget Sound's kelp forests based on scientific research, and included as one of its six strategic goals to "Describe kelp distribution and trends." In identifying this strategic goal it notes that "synoptic data on kelp distribution throughout Washington State is limited to the 1990s-era ShoreZone Inventory. More detailed and recent information is needed on the distribution of both canopy-forming and understory species." It goes on to describe the patchwork of kelp canopy monitoring activities taking place around Puget Sound (more on that in Section 2.2.2), but notes that in order to distinguish natural interannual variation in kelp forest extents and long-term trends, many spatial and temporal gaps in the data record need to be filled and strategic monitoring efforts need to be substantially expanded. This last point served as a primary motivation for this project and the search for additional methods with which kelp canopies could be monitored.

The use of aerial photography captured from fixed-wing aircraft for documenting the location of kelp forests dates back to the 1930s in California (Deysher, 1993). These early surveys were simple presence/absence obliques, however systematic surveys using gridded flight lines and nadir imagery began being evaluated in 1955 by the California Department of Fish and Wildlife and have continued in one form or another as a means of monitoring kelp canopies along the CA coast since 1967 (CDFW, 2004). Similar projects to map the extent of kelp forests using fixed-wing photography surveys have taken place in Alaska in the early 2000s (Stekoll et al., 2006), and in Oregon periodically since about 1996 (Fox et al., 1996; Merems, 2011). In Washington, the Washington State Department of Natural Resources (WA DNR) has conducted fixed-wing aerial photography surveys of kelp forests in the Strait of Juan de Fuca and the Pacific coast since 1989 (Berry et al., 2005; Van Wagenen, 2015). While found to be effective in each of case, these methods require the investment of significant resources to plan and conduct surveys, and are best suited to large offshore kelp forests as opposed to the often small, low-density fringing forests found in Puget Sound (H. Berry, pers. comm.).

By contrast, the use of unmanned aerial vehicles (UAVs) for the mapping of coastal environments is a nascent, but rapidly growing field due to the promise these platforms hold for capturing high resolution data at comparatively lower costs (Anderson & Gaston, 2013; Klemas, 2015; Turner et al., 2016; Manfreda et al., 2018). Consistent and ongoing improvement of UAV technology and imagery processing tools in recent years has led to a proliferation of studies investigating potential monitoring applications directed towards coastal wetlands (Zhou et al., 2018; Doughty & Cavanaugh, 2019), intertidal reefs (Murfitt et al., 2017; Collin et al., 2019), algal blooms (Kislik et al., 2018; Taddia et al., 2019), and seagrasses (Ventura et al., 2018; Nahirnick et al., 2019), among others. In addition, there have been a small number of recent studies targeting brown macroalgae specifically including species of the order Fucales (Thomsen et al., 2019; Rossiter et al., 2020), and giant kelp (Cavanaugh et al., 2021b). To date, there has been no research published in peer-reviewed literature specifically examining the mapping of *N. luetkeana* using UAVs that this author was able to locate, though it is the subject of ongoing research currently taking place in British Columbia led by the Hakai Institute and the University of Victoria (L. Reshitnyk, pers. comm., January 2021; B. Timmer, pers. comm., March 2021). Overall, this wealth of research indicates there is significant promise in the use of UAVs to map the bull kelp forests in Puget Sound, and that work to investigate and develop methods related to that task is worthwhile.

This pioneering project sought to answer the question of whether consumer-level UAVs can be used to reliably generate geospatially accurate maps of floating bull kelp forests in Puget Sound. To achieve this, a low-cost UAV called the DJI Mavic 2 Pro was deployed to conduct automated gridded surveys of bull kelp forests at five sites across the extent of Puget Sound. The imagery from these surveys was then processed using the photogrammetry software Agisoft Metashape into large continuous image products known as orthomosaics, and assessed for overall quality and fidelity against georeferenced satellite and aerial imagery products. Orthomosaics that were deemed to be fit for further examination were then subjected to a series of potential analyses that could quantify the amount of kelp in each survey.

A potential method of analyzing these UAV-based survey products that was tested was the manual delineation of kelp forest perimeters and calculation of overall bed area contained within the imagery. These results were compared against similar bed perimeter delineation boundaries generated by WA DNR scientists using boat-based survey methods. Orthomosaics were also subjected to supervised image classification using an object-based random forest classifier and from those results metrics for canopy area and percent cover of the kelp canopy at each site were generated. The results of this classification were assessed for accuracy using a stratified random point generation and manual validation method, and summarized using the standard remote-sensing error matrix format. Finally, based on the efficacy of the tools used in this project and the results of these analyses, a summary of my perspective on the current prospect for mapping bull kelp forests in Puget Sound with UAVs and potential questions and challenges that future research projects should address is offered.

This project serves as the first major study of the use of UAVs to map bull kelp forests in Puget Sound, and one of only a very limited number in the Northeast Pacific region as a whole. It therefore offers many insights into both the great potential for expanding these methods into a more robust monitoring regime, as well as the many challenges associated with UAV mapping and image analysis of the variable conditions found in this region. It is this author's hope that through ongoing collaborations with WA DNR and other organizations invested in preserving the bull kelp forests of Puget Sound, this project marks just the beginning in a long series of research efforts to develop and refine these UAV-based mapping methods.

2. Literature Review

2.1 Bull Kelp Biology & Ecology

2.1.1 Evolutionary history and geographic distribution

There are currently more than 130 recognized species of kelp (Guiry & Guiry, 2021), though our understanding of their evolutionary history and phylogeny is still evolving. As a result of ongoing phylogenetic research and advances in genetic sequencing, new species are still being identified (Kawai et al., 2019; Kawai et al., 2020) and revisions to the taxonomic organization of Laminariales happen frequently (Klochkova et al., 2010; Rothman et al., 2015; Klimova et al., 2018). It was not until recent decades that the exact place on the evolutionary tree that algae and plants diverged became known, and for most of history many algae were simply grouped with plants or mischaracterized as fungi.

Using "molecular clock" analysis based on modeling the mutation rates in certain genes over time, it is now known that red and green algae split somewhere around 1,500 Ma (million years ago), and out of green algae evolved vascular plants. Brown algae (class Phaeophyceae) by contrast, are hypothesized to have evolved from an ancestral protist that underwent a second endosymbiosis and subsumed photosynthetic plastids from a species of red algae (Figure 1) (Yoon et al., 2004). In this way, red and brown algae are not directly linked evolutionarily, and brown algae are therefore classified as belonging to a diverse group of protists known as heterokonts (Schiel & Foster, 2015). Further genetic analyses of kelp populations have indicated that their common ancestor – the first species of Laminariales – likely originated in the cold-temperate regions of the Northwest Pacific around 25 Ma, possibly near northern Japan, and spread from there throughout the Pacific, Arctic, and Atlantic basins (Bolton, 2010; Rothman et al., 2017). Many of the genera of kelp present today radiated more recently: around 3-6 Ma (Schiel & Foster, 2015).

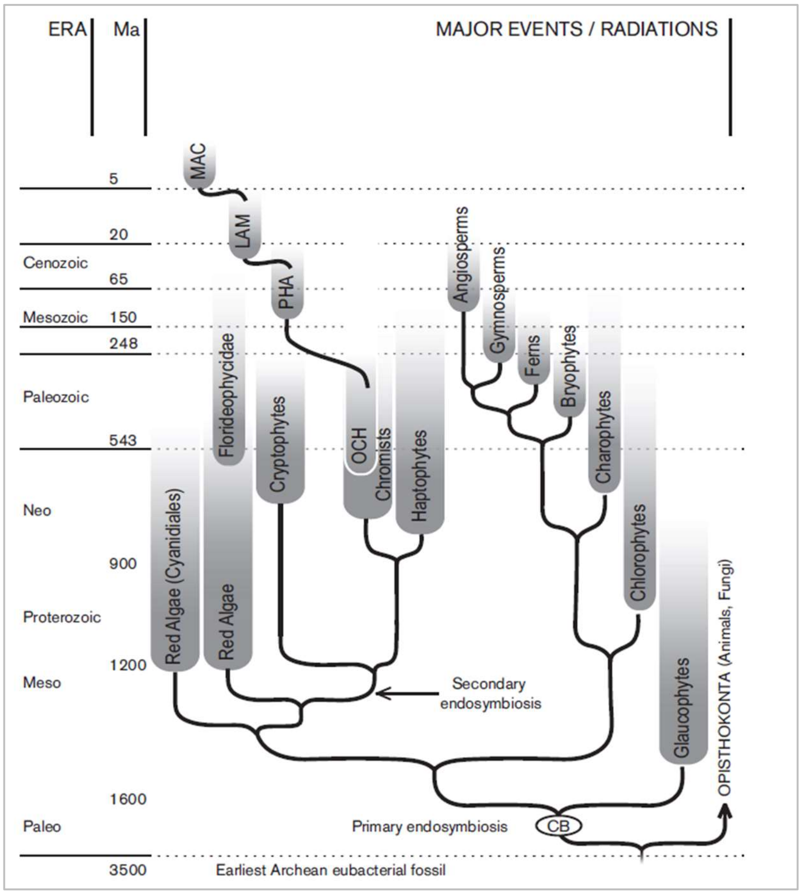


Figure 1. Hypothesized evolutionary timing and relationships between algae and plant taxa based on genetic analysis. Laminariales can be seen in the top left as indicated by "LAM," with *Macrocystis pyrifera* branching off at ~5 Ma; *Nereocystis luetkeana* would have branched from their common ancestor on a similar time scale. The node "CB" stands for cyanobacteria, and marks the oldest common ancestor of all photosynthetic life.
Source: Reprinted from Schiel & Foster (2015).

Modern day kelp populations occur most commonly in temperate and Arctic ecoregions, though they have also been found in tropical areas where significant local upwelling of cooler deep ocean water is present, such as the coast of Northern Namibia or in the vicinity of the Galapagos Islands (Figure 2) (Bolton, 2010). Despite Laminariales having a relatively low degree of taxonomic diversity, kelps exhibit a high degree of structural and functional diversity and many genera can therefore coexist in the regions they are found (Steneck et al., 2002). Four of the eleven world marine regions identified by Bolton (2010, adapted from Spalding et al., 2007) have more than ten genera of kelp present; the Alaska and the Northeast Pacific regions have the most with 16 and 19 respectively. In addition, kelps have some of the highest primary productivity rates of any vegetation observed in nature (Mann, 1973). These traits have led to kelps fulfilling a multitude of essential roles in the coastal ecosystems they inhabit.

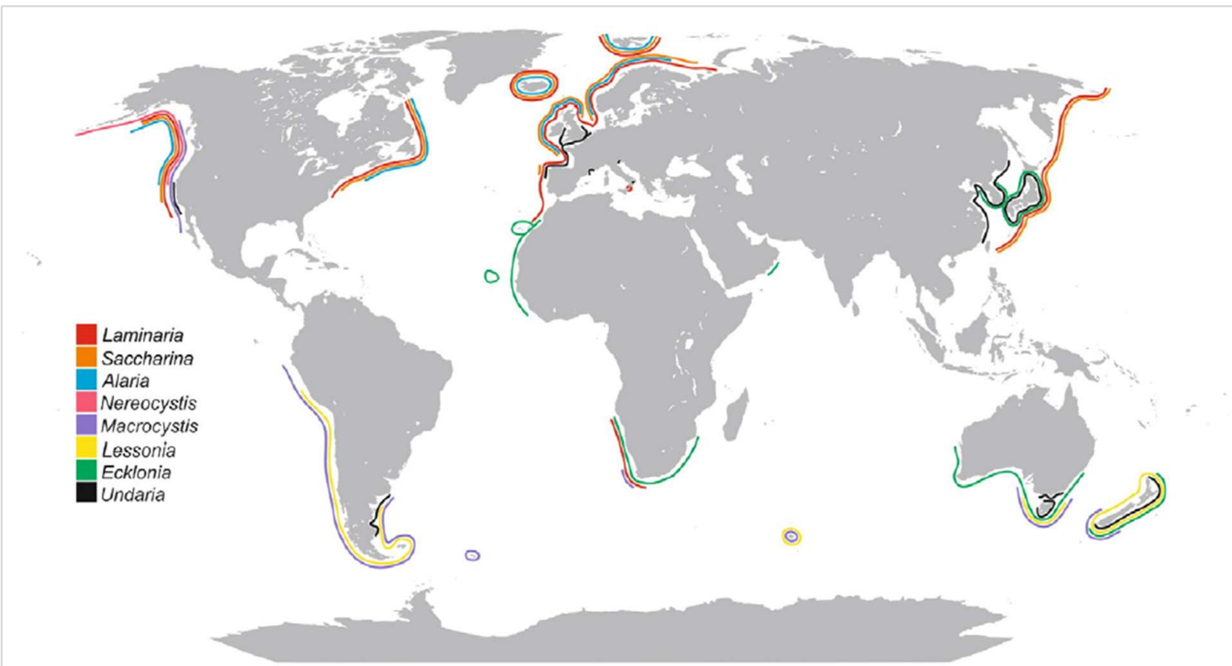


Figure 2. Approximate global distribution of dominant genera of Laminariales (kelps). The subject of this project, *Nereocystis luetkeana*, can be seen ranging from Alaska to central California.
Source: Reprinted from Teagle et al. (2017) .

Some species of kelp form large floating canopies with their vegetative tissues, which are commonly referred to as kelp forests. There are two species of canopy-forming kelp in particular that are found throughout the "Cold Temperate Northeast Pacific" (TNEP)[1] coastal province identified by Spalding et al. (2007). These species are bull kelp (*Nereocystis luetkeana*) and giant kelp (*Macrocystis pyrifera*), both of which comprise monotypic genera (Bolton, 2010; Schiel &

[1] Consists of the Aleutian Islands; Gulf of Alaska; North American Pacific Fijordland; Puget Trough/Georgia Basin; Oregon, Washington, Vancouver Coast; and Northern California ecoregions (Spalding et al., 2007).

Foster, 2015; Guiry & Guiry, 2021). *N. luetkeana* is endemic to this region (Mondragon & Mondragon, 2003; Druehl & Clarkston, 2016), while *M. pyrifera* can also be found in coastal regions throughout the southern hemisphere including South America, South Africa, Australia, New Zealand and even some subantarctic islands (Steneck et al., 2002; Schiel & Foster, 2015). In fact, *N. luetkeana* has been found as far west as Umnak Island in the Aleutian Island chain (Miller and Estes, 1989) and floating rafts have floated as far away as Japan, however established populations are only known to exist in the TNEP region.

2.1.2 Kelp forest morphology

Though *N. luetkeana* and *M. pyrifera* are distinct species, they are relatively similar in terms of their morphology. Both species grow into large floating kelp forests found in WA and consist of long fibrous stems called stipes that can reach tens of meters in length and are anchored to the seafloor by holdfasts that attach to the rocky substrate (Mondragon & Mondragon, 2003; Schiel & Foster, 2015; Druehl & Clarkston, 2016). The upper limit of the growth of these forests is mediated by a red light phytochrome-mediated response (Duncan & Foreman, 1980), which results in these forests typically being found in coastal waters with an average depth of 30 meters or less. In order to reach adequate sunlight from these depths, both species also grow gas-filled pneumatocysts (small bulbs) which lift the blades that grow out of them towards the surface; however, the configuration of these bulbs for each species is different. *M. pyrifera* stipes are dotted with dozens of small pneumatocysts along their length that all have multiple blades growing out of them, whereas *N. luetkeana* is characterized by a single large terminal bulb with all of its numerous blades – sometimes up to 60 (Springer et al., 2007) –

originating from a single surface (Figure 3) (Mondragon and Mondragon, 2003; Gabrielson et at., 2012; Schiel & Foster, 2015; Druehl and Clarkston, 2016).

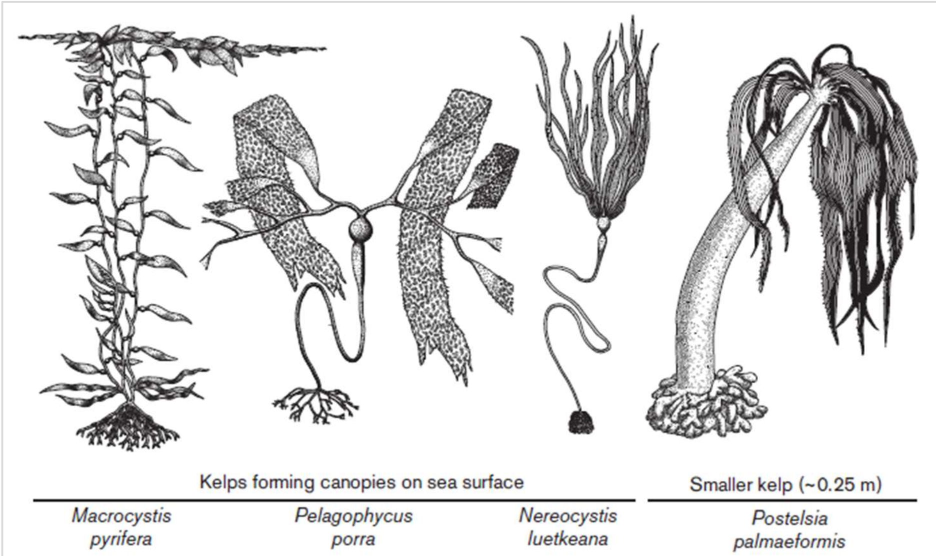


Figure 3. Morphologies of a number of common canopy forming kelps including *Macrocystis pyrifera* (far left) and *Nereocystis luetkeana* (second from right). Source: Reprinted from Schiel & Foster (2015).

Perhaps because of these similarities, bull kelp and giant kelp occupy similar niches in nearshore coastal ecosystems and regularly coexist in the TNEP region, sometimes forming mixed beds (Foster and Schiel, 1985; Springer et al., 2007). The similarity between these two species allowed for studies of giant kelp to be consulted in the design of this project. Studies investigating giant kelp forests have proliferated in recent years (Cavanaugh et al., 2010; Bell et al., 2015; Friedlander et al., 2020; Hollarsmith et al., 2020; Mora-Soto et al., 2020), and historically have been more numerous than those on bull kelp (Maxell & Miller, 1996). The comparative paucity of studies focused on *N. luetkeana* population dynamics has remained largely unchanged as of the time of writing (Calloway et al., 2020), particularly in the field of remote sensing (Schroeder et al., 2019). Studies such as this one aim to fill gaps in our understanding of bull kelp forest populations and illuminate in what ways they are similar and distinct from giant kelp forest counterparts.

2.1.3 Bull kelp life cycle

The final aspect of *Nereocystis luetkeana*'s unique biology that bears closer examination, and that is of particular relevance to the subject of population monitoring, is its annual life cycle. Bull kelp – indeed all brown algae (class Phaeophyceae) – undergo a reproductive cycle known as alternation of generations, consisting of both diploid and haploid stages (Figure 4) (Dayton, 1985; Mondragon & Mondragon, 2003; Springer et al., 2007; Hurd et al., 2014). Alternation of generations is also exhibited in a variety of other photosynthetic organisms including multicellular green and red algae, mosses, ferns, liverworts, and hornworts, though the reproductive process and role of each life stage varies dramatically from one taxa to another[2].

In bull kelp, the vegetative "plants[3]" that form the characteristic floating forest canopies are diploid sporophytes. These sporophytes form reproductive patches known as "sori" on their blades, which generate haploid spores via meiosis. The process of sori formation typically occurs some time in late summer to early fall (Foreman, 1984; Maxell & Miller, 1996), and then the sori are entirely shed from the blade and sink to the sea floor by early winter, distributing spores along the way (Dayton, 1985; Hurd et al., 2014). From here, these spores will settle out onto the seafloor and germinate into microscopic haploid gametophytes which overwinter in the environment in a semi-dormant state before releasing gametes in the spring (Edwards, 2000; Springer et al., 2007; Hurd et al., 2014). Unlike seeds, these gametophytes are photosynthetically and metabolically active and there is some evidence to suggest that they can survive for multiple years in this state before producing gametes (Edwards, 2000; Carney & Edwards, 2006). It is

[2] For instance, multicellular red algae are regarded as having some of the most complex life cycles ever discovered, often consisting of a triphasic life cycle which includes a second diploid phase called a "carposporophyte," and where the haploid phase is vegetative rather than the diploid (Lee, 2008; Hurd et al., 2014; Garcia-Jimenez & Robaina, 2015).

[3] Kelps are not in the kingdom Plantae, but rather the clade SAR or Harosa (Cavalier-Smith, 2010; Adl et al., 2012). However, kelp vegetative structures are often called "plants" and I will also use that convention herein as well.

hypothesized that this is an evolutionary adaptation which allows for kelp populations to weather periods of poor environmental suitability and then rapidly repopulate once favorable conditions return, though further research is still needed on the environmental factors that trigger this phenomenon (Carney & Edwards, 2006).

Following syngamy (fertilization) of the sessile female gametophyte oogonium by the motile sperm released by the male gametophytes, the resulting diploid juvenile sporophyte becomes rooted by a holdfast to the rocky substrate and begins to grow. By mid-summer, these sporophytes – which can grow up to 6 cm a day (Springer et al., 2007) – reach maturity and form the conspicuous forest canopies that can be seen floating at the surface from shore (Springer et al., 2007; Britton-Simmons et al., 2008; Druehl and Clarkston, 2016).

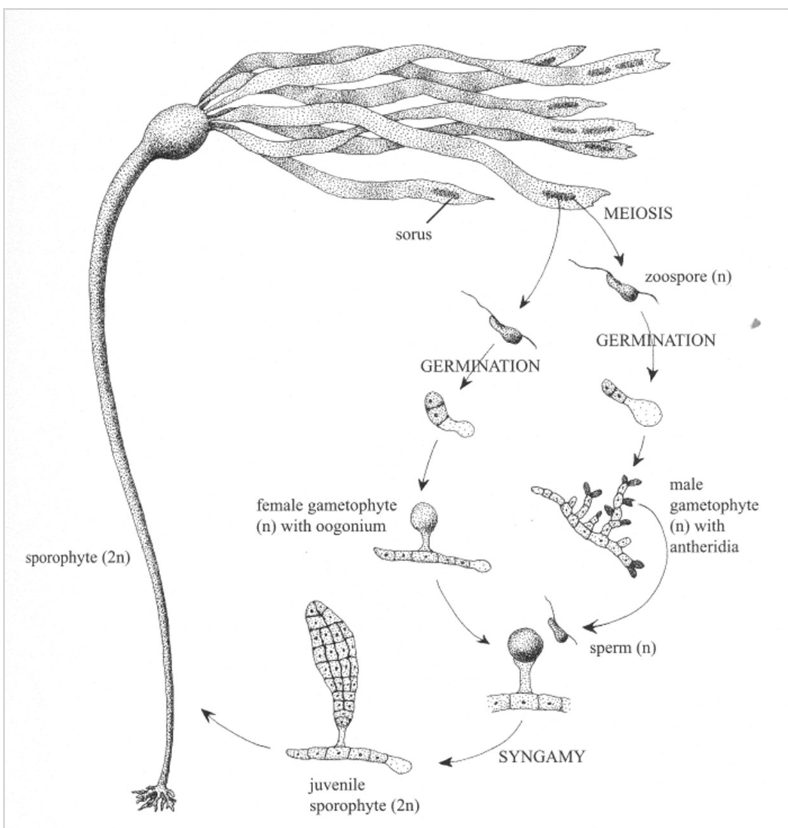


Figure 4. Diagram of life stages and reproductive cycle of Nereocystis luetkeana.
Source: Reprinted from Mondragon & Mondragon (2003).

Following successful sori abscission in the fall, bull kelp often begins to rapidly senesce, first losing their blades and eventually becoming completely detached from their holdfasts. This process is accelerated with the arrival of winter storms and by mid-winter bull kelp forests typically completely disappear[4] (Maxell & Miller, 1996; Duggins et al., 2001). This means that bull kelp is essentially an annual species, which has significant implications for population monitoring efforts. From year to year, there can be a high degree of variability in the density and distribution of plants at a given site, even though the population within a larger subregion is remaining stable (Pfister et al., 2017). Therefore, to be able to determine with confidence whether there are long-term trends in the distribution and abundance in Puget Sound – as has been cited as a major goal of the Puget Sound Kelp Conservation and Recovery Plan (Calloway et al., 2020) – it is essential that monitoring efforts capture data of the entire population on an annual basis over many years. This is where UAV surveys could offer a potential technological solution to increasing the reach of environmental scientists working on this problem.

2.1.4 Ecological role of kelp forests

At this point one might ask why the conservation of bull kelp forests in Puget Sound is important, such that investment in widespread monitoring efforts are merited. There is perhaps no ecological function more foundational that kelps perform than primary production - the fixing of carbon from the atmosphere and ocean into vegetative tissue via photosynthesis. Generating accurate estimates of primary productivity rates for kelps can be challenging due to a number of factors including: the variability they display between different populations of the same species,

[4] There has been evidence that some Nereocystis individuals are able to survive winter and reproduce the following year in locations such as Kachemak Bay, AK (Chenelot, 2003), however the overwhelming majority of published research on bull kelp indicated these are outliers.

the impact of dynamic environmental conditions that are difficult to replicate in the lab, and for large canopy forming kelps, accounting for the impact the canopies themselves have on their local environment as they grow (Hurd et al., 2014). Despite these challenges, long-held contentions that kelp forests are among the most productive ecosystems on earth (Mann, 1973; Dayton, 1985; Jackson, 1987) have been confirmed as advances in population monitoring and biomass modeling have been achieved (Reed et al., 2008; Graham et al., 2010; Cavanaugh et al., 2011; Hurd et al., 2014; Schiel & Foster, 2015; Rodgers & Shears, 2016; Navarrete et al, 2021).

The incredible productivity rates of kelps are due in large part to their high photosynthetic tissue surface-area-to-volume ratios; they the lack dead tissues that vascular plants rely on for structural support and protection. This means that even the largest canopy forming kelps such as *M. pyrifera* and *N. luetkeana*, which invest significant energy into structural tissues, exhibit higher productivity rates than their terrestrial counterparts (Starko & Martone, 2016). As a result, macrophytic algae populations represent a significant proportion of fixed organic matter in nearshore coastal ecosystems around the world (Klinger, 2015), and in many places exceed 50% of the total carbon fixation happening therein (Gattuso et al., 2006).

The organic matter that kelps generate through primary production can enter coastal food webs through a variety of different pathways (Figure 5) that can be roughly broken down into the direct grazing of living tissue and the consumption of kelp detritus after senescence. It is thought that kelps are also consumed in their spore and gametophyte life stages by a variety of small organisms (protozoans, bivalves, etc.) (Dayton, 1985), though these forms of predation have been less studied. As juvenile kelp plants grow beyond these microscopic stages they experience grazing by a number of invertebrate species including isopods, polychaetes, gastropods, small crustaceans, abalone, and most notably sea urchins (Dayton, 1985; Springer et al., 2007; Schiel and Foster, 2015). Within Puget Sound, kelps experience grazing primarily from snails such as *Lacuna vincta* (Duggins et al., 2001) and kelp crabs (Berry et al., 2019), though multiple species of urchin are also present (Calloway et al., 2020).

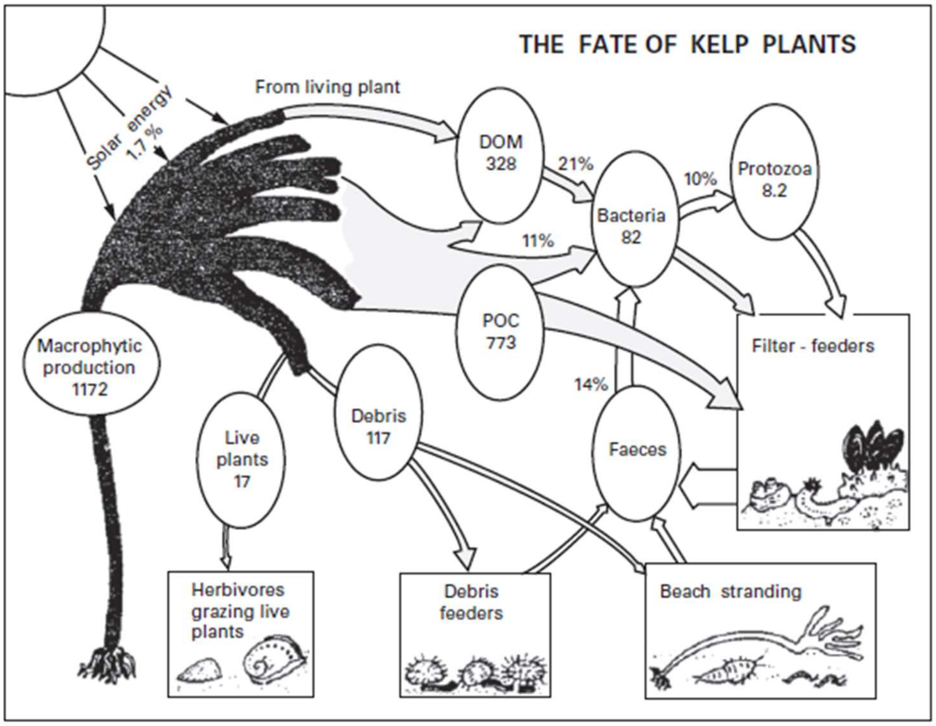


Figure 5. The fate of seaweed productivity in nearshore ecosystems. Production and consumption are in grams of carbon per m^2 per year. Source: Reprinted from Hurd et al. (2014).

In addition to direct herbivory, nutrients fixed by kelp forests also enter food webs in the form of detritus as their tissues decay. This process can begin when individuals become dislodged from their holdfasts, live vegetative tissue is excised due to physical oceanographic forces, or simply as a result of incremental blade erosion[5]. The resulting detrital matter gets consumed by a wide variety of organisms including many of the same grazers already mentioned above, as well as benthic invertebrates, microbial detritivores and suspension and filter feeders

[5] The significance of the final of these three pathways is likely to be minimal relative to the other two. Yorke et al. (2013) found that in Macrocystis forests near Santa Barbara, CA, blade erosion accounted for only roughly 0.2% of total suspended reef particulate organic carbon. They do note that larger pieces of detritus probably represent a much larger constituent of the detrital food webs there.

(Krumhansl & Scheibling, 2012; Schiel & Foster, 2015). This vector of organic material assimilation into nearshore food webs is in fact far more significant than direct grazing and in some instances has been estimated to account for the fate of up to 80-90% of the net production of kelps (Mann, 1973; Krumhansl & Scheibling, 2012). Benthic communities within kelp forests are diverse and productive because in addition to the high primary productivity rates of kelps, the structure of canopies can reduce currents and flow rates near the seafloor, allowing more of the detritus to settle out and be consumed (Eckman et al., 1989). Providing a base for detrital food webs represents a major foundational role kelp forests play (Krumhansl & Scheibling, 2012).

Finally, after being consumed by herbivores and detritivores kelp-derived organic matter is carried further up the food chain by successive tiers of predators. In some ecosystems kelp-derived nutrients can represent a significant proportion present within the entire food web (Duggins et al., 1989). These higher trophic levels often include valuable fisheries humans rely on for food and commerce (Krumhansl & Scheibling, 2012). As one example, Von Biela et al. (2016) conducted a study of black rockfish and kelp greenling along the Northeast Pacific Coast region using carbon isotope analysis and found that on average 57% of the carbon found in the fish muscle tissue was originally fixed by kelps. Similar studies have shown that comparable proportions of carbon in a variety of nearshore predators can be linked back to kelps including copper rockfish (Markel & Shurin, 2015); predatory snails, filter feeders, urchins, and seabirds in Norway (Fredriksen, 2003); and a multitude of fish species off the coast of Santa Barbara (Koenigs et al., 2015). What all of this shows is that the primary productivity of kelp forests can have ripple effects all the way to the top of food webs. The role of bull kelp as a foundational species in Puget Sound in this regard is unquestionably a strong motivation for studying and preserving kelp forests.

In addition to primary production, there are many other important ecosystem functions that kelp forests perform which will not be explored in great depth in this review, but that further highlight the importance of monitoring and to the extent possible conserving and restoring the kelp forests of Puget Sound. Foremost among these is that kelp forests create critical habitat for a diverse range of marine life including invertebrates, finfish, and marine mammals, and promote higher levels of biodiversity than surrounding open water environments (Carr, 1991; Siddon et al., 2008; Christie et al., 2009; Klinger, 2015; Teagle et al., 2017; Miller et al., 2018; Layton et al., 2019). A major factor in this habitat creation is that kelp forests attenuate wave and tidal energy, which acts as a buffer for other organisms to utilize for feeding, resting, mating, and larval dispersal and settlement (Eckman et al., 1989; Eckman et al., 2003; Shaffer et al., 2020).

The decline of kelp forests is associated with significant changes to understory assemblages of sessile and invertebrate marine life (Bishop et al., 2009; Flukes et al., 2014). These declines can in turn have a ripple effect that threatens higher trophic levels of marine life (Smith et al., 2020), and in some cases devastates important economic fisheries of finfish and shellfish (Bertocci et al., 2015; Hinojosa et al., 2015; Roger-Bennet & Catton, 2019). What is perhaps most concerning about kelp forest losses is that if the declines are significant enough, new stable-states can be reached where the lack of reproducing sporophytes and grazing pressures lead to permanent changes in regional ecology away from rich and diverse communities to homogonous urchin barrens (Filbee-Dexter & Scheibling, 2014; Wernberg et al., 2016; Ling & Keane, 2018; Roger-Bennet & Catton, 2019).

The information provided in this Section 2.1 is intended to present a picture of the unique and vital nature of kelp forests. The literature on the many functions species such as *Nereocystis luetkeana* perform in marine ecosystems including primary productivity, habitat creation, and the support of important human fisheries is rich and extensive. This represents just a subset of that literature but hopefully has provided a compelling case for the need to monitor, conserve, and restore the forests created by this critical species.

2.2 Bull Kelp Forests in Puget Sound

2.2.1 Kelp forest biogeography in the Salish Sea

Both *Macrocystis pyrifera* and *Nereocystis luetkeana* occur in abundance along the Pacific coast of Washington State and in the Strait of Juan de Fuca (Figure 6) (Shaffer, 2000; Berry et al., 2005; Mumford, 2007). Populations there appear to have on average remained healthy in recent decades, despite significant variability in canopy extent between years (Van Wagenen, 2015; Pfister et al., 2017). However, within Puget Sound proper – defined here as beginning at Admiralty Inlet – only bull kelp populations currently exist (Berry et al., 2019; Calloway et al., 2020). Giant kelp is not known to have extended further inland than this historically either (Mumford, 2007), at least dating back to when European colonizers began keeping records (Thom & Hallum, 1990).

This distribution pattern is mirrored to the north in British Columbia as well where bull kelp and giant kelp both occur on the Pacific coast (Druehl & Clarkston, 2016; Nijland et al., 2019), but within the Strait of Georgia only bull kelp is present (Lamb et al., 2011; Schroeder et al., 2019). The evidence supports this having been the case historically in this region as well (Druehl, 1977; Costa et al., 2020).

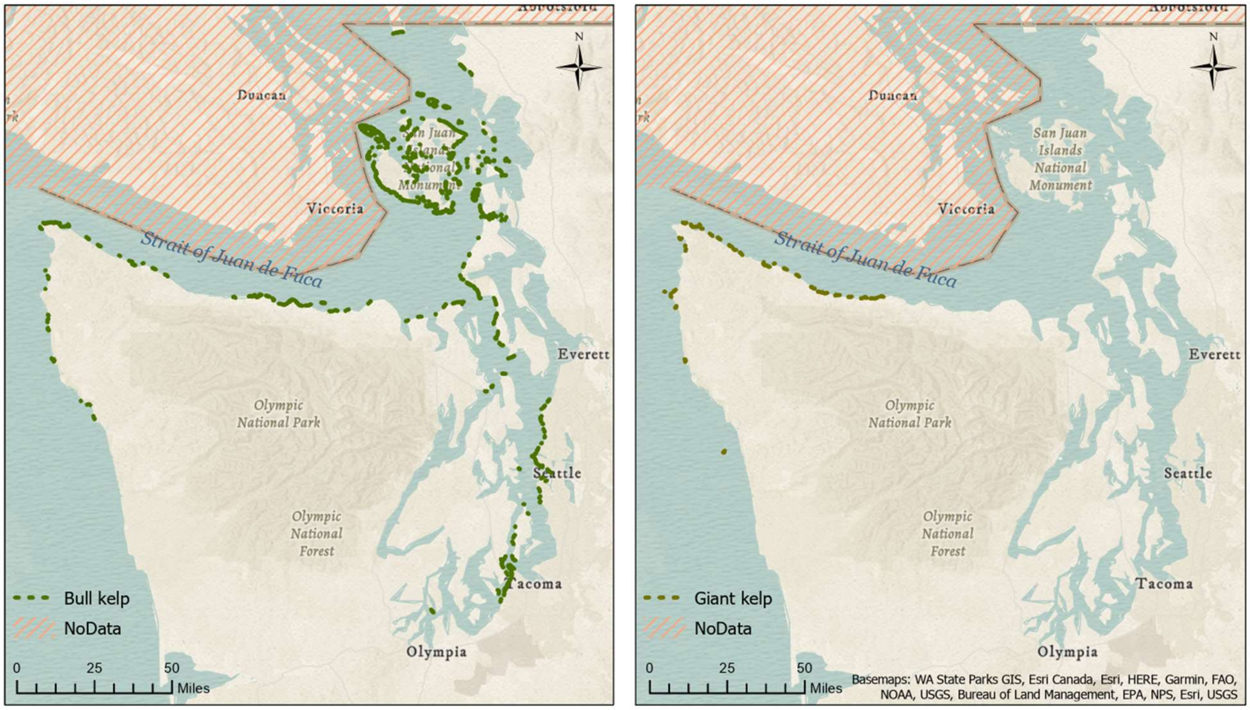


Figure 6. Distribution of floating canopy-forming kelp species in WA state per the ShoreZone Inventory conducted in the 1990s: (left) Nereocystis luetkeana and (right) Macrocystis pyrifera.
Map credit: Tyler Cowdrey | Data source: Nearshore Habitat Program, 2019.

The exact combination of environmental conditions that have led to these broad distributional patterns is not known, though factors such as water temperature, tidal currents, nutrient availability, grazing pressure, sediment characteristics, and recruitment dynamics are all likely to have played a role (Vadas, 1972; Duggins et al., 2001; Springer et al., 2007; Pfister et al., 2017; Berry et al., 2019; Dobkowski et al., 2019). Confounding any effort to investigate the influence of these variables further though is the lack of spatial and temporal data sets describing the distribution and abundance of bull kelp canopy in Puget Sound in a detailed manner. The recently published Puget Sound Kelp Conservation and Recovery Plan (Calloway et al., 2020) describes this as part of the strategic goal to "Describe kelp distribution and trends." It elaborates that current population distribution information is limited to the 1990s-era ShoreZone Inventory (kelp canopy data pictured above), a patchwork of kayak surveying efforts by WA DNR and the Northwest Straits Commission, and a number of smaller targeted efforts such as monitoring of the San Juan Islands by the Samish Indian Nation (these methods will be described in the next section). The lack of robust contemporary monitoring data of bull kelp population distributions and trends in Puget Sound is a primary motivation for developing additional monitoring methods such as the on in this project.

2.2.2 Bull kelp mapping efforts in Puget Sound

Historically, efforts to conduct detailed surveys of kelp forest distribution in Washington have been few and far between. Maxell and Miller (1996), note in their seminal study of bull kelp in South Puget Sound that prior to the early 1990s there had been relatively few demographic studies of bull kelp anywhere and claim that their study was the first of its kind to quantitatively describe the timing of recruitment, reproduction, and mortality of the species. However, owing to kelps' importance for the production of alkali (soda ash and potash) in the 18th and 19th centuries, and the fact that kelp forests were used as navigational aids dating back to the earliest explorations of the Northeast Pacific coast by colonizers, records do exist as to their historic distributions.

The most detailed examination of these historical documents was conducted by Thom and Hallum (1990), with the authors consulting a variety of sources (Figure 7). The earliest record of kelp forests they located was a map drawn by the Wilkes expedition in 1841, as well as hydrographic surveys that noted the locations of both kelp and eelgrass conducted by the US Department of Commerce from roughly 1892 to 1924. Other sources they examined were detailed surveys conducted by George B. Rigg of the US Department of Agriculture in 1912, Coast Pilot navigation serials published (though not updated) every year from the late 1800s onward, and the first attempt at aerial photography mapping conducted in 1978 by the then

Washington Department of Wildlife (now Washington Department of Fish and Wildlife). This review served as an important baseline for the information that exists on the historic extent of kelp forests in Puget Sound, and the authors calculated significant differences in the extent over time, but were also cautious to state that differences could be due to any number of differences in methodologies and motivations between each project.

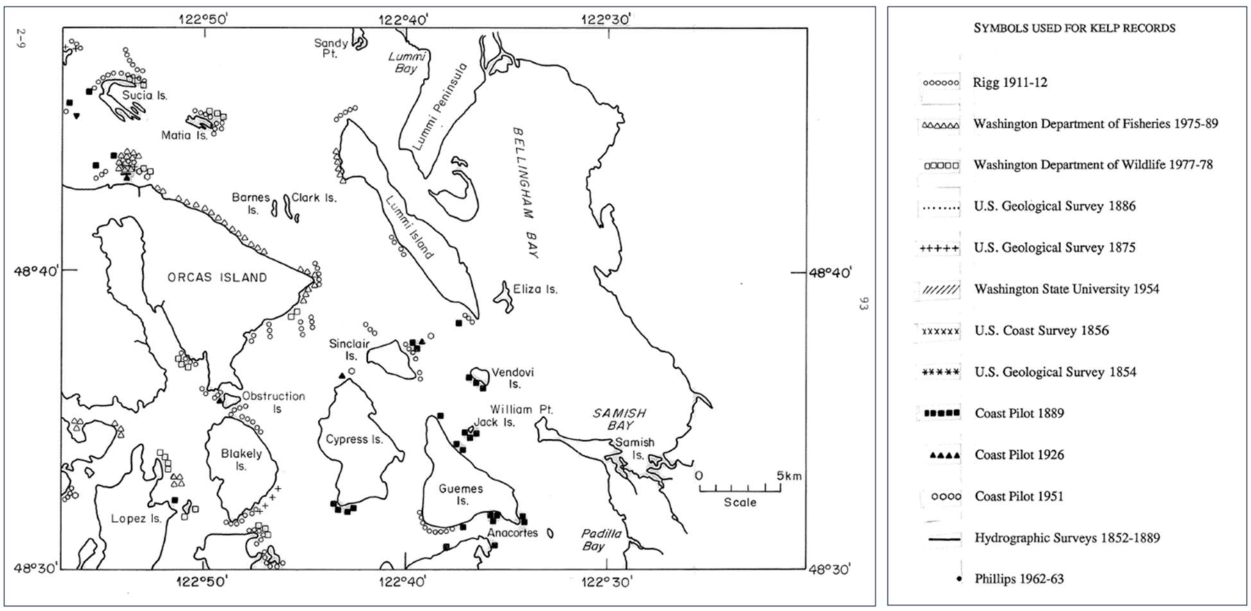


Figure 7. Chart showing the mapped locations of bull kelp forests in a subsection of Puget Sound prior to 1980 based on historical surveys and navigation charts.
Source: Reprinted from Thom & Hallum (1990).

In 1989, the Washington Department of Natural Resources began conducting aerial surveys of kelp forests in the Strait of Juan de Fuca and the Pacific coast (Berry et al., 2005), and has continued these surveys on an annual basis since then. The surveys originally relied on 70 mm color-infrared film, but then switched to an enhanced digital camera after 2008 due to the discontinuing of the film (Van Wagenen, 2015). Imagery is captured from a manned fixed-wing aircraft in late summer (August to October) within an hour of low tides that are less than +1.0 ft MLLW on days with suitable weather conditions. Once collected, survey imagery is projected onto sectional maps and the extent of the kelp canopy is hand delineated. From 1989 to 2015 it was found that kelp forests in these regions were overall stable, though significant interannual variability did occur, particularly in the eastern extents closer to Puget Sound (Pfister et al., 2017). These annual surveys certainly represent the most continuous and long-term data set of kelp forests in Washington State to date, but the surveys do not extend into Puget Sound proper and thus cannot assist with filling gaps in the data there unless they get extended in the future.

A similar effort has been undertaken by the Samish Indian Nation to document the distribution of bull kelp forests in the San Juan Islands using aerial photography, beginning in 2016 (Palmer-McGee, 2021). This imagery was compared to a comparable imagery set collected by an independent group in 2006, as well as to Traditional Ecological Knowledge passed down by tribal elders. The Samish Indian Nation Department of Natural Resources is an active partner in the development of a Sound-wide indicator for kelp forest extent and has expressed interest in continuing aerial surveys in their Usual and Accustomed fishing areas (H. Berry, pers. comm., October 2021). This could serve as a valuable data set for filling data gaps going forward and a possible source to compare UAV-based imagery to as part of some future project.

The final method actively being used to monitor kelp forests in Puget Sound is kayak-based perimeter extent mapping and transect surveys. The former is most widely deployed in North Puget Sound by volunteers supporting the Northwest Straits Commission (NW Straits), who are overseen by county-level Marine Resource Committees. The surveys currently take place at more than 15 sites across 6 counties, and consist of volunteers kayaking around the perimeter of the visible kelp forest at each site while carrying a handheld GPS unit, with certain conditions for whether individual kelp plants are included or not (Bishop, 2016). While these efforts are incredible as a means of grassroots engagement and the promoting of community science, they are less valuable as a scientifically rigorous measure of kelp forest abundance.

Many sites have only recently started to be surveyed, and methods are not entirely consistent between groups, or indeed within the same group from year to year, which has led to many anomalies in the data and the need for extensive cleaning and masking in order to compare areas across years (J. Ledbetter, pers. comm., November 2021). However, on a fundamental level these survey efforts still provide meaningful presence/absence data and greater knowledge of areas that are worth surveying using more rigorous scientific means.

WA DNR also recently began performing kayak surveys similar to those conducted by NW Straits volunteers at sites throughout South and Central Puget Sound. These surveys focused primarily on sites from the Tacoma Narrows southward in the years from 2013 to 2018 (Berry, 2017; Berry et al., 2019), however efforts expanded to sites in Central Puget Sound beginning in 2019 (based on first-hand knowledge and experience). The surveys WA DNR conducts also include the mapping of the overall perimeter of the kelp forests, but also more detailed data collection along predetermined transects including depth measurements, density and percent cover estimations, and observations of morphological conditions. Robust analysis of these additional data has been limited so far, but the motivation for collecting them is to begin to have multiple dimensions over which diverse kelp forests can be compared. While these and the NW Straits kayak-based surveys have the advantage of being low cost and relatively easy to perform, limitations still exist as to the coverage they can achieve, even with significant expansion of the respective programs.

Overall, these many diverse methods currently being deployed to map the extent of kelp forests in Puget Sound offer a fantastic starting point in the seeking of Sound-wide annual estimates of distribution and abundance. It is certain that in the near term, a mosaic of methods will be necessary to achieve total coverage of the entire region such that major losses can be detected. However, the many persistent gaps in the data create urgency for the need to develop additional methods that can capture meaningful data over large areas of Puget Sound.

2.2.3 Evidence of historic and future population decline

In recent decades, there has been a growing recognition that kelp forests around the world occupy fragile niches in coastal ecosystems and are vulnerable to deforestation due to a variety of factors such as disease, overabundance of herbivores, and oceanographic anomalies in temperature, salinity, or nutrient loading (Steneck et al., 2002; Krumhansl et al., 2016). This has been born at least in part out of a growing body of research showing that kelp forests are increasingly vulnerable to the potential impacts of climate change. Among the many proximal causes for declines in kelp populations that can be sourced back to climate change are rising ocean temperatures (Schiel et al., 2004; Bolton et al., 2012; Harley et al., 2012; Verges et al., 2016; Smale et al., 2019; Lowman et al., 2021), ocean acidification (Hollarsmith et al., 2020), nutrient loading (Benedetti-Cecchi et al., 2001; Norderhaug, et al., 2015), and grazing pressure due to trophic imbalances (Filbee-Dexter & Scheibling, 2014; Ling et al., 2015). In addition to this, there have been a number of high profile cases of mass die-off events of kelp forests due to marine heat waves in northern California (Rogers-Bennet and Catton, 2019), western Australia (Wernberg et al., 2016), and New Zealand (Thomsen et al., 2019). All of this serves as a harbinger for what may lay ahead for bull kelp forests in Puget Sound.

The growing global awareness of the decline of kelp forests has been mirrored in Puget Sound, where people are increasingly aware of the foundational role bull kelp plays in regional nearshore ecosystems, and the real possibility of substantial populations losses occurring in the future (Calloway et al., 2020; Doughton, 2021). This concern is backed up by research validating anecdotal evidence that bull kelp forests currently inhabit a fraction of their former extent in Puget Sound, and that shows losses in some sub-regions are happening in real time.

In an examination of historical records similar to the one conducted by Thom & Hallum (1990) described in Section 2.2.2, Berry et al., (2021) recently reanalyzed navigation maps and agricultural inventories dating back to 1878. By standardizing these documents into 1-km shoreline segments representing all of South Puget Sound, they were able to quantify changes in linear extent over a time span of close to 150 years. What they found was that basin-wide, South Puget Sound has lost over 60% of its historic bull kelp forest extent, with individual sub-basins losing up to 96% (Figure 8). Comparing these losses to data on water quality, they correlated losses with elevated temperature, lower nutrient cycling, and low current velocities. While this is not strictly an areal estimation of the total forest area that has been lost since colonization of the Puget Sound region in the mid-19th century, it is a striking and significant finding, and suggests that many other kelp forests in Central and North Puget Sound could be at similar risk of loss in the future.

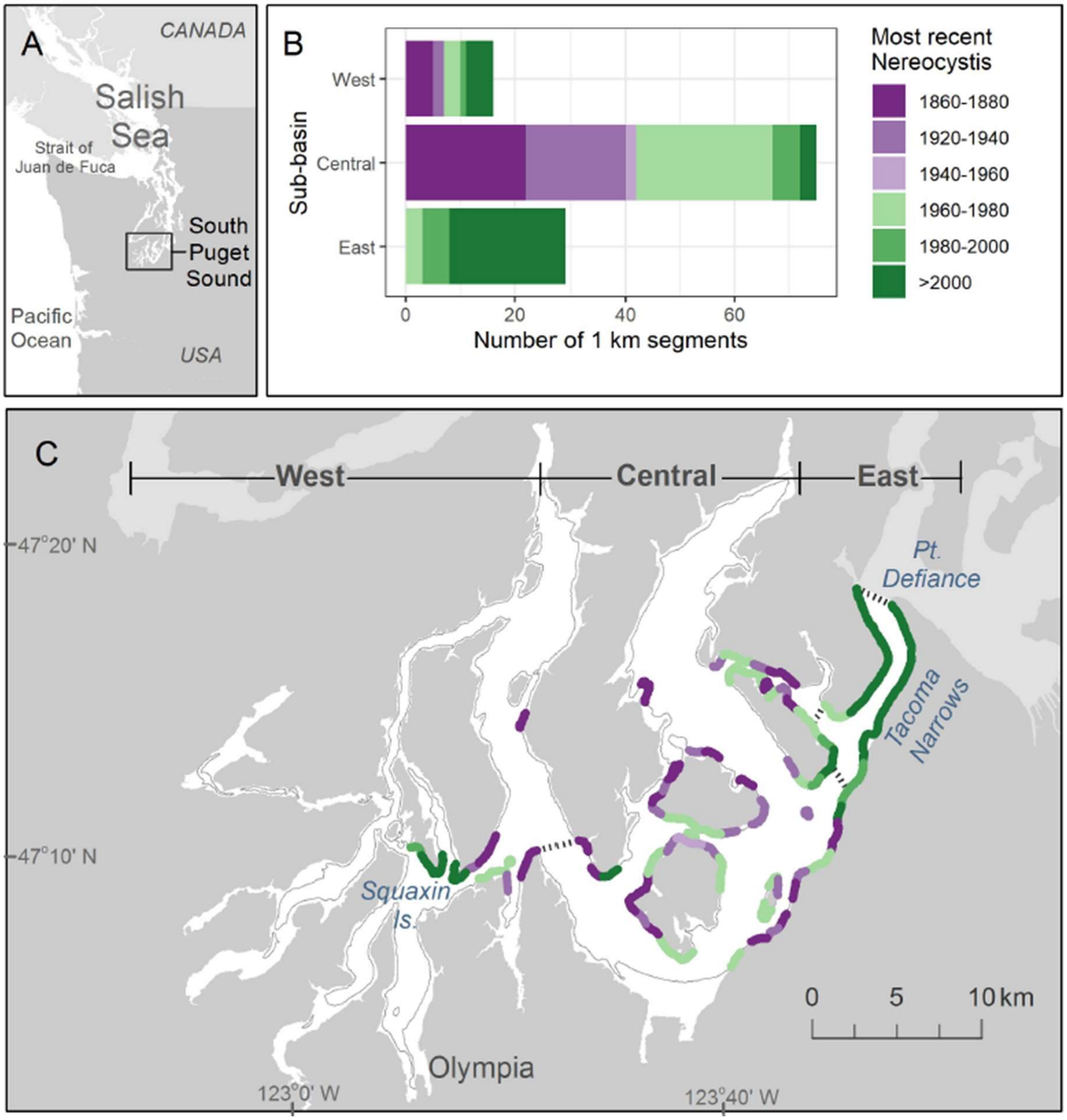


Figure 8. Most recent observation of Nereocystis presence along shorelines in South Puget Sound (SPS) between 1873 and 2018, with SPS divided into three sub-basins. Full caption from source: "(A) The location of SPS, the southern terminus of the Salish Sea. (B) Bar charts show the most recent year Nereocystis was present in 1-km segments within each sub-basin. Years were binned into 20-year increments, with two bins excluded due to lack of data. (C) The -6.1 m bathymetric contour line denotes all shorelines where Nereocystis occurrence was assessed, classified by the most recent observation of presence (same legend as in B). The gray line denotes absence throughout the time period."
Source: Reprinted from Berry et al., 2021.

Contemporary studies of the kelp forests in South Puget Sound by WA DNR have also found that kelp forest declines in this region are ongoing. In one focused comparison of the canopy area of the kelp forest found at the southern tip of Squaxin Island over a period of four years, they found that total canopy area, maximum depth, plant density, and morphological conditions all degraded (Berry, 2017). The most striking metric from this study was that the overall canopy extent in 2016 was only 28% of that found in 2013, at 2.7 and 9.5 hectares respectively (Figure 9). This project surveyed the forest here in 2020 and found that it is still present, but has not rebounded from the losses recorded here (Section 4.2.2).

Figure 9. Bull kelp canopy extent at Squaxin Island from 2013 to 2016.
Source: reprinted from Berry, 2017.

This monitoring work by WA DNR was expanded to other sites in South Puget Sound in 2017 and 2018, and the results were also dire (Berry et al., 2019). Of the four locations monitored in this time, each experienced declines in overall canopy extent compared to surveys conducted in 2013, and two sites at Brisco Point and Devil's Head disappeared entirely. These sites have been revisited in the years since and no rebound has been observed at either (H. Berry, pers. comm., September 2021).

Losses to kelp forest extent have also been documented by Samish Indian Nation in the San Juan Islands over a period of ten years between 2006 and 2016. These estimates relied on two sets of aerial photography, as well as Traditional Ecological Knowledge. The methods involved in this research are outlined in more detail in Section 2.2.2. From the data they examined, it was determined that many areas had experienced significant decline from historic extents, and that the canopy area detected in 2016 was over 30% less than that detected in 2006 (**Figure 10**). This finding is significant in that it shows that recent losses have not been confined to just South Puget Sound, and serves as a warning that losses may be happening in other regions that are not currently being document.

Figure 10. Areas of kelp forest canopy gain (green) and loss (maroon) between 2006 and 2016 detected by Samish Indian Nation at Stuart Island, in the San Juan Archipelago.
Source: Reprinted from Palmer-McGee (2021).

Overall, these efforts by WA DNR and Samish Indian Nation to document the declines of bull kelp populations in Puget Sound serve as a warning shot across the bow for the region as a whole. They also serve as confirmation that the research findings predicting negative impacts to kelp forests due to climate change may already be coming to fruition, and that time may be running out to save these critical habitats.

2.3 Remote Sensing of Aquatic Vegetation

2.3.1 Plane-based aerial monitoring

Manned fixed-wing aerial photographic surveying is a well-established method for obtaining monitoring data of marine vegetation in nearshore environments (Foreman, 1984; Deysher, 1993; Stekoll et al., 2006; Orth et al, 2019). These methods provide moderate to high resolution data and can cover large geographic areas, but also require the investment of significant resources, extensive planning, and the employment of highly trained pilots to ensure quality of the data collected. Many similarities exist between UAV and plane-based aerial monitoring, and therefore it is worthwhile to explore historic and ongoing efforts to use the latter for mapping marine vegetation.

The first effort to systematically map the extent of kelp forests with aerial photography on the west coast of the United States may have occurred as far back as the early 1950s (Deysher, 1993). While interesting as a historical milestone, not much can be found (by this author) about early methodological developments and challenges that were addressed by these early efforts. However, in the mid-1960s a method for mapping giant kelp forest was developed by Dr Wheeler North at the California Institute of Technology that has continued to this day (MBC, 2010; MBC, 2017). This method includes preconditions for surveying including a tidal height of less than +1.0 ft MLLW, and sun angles of less than 70°. While the mapping of giant kelp canopies in the relatively calm environmental conditions of southern California is not a perfect analog to efforts that would be undertaken to map bull kelp in Puget Sound, the use of this method over such a long time period is a strong indication of its utility.

Research efforts investigating the use of aerial photography for mapping of kelp forests were also conducted in Oregon and Alaska, which may provide additional insights about environmental conditions more closely aligned with those found in Puget Sound. The Oregon Department of Fish and Wildlife conducted periodic surveys of kelp forests on sections of its Pacific coast beginning in 1996, with some success (Fox et al., 1996). This first effort did not include much documentation on precise methods, but the survey was conducted in September at tidal heights ranging from +1.7 to +2.7 feet MLLW. The authors noted in their recommendations that horizontal accuracy control should be added using GPS locations of buoys. A more recent effort to repeat this work in 2010 using multispectral imagery was hampered by unsuitable weather conditions in September and surveys were pushed back to October and conducted as tidal heights of +1.1 to +5.4 ft MLLW. The authors note that these tide levels were not ideal, but imagery was successfully collected nonetheless.

A similar study conducted in southeast Alaska in 2002 and 2003 attempting to estimate biomass from aerial imagery also found that inclement weather was the main challenge with acquiring useable data (Stekoll et al., 2006). The authors also found that tidal currents had a dramatic effect on the appearance of kelp forest canopies, and could be spatially variable depending on the geography of a site. Despite these challenges, capturing imagery when the conditions were suitable yielded data that closely correlated with ground-based biomass estimates. Surveys were conducted in September at tidal heights between -0.21 and -0.66 meters.

This study and those from Oregon above show that the main challenge to collecting useable aerial imagery of kelp forests may be having good weather conditions on days where tide and sun angles are also favorable, but that aerial mapping methods are tractable and show promise for use in places such as Puget Sound.

Finally, there is ongoing work at WA DNR to map kelp forests in the Strait of Juan de Fuca and along Washington's Pacific coast, which would be the most directly related of the above efforts to UAV mapping in Puget Sound. The methods of this monitoring project are outlined in detail in Section 2.2.2, but similar environmental conditions were targeted including tidal heights of less than +1.0 ft MLLW, clear skies and calm seas, and sun angles less than 60° (Van Wagenen, 2015). As with the previous surveys, weather was the most common impediment to collecting data. Overall, these efforts have proved successful and have created a long-term database of kelp canopy in these regions that has been used to support other research regarding kelp forest stressors and ecology (Pfister et al., 2017; Shelton et al., 2018).

The use of manned fixed-wing aircraft to capture survey imagery of kelp forests serves as an important source of context for this project. While equipment and flight parameters may vary between these platforms and UAVs, the general concept and workflow are very similar. We therefore can take note of the fact that inclement weather most often was the primary impediment to collecting imagery, and build redundancy into the study design accordingly by planning to repeat surveys over the course of the field season. The most successful aerial mapping efforts also occurred when tides were below +1.0 ft MLLW and with sun angles less than 60-70°, so those minimum conditions will be targeted for this project as well. Overall, there is significant overlap between UAV and fixed-wing aerial mapping and lessons from each can be applicable to both.

2.3.2 UAV mapping of nearshore habitats

With UAVs being a relatively new technology, the literature on their use for habitat mapping is only about a decade or so old. However, in this short time an abundance of research has been conducted and many significant findings have been produced. Early assessments of the technology hypothesized that they held incredible promise for use in coastal and nearshore environmental monitoring due to their low cost (comparatively), their ease of deployment, and extremely high spatial resolution capabilities (Anderson & Gaston, 2013; Klemas, 2015; Turner et al., 2016; Manfreda et al., 2018). These predictions proved correct in that UAV mapping of a wide range of habitats has proven successful, as the various studies included below will show. Improvements to UAV technology and mapping capabilities are continually being developed (Flores-de-Santiago et al., 2020), so there is no reason to believe this trend will slow any time soon.

Among the wide array of different applications UAV mapping is suited to are everything from coastal erosion mapping (Turner et al., 2016) to terrestrial forest species surveys (Grybas & Congalton, 2021). Other applications in marine and coastal ecology include the mapping and biomass estimates of coastal wetlands (Zhou et al., 2018; Doughty & Cavanaugh, 2019), the differentiation of diverse species in intertidal habitats (Murfitt et al., 2017; Collin et al., 2019; Tait et al., 2019), and the tracking and quantification of large algal blooms (Kislik et al., 2018; Taddia et al., 2019). These research projects involved the use of many different models of UAV, flown with different software and flight parameters, and a diverse set of image processing tools. However, the central takeaway from them is that UAVs can successfully be deployed to capture meaningful data in coastal nearshore environments.

In addition to the variety of studies listed above, there have been others with more similar aims to this project as well including two that surveyed other species of brown macroalgae. The first of these, conducted by Thomsen et al. (2019), sought to map four different reefs in southern New Zealand containing kelps of the genus *Durvillaea* before and after a marine heatwave in 2017 and 2018. To accomplish this they flew a DJI Phantom UAV at the sites each year, georeferenced and orthorectified the RGB imagery, and estimated percent cover using a projected grid method. Overall, they found that the method was effective, but kelp that was deeper in the subtidal zone was often difficult to distinguish. A similar study conducted by Rossiter et al. (2020) in western Ireland deployed a DJI Inspire UAV to capture high resolution RGB imagery of the species *Ascophyllum nodosum,* a macroalgae of the order Fucales and a close relative to Laminariales, along a stretch of shoreline there. After successfully processing the imagery into orthomosaics, the authors noted that species could be confidently identified due to the high resolution of the imagery and distinct morphological characteristics of the vegetation. These studies both show that species of brown macroalgae can successfully be processed into geospatially meaningful products using UAV-based imagery platforms, and bolsters the case for their use to map floating bull kelp forests.

There are two final studies that served as perhaps the most direct inspiration for and that informed the development of this project. The first of these was a study assessing the use of low-cost UAV technology to map eelgrass (*Zostera marina*) meadows in British Columbia (Nahirnick et al., 2018). Eelgrass habitat and bull kelp habitat differ in some ways (particularly substrate type), but are similar in many others, and in Puget Sound these species sometimes exist in close proximity to each other (direct observation). This project had many of the same methodological underpinnings that this one did including the use of object-based image classification, kayak-based ground surveys, and the need for manual assessment of accuracy of classified results. It also investigated the various environmental conditions in the Salish Sea region that can hamper data collection and processing including high sun angles and tidal height, patchy cloud cover, windy conditions, and water turbidity. These findings backed up those from the fixed-wing monitoring studies regarding target sun and tide conditions, and added a second tier of weather conditions to consider. Overall, the project was successful and showed that these methods resulted in accurate classified maps with mapping accuracy values of 87-96%, lending legitimacy to this project's aim.

The second of these two surveys that provided methodological context for this project is the thesis work of K.C. Cavanaugh (2020). This project sought to map giant kelp forests in Santa Barbara, California using a DJI Matrice UAV carrying a multispectral camera. Repeat surveys were also conducted in the same day to assess the impact that tide height and current had on the extent of the floating canopy. Their results showed that imagery captured of giant kelp forests could successfully be mosaiced and orthorectified in most cases, but that changes in illumination conditions while surveying complicated this process. The presence of large patches of glare when flying over open water was also noted as a potential hinderance, but an open-source tool to remove those pixels mitigated that effect. Finally, it was found that the tidal height during surveys did have a significant effect on the floating kelp canopy extent, in some cases by as much as 30% with a 2 meter difference in tides. This further cements the need for consistent survey conditions, and the guidepost of targeting low tides that are less than +1.0 ft MLLW for this project.

Although the equipment used and the environmental conditions surveyed in by Cavanaugh were less comparable to the subject of this report than Nahirnick et al. (2018), the subject of the surveys was far more similar. As was detailed extensively in Section 2.1 bull kelp and giant kelp are incredibly similar in terms of their morphology and spatial distribution, and thus the results of this project are critical as evidence for the efficacy UAV mapping of bull kelp forests in Puget Sound might achieve.

Overall these studies show that UAVs can successfully be used to map coastal nearshore habitats in a detailed and efficient way. Many projects highlighted the need for ideal survey conditions to ensure the quality of imagery is high enough for further analysis to take place. These included sun angles commensurate or less than those used in fixed-wing aerial mapping (45-50% max), consistent low tides, minimum current, and various weather conditions. Of particular note were the studies that successfully mapped species of brown macroalgae (Thomsen et al., 2019; Cavanaugh, 2020) and that were able to achieve accurate classification of UAV-based imagery products in environmental conditions similar to those found in Puget Sound (Nahirnick et al., 2018). The collective lessons learned and shared in the extensive body of work presented here in Section 2.3 were relied upon heavily in the development of this project's methodology presented below.

3. Methods

3.1 Study Area

Surveys were conducted from mid-July to late September of 2020 at 5 kelp forest sites throughout the Puget Sound, Washington, where large seasonal floating canopies of *Nereocystis luetkeana* are present (Table 1). These sites were distributed throughout the latitudinal gradient of Puget Sound and represented a diverse set of oceanographic and tidal conditions (Figure 11). It is well established that bull kelp populations throughout this region exhibit a variety of distributional and morphological characteristics, likely due to those diverse conditions (Calloway et al., 2020). In order assess the methodology in this project in a robust and defensible way, it was deemed important to survey sites that represented a range of these conditions.

Table 1. Location and dates of UAV kelp forest surveys conducted for this project. Survey boundaries often expanded or contracted with subsequent surveys to ensure both complete coverage and efficiency as methods were optimized.

Site Name	Latitude	Longitude	Area surveyed	Dates surveyed
North Beach County Park, Port Townsend	48°8’38”N	122°46’38”W	16.6 ha 16.6 ha 19.6 ha 23.0 ha	7/18/2020 8/16/2020 8/30/2020 9/30/2020
Squaxin Island SW	47°10’6”N	122°53’47”W	15.5 ha 16.1 ha 19.8 ha	7/21/2020 7/30/2020 8/28/2020
Lincoln Park, Seattle	47°32’3”N	122°23’52”W	12.0 ha 10.3 ha	7/31/2020 8/7/2020
Norwegian Point, Hansville	47°55’15”N	122°34’5”W	13.0 ha 12.4 ha	8/3/2020 8/17/2020
Vashon Island NE	47°28’45”N	122°26’53”W	26.4 ha	8/15/2020

Squaxin Island and North Beach County Park have been the subject of previous kayak-based survey efforts conducted by the WA DNR Nearshore Habitat Program (Berry et al., 2019).

All of the remaining sites are the targets of expanded monitoring efforts by the NHP started in summer 2020 (H. Berry, pers. comm., June 2020).

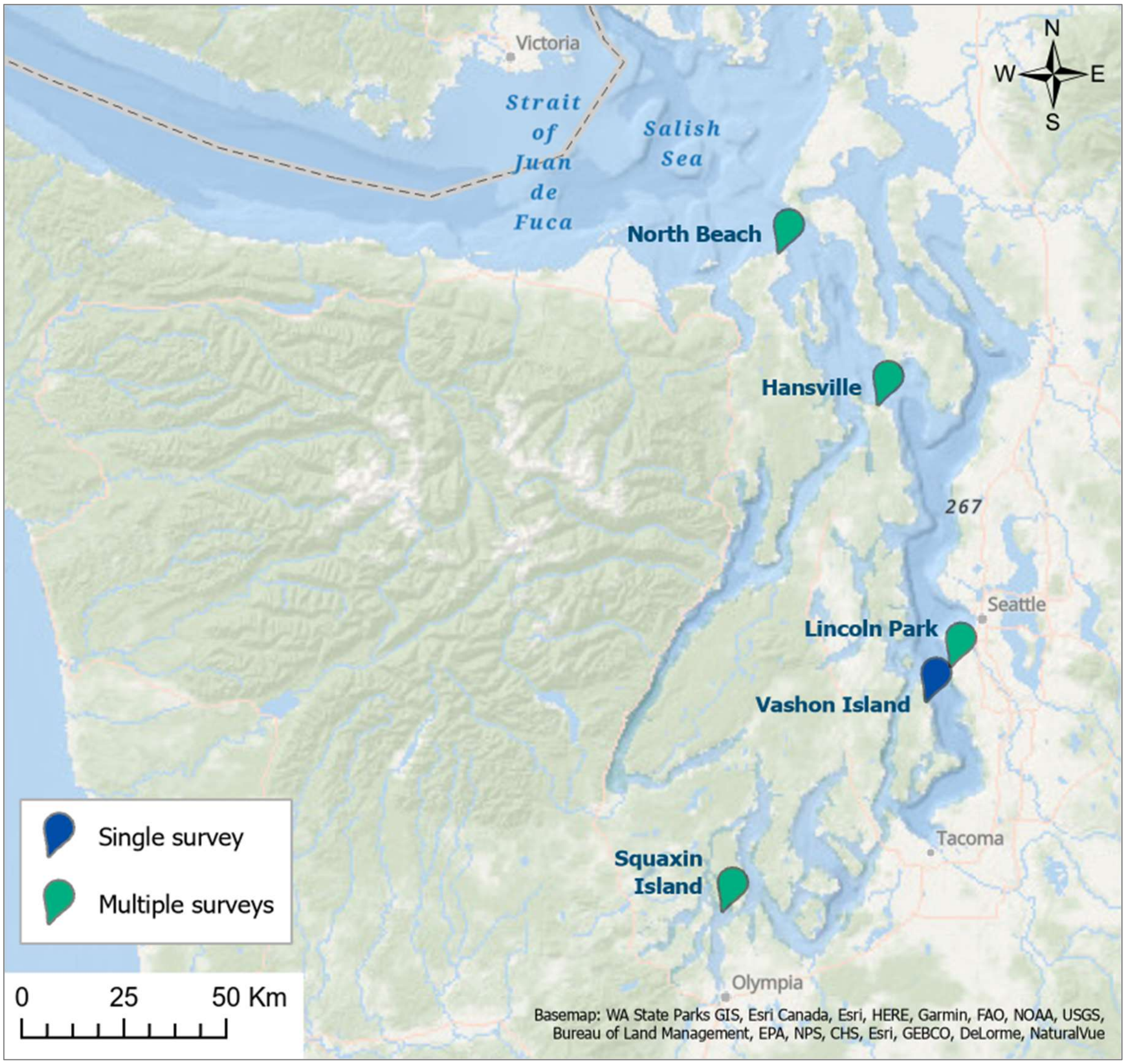


Figure 11. The location of study sites for this project located throughout Puget Sound in Washington State. Map credit: Tyler Cowdrey

3.2 Field Data Collection

3.2.1 UAV equipment, flight planning, & ground control points

The primary unmanned aerial vehicle (UAV) used for this project was a DJI Mavic 2 Pro quadcopter (Figure 12) (DJI, Nanshan, Shenzhen, China), which carried the stock Hasselblad

L1D-20c f/2.8 28mm camera with a 1" Sony CMOS sensor capable of capturing 20MP RGB imagery with a field of view of approximately 77°. This UAV platform was deployed on each survey using the automated flight planning application, Map Pilot (Drones Made Easy, San Diego, CA, USA) (Figure 13). Using this application, survey grids were created at an altitude of 80-100 m AGL (above ground level) with 75-80% overlap in ground sampling, both along and across survey tracks. These parameters resulted in a ground sampling distance of ~2cm/pixel, and were chosen using general guidance from DJI and Map Pilot, as well as comparable UAV nearshore mapping efforts in nearshore marine environments found in the peer-reviewed literature (Nahirnick et al., 2018; Doughty & Cavanaugh, 2019; Taddia et al., 2019). When available, GPS markers generated from previous boat-based surveys conducted by NHP were used as boundary vertices for survey areas. Maximum flight speeds were set to 5 m/s, though often automatically confined to less than that by Map Pilot in order to reduce motion blur.

Figure 12. DJI Mavic 2 Pro on the launch pad prior to a survey in Hansville, WA.
Photo credit: Tyler Cowdrey

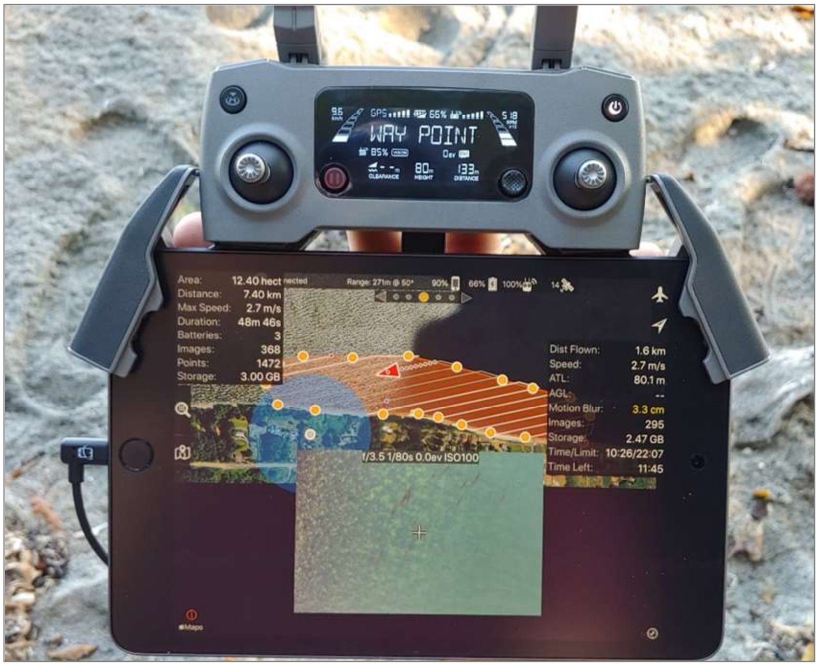


Figure 13. View of Map Pilot automated survey grid generated for survey at North Beach County Park.
Photo credit: Tyler Cowdrey

Before each survey was conducted, five to six ground control points (GCP) were distributed along the shoreline within the survey area. These GCPs consisted of 40x40 cm high-contrast black and white checkerboard panels that could be clearly distinguished in the imagery captured at altitudes of up to 120 m AGL (Figure 14). Once placed, 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. These field-collected GPS positions were later post-processed in Trimble GPS Pathfinder Office (Trimble Inc., Sunnyvale, California, USA) using real-time continuously operating reference stations (CORS) reference data hosted by 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 each GCP. By capturing these markers in the survey imagery and referencing them during orthomosaic creation (see Section 3.3.2), the geospatial accuracy of the final products was dramatically improved.

Figure 14. Ground control point (GCP) panel in situ, with position being recorded by Trimble GeoExplorer 6000 GeoXH device.
Photo credit: Tyler Cowdrey

3.2.2 Environmental conditions

Flights were conducted during summer low tide series, within one hour on either side of low tides that were +1.0 ft mean lower low water (MLLW) or lower based on the NOAA Tides & Currents: Tide Predictions product (NOAA, 2021). This requirement is the same as the one used by WA DNR in their aerial monitoring efforts of kelp forests along the Strait of Juan de Fuca and the Pacific Coast of WA (Van Wagenen, 2015). The confinement to one hour before or after low tide is chosen primarily because previous research has shown that there is a significant impact on the appearance bull kelp canopy cover caused by tidal currents (Britton-Simmons et al., 2008). Puget Sound experiences mixed semidiurnal tides, so days where the lower of the two low tides occurred in the early morning were prioritized to minimize the impact of sun-angle glint on the water's surface (Nahirnick et al., 2018).

Other environmental considerations when planning surveys included wind and weather conditions; on days with rain or winds higher than 5 m/s forecasted, surveys were postponed. It also has been published that cloud conditions of <10% or >90% are preferable to minimize spectral variability in nearshore reflectance (Nahirnick et al., 2018). Though this was not used as a precondition to conduct surveys, photos were taken of the sky conditions prior to and during surveys using a Nikon D5200 DSLR (Nikon, Minato City, Tokyo, Japan) with a Rokinon 8mm f/3.5 aspherical fisheye lens to document cloud cover for later analysis purposes. In addition, a Vernier ANM-BTA Anemometer (Vernier Software & Technology, Beaverton, Oregon, USA) was deployed during each survey to record wind speed. Early in the field work season it was discovered that this device suffered from a drifting baseline such that wind speeds were recorded as increasing over time, even on days that were completely calm. This was due to a loose serial connection port. This data continued to be collected for the rest of the project in order to have some reference to wind speed at the site, but with the understanding that it would not be reliable for quantitative/analytical purposes.

3.2.3 Ground-truth kayak surveys

Kayak-based surveys were conducted at each site by WA DNR scientists, which created multiple ground-reference data types that could be potentially used in correlational analyses with UAV-based results. These products are described more in Section 2.2.2. The one that was used for this project was a continuous boundary path taken using the marine handheld Garmin GPSMAP 78 (Garmin Ltd., Olathe, Kansas, USA) held by a member of the team while kayaking around the perimeter of the bed visible from the water. An aggregation/averaging of multiple of these paths results in a “bed perimeter” polygon that NHP uses for annual monitoring (Figure 15).

Figure 15. The kelp bed perimeter generated by DNR NHP scientists at Squaxin Island (pictured in yellow). The red and orange track lines represent the two kayak surveys conducted on July 30, 2020 that were aggregated to produce the overall area polygon.
Map credit: Tyler Cowdrey | Data source: WA DNR NHP, 2020

3.3 Image Processing

3.3.1 Glint masking

UAV survey imagery was pre-processed by running it through the open-source software tool called “GlintMaskGenerator” (https://github.com/HakaiInstitute/GlintMaskGenerator), which was created by the Hakai Institute in order to generate masks of pixels producing glare from sun glint and crashing surf (Figure 16). These pixels have been shown to disrupt the mosaicking process for imagery taken over water in nearshore environments, as they are inconsistent across images as the UAV moves and time passes (Cavanaugh et al., 2021). During mosaicking, these masks are applied to the imagery such that the stitching algorithms ignore these pixels. The "GlintMaskGenerator" tool works by selecting pixels that have irradiance values higher than user-determined thresholds as a ratio value from 0-1 along a histogram calculated for each image (L. Reshitnyk, pers. comm., January 2021). These thresholds can be set on individual or a combination of bands simultaneously. The threshold values that effectively masked only glint and surf for each survey were somewhat variable depending on lighting and oceanographic conditions, so a range of threshold values would be tested on a subset of each survey to determine the appropriate setting. For the majority of surveys, values between 0.8 and 0.9 (filtering out the highest 20% and 10% of irradiance values respectively) on the blue band was found to be the most effective at isolating sun glint pixels based on trial and error.

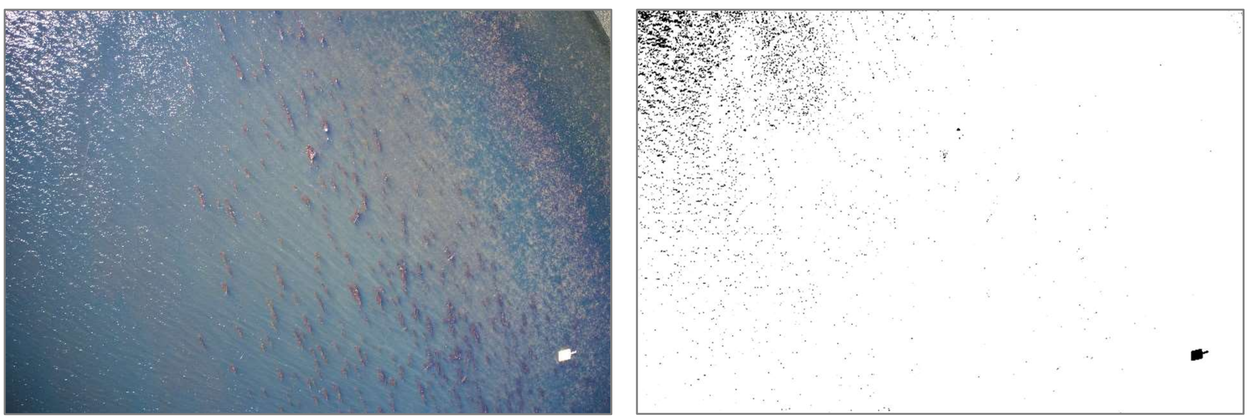


Figure 16. Left: A survey image taken at Vashon Island on August 15, 2020 showing considerable sun glare in the top left corner. Right: The result of running the GlintMaskGenerator tool on this image at a 0.8 threshold on the blue channel, where black pixels are the mask.

3.3.2 Photogrammetry

Following pre-processing of survey imagery using the GlintMaskGenerator, it was imported with the accompanying pixel masks into Agisoft Metashape (v1.7) (Agisoft LLC, St Petersburg, Russia) for the photogrammetry stage of the workflow. Ground control point coordinates were then imported and manually linked with multiple images where the panels were visible to improve the georeferencing accuracy. Image alignment was initially conducted using the “medium” quality setting such that the photos were analyzed at one-quarter resolution. This significantly reduced the processing time required to finish this step, usually by around half (e.g. 22 mins vs. 52 on high for a survey at North Beach on 7/18/20). If this initial alignment was mostly successful the alignment was accepted (Figure 17), otherwise only then would the alignment be run on high to attempt to get more images to align.

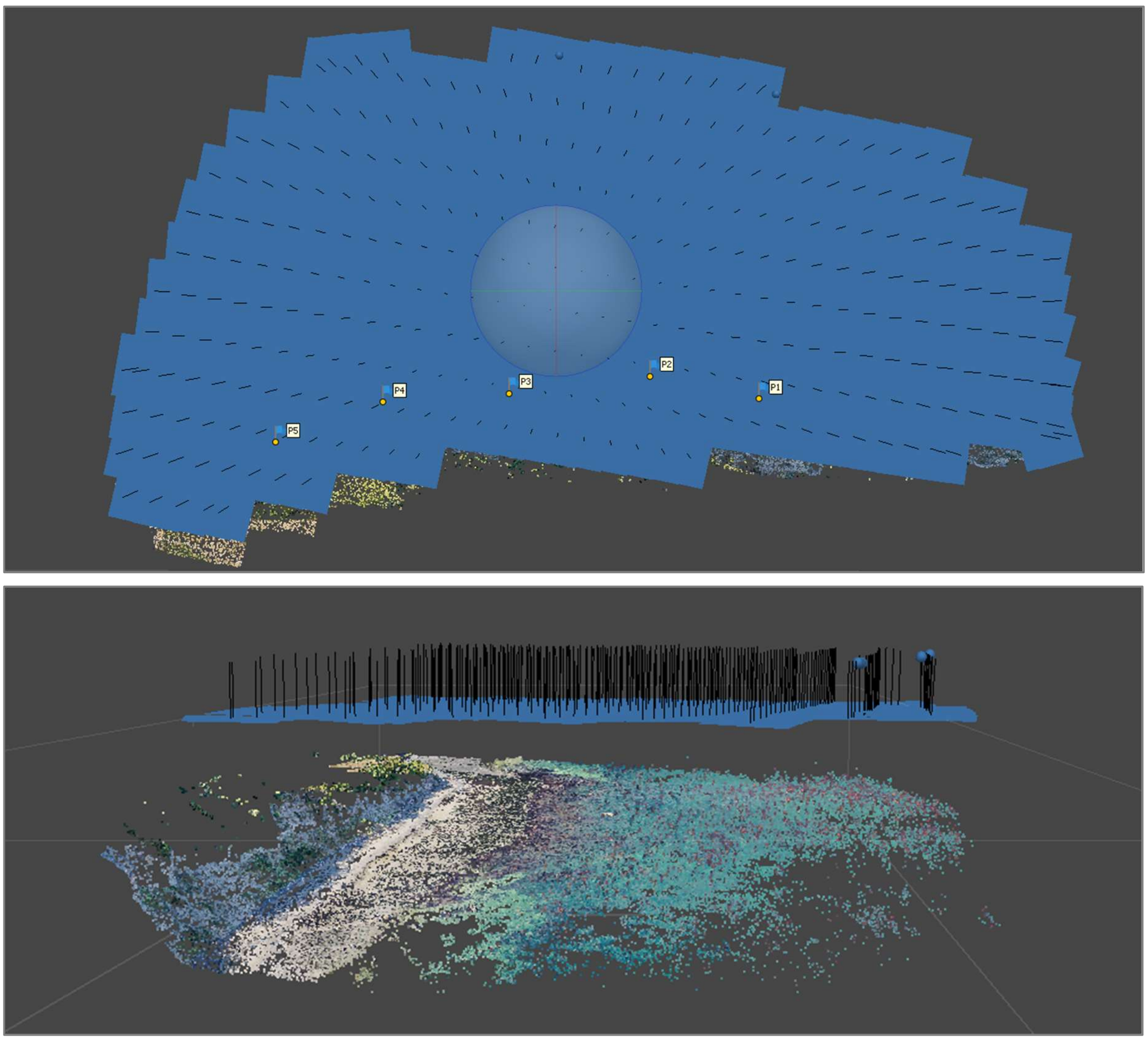


Figure 17. The result of image alignment in Metashape, showing 315 out of 320 photos aligned from overhead (above), and from an oblique view (below). The top image also shows the georeferenced GCP panels for this survey as they fall within the imagery. The survey pictured was at North Beach County Park on 8/30/2020.

Often times, some swath of photos at the outermost edge of the survey over water would not be able to align on any setting (Figure 18), in which case the result had to be accepted as-is. This typically occurred when optimal lighting and water surface conditions were not observed. It was found later that often many of these photos would still be included in the orthomosaic output, minimizing the impact of the lack of alignment, but this was not always the case.

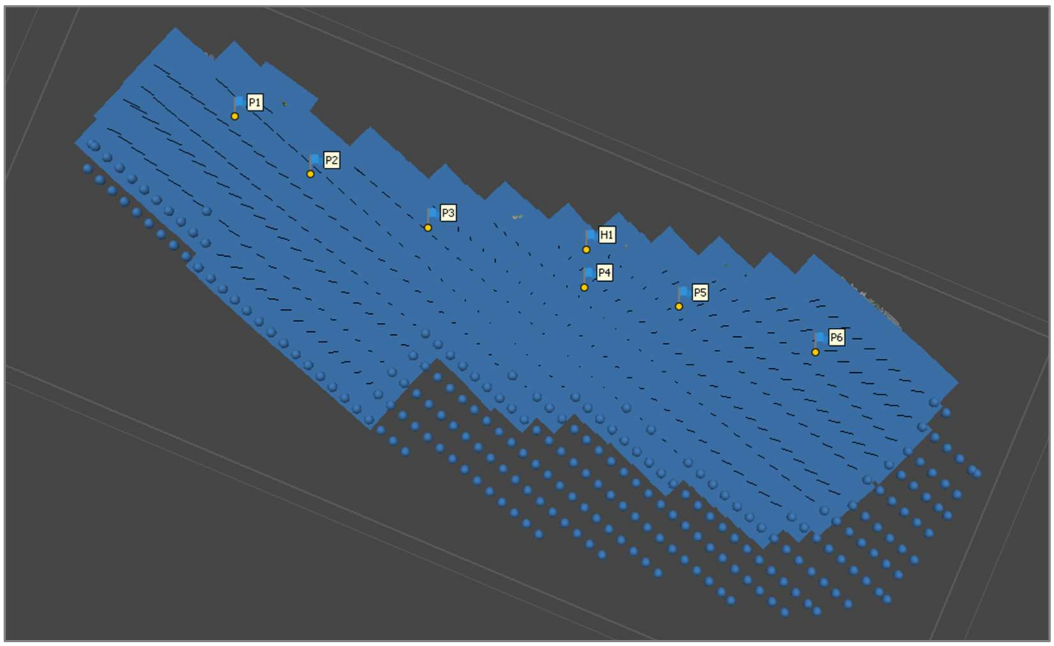


Figure 18. Example of a survey with photos on the outer edge (away from shore) that are not able to be aligned (224 out of 550). This survey was from at Squaxin Island on August 28, 2020.

The initial photo alignment stage resulted in a sparse point cloud of pixels that were able to be triangulated from the aligned imagery. This point cloud often had a great deal of noise, particularly over water, that needed to be cleaned up. The process for cleaning this point cloud into one with a smooth and accurate surface on which imagery could be projected was iterative and involved two main steps. First, areas with clear perturbations were manually selected and removed, and then a Gradual Selection tool within Agisoft Metashape was used to select pixels with the lowest accuracy score (Figure 19) and removed. As a better result was achieved, a final cleaning often included much panning and zooming to different areas to find errant pixels that could be removed.

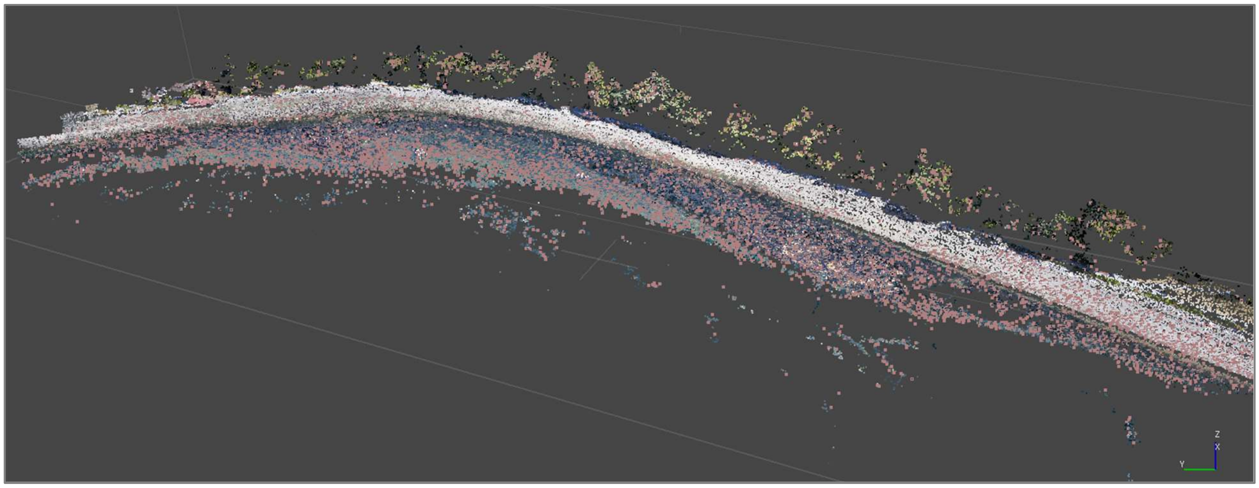
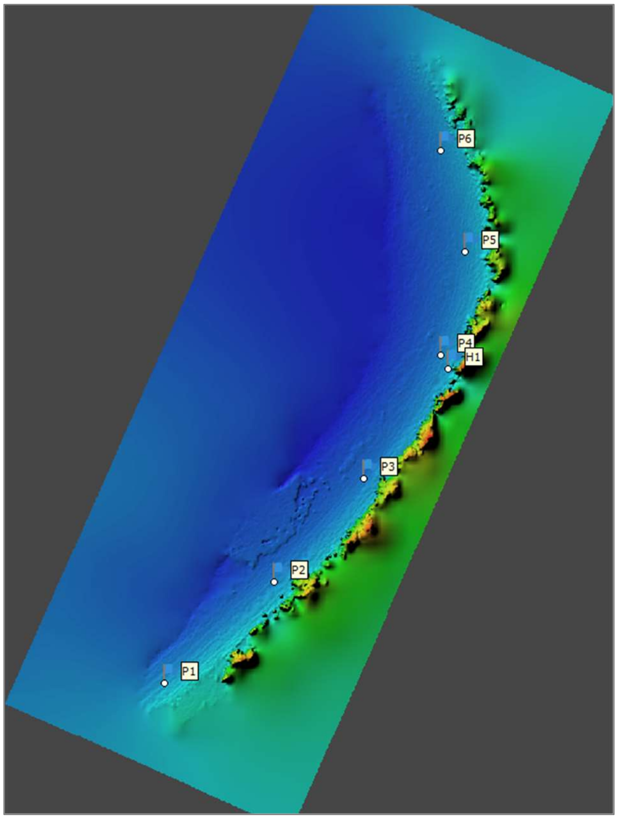


Figure 19. A sparse point cloud generated from image alignment of a survey at Lincoln Park on August 7, 2020. The pixels highlighted in pink were selected using the “gradual selection” tool and removed in order to achieve a smooth surface.

Once a sparse cloud was cleaned to a degree where no obvious noise or perturbations were visible, a digital elevation model (DEM) was generated from the cloud (Figure 20). This surface was then viewed within Agisoft Metashape to assess if there were any areas where further cleaning of the sparse point cloud was necessary, after which a new DEM would be generated and so on. This iterative process typically took a few revisions until a DEM was ready for use. Once the DEM was deemed final, it was used to generate an orthomosaic from the survey imagery, and the resulting orthomosaic was exported to a TIFF file for use in the ArcGIS Pro software suite (ESRI, Redlands, California, USA). Final orthomosaics had a GSD/resolution of 1.3-2.4 cm/pixel for the Mavic 2 Pro surveys.



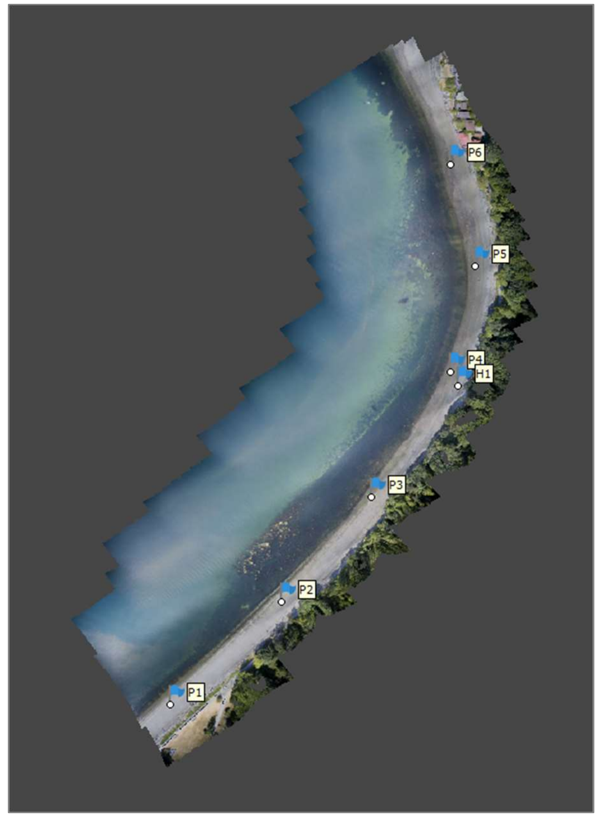


Figure 20. (Left) Digital elevation model generated following sparse point cloud cleaning of a survey at Lincoln Park on August 7, 2020. (Right) The orthomosaic generated on top of that DEM.

3.3.3 Projection onto State Plane Washington North

Each orthomosaic generated in Agisoft Metashape was output to a TIFF file in the WGS 84 (World Geodetic System 1984) coordinate system, the current universal standard for all GPS based data. However, GIS best practices dictate that areal calculations and analyses be performed within a projected coordinate system (PCS) suitable to the area of interest, in order to minimize potential errors from accruing. Therefore, the first step to analyzing the orthomosaics generated for each survey was to project them onto a PCS. For this project, the PCS that was chosen was the NAD 83 (North American Datum 1983) StatePlane Washington North projection. This coordinate system is one of two zones of the current StatePlane projections in Washington, which both use a Lambert Conformal Conic projection to preserve angular fidelity. The

StatePlane Washington South projection is more widely adopted in the state, and was considered for use, but the North zone minimized error throughout the Puget Sound to a greater degree (on the order of <50 parts per million) and was therefore considered preferable.

3.4 Supervised Image Classification

3.4.1 Shoreline masking

The first step in the classification workflow was to create shoreline masks removing terrestrial areas (e.g. sand, rocky shore, trees, etc.) from the area of interest. This was accomplished by hand drawing a polygon that ran along the tide line on shore, and then was closed to include the rest of the intertidal and subtidal survey area (Figure 21). In some cases, it would have been possible to draw a mask that excluded the intertidal region of the survey, if no kelp was seen to be present there, but it was decided that those areas should be kept in order to be consistent across all sites. Keeping the intertidal zone of each nearshore environment also allowed for a more accurate investigation of the accuracy of the image classification process, given that the intertidal often has species of other algae and seagrasses that often have similar spectral signatures to bull kelp. Once a mask had been created that accurately fit the shoreline, the projected orthomosaic was “clipped” to that area (using the Clip Raster tool in ArcGIS Pro).

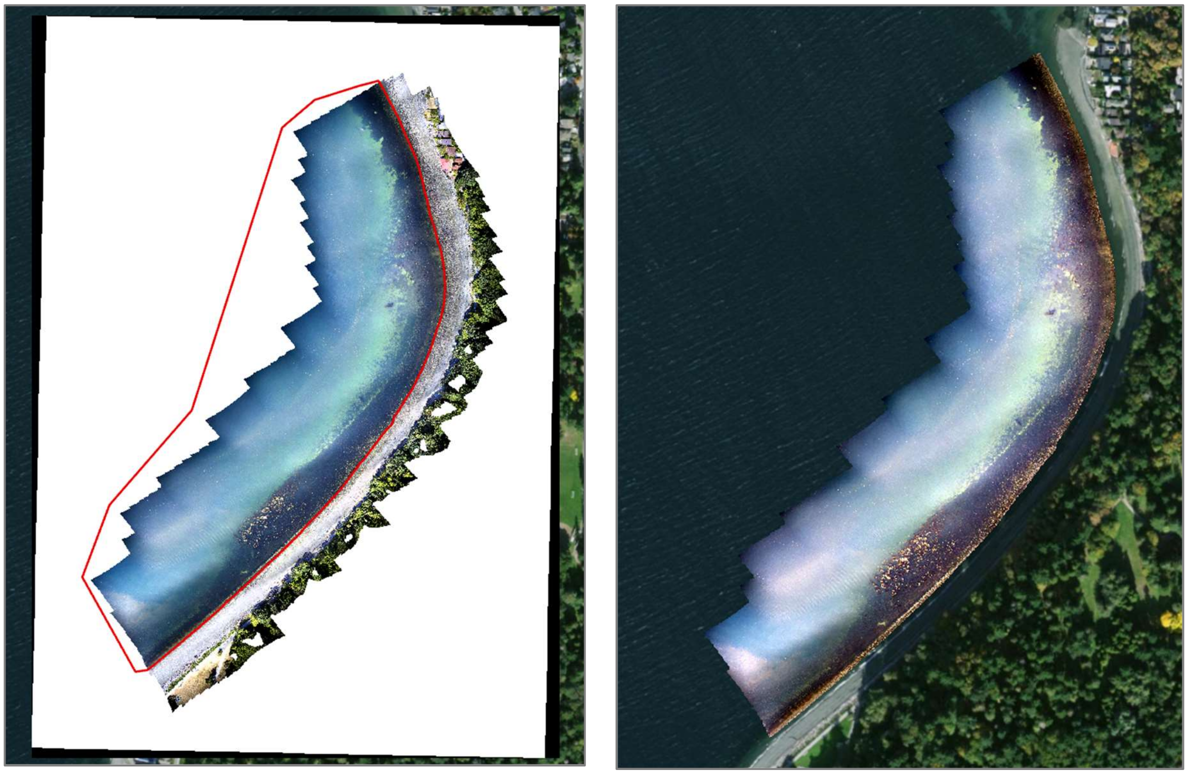


Figure 21. (Left) The original projected orthomosaic for the August 7, 2020 survey at Lincoln Park, showing both the shoreline mask in red, as well as the white background pixels to be set as NoData.
(Right) The result of running the "Clip Raster" on the orthomosaic to isolate the area of interest for analysis.

3.4.2 Image segmentation

The next step in the image classification workflow was to group pixels into "objects" of similar spectral and spatial quality using the Segmentation/Segment Mean Shift tool in ArcGIS Pro. This tool produces objects using spectral, spatial, and minimum size in pixels settings specified by the user, as well with many meaningful attributes associated to each such as active chromaticity color, mean digital number, count of pixels, compactness, etc. (Figure 22). The additional attributes enable object-based image analysis (OBIA) to be performed on the orthomosaic, rather than classification that relies on just the spectral qualities of each individual pixel.

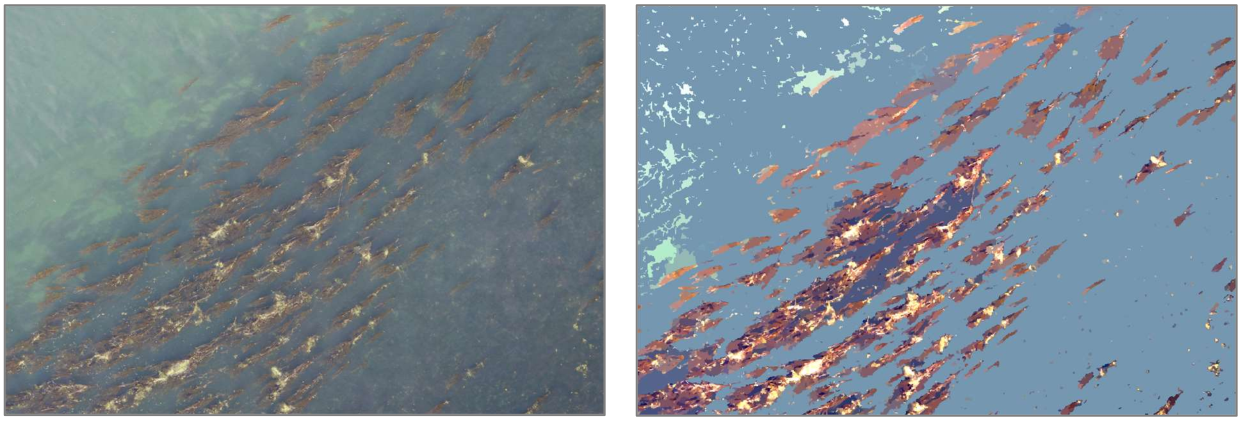


Figure 22. Comparison of original full resolution orthomosaic (left) and the result of image segmentation (25 pixels) on the same region (right). This shows how bull kelp plants are grouped into discrete objects prior to classification.

OBIA is widely used in remote sensing applications, and has been found to be particularly useful in the classification 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 in particular (Schroeder et al., 2019). The initial testing phase of this project immediately confirmed that this method produced less noise and variability in the classified output, and it was therefore chosen as standard procedure for classifying bull kelp canopies from this imagery.

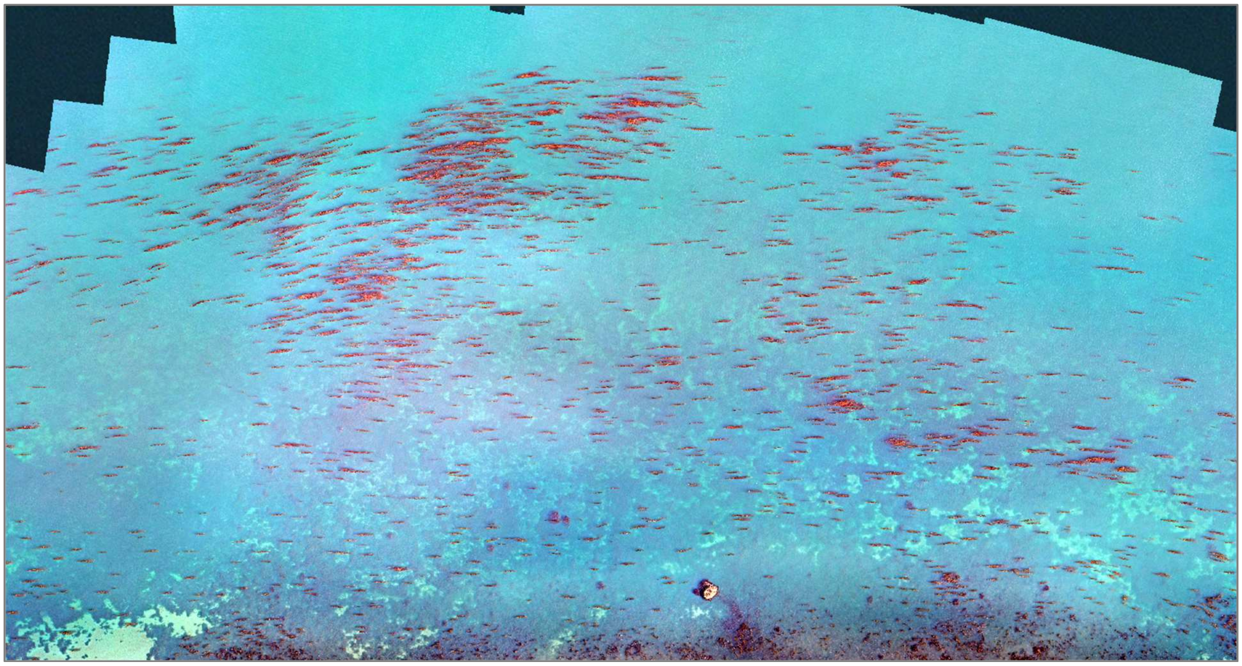
In order to achieve the best classified result for each survey, the user input settings for the Segmentation tool were customized to a small degree for each orthomosaic. The best settings for this application for “Spectral detail” and “Spatial detail” were both found to be nearly maximum, and were set to 19 and 17 respectively (they are on a scale from 1-20 in ArcGIS Pro) for each survey. However, the ideal setting for “Minimum segment size in pixels” varied somewhat between surveys depending on their resolution and the characteristics of the bull kelp canopy, and was found to range from 15 to 30.

3.4.3 Random forest classifier

The final and most critical step in the image classification workflow for this project is to run a random forest classifier on the segmented/object-based orthomosaic. The general purpose of this (as well as other) classifiers is to determine which class pixels and/or objects fall into, given some predetermined training data. Random forest is a machine learning algorithm that uses a series of random decision trees (on the order of 100s to 1000s of iterations) and then uses a consensus algorithm to properly weight those decision outcomes based on a set of user-supplied training data. For the purposes of this project, the class of interest seeking to be generated by the Random forest classifier was simply all the floating kelp canopy contained in the imagery. Within ArcGIS Pro the image classification tool for this is called simply Classify, and the tool contains options for a number of different supervised pixel-based and object-based image classification algorithms including: maximum likelihood, support vector machine, and random forest (ESRI calls this "random trees").

In order to train the random forest model, training data was created for two classes: "floating kelp canopy" and "water." This training data consisted of anywhere from 6-15 sample polygons for each class, considered sufficient given the number of classes being targeted (Congalton & Green, 2019). These were drawn to include a variety of spectral expressions that captured the range of values present in the survey. The water class ended up becoming a catch-all for everything in the survey other than bull kelp (e.g. bottom algae, sand, exposed rocks, etc.), though intertidal masking reduced the occurrence of these "other" classes to some degree. A future study could look at classifying these same surveys with an increased number of target classes to see if that impacts the accuracy of kelp canopy detection.

Following the creation of training data, the random forest classifier was run on each survey on the 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 classified raster containing pixels designated as either kelp or water (Figure 23). Initial trials of this tool found that the changing of training data had a far more significant impact on the result of the classification than changing any one of these settings, so they were left at these values throughout the project. This initial classified result was compared against the original orthomosaic for areas of strong agreement and disagreement with visual inspection, and then training data was added or removed to augment those results. After this the classifier was run again, the result inspected, training data tweaked again, and so on in an iterative fashion until the result of the survey was considered satisfactory or as good as could be achieved given the quality of the orthomosaic. Last, this “final” classified raster was exported to a TIFF file as a stand-alone product to be used in accuracy assessment.



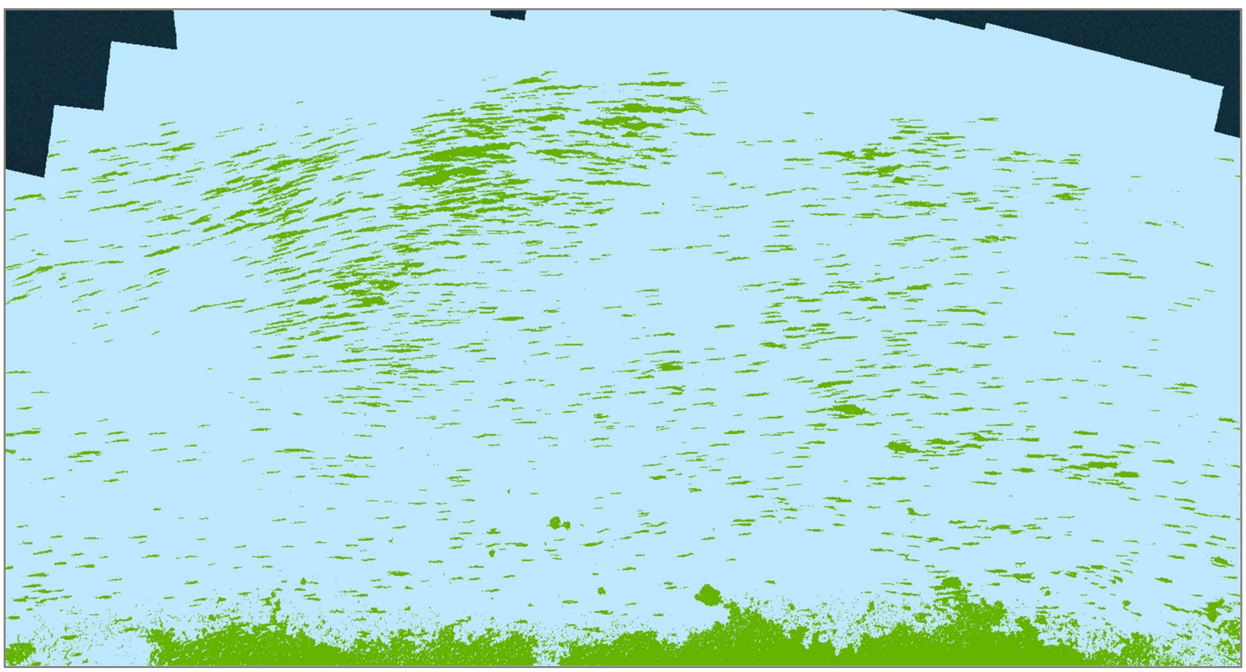


Figure 23. (Top) Orthomosaic of survey conducted at North Beach County Park on August 30, 2020. (Bottom) Classified raster showing floating kelp canopy (green) and water (blue) following OBIA and random forest classification.

3.5 Accuracy Assessments

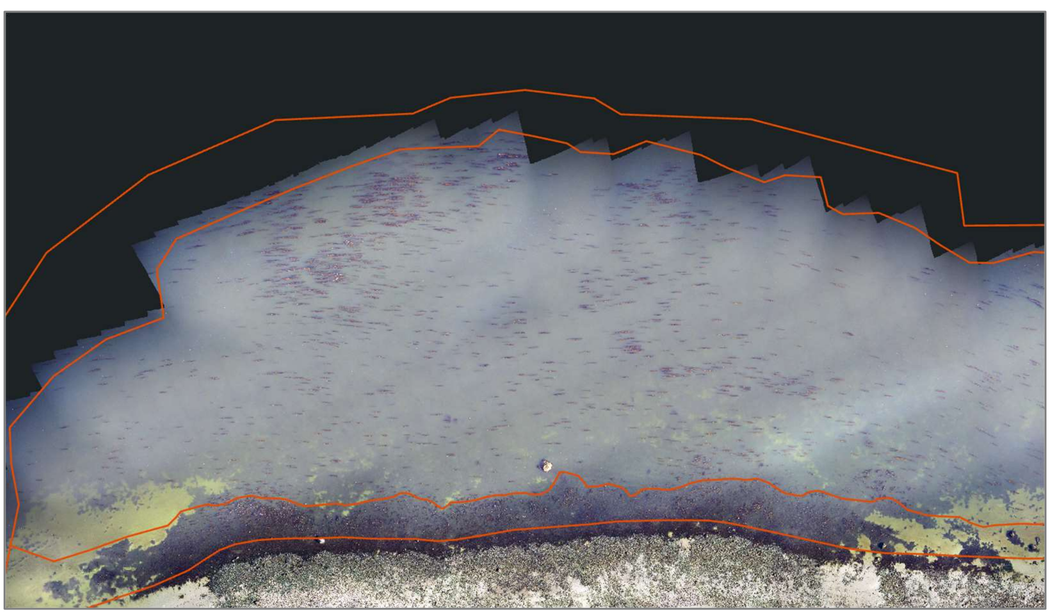
3.5.1 Ground-truth data

In order to assess the accuracy of the classified rasters generated by the object-based random forest classifier in differentiating floating kelp canopy from the surrounding environment, a random point verification method was employed. This method relied upon a technician with expert knowledge of the sites (the author) to examine the imagery and determine which pixels were part of the kelp canopy, and which were not. A preferable method would have been to use a ground truth dataset for the presence and absence of bull kelp plants at the survey site generated concurrently to the acquisition of the imagery, but no such datasets exist for these surveys at the spatial resolution necessary to automate the process in this way. Indeed, it is challenging to envision what level of ground truth data resolution is even possible from boat-based methods to be captured within the prescribed low-tide survey window. Therefore, manual technician verification, which is a published method for accuracy assessment of this sort (Nahirnick et al., 2018; Ventura et al., 2018; Visser et al., 2018), was considered the best and only option.

3.5.2 Masking AOI into sub-regions

Prior to generating random points, the classified raster results were compared visually against the original orthomosaic and masks were created of sub-regions where accuracy results were anticipated to be significantly different. The first of these was any boundary areas where significant spectral distortion or warping of the imagery hampered classification. These did not occur in every survey, but when present were considered a permanently masked region for accuracy analysis. The reason for not excluding these regions prior to classification is that a primary motivation of this project is to document the presence of kelp to the fullest extent possible, and if the classifier was able to differentiate kelp in these boundary areas it would be valuable to include in the final result.

Following this boundary masking, the primary two sub-region delineations that were created for each survey were between bull kelp canopy that was located firmly in the sub-tidal region off shore, and that which abutted the shallow intertidal region where other algae and vegetation was often found (Figure 24). Every kelp forest surveyed was somewhat different in this regard, with some existing only far enough off shore as to not be confused with other vegetation (e.g. at Hansville) and others having significant bull kelp presence in the very shallow sub-tidal zone. The delineation of these zones was done by consulting both the initial imagery, as well as the classified result, and was drawn with the main priority being to separate areas where understory was correctly marked as water, and those where it was misclassified. This effort was done not to artificially enhance the accuracy score of the main region (results of the entire AOI are reported below as well), but to fairly assess the relative strength and weakness of this classification method in these varied nearshore zones.



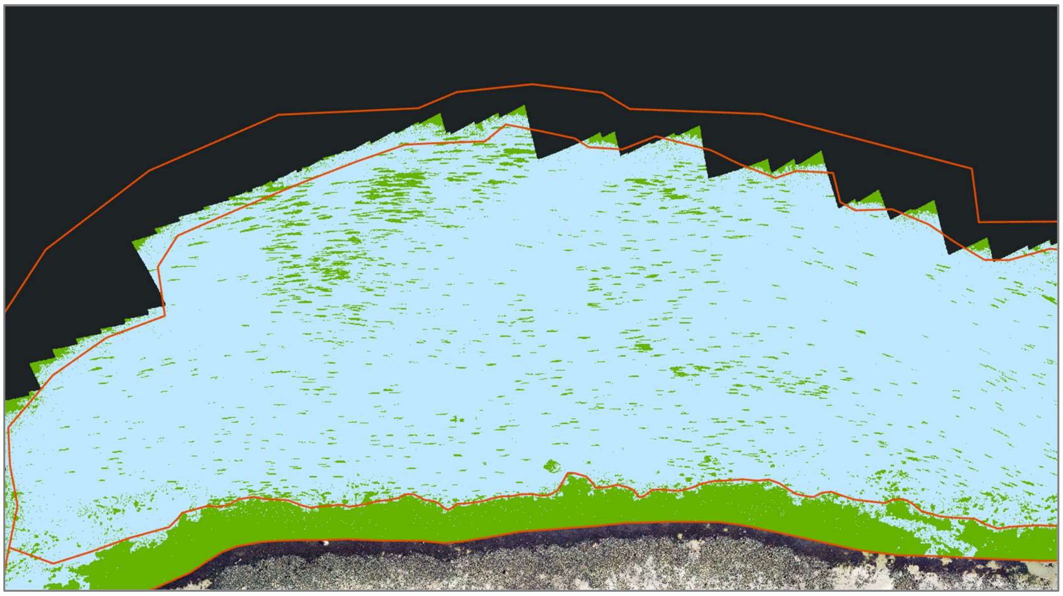


Figure 24. (Top) Orthomosaic of survey from North Beach on August 16, 2020 showing the three sub-regions created for accuracy assessment purposes. (Bottom) the same survey classified into kelp canopy (green) and water (blue) classes.

3.5.3 Accuracy assessment point generation

To generate accuracy assessment points in the overall AOI and two sub-regions of each survey, the percent of each kelp canopy and water class were calculated based on the number of pixels of each found therein. Then, the equation in Congalton & Green (2019) (Equation 3.1) based on a predetermined confidence interval was used to calculating the accuracy assessment point quotas for each sub-region.

$$n = B * \rho(1 - \rho)/\beta^2 \qquad \text{(Equation 3.1)}$$

$$B = 1 - \alpha/k \qquad \text{(Equation 3.2)}$$

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 3.2)
- 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 precision

In general, this equation produces more points the closer to equal distribution the classes are, and fewer when a class is a small percentage of the total area. As an example of this, a survey where the main subtidal region has 90% water and 10% kelp canopy, and where α and β are both set at 5%, the above equation calculates that n = ~181 points, whereas changing those to 95% water and 5% kelp reduces that number to n = ~96 points. For every main subtidal region a 95% confidence level was chosen, however in the intertidal fringe region sometimes the number of points required was not feasible to process manually, and the confidence level was reduced to 90%.

Once the number of assessment points needed for each survey was determined, the final consideration was how to distribute these points using the *Create Accuracy Assessment Points* tool in ArcGIS Pro. The two main alternatives were to use simple stratified random points, or equalized stratified random points. The difference between these two is that the former apportions the number of points to each class proportionally, whereas the latter divides the total number of points between classes evenly regardless of percent coverage. Initial tests confirmed references in the literature that which method is chosen can alter the accuracy results produced, therefore a combined method suggested in Congalton & Green (2019) was employed. In this method, 40 equalized stratified random points were created first, such that each class had at least 20 points, and then the remaining point quota as determined by Equation 3.1 were distributed in a simple stratified or proportional manner. As a final matter of cleanup, any points that fell within the training data polygons as a result of this process were excluded from accuracy assessment so as to avoid any bias.

3.5.4 Manual technician verification

The final step in the accuracy assessment process was to populate the "ground truth" value for each point to compare with the classified outputs. As described in section 3.5.1 above, ground truth data at the spatial scale necessary to assess the accuracy of the results in this project do not exist, therefore manual technician verification was employed. This process involved the somewhat laborious process of zooming in on each accuracy assessment point overlayed on the initial orthomosaic (without either the classified raster result or attribute for each point visible) and manually populating the point's attribute for "ground truth" with the value as the technician (the author) saw it. This process was repeated for each accuracy assessment point, for each sub-region of each survey. For a small subset of points, the technician was unable to determine which class the point should be classified as and was marked as "other."

Once these values had been fully populated, an error/confusion matrix was generated with the Compute Confusion Matrix tool in ArcGIS Pro (Figure 25). This error matrix shows the user's accuracy (type 1) and producer's accuracy (type 2) as a percentage for each class, an overall accuracy percentage, and a Cohen's kappa value, which is used to determine if one error matrix is statistically different from another. Per the remote sensing literature an accuracy rating of 85% among any of these dimensions is considered to be a standard threshold for whether a classified result should be used (Sim & Wright, 2005; Congalton & Green, 2019). Furthermore, a breakdown of kappa values into the following four categories adapted from the same sources is used to assess the overall quality of the result (Table 2). Substantial accuracy can be thought of as results that would be useful but not strictly repeatable, whereas excellent accuracy indicates the result can likely be used for long-term trend analysis, etc.

Table 2. The categorical breakdown of potential Cohen's kappa values generated during accuracy assessment, adapted from Sim & Wright (2005), and Congalton & Green (2019).

Cohen's kappa result	Categorical label
Less than 0.40	Poor
0.40 – 0.60	Moderate
0.60 – 0.80	Substantial
0.80 and above	Excellent

	Technician verification				
	Water	Kelp Canopy	Total	User's Accuracy	
Water	122	5	127	96.1	
Kelp Canopy	3	22	25	88.0	
Total	125	27	152		
Producer's Accuracy	97.6	81.5		Overall Accuracy	94.7
				Kappa	0.81

Figure 25. Example of an error matrix generated for the classification resuls of the kelp forest canopy from an orthomosaic. The table shows the number of points correctly identified by the classifier. User's, Producers, and Overall Accuracy values are all percentage values.

These error matrices were the primary data product used to assess the efficacy of this project's methodology for detecting bull kelp canopy at sites throughout Puget Sound, as well as an indicator for further investigation as to which kelp forest characteristics, and environmental conditions had the greatest impact on preventing accurate results from being generated. They also served as a gate on whether a classified survey product was accurate enough to be used to generate the kelp forest canopy metrics described in Section 3.6.

3.6 Canopy area metrics

Classified results that were assessed to have met the 85% accuracy thresholds and had substantial or excellent accuracy based on categorical Cohen's kappa values were used to generate metrics that described the characteristics of the kelp forest at each site. This meant that they could not reliably be generated over the entire AOI at each site, but could be calculated within the confined subtidal zone of every survey. Thought this necessarily meant that some portion of kelp canopy would be excluded, for the purposes of this exploratory project the analyses were still expected to yield meaningful results. These two metrics were rather simple, but represent significant potential data sets that could be used in the long-term monitoring of the abundance of kelp at each site.

The first of these metrics generated was the canopy area present at the surface, as detected by the random forest classifier. To calculate this, the results of the classification within the confined subtidal AOI were summarized on a pixel basis using the tool *Summarize Categorical Raster*. This tool gave an output of the raw count of pixels of each class within the AOI. These pixel counts could then be multiplied by the resolution of the classified raster as expressed in m^2 to generate area totals for that individual class (Equation 3.3). This calculation was conducted only on the "floating kelp canopy" class as the area of water within the survey AOI was not needed.

(Equation 3.3)

$$(\# \, of \; pixels \; in \; class \; x) * (raster \; resolution \; in \; m^2) = area \; of \; class \; x \; within \; AOI$$

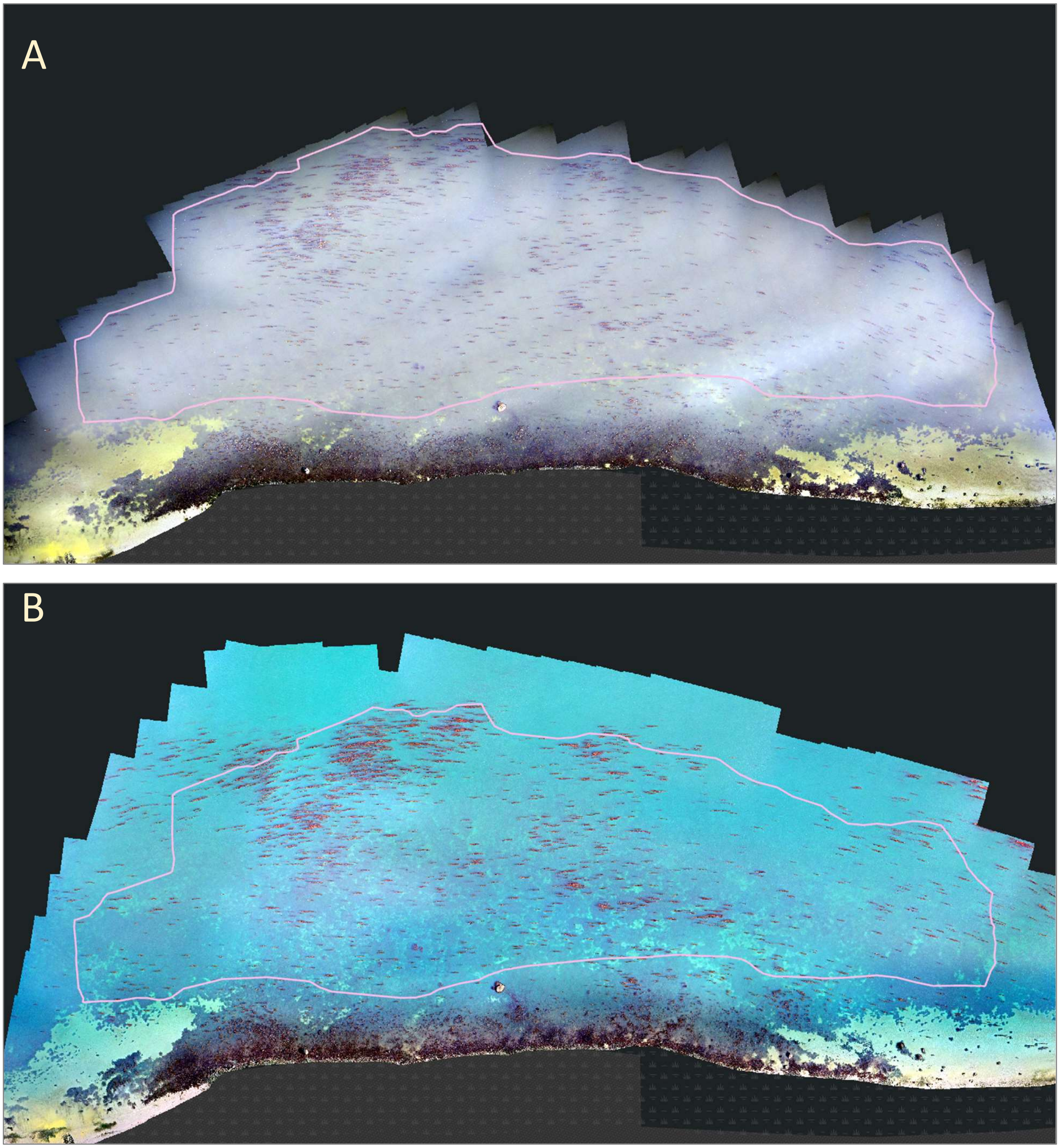
The second metric generated from the classified raster results at each site was the percent cover of kelp canopy within the AOI. This was generated by dividing the number of kelp canopy pixels by the total number of pixels within the AOI (Equation 3.4).

(Equation 3.4)

$$\frac{\# \, of \; floating \; kelp \; canopy \; pixels}{total \; \# \, of \; pixels \; in \; AOI} = kelp \; canopy \; \% \; cover \; in \; AOI$$

Despite the simple nature of these metrics, they represent powerful tools for characterizing the abundance of bull kelp forest sites that could be used to track their health over time. For example, it is conceivable that a kelp forest's overall area might stay consistent from year to year even while it gets thinner. A method that only detects the overall footprint would fail to catch that this forest is declining. Currently, the only other method being deployed within Puget Sound proper taking this into account is the WA DNR kayak transect method. Therefore, this represents a critical methodological development that must be refined and deployed in order to effectively track the abundance of bull kelp forests in Puget Sound.

At North Beach, metrics for canopy area and percent cover were also run on an area of minimum overlap between three surveys conducted on August 16, August 30, and September 30 in an attempt to examine repeatability. This minimum area in common was drawn using the confined subtidal area of interest polygon for each survey, and taking the innermost border of each (Figure 26). This resulted in a central area 10.6 hectares in size that covered 88.2%, 63.1%, and 67.0% of the original area of those confined areas respectively (chronological order).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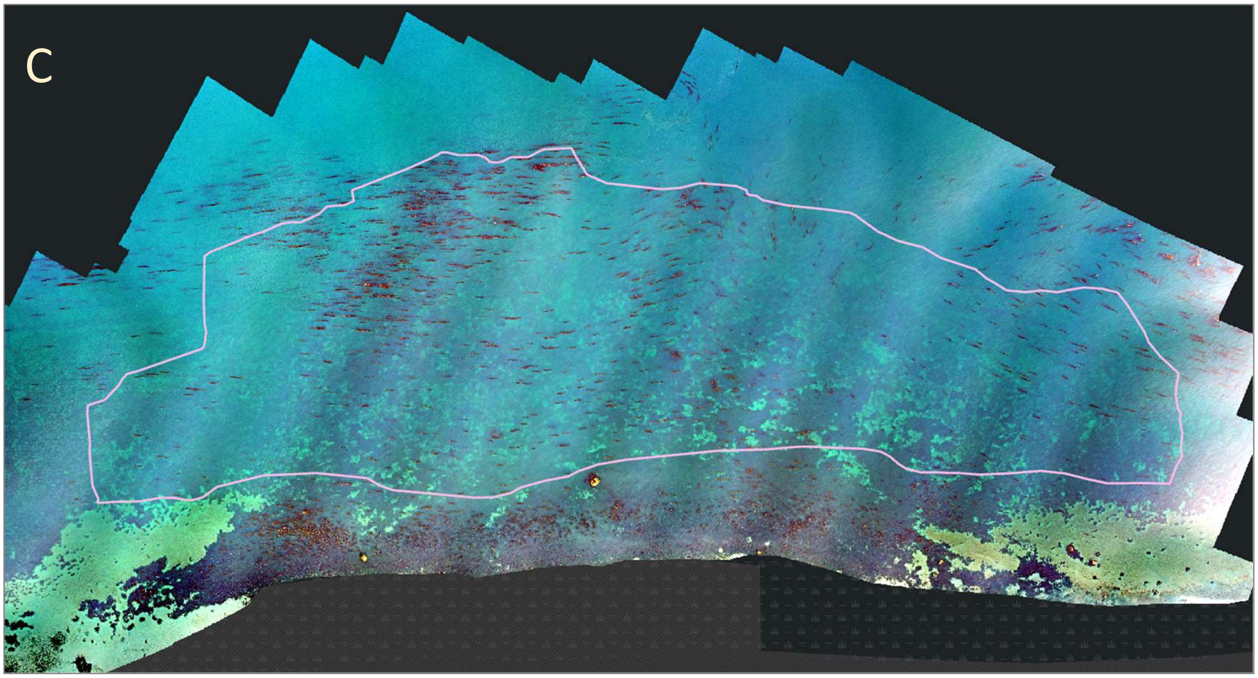

Figure 26. The central minimum area in common between the confined subtidal accuracy assessment regions of three surveys at North Beach. The three surveys occurred on (A) August 16, (B) August 30, and (C) September 30.

3.7 Manual delineation of kelp bed perimeter

The final method used for assessing the performance of the image collection and processing methodology devised for this project involved manually delineating the boundary of the kelp forest from the imagery. This method was intended to mirror the protocol used during WA DNR kayak surveys and therefore a few basic rules were employed: 1) multiple kelp plants within 5 meters were considered to be a “bed”, 2) individual kelp plants within 20 meters of a designated kelp bed will be included in that bed, 3) the surveyor proceeds to follow the boundary of the kelp bed based on those two rules in either a clockwise or anti-clockwise direction until they return to the point they started at (Berry et al., 2019). The digital equivalent of this involved drawing vertices of a polygon feature class over top of the imagery in ArcGIS Pro rather than paddling a kayak in the field, but yielded results that could just as easily be mistaken for the latter being viewed in a GIS (Figure 27).

In order to aid in the determination of the distance between individual kelp plants, a 20 meter grid was displayed in ArcGIS Pro while delineating vertices. This grid was not relied upon explicitly in every case where kelp individuals were near the 20 meter threshold, but rather was used as a guide to make on-the-fly decisions. This decision was made in the interest of efficiency, but also mirrors the real-time decisions that kayak surveyors need to make without the means for calculating exact distances between plants.

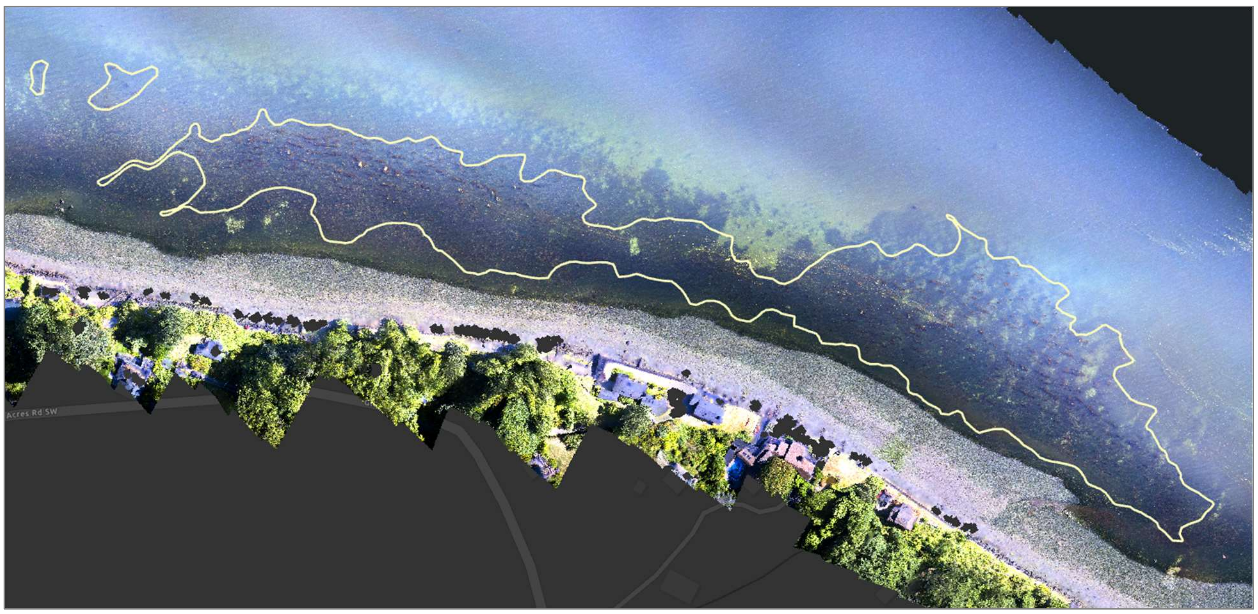

Figure 27. Example of hand-delineated kelp canopy perimeter over top of an orthomosaic generated from a survey at Vashon Island on August 15, 2021.

Following the completion of a hand-delineated perimeter polygon, they were assessed for any places where apparent errors were made and corrected. Once each boundary was deemed to be complete, the geodesic area contained within it was calculated in ArcGIS Pro in order to generate a metric for “overall bed area” of the kelp forest. This metric is the same one used by WA DNR and NW Straits in their comparison of multi-year data of the extent of kelp forests using kayak-based methods.

4. Results

4.1 Photogrammetry results

The following are the results of the photogrammetry workflow outlined in Section 3.3.

4.1.1 Image alignment & mosaicking

In total, all thirteen surveys conducted at the five target sites were successfully processed into final orthomosaics. In each instance, some number of survey photos did not align and therefore were excluded from the final orthomosaic. However, in all but two surveys, this number was less than 20% of the photos captured, and in nine out of thirteen this ratio was 15% or less (Table 3).

Table 3. Summary of photogrammetric results from 13 surveys conducted at the five target sites.

Site	Date	Aligned photos	Total photos	% photos aligned	Altitude	Pixel Resolution
North Beach	7/18/2020	375	419	89%	80	2.6 cm
	8/16/2020	409	420	97%	80	2.7 cm
	8/30/2020	278	320	87%	100	3.3 cm
	9/30/2020	407	477	85%	110	3.5 cm
Squaxin Island	7/21/2020	418	484	86%	80	2.6 cm
	7/30/2020	489	508	96%	80	2.5 cm
	8/28/2020	326	550	59%	60	2.0 cm
Lincoln Park	7/31/2020	250	379	66%	80	2.6 cm
	8/7/2020 (1)	313	327	96%	80	2.6 cm
	8/7/2020 (2)	297	333	89%	80	2.6 cm
Hansville	8/3/2020	348	414	84%	80	2.7 cm
	8/17/2020	383	383	100%	80	2.7 cm
Vashon Island	8/15/2020	363	430	84%	100	3.3 cm

4.1.2 Orthomosaics selected for image analysis

Of the thirteen orthomosaics generated, eleven were determined to be fit for analysis by hand delineation, and nine were determined for supervised classification. Reasons for excluding surveys included poor light conditions due to dynamic cloud cover and sun glare present despite targeting low sun angles that made kelp difficult to distinguish in the imagery (Table 4).

Table 4. List of orthomosaics that were determined fit for use in image analysis. Reasons are listed for those that were excluded from this next phase.

Site	Date	Survey quality	Used in further analysis	Reason for exclusion
North Beach	7/18/2020	Good	Yes	
	8/16/2020	Good	Yes	
	8/30/2020	Good	Yes	
	9/30/2020	Good	Yes	
Squaxin Island	7/21/2020	Fair	Yes	Suitable for hand delineation, too dark for automated classification
	7/30/2020	Good	Yes	
	8/28/2020	Poor	No	Poor lighting condition, minimal visibility in water column
Lincoln Park	7/31/2020	Fair	Yes	Suitable for hand delineation, too much glare for automated classification
	8/7/2020 (1)	Good	Yes	
	8/7/2020 (2)	Good	Yes	
Hansville	8/3/2020	Poor	No	Extreme glare on surface of water, minimal visibility in water column
	8/17/2020	Good	Yes	
Vashon Island	8/15/2020	Good	Yes	

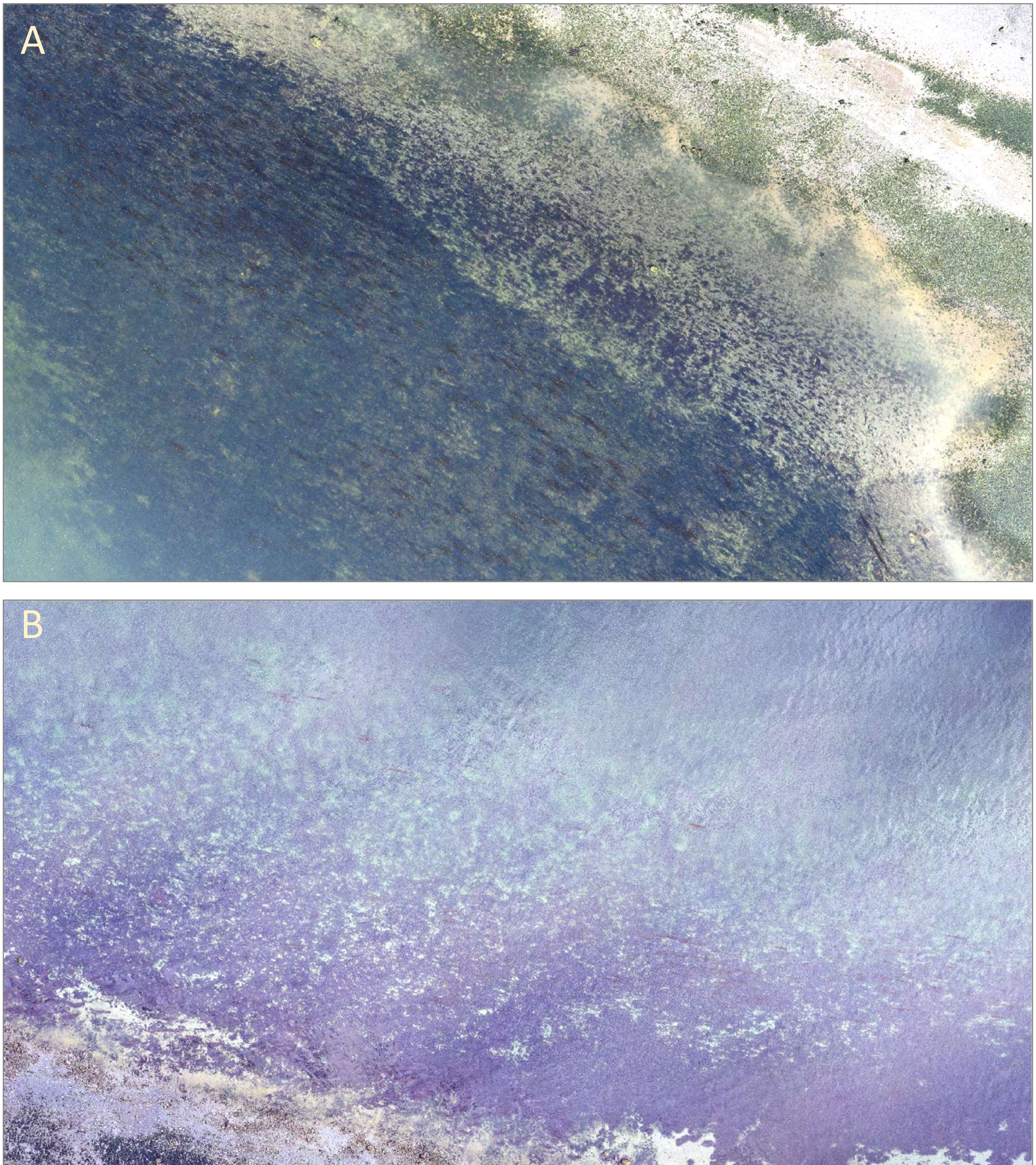
A
B

Figure 28. Three orthomosaics showing varying levels of quality for image classification. (A) Squaxin Island on July 21 suffered from poor light conditions during survey making the scene too dark to distinguish kelp. (B) Hansville on August 3 had extreme glare from too much overhead sunlight that made much of the canopy impossible to see. (C) Lincoln Park on July 31 shows much better contrast between the kelp canopy and surrounding water and was the only one of these three deemed to be suitable for image analysis.

4.2 Image classification

The following are the results generated from the supervised image classification (Sections 3.5 – 3.7).

4.2.1 Accuracy assessment

Accuracy assessment of the results of supervised classification of survey orthomosaics were first performed over the entire area of interest of each kelp bed. Each accuracy assessment yielded an error matrix showing user's and producer's accuracy for both kelp and non-kelp/water pixels, as well as overall accuracy and kappa values. These error matrices were then combined into one table showing the most pertinent metrics to this project for each survey so that values could more easily be compared (Table 5).

Mean overall accuracy across all surveys was 84%, with all but three classification results coming in higher than the 85% standard for usability. However, producer's accuracy (PA) for kelp canopy was significantly higher than user's accuracy (UA) on average (89% and 40% respectively), and was higher in every instance. This lower UA than PA means there is a greater chance of an area classified as kelp canopy being incorrect (type 1 error) than there is for an area that is kelp canopy being misclassified as water (type 2 error). For this project the final result of interest is kelp canopy presence, so a 40% average UA would be considered far too low to be reliable. Cohen's kappa values for the results are indicative of this as well with only three classifications coming in at the "substantial" agreement range of 0.60 – 0.80, and no results achieving the "excellent" range of greater than or equal to 0.80.

Table 5. Combined error matrix results generated for the nine UAV survey orthomosaics considered fit for supervised classification. These results represent accuracy assessed over the entire area of interest for each kelp forest site.

Site	AOI (m2)	kelp PA	kelp UA	overall accuracy	kappa
North Beach					
7/18/2020	138,688	95%	47%	89%	0.59
8/16/2020	156,309	88%	38%	86%	0.49
8/30/2020	199,587	81%	55%	89%	0.61
9/30/2020	206,869	80%	40%	81%	0.41
Squaxin Island					
7/30/2020	44,142	100%	10%	78%	0.16
Lincoln Park					
8/7/2020 a	37,128	90%	60%	87%	0.63
8/7/2020 b	37,128	95%	61%	90%	0.66
Hansville					
8/17/2020	84,893	100%	23%	74%	0.33
Vashon Island					
8/15/2020	135,547	75%	27%	86%	0.33

Accuracy assessment results of the confined subtidal region of each kelp forest site (per Section 3.5.2) showed dramatic improvement across every metric (Table 6). In these "open-water" areas where contrast between floating bull kelp canopy and the surrounding water column were highest, mean overall accuracy increased to 94%. Mean producer's accuracy for kelp canopy increased to 98% and mean user's accuracy increased to 83% (an increase of 43%). Kappa values showed a marked improvement as well with every survey result achieving at least 0.60 to be considered "substantial" agreement, and all but three achieving greater than 0.80 to be considered "excellent" agreement.

Table 6. Combined error matrix results for the nine UAV orthomosaics confined to just the main subtidal region of each survey where confusion due to substrate conditions was minimized.

Site	reduced AOI (m2)	kelp PA	kelp UA	overall accuracy	kappa
North Beach					
7/18/2020	106,979	100%	82%	94%	0.86
8/16/2020	120,449	100%	97%	99%	0.98
8/30/2020	168,201	97%	97%	98%	0.98
9/30/2020	158,542	97%	96%	98%	0.95
Squaxin Island					
7/30/2020	37,856	100%	81%	93%	0.84
Lincoln Park					
8/7/2020 a	31,332	100%	83%	94%	0.84
8/7/2020 b	31,332	96%	73%	90%	0.76
Hansville					
8/17/2020	79,865	100%	69%	89%	0.75
Vashon Island					
8/15/2020	41,948	95%	67%	91%	0.74

4.2.2 Canopy area & percent cover estimates

Bull kelp canopy area and canopy percent cover estimates generated using the pixel count-based calculation methods outlined in Section 3.6 generated the following results for the confined area of interest of each kelp forest site (Figure 29). The site with the largest kelp canopy area estimate was North Beach, where 6,321 m^2 of kelp canopy were accurately detected. This was more than double any other site surveyed, and is indicative of this site being at the boundary between the smaller fringing sites in Puget Sound, and the large expansive ones in the Strait and outer coast. The results for detected canopy area at the other sites were as follows (from large to small): Lincoln Park – 2,784 m^2, Vashon Island – 1,098 m^2, Hansville – 441 m^2, and Squaxin Island – 160 m^2.

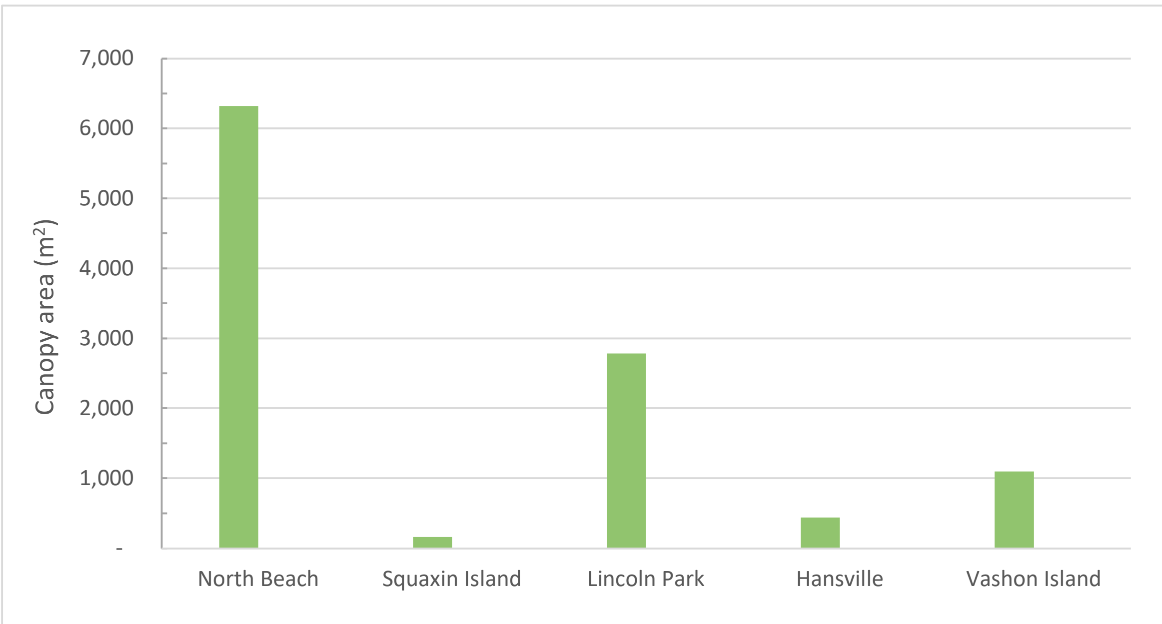

Figure 29. The floating kelp canopy area accurately detected within the confined subtidal region at each target site.

The results for percent cover at each site followed a different pattern (Figure 30). The site with the highest percent cover of kelp canopy was Lincoln Park, with an estimated 8.9% cover. This matched visual inspection of the orthomosaic showing that the patches here were quite dense with many stipes, bulbs and blades overlapping each other throughout the survey area. The results for percent cover at the remaining sites were as follows (from large to small): North Beach – 3.9%, Vashon Island – 2.6%, Hansville 0.6%, and Squaxin Island – 0.4%.

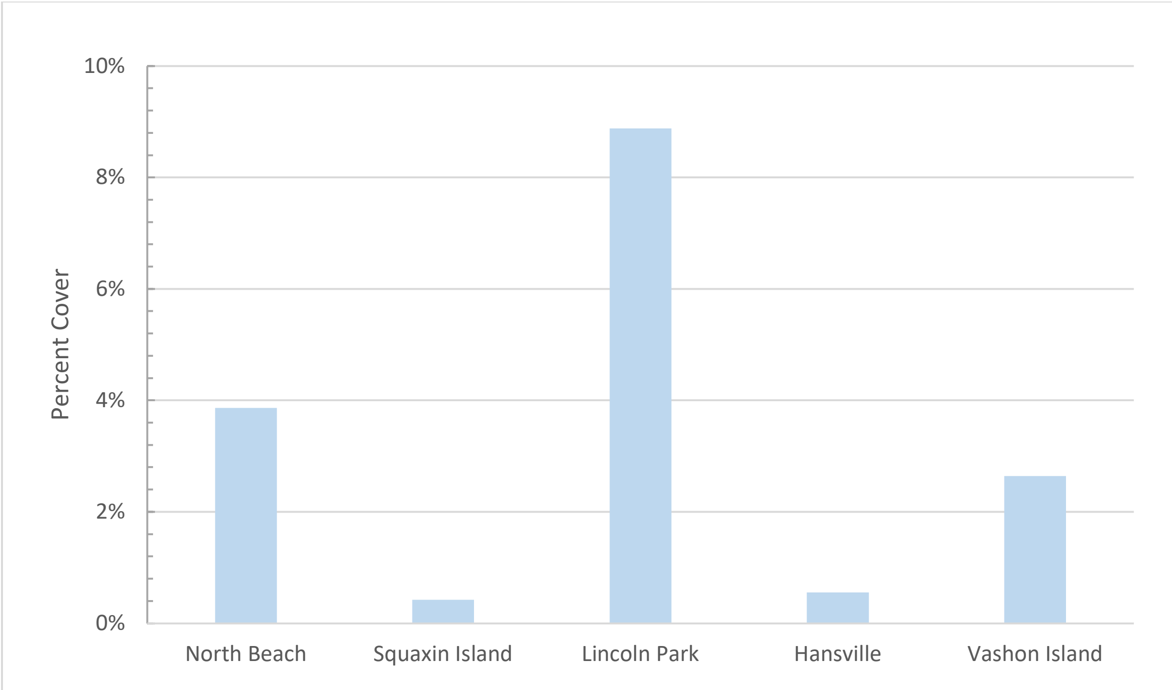

Figure 30. The percent cover of floating kelp canopy area detected within the confined subtidal region of each site.

Comparing these two metrics within the confined subtidal region of each site, we can see that there is not a clear relationship between them (Figure 31). A correlation analysis of the two metrics across the five sites found a moderate positive correlation but the correlation was not significant: $r(4) = .48$, $p = .41$. It is possible that these results are an artifact of having so few points of comparison, however it also matches the qualitative findings of these surveys that the kelp forests studied exhibited a high degree of diversity in terms of overall area and density.

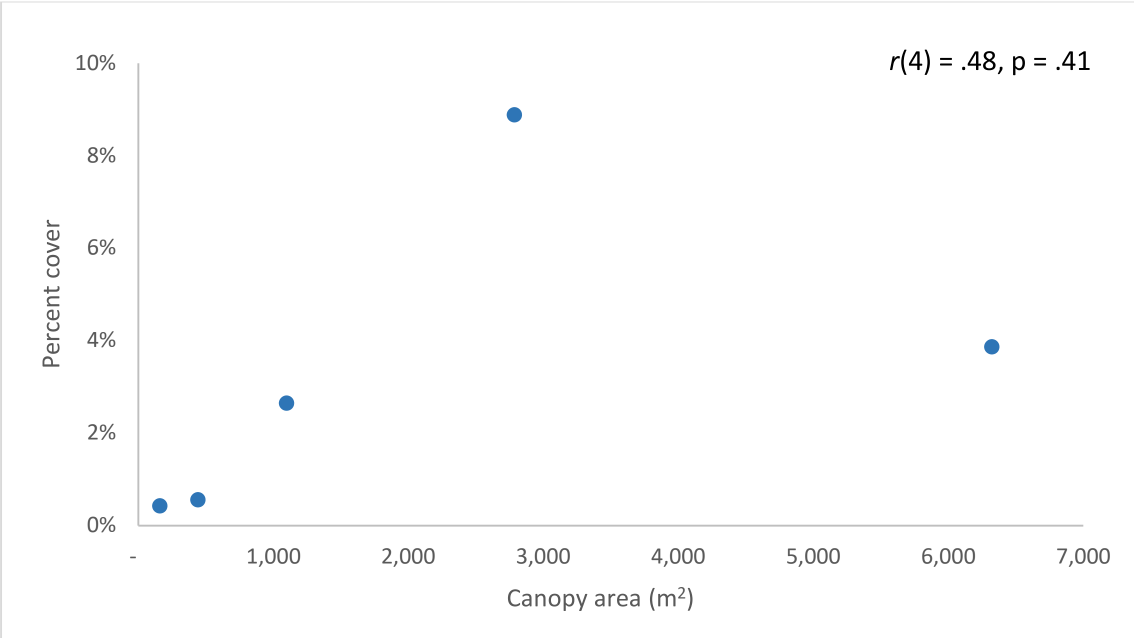

Figure 31. Correlation of canopy area and percent cover estimates for the five analysis sites: $r(4) = 0.48$, p = .41. This indicates there is a moderate positive correlation, but that it is not significant.

4.2.3 North Beach repeat survey comparison

The same estimation of bull kelp canopy area and percent cover conducted within the minimum area in common between three surveys conducted at North Beach on August 16, August 30, and September 30 (Section 3.6) yielded the following results (Figure 32). The canopy area and percent cover estimates from the first two of these survey dates showed remarkable similarity: 4,793 m^2 and 4.5% cover on Aug 16, and 4,777 m^2 and 4.5% on Aug 30. By contrast, the classified survey from Sep 30 shows a roughly 46 – 47% reduction in both canopy area and percent cover estimates (these two tracked each other directly due to the area constraint).

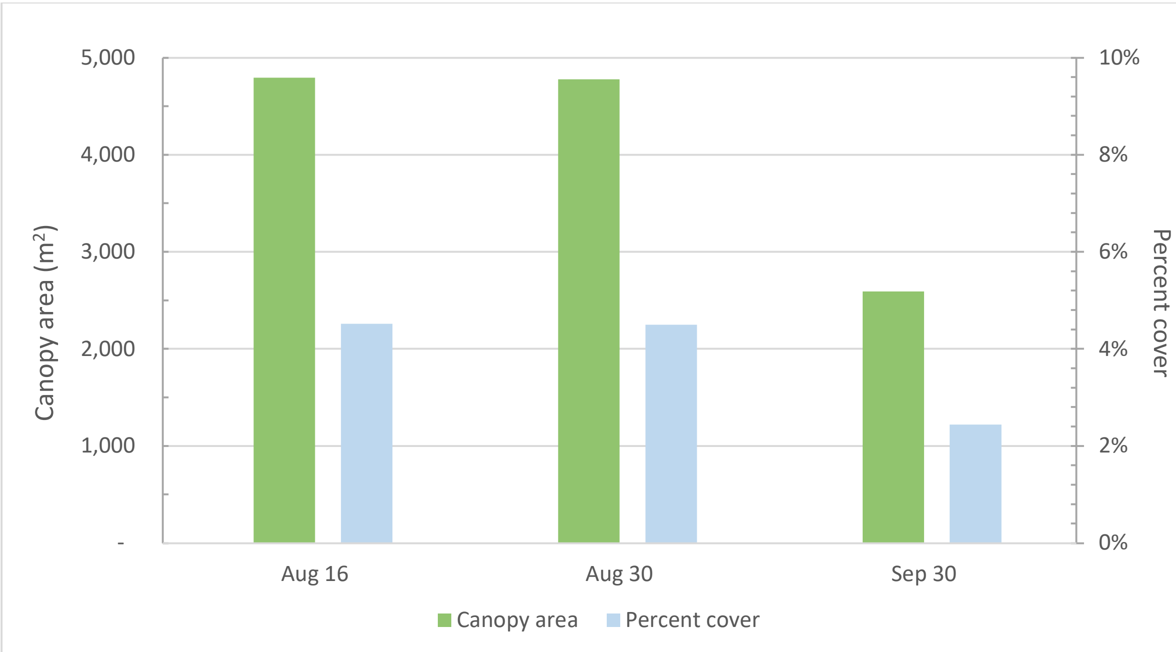

Figure 32. The canopy area and percent cover estimated within the minimum area in common (10.6 ha) across three separate survey dates at North Beach. August 16 and 30 estimates are nearly identical while September 30 shows a ~46% reduction in both metrics.

4.3 Hand delineation of kelp bed perimeters

The following are the results of the comparison of DNR kayak-based perimeter surveys and UAV imagery-based hand delineated kelp bed boundaries as outlined in Section 3.7.

4.2.1 Visual comparison to kayak survey tracks

Comparisons between DNR kayak survey bed perimeters and those generated using the hand-delineation method shows general agreement between the location and distribution of bull kelp at a majority of sites surveyed. Differences between methods were commonly the result of disagreement over the inclusion of low density patches in the kelp forest, in the range near the 20 meter threshold for including individual plants in the overall bed perimeter used in both methods. At Squaxin Island, Lincoln Park, and Vashon Island, the result of these differences was that the kayak surveys generated a slightly larger and more broadly inclusive bed perimeter than that drawn using the UAV survey imagery (Figure 33 thru Figure 35).

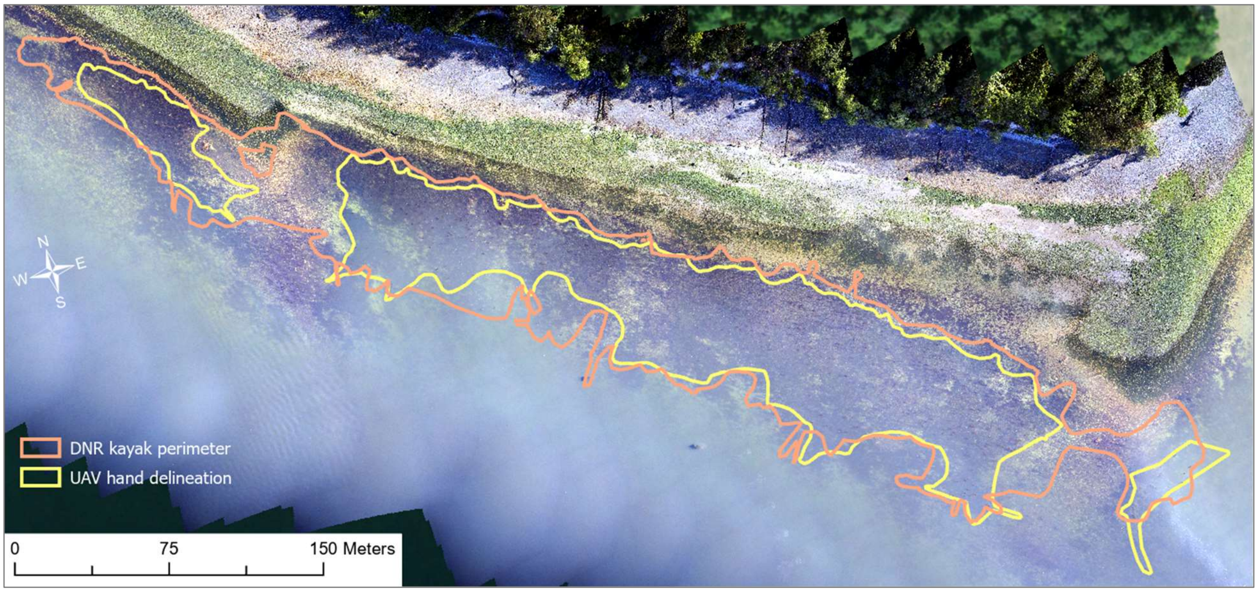

Figure 33. UAV survey imagery taken at Squaxin Island on July 30 showing the hand delineated kelp bed perimeter (yellow) and the DNR kayak perimeter (orange), also captured on July 30. Overall, the perimeters show a high degree of agreement, though there are small sections included in the kayak perimeter that the imagery revealed to be too low density to meet the 20 meter density requirement for both the kayak and aerial surveys.

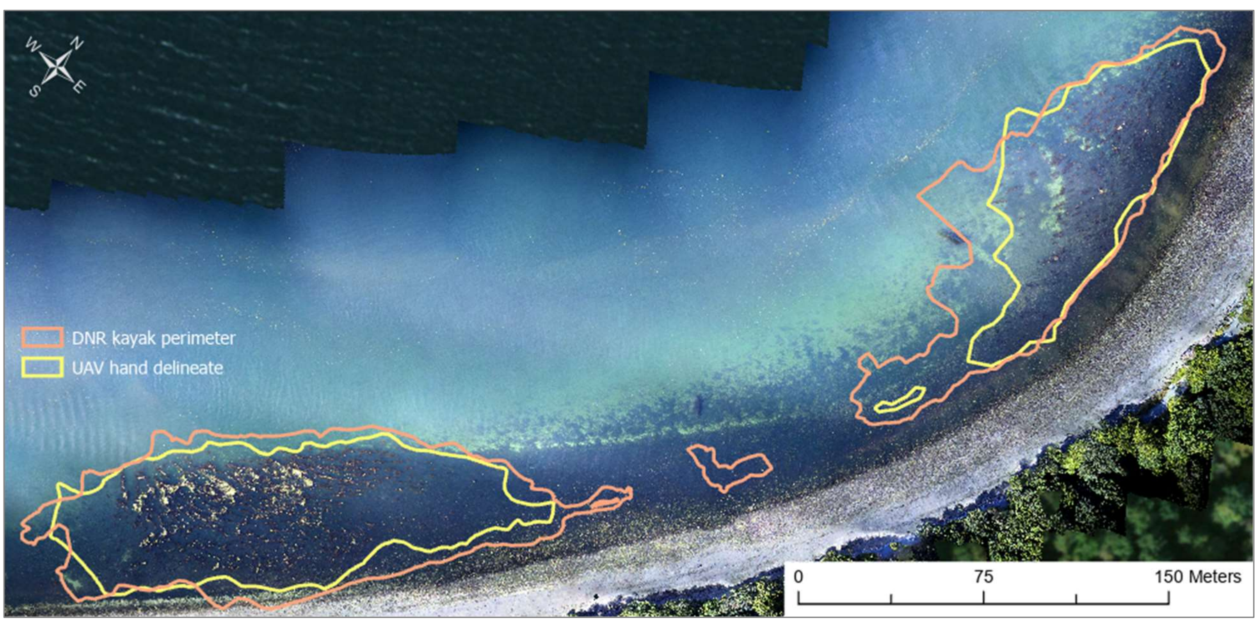

Figure 34. UAV survey imagery taken at Lincoln Park on Aug 7 showing the hand delineated kelp bed perimeter (yellow) and the DNR kayak perimeter (orange), captured on Aug 4. Overall, the perimeters show a moderate degree of agreement, though there are some sections included in the kayak perimeter that the imagery revealed to be too low density to meet the 20 meter requirement, particularly in the northern portion of the bed. There is also a small central patch included in the kayak perimeter that did not appear to contain any kelp in the imagery.

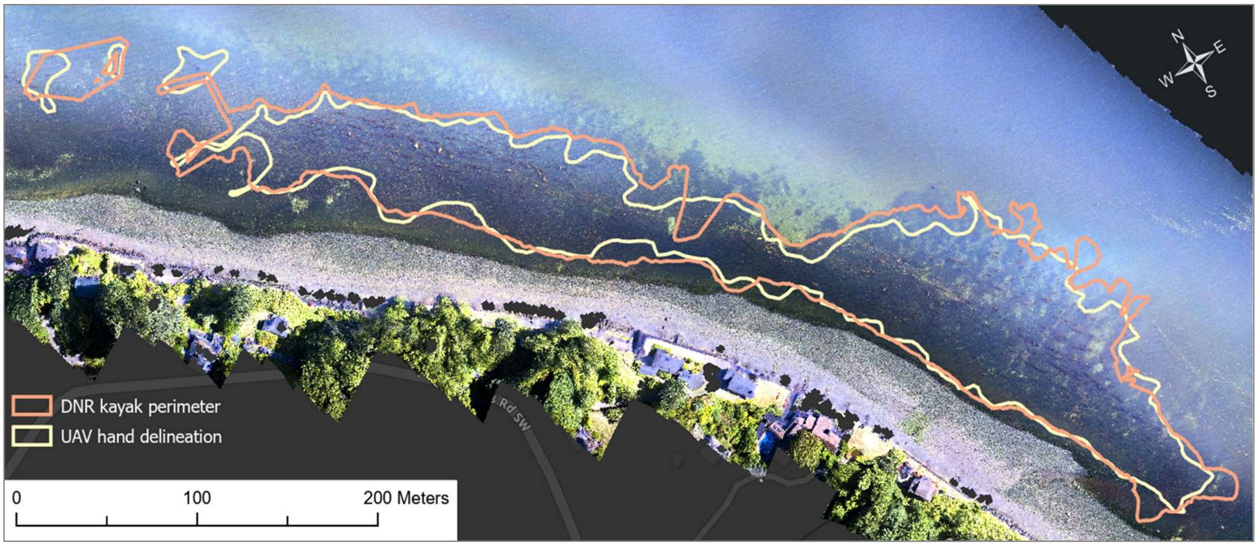

Figure 35. UAV survey imagery taken at Vashon Island on Aug 15 showing the hand delineated kelp bed perimeter (yellow) and the DNR kayak perimeter (orange), captured on Aug 18. Overall, the perimeters show a high degree of agreement, with small differences along the border of the perimeter.

The kelp forest at North Beach is surveyed differently by WA DNR and NW Straits than the other three above, in that the east and west boundaries are artificially set. This is because the forest continues to the east all the way to Fort Worden, and to the west to McCurdy Point (a section of shoreline over 7 km long). The boundaries used for this project were taken from the NW Straits Commission guidelines used in their kayak monitoring of the site. This site showed more significant patches of kelp canopy that were excluded by kayak surveyors than the previous three, particularly in the NW corner of the bed (Figure 36).

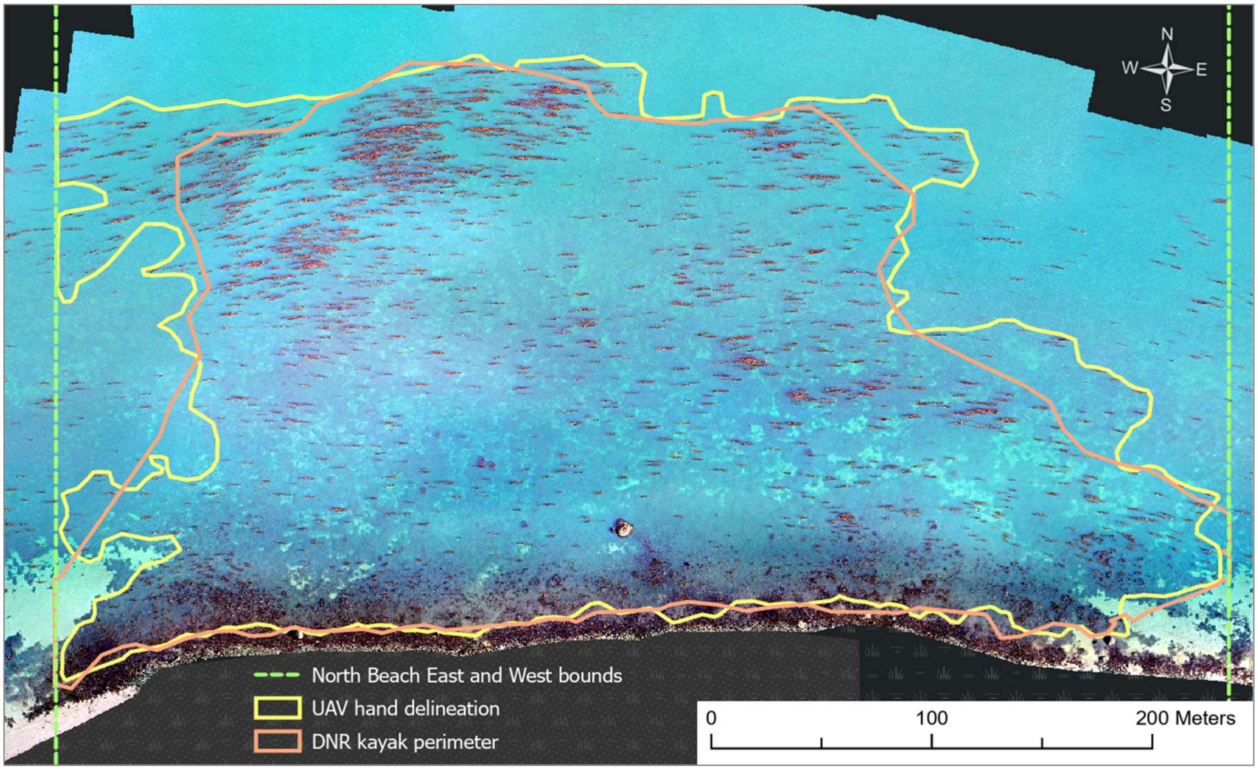

Figure 36. UAV survey imagery taken at North Beach on Aug 30 showing the hand delineated kelp bed perimeter (yellow) and the DNR kayak perimeter (orange), captured by DNR and NW Straits volunteers on Aug 26. Overall, the perimeters show a high degree of agreement. There is also a small central patch included in the kayak perimeter that did not appear to contain any kelp in the imagery, possibly due to them blending in with other surface algae.

Of the five target sites, Hansville showed the greatest difference between the two perimeter defining methods. Both methods missed patches that the other method detected, and disagreement was highest on the western side of the site (Figure 37).

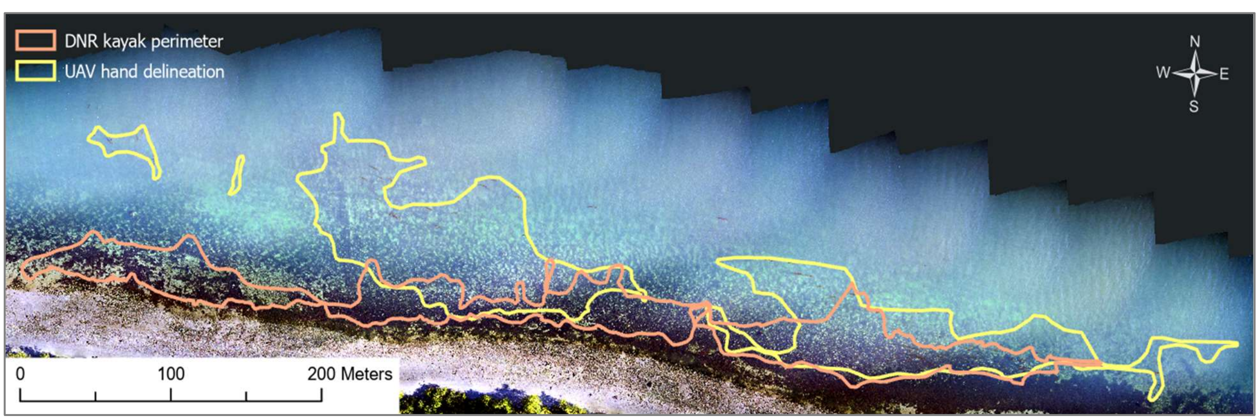

Figure 37. UAV survey imagery at Hansville taken on Aug 17 showing the hand delineated kelp bed perimeter (yellow) as well as the DNR kayak perimeter (orange) captured on Aug 3. While there is some agreement in the shallow subtidal, sections of deeper kelp individuals were missed by boat. Conversely, bull kelp plants that were difficult to distinguish from other brown algae in the SW extent of the survey area were missed by the UAV.

4.2.2 Overall bed area calculations

The geodesic area calculated within the kayak perimeters and imagery-based delineations further illustrates that some agreement exists between methods, but that significant variation was found in that the UAV hand-delineated imagery estimates were sometimes greater and sometimes less than the kayak areal estimates. In terms of percentage of the kayak based area estimates at each site, the UAV imagery-based hand delineation resulted in estimates were: 107% at North Beach, 68% at Squaxin Island, 72% at Lincoln Park, 145% at Hansville, and 84% at Vashon Island (Figure 38).

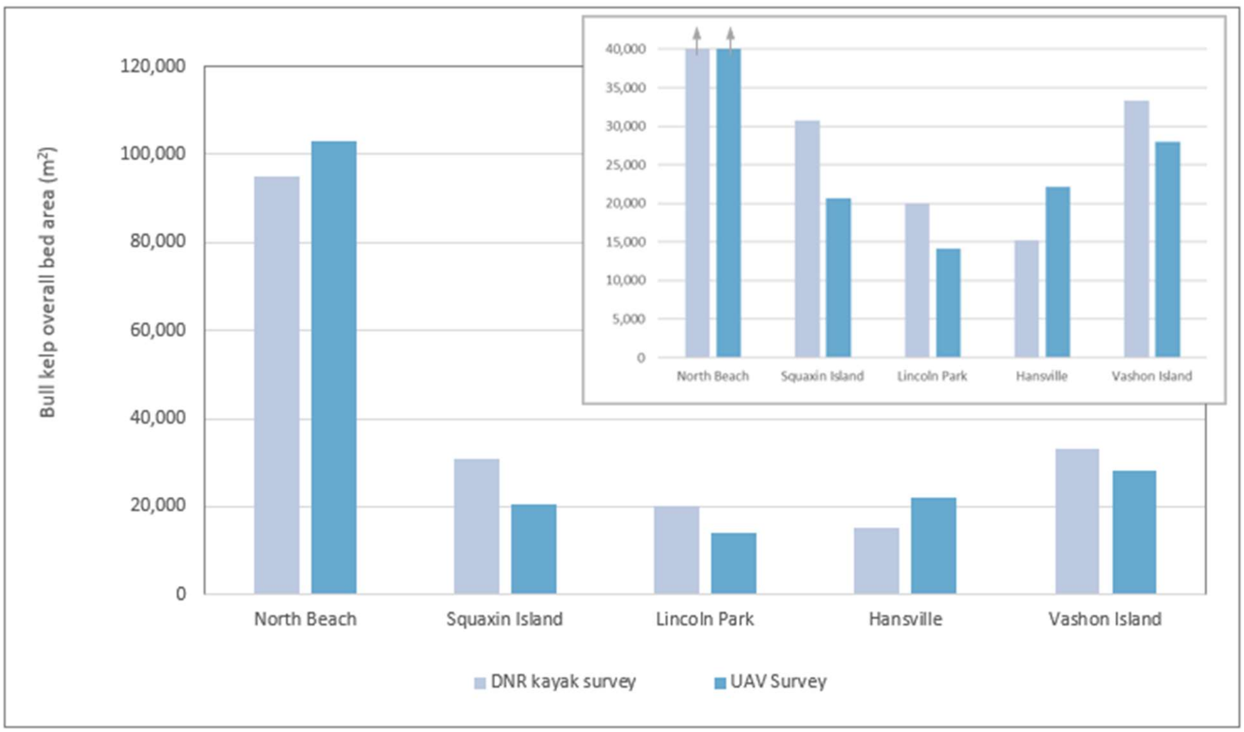

Figure 38. Bull kelp overall bed area calculated within DNR kayak survey and UAV hand delineated boundaries for each of the five target sites. The top right chart inset shows a reduced y-axis range to better represent the differences within sites other than North Beach, where bed area was significantly higher.

5. Discussion

This project sought to answer the central research question of whether low-cost UAV imaging platforms can reliably generate geospatially accurate maps of floating bull kelp forests in Puget Sound. On its face this is a simple enough question, but with the subtext of this investigation ultimately being the need for additional monitoring capacity to prioritize conservation and restoration efforts of these vital habitats, the scope of the project takes on added dimensions. Therefore, this discussion will address the question from three different angles: 1) the technical and logistical feasibility of mapping bull kelp forest canopies with UAV imagery, 2) the efficacy of supervised classification of bull kelp forest orthomosaics in generating metrics of canopy distribution and abundance, and 3) how UAV-based imagery surveys fit into the broader picture of existing bull kelp forest monitoring efforts in Puget Sound.

5.1 Technical and logistical feasibility of UAV mapping

The first question as to whether bull kelp forests could successfully be surveyed and processed into meaningful image products is perhaps the most straightforward to answer. In successfully conducting surveys and processing imagery into accurate orthomosaics for thirteen surveys across five kelp forest sites in Puget Sound, this project has unequivocally shown that the methodology developed herein is tractable for the purpose. Based on existing research into the field of nearshore habitat mapping using UAVs with RGB sensors (Nahirnick et al., 2018; Tait et al., 2019. Cavanaugh et al., 2021b), this author had a reasonable expectation at the outset of this project that utilizing similar methods on bull kelp canopies had a good chance of being successful. However given the unique challenges to capturing bull kelp canopies in the context of the dynamic environment of Puget Sound in a consistent and repeatable manner (Britton-Simmons et al., 2008), this result was in fact far from certain.

In retrospect, there were a myriad of factors that could have led to this project failing before it ever got going. For one, prior research into the impact various environmental conditions such as tides and currents can have on the appearance of floating kelp canopies (Steneck et al., 2002; Britton-Simmons et al., 2008; Van Wagenen, 2015; Schroeder et al., 2019) were absolutely essential to planning field surveys to occur during proper low-tides. In addition to this, previous research investigating the impact of sun glint on aerial imaging in aquatic environments (Kay et al., 2009; Nahirnick et al., 2018; Cavanaugh, 2020) contributed significantly to this authors understanding of the narrow window in each tide series where there were suitable low tides that *also* occurred early enough in the day to avoid extreme sun angles. Finally, the wealth of peer reviewed sources detailing UAV mapping best practices with regard to things such as ground control panels and proper flight planning settings (Manfreda et al., 2018; Nahirnick et al., 2019; Flores-de-Santiago et al., 2020) ensured that the data collected had the best chance of being useable. If any of these parameters or conditions were consistently out of place, the results of this project surely would have been worse.

To illustrate this point, it is worth revisiting Table 4. In it, we can see that out of the thirteen surveys conducted at the five target sites, four of them were deemed to be unsuitable for detailed analysis (a “fail” rate of 30.7%). In addition to these, there were in fact two more surveys conducted at two additional sites during the summer of 2020 that were not included here as well due to poor results, which would increase the fail rate to 40%. This highlights how even when target conditions were met in planning, useable results are not assured. There was not a clear indication from the surveys that failed of any one target condition in particular being the cause, though additional research could examine each of them individually to determine if changes are merited

This brings up the issue of logistics in using UAV to survey bull kelp forests across Puget Sound. Given the above uncertainty in obtaining useable results from every survey, building redundancy into annual field plans would be advisable. If the quality of results could be confirmed rapidly enough, this would free up time to expand efforts in a given field season, but tiers of priority sites should be identified ahead of time each year, and repeat surveys scheduled accordingly. Finally, additional research into the effects environmental conditions such as tides, currents, and sun angle have on survey results in Puget Sound specifically should be conducted. This would potentially enable surveys to be conducted outside of the narrow window at the beginning of each tide series where low tides are less than +1.0 ft *and* where sun angle during the survey is less than 45-50°. Until such information is made available, the number of suitable survey days in a given field season remain limited, and therefore act as a major constraint on the scope of monitoring one individual or team could reasonably achieve.

Overall, the tools used and the imagery processing methodology developed in this project show immense promise for mapping not only bull kelp canopies, but other important species found in nearshore environments. The major limiting factors are the high failure rate of obtaining high quality final products from each survey, the narrow window at the beginning of each low tide series with suitable conditions, and the steep learning curve associated with much of the software used for processing and analysis. It is this author's belief that with the investment of sufficient resources, a bull kelp forest canopy monitoring program consisting of a small number of individuals could effectively map large portions of Puget Sound on an annual basis. However, additional research and further methodological refinements are warranted given the findings of this project.

5.2 Efficacy of supervised classification

The second major element of UAV mapping that this project sought to investigate was the use of automated image analysis tools to aid in the characterization of bull kelp forest canopies once they had been captured. Being able to successfully analyze large amounts of imagery with minimal effort would lead to resources being freed up for additional data acquisition and/or targeted research projects and could significantly expand the potential scope of monitoring efforts with this methodology. The supervised object-based random forest classifier used in this project was found to be a promising option for enabling this kind of analysis, though with some potential limitations.

The robust accuracy analysis of the classified raster outputs of the random forest classifier for each survey via stratified random point generation revealed many strengths and weaknesses of this method, as represented by Table 5 and Table 6. When applied to the entire area of interest at each site, the classified results were found to have very mixed accuracies. For example, surveys like the one performed at North Beach on August 30, and at Lincoln Park on August 7 were found to have overall accuracy values of 89% and 90% and Cohen's kappa values of 0.61 and 0.66 respectively and would be considered suitable for further analysis. However, these two were in the minority of the nine orthomosaics the random forest classifier was applied to and results for the majority of surveys would be considered unusable. Furthermore, while producer's accuracy for kelp canopy across these surveys was consistently high (89.3% on average), kelp canopy user's accuracy was significantly lower (40.1% on average). This is indicative of the extent to which other vegetation and substrate were classified as kelp in the results, and would prevent kelp canopy data from these areas being useful.

Confined to the open water subtidal zone of each survey (extending shoreline mask by 5-40 meters), the accuracy of the classifier was markedly better. Over half of the surveys had kappa values over 0.80 (considered excellent accuracy) and kelp canopy user's accuracy jumped to 82.7% on average. However, the exact location of the shallow boundary of this open water zone appeared to vary from site to site, and it is conceivable that the extent of the shallow subtidal mask could even vary at the same site depending on factors like water quality, light conditions, and the abundance of other vegetation (indeed evidence of this could be seen in the repeat surveys at North Beach). Therefore, the consequences of having to exclude portions of a site from supervised classification analysis need to be weighed. Depending on the proportion of kelp forest canopy that is masked in this way, the impact to overall monitoring may be insignificant, or could prevent long-term trends from being accurately calculated altogether. In Washington, the proportion of kelp forests found in this region 5-40 meters from a ~0.0 m low tide line is not described in a detailed way, but examination of prior research shows that depth distributions of kelp beds can vary widely depending on location and geographic characteristics (Pfister et al., 2018, Berry et al., 2019). Further research is therefore needed to determine better estimates of these distributional patterns to inform the significance of the limitations of classification in shallow subtidal regions.

From the above information, it can be concluded that the random forest classifier is incredibly effective at distinguishing kelp canopy from the surrounding environment if certain conditions are met. The impact these considerations have on the ability for data to be compared within the same footprint year after year is something that will require further research.

Regardless of the classification method utilized, a separate discussion as to the importance of metrics that can generated from classified results is merited. The generating of canopy area and percent cover from classified rasters was found to be exceedingly simple and powerful. Quantifying the amount of canopy and its relative distribution within an overall bed area provides another dimension for tracking the abundance of kelp forests in Puget Sound, and would prevent a scenario like the one laid out previously where the decline of a kelp forest was missed due to only having data on the outermost extent.

The targeted case study looking at canopy metrics at North Beach showed that when survey conditions were in line with the guidance in Section 3.2, estimates of canopy area can be incredibly consistent (Figure 32). However, it was also found that the survey on September 30th, which occurred at a tide ~2 ft higher than those conducted on August 16th and 30th, only detected half of the total canopy area as the previous two surveys. Prior research on survivorship of bull kelp in Puget Sound found that the timing of senescence can vary from as early as mid-August in South Puget Sound (Berry et al., 2019) to early October elsewhere (Maxell & Miller, 1996). Anecdotal accounts of bull kelp forests at North Beach indicated persistence well into October (E. Bishop, pers. comm., August 2020), however the exact timing of growth and survivorship has not been systematically documented. Without more data on the annual cycle of bull kelp extent at this site, it is difficult to determine to the relative impact that seasonality and other environmental factors such as tide height had on the canopy area detected.

Conducting more repeat surveys at the same site over the course of a season would allow for further assessment of the error bars that should be assigned to these estimates. Computing the same metrics for canopy area and percent cover across all five sites showed that they are only moderately positively correlated, but that the correlation was not significant: $r(4) = .48$, $p = .41$

(Figure 31). Given anecdotal evidence and visual inspection of the survey imagery, this is not surprising. Kelp forests in Puget Sound exhibit an incredible amount of diversity in terms of their distribution and patch dynamics, with no two forests appearing exactly the same. This lends impetus to the need for calculating both metrics at each site, and the need for establishing long-term boundaries inside of which percent cover could be compared across years.

Supervised classification of the orthomosaics generated by UAV mapping is without a doubt a powerful tool for quantifying and characterizing the abundance of bull kelp within a forest. However, there are many methods to achieve this end, of which random forest is just one that is currently considered an advanced option. Other methods of classification should be applied to surveys of bull kelp in Puget Sound to assess which performs the best in not only the open water region of each site, but also the shallow subtidal where other vegetation is present. In the future, deep learning tools could also be applied to this purpose, and might obviate the need for manually delineating training data for each survey.

5.3 UAV mapping within context of Puget Sound monitoring

The final aspect of this project that bears contemplation is the role that UAV mapping could potentially play in the overall picture of ongoing bull kelp forest monitoring in Puget Sound. As was explored in the previous two sections, there are immense environmental and technical hurdles to cross in going from the capturing of aerial survey imagery to meaningful data products and metrics, and this limits the potential for these methods to be deployed in a widespread manner without significant resource investment and training of additional personnel. In the absence of that, this leads to the question of what is the most efficient and applicable uses of this technology given current resources and monitoring capacity (primarily as it relates to my ongoing work).

It was because of this question that the comparison of kelp bed perimeters from kayak-based surveys and hand-delineated imagery were originally performed, and the motivations for doing so were twofold. First, hand delineating the kelp bed perimeter for each survey is an incredibly efficient means of analysis compared to image classification and could be applied to many more sites in a given survey year. Showing that hand-delineations was an effective tool would therefore allow for the acquisition of data at more sites without creating an ever-growing backlog of unprocessed imagery. Second, if hand-delineation and kayak surveys were found to be sufficiently comparable, this would mean that the same data set could be populated using multiple methods. This would again enable broader monitoring coverage as different efforts could be spread out in the same time period.

Based on those motivations, the results of the analysis in Section 4.3 offer a promising initial result. Overall, bed area perimeters between methods were very comparable, with significant overlap in the boundaries and agreement as to the general shape and distribution of the kelp beds. Places where there was disagreement between the two methods most often appeared to be patches with low density in the imagery, where the exact distance between bull kelp individuals would be hard to distinguish from a kayak. Area calculations from both methods at all five sites showed that there was general agreement in terms of broad scope, but far less consistency when it came to detailed looks at each site (Figure 38). North Beach was the closest with imagery delineation equaling 109% of the kayak-based perimeter, but results at the other sites ranged from 67% to 145% between the same estimates. These result shows that refinement of one or both methods is probably needed to get them into better alignment.

In a more practical sense, the question of how UAV mapping fits into the broader ongoing efforts to monitor bull kelp in Puget Sound takes a different tack. Funding for science is always in greater demand than supply, and petitioning for additional resources to expand UAV monitoring efforts requires the presenting of strong tangible results and benefits. This project was graciously supported by WA DNR Nearshore Habitat Program staff with no additional external funding, and strong interest remains to continue developing this work. However, different applications require different tools, and it may be the case that UAV mapping has more applicability for conducting focused research projects at certain priority sites than it does for widespread monitoring, where other methods such as manned fixed-wing aerial photography and boat-based methods would be better suited.

5.4 Potential future research directions

This project pioneered the use of low-cost UAVs for mapping bull kelp forests in Puget Sound, and as such raised many more questions than it answered. As such, there are many potential research topics that could be explored further that would greatly enrich the field of UAV mapping as it applies to marine vegetation and challenging environmental conditions.

The first research project that comes to mind as a pressing need would be a focused investigation of the role of tides and currents on the appearance and estimated size of kelp forest canopies. The only in depth study addressing this question is Britton-Simmons et al. (2008), which quantified these (significant) impacts in the San Juan Islands using oblique photography captured from shore. Cavanaugh et al. (2021) also looked into this question using UAVs in southern California and found that small changes in current resulted in dramatic changes in canopy area, albeit with regard to giant kelp in a different current regime. A study that captured

UAV surveys at one of more sites in Puget Sound repeatedly over the course of multiple tide-series could do a lot to advance our understanding of how kelp canopies in this region can change in relatively short periods of time.

Another research topic that this project revealed to be ripe for focused investigation is the use of various classification tools on kelp forest surveys. This project only utilized one tool – the random forest classifier – based on initial testing, but there are numerous that could prove to be better suited to this task. One example of a different approach would be to use spectral indices rather than supervised classification to identify kelp plants. This was tested briefly in the development of this project and found to be less reliable – spectral indices typically perform better on multispectral imagery (Cavanaugh et al., 2021) – but there are many potential indices that have yet to be tested that could yield interesting results. There also are a multitude of other machine learning classification tools including support vector machine, and deep learning models that have yet to be widely deployed on the classification of bull kelp forest canopies. Comparing any number of these methods to each other on the same imagery would provide greater insights into how these tools work and which are best suited to this task.

These are just a couple relevant examples, there are yet more research topics that could be explored as well in the field of UAV mapping of kelp forests including the use of multispectral imagery platforms (this is currently being researched at WA DNR and initial results should be published soon), more in depth quantifications of distributional dynamics within individual kelp beds, differences in seasonality among bull kelp populations in different parts of Puget Sound, and many others.

6. Conclusion

Overall this thesis project demonstrated that consumer-level UAVs can in fact be deployed to reliably generate geospatially accurate and continuous orthomosaics of bull kelp forests in Puget Sound. Study design elements including the use of high accuracy (on the order of 10 cm) ground control panels, high image overlap flight settings (75-80%), and conducting surveys during target environmental conditions (< +1.0 ft MLLW tide, < 45° sun azimuthal angle, calm sea state and clear skies, etc.; Section 3.2.1) all contributed to the successful refinement of the photogrammetric workflow (Section 3.3). Environmental conditions that strayed from these targets in one or more way were found to be a significant factor in whether survey orthomosaic were suitable for image analysis, with reasons such as low light conditions or extreme glare resulting in products that could not be used (Table 4).

Supervised image classification via an object-based random forest method was found to be a valid and effective means of quantifying and characterizing the floating kelp canopy present at each site, with one significant caveat. Accuracy assessments of the classified results found that within the overall area of interest at each site the random forest classifier exhibited mixed results (Table 5), often times resulting in accuracy values too poor to consider the product useable. However, by extending the shoreline mask an additional 5-40 meters off shore to isolate what was designated as the main subtidal region of each survey, the classified results significantly approved across all metrics to where the products could confidently be used to quantify kelp canopy.

The two metrics generated from the classified results of each survey were canopy area and percent cover. Comparing these results across all five study sites showed an extremely high degree of variability, and no significant correlation between the two (Figure 31). This confirmed observational findings that bull kelp forests in Puget Sound are incredibly varied in their distributional characteristics, likely due to the diversity in geography and oceanic conditions in the region. A targeted examination of these two metrics across three separate surveys at North Beach showed that when consistent conditions are met, kelp canopy metrics match. However, the third survey conducted one month later and at a tide height that was ~2 ft higher resulted in an estimate of canopy area that was half the other two. This latter analysis is not statistically robust, but indicates that further work on the impact to canopy area estimates of seasonality and other environmental conditions such as tides and currents is warranted.

Finally, a comparison of the kayak-based canopy perimeter tracks collected by WA DNR scientists at each site and an imagery-based hand delineated perimeter was conducted. The results of that comparison at each site showed that overall the methods agreed in terms of the overall shape and extent of the kelp forest at each site. However, low density patches of kelp that had distances between individuals close to the 20 meter threshold used in the kayak protocol were often the source of disagreement, and further methodological refinement of one or both methods should be explored to bring the estimates each generate into closer alignment.

There are many questions this project raised that future research efforts could investigate further. One such project would be a revisiting of the work conducted by Britton-Simmons et al. (2008) to quantify the impact that tide height has on the visible canopy area of kelp forests in Puget Sound. This work would be vital to informing the implementation of any long-term UAV mapping program, in that it would enable estimates generated across years to be confidently compared. Additional research topics that are ripe for further exploration include the efficacy of different imaging platforms (e.g. multispectral and hyperspectral) and classification techniques (e.g. spectral indices, support vector machine, deep learning tools), assessing the proper size threshold beyond which a kelp forest becomes too large to effectively map by UAV, and many more. It is my hope that these potential research questions continue to be developed and expanded, and that efforts to do so enrich the field of UAV mapping of nearshore habitats and marine vegetation. Bull kelp forests are a vital resource to all life in Puget Sound, and it will require sincere exploration of every science-based monitoring, management, conservation, and restoration avenue possible to ensure that they persist for future generations to enjoy.

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Appendix A: Survey Summary Table

Flight parameters

Date	Site Name	Altitude (m)	Area (ha)	Front overlap (%)	Side overlap (%)	Time Start	Time End
7/18/2020	North Beach	80	16.6	75	75	9:33	10:24
7/21/2020	Squaxin Island	80	15.53	80	75	11:31	12:26
7/30/2020	Squaxin Island	80	16.13	80	75	8:28	9:47
7/31/2020	Lincoln Park	80	12.03	80	75	8:59	9:55
8/3/2020	Hansville	80	12.98	80	75	10:13	11:07
8/7/2020	Lincoln Park	80	10.27	80	75	13:35	14:10
		80	10.27	80	75	14:27	15:05
8/15/2020	Vashon Island	100	26.39	75	75	9:00	10:05
8/16/2020	North Beach	80	16.6	75	75	9:08	10:06
8/17/2020	Hansville	80	12.4	80	75	8:59	9:39
8/28/2020	Squaxin Island	60	19.75	70	70	9:42	11:14
8/30/2020	North Beach	100	19.61	75	75	9:06	9:56
9/30/2020	North Beach	110	22.97	80	80	9:40	11:08

[continued on next page]

Environmental conditions

Date	Site Name	Tide station	Distance to Station km	Tide Start ft	Tide Start Corrected	Tide start Condition	Tide End ft	Tide End Corrected	Tide End Condition	Sun Angle Start deg	Sun Angle End deg
7/18/2020	North Beach	9444900 Port Townsend	3.8	-1.33	-1.37	rising	-0.78	-0.74	rising	37.8	45.9
7/21/2020	Squaxin Island	9446800 Dofflemeyer Point	3.0	-0.32	-0.14	falling	-2.06	-1.61	falling	55.4	61.1
7/30/2020	Squaxin Island	9446800 Dofflemeyer Point	3.0	-0.59	-0.20	falling	-0.80	-0.25	rising	25.1	38.4
7/31/2020	Lincoln Park	9446025 Point Vashon	5.6	-1.61	-1.25	falling	-1.25	-0.82	rising	30.5	39.7
8/3/2020	Hansville	9445526 Hansville	0.9	-1.15	-0.81	falling	-1.94	-1.63	low	41.8	49.5
8/7/2020	Lincoln Park	9446025 Point Vashon	5.6	0.78	0.61	falling	0.71	0.57	rising	58.3	56.6
		9446025 Point Vashon	5.6	0.80	0.70	rising	1.43	1.36	rising	55.3	51.3
8/15/2020	Vashon Island	9446025 Point Vashon	5.1	-0.31	-0.51	rising	0.56	0.37	rising	27.9	38.4
8/16/2020	North Beach	9444900 Port Townsend	3.8	-1.04	-1.02	rising	-0.37	-0.20	rising	28.7	37.8
8/17/2020	Hansville	9445526 Hansville	0.9	-0.80	-0.23	falling	-1.50	-0.83	falling	27.2	33.7
8/28/2020	Squaxin Island	9446800 Dofflemeyer Point	3.0	0.01	0.32	rising	3.21	3.41	rising	31.8	44.6
8/30/2020	North Beach	9444900 Port Townsend	3.8	-0.69	-1.17	rising	-0.32	-0.76	rising	25.4	33.1
9/30/2020	North Beach	9444900 Port Townsend	3.8	1.49	1.25	low	2.01	1.71	rising	22.7	33.1

Appendix B: Individual Survey Records

North Beach – 7/18/2020

Survey conditions

Survey date	July 18, 2020
Flight time	9:33 – 10:24 am (51 mins)
Area surveyed	16.6 hectares
Tide (predicted)	Start: -1.33 ft | End: -0.78 ft | Low: -1.39 ft @ 9:06 am
Tide (corrected)	Start: -1.37 ft | End: -0.74 ft | Low: -1.41 ft @ 9:06 am
Sun altitude angle	Start: 37.8° | End: 45.9°
Altitude | GSD	80 meters | 1.81 cm/pixel

General observations on weather conditions:

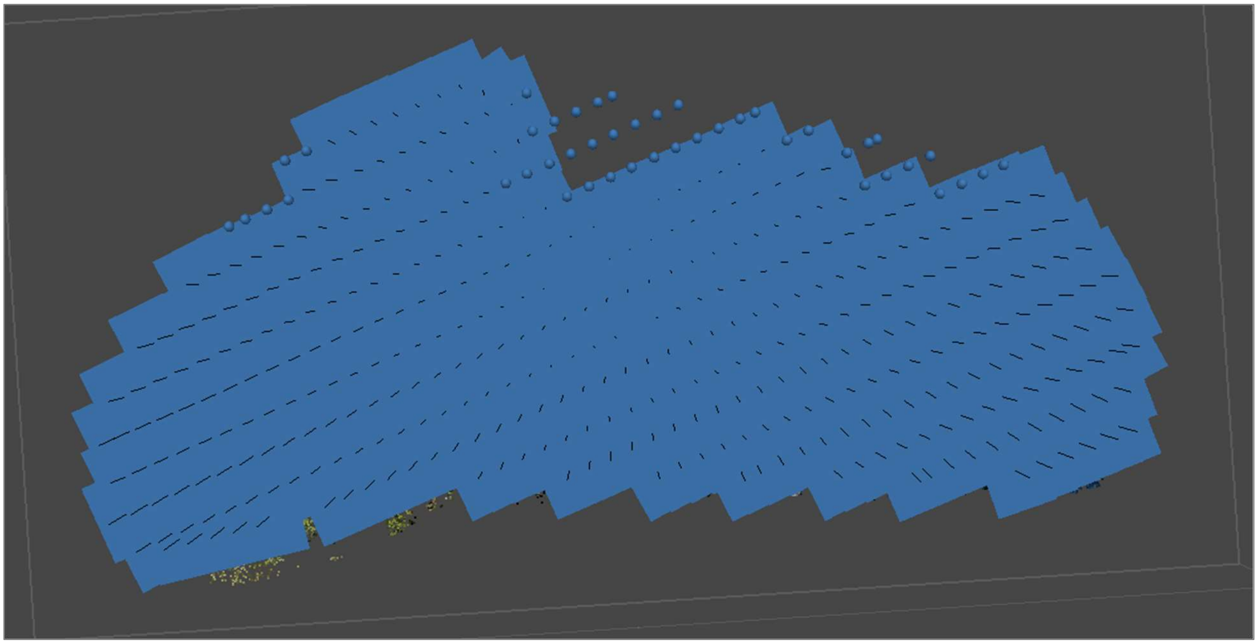
Conditions were very clear and calm overall. Some moderate wind, but no gusts.

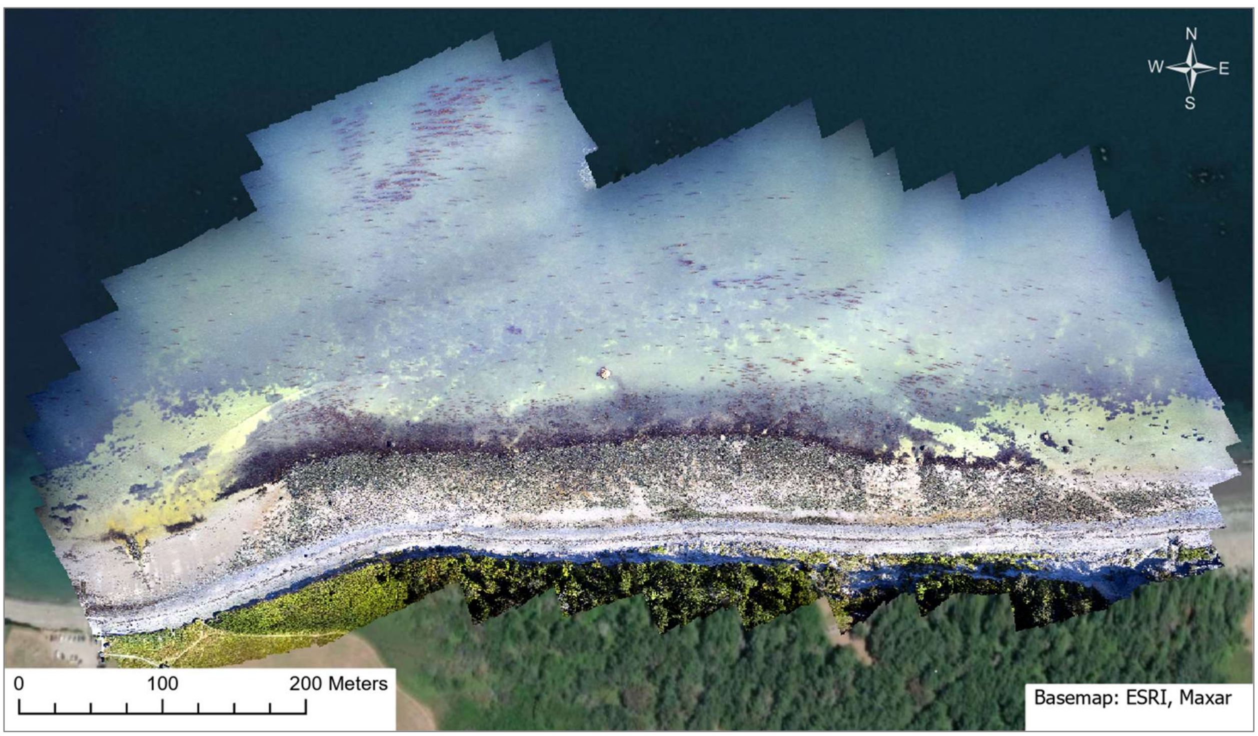
Imagery inspection

Inspection of the raw RGB imagery shows that there was:
- Good water clarity, moderate penetration to substrate in and around kelp bed
- High contrast between kelp and water
- Small patch of glare in the SE corner of imagery, impacts about ¼ of the image frame over water

Orthomosaic output

Initial photogrammetric results of this survey were very successful:
- 375 out of 419 images aligning (0 cameras disabled)
- High degree of fidelity to the regularly spaced survey grid
- Orthomosaic shows minimal distortions and almost no missing images

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Basemap: ESRI, Maxar

North Beach – 8/16/2020

Survey conditions

Survey date	August 16, 2020
Flight time	9:08 – 10:06 am (58 mins)
Area surveyed	16.6 hectares
Tide (predicted)	Start: -1.04 ft | End: -0.37 ft | Low: -1.13 ft @ 8:36 am
Tide (corrected)	Start: -1.02 ft | End: -0.20 ft | Low: -1.09 ft @ 8:36 am
Sun altitude angle	Start: 28.7° | End: 37.8°
Altitude | GSD	80 meters | 1.81 cm/pixel

General observations on weather conditions:

Conditions were very clear and calm overall. Light wind, no gusts.

Imagery inspection

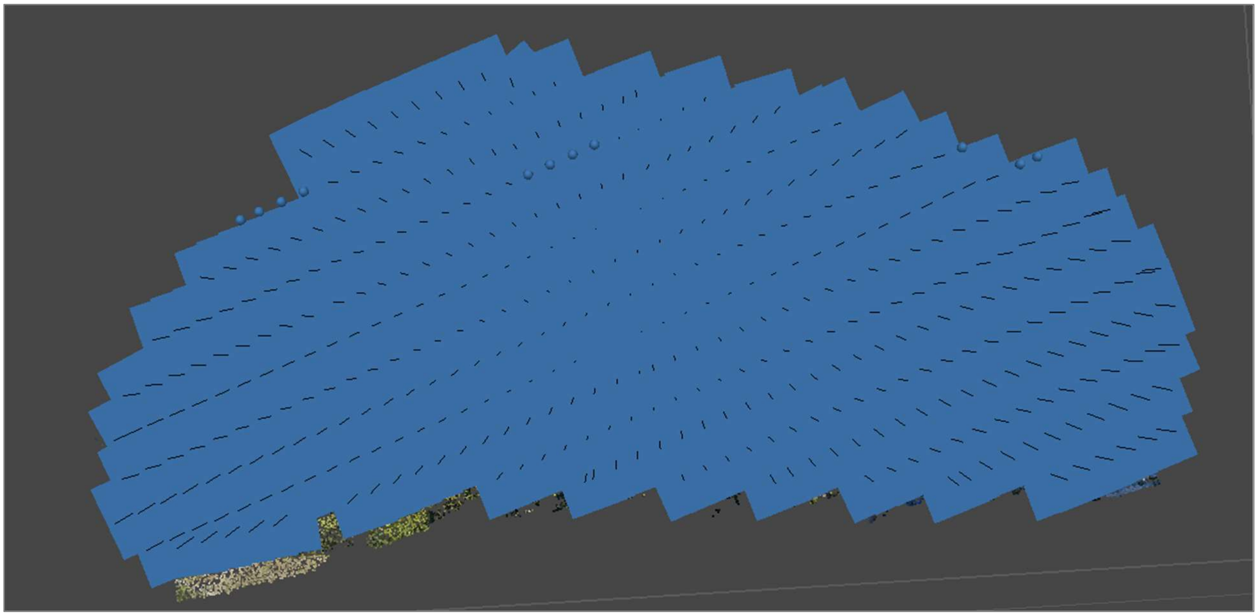
Inspection of the raw RGB imagery shows that there was:

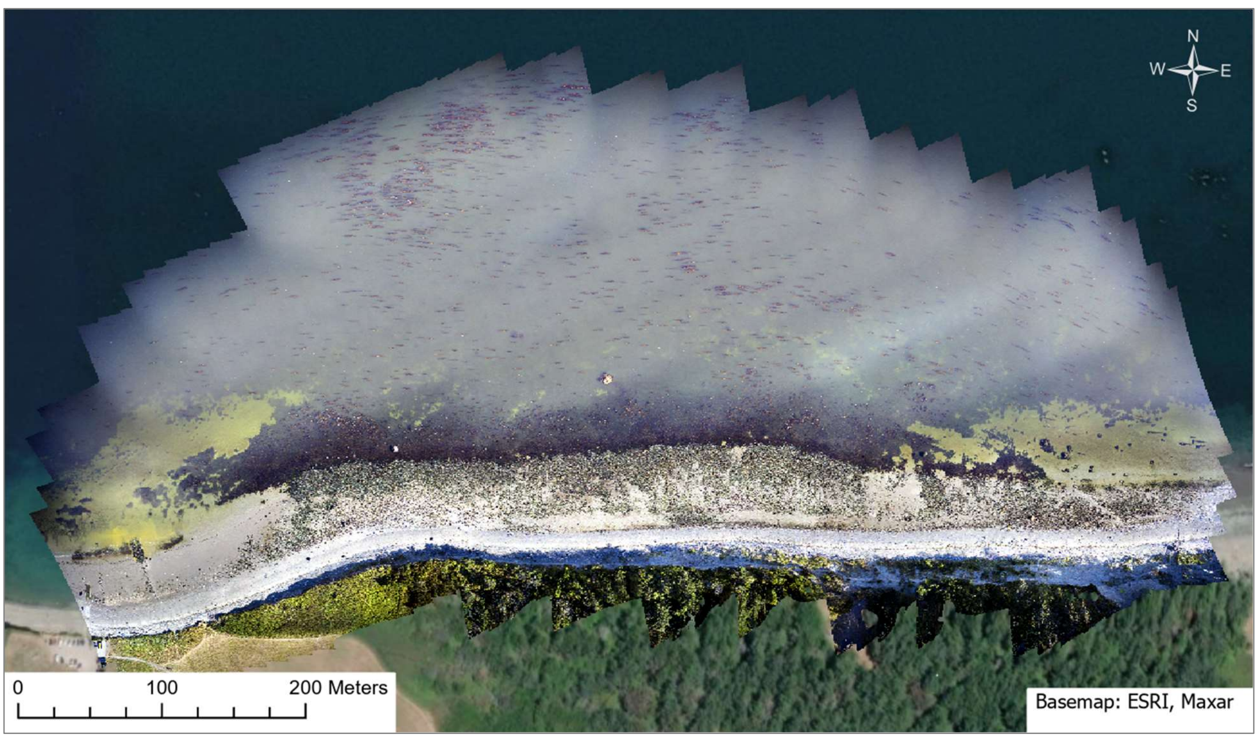
- Good water clarity, moderate penetration to substrate in and around kelp bed
- High contrast between kelp and water
- No glare, but rather a general flow from the SE corner

Orthomosaic output

Initial photogrammetric results of this survey were very successful:

- 409 out of 420 images aligning (0 cameras disabled)
- High degree of fidelity to the regularly spaced survey grid
- Orthomosaic shows minimal distortions and almost no missing images

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Basemap: ESRI, Maxar

North Beach – 8/30/2020

Survey conditions

Survey date	August 30, 2020
Flight time	9:06 – 9:56 am (50 mins)
Area surveyed	19.6 hectares
Tide (predicted)	Start: -0.69 ft | End: -0.32 ft | Low: -0.73 ft @ 8:48 am
Tide (corrected)	Start: -1.17 ft | End: -0.76 ft | Low: -1.22 ft @ 8:54 am
Sun altitude angle	Start: 25.4° | End: 33.1°
Altitude | GSD	100 meters | 2.26 cm/pixel

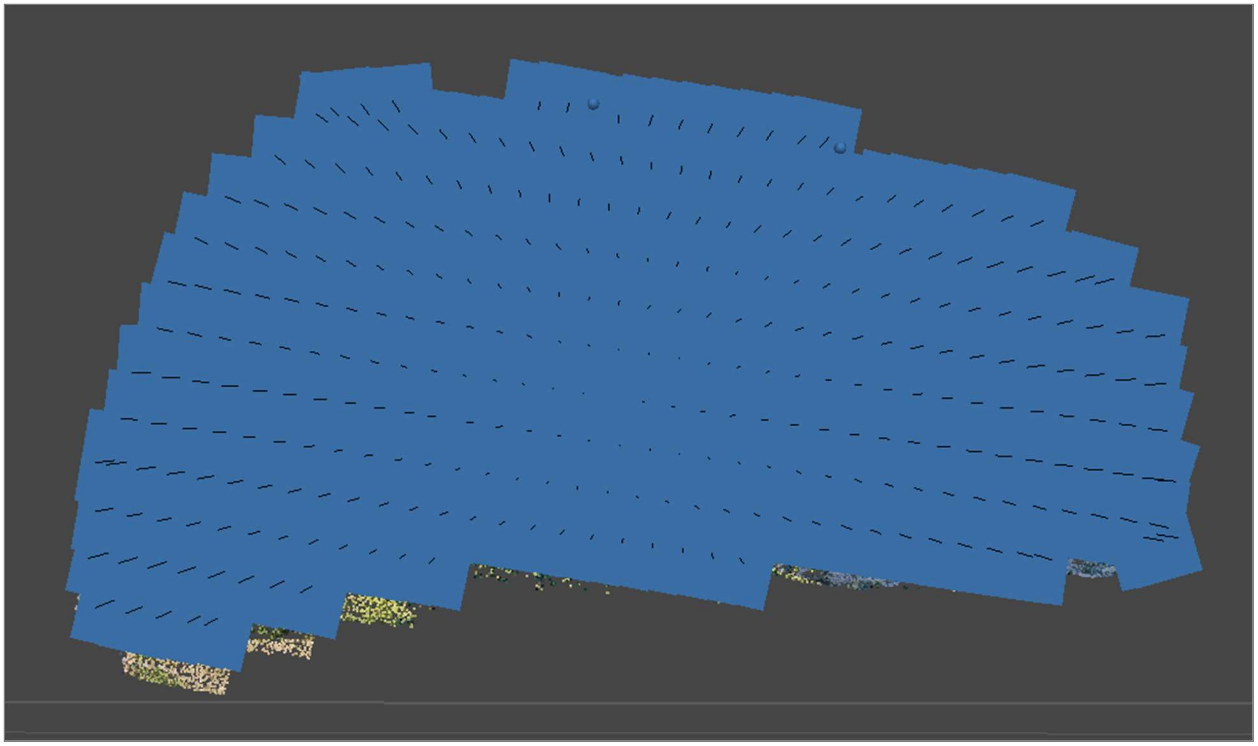
General observations on weather conditions:
Conditions were very clear and calm overall. Some moderate wind, minimal gusts.

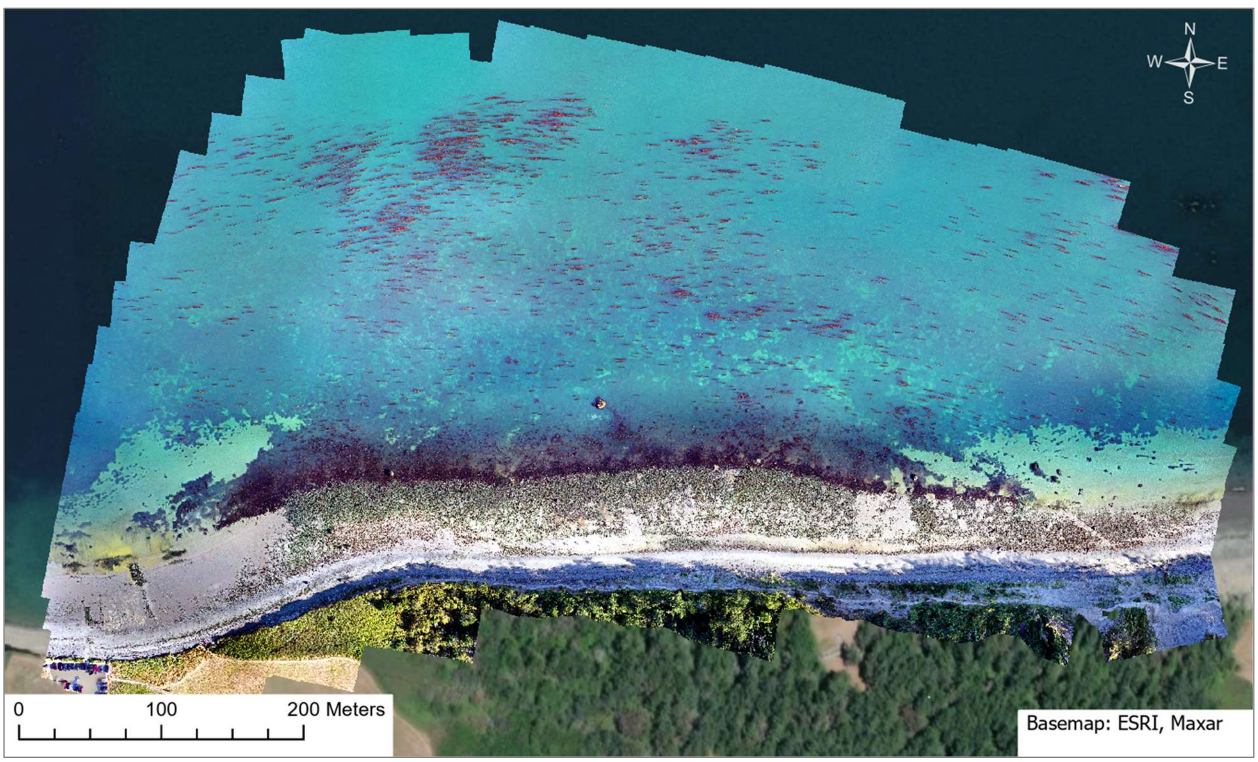
Imagery inspection

Inspection of the raw RGB imagery shows that there was:
- Superb water clarity, full penetration to substrate in and around kelp bed
- High contrast between kelp and water
- Very small amount of glare visible towards end of survey

Orthomosaic output

Initial photogrammetric results of this survey were very successful:
- 318 out of 320 images aligning (0 cameras disabled)
- High degree of fidelity to the regularly spaced survey grid
- Orthomosaic shows minimal distortions and essentially no missing images

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Basemap: ESRI, Maxar

North Beach – 9/30/2020

Survey conditions

Survey date	September 30, 2020
Flight time	9:40 – 11:08 am (68 mins)
Area surveyed	23.0 hectares
Tide (predicted)	Start: 1.49 ft | End: 2.01 ft | Low: -1.50 ft @ 9:48 am
Tide (corrected)	Start: 1.25 ft | End: 1.71 ft | Low: -1.22 ft @ 10:06 am
Sun altitude angle	Start: 22.7° | End: 33.1°
Altitude | GSD	110 meters | 2.49 cm/pixel

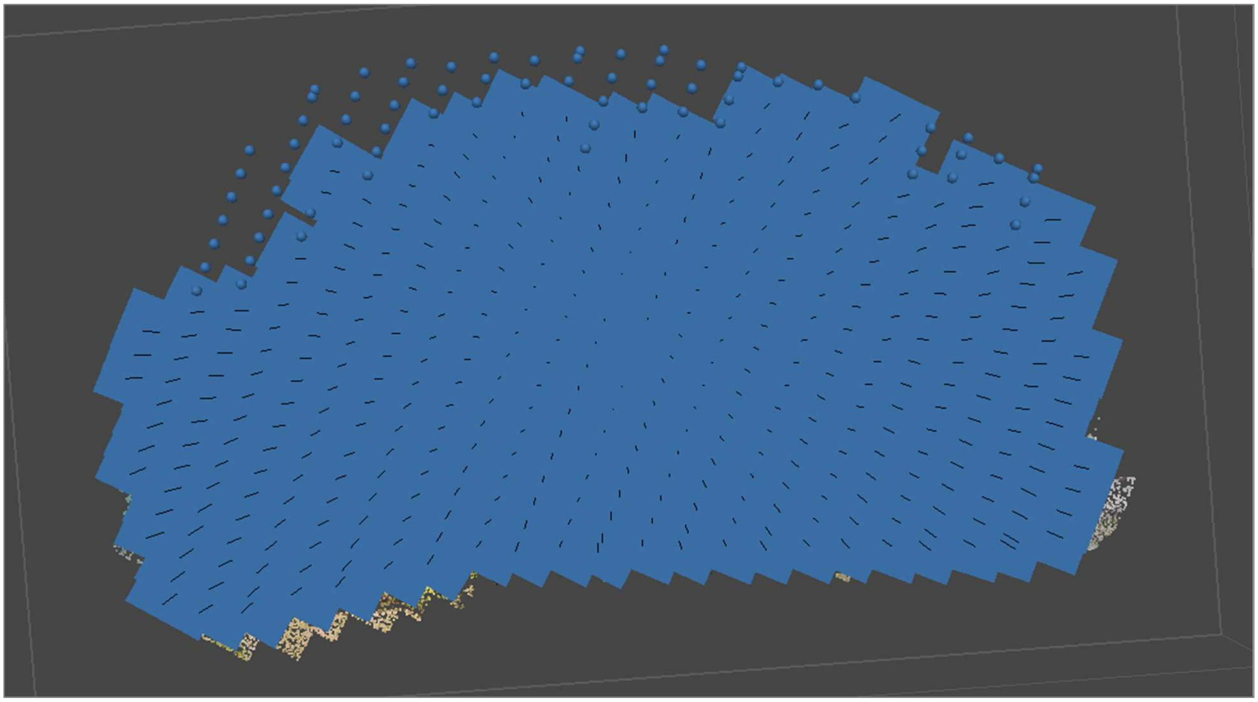
General observations on weather conditions:
Thick haze from wildfires in the air dimmed conditions. Sea state generally calm. Very minimal wind.

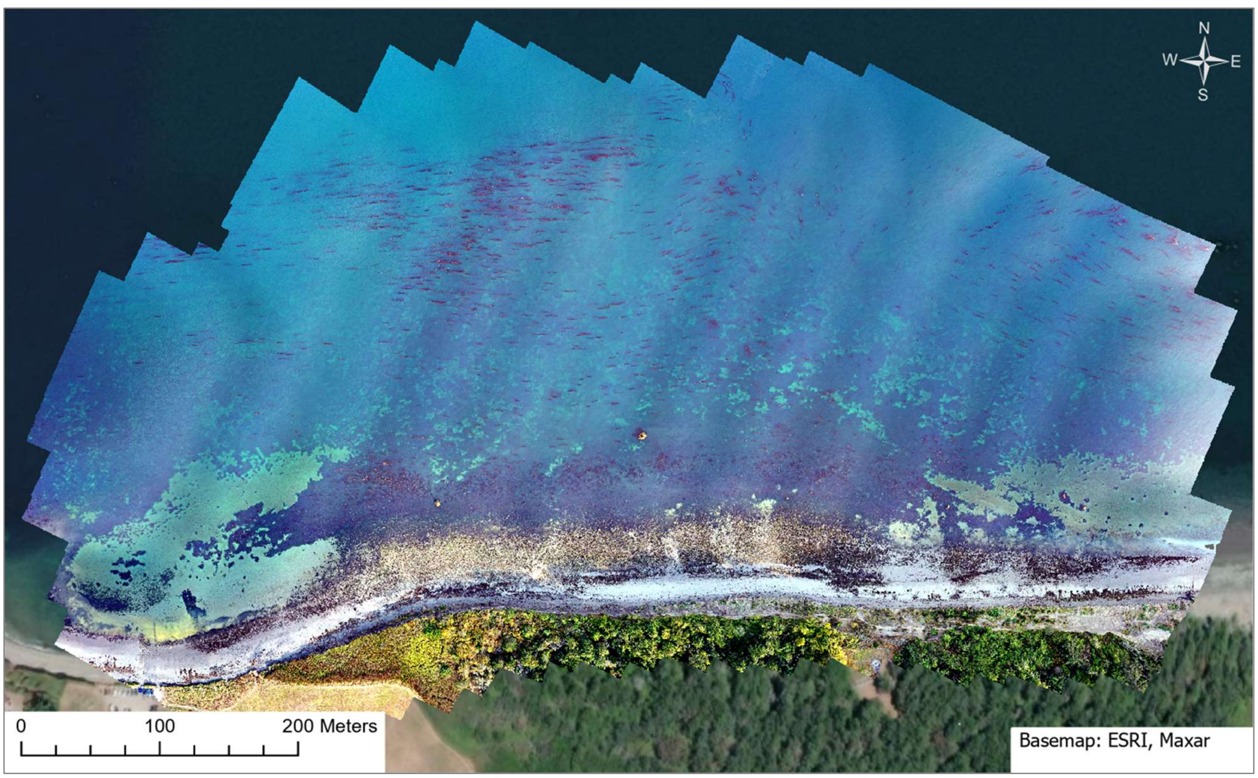
Imagery inspection

Inspection of the raw RGB imagery shows that there was:
- Good water clarity, moderate penetration to substrate in and around kelp bed
- High contrast between kelp and water
- No glare patch, but general haze effect in the SE side of imagery

Orthomosaic output

Initial photogrammetric results of this survey were very successful:
- 407 out of 477 images aligning (0 cameras disabled)
- High degree of fidelity to the regularly spaced survey grid
- Orthomosaic shows minimal distortions and few missing images, primarily at the outer edge

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Basemap: ESRI, Maxar

Squaxin Island – 7/21/2020

Survey conditions

Survey date	July 21, 2020
Flight time	11:31 – 12:26 pm (55 mins)
Area surveyed	15.5 hectares
Tide (predicted)	Start: -0.32 ft | End: -2.06 ft | Low: -2.99 ft @ 1:02 pm
Tide (corrected)	Start: -0.14 ft | End: -1.61 ft
Sun altitude angle	Start: 55.4° | End: 61.1°
Altitude | GSD	80 meters | 1.81 cm/pixel

General observations on weather conditions:

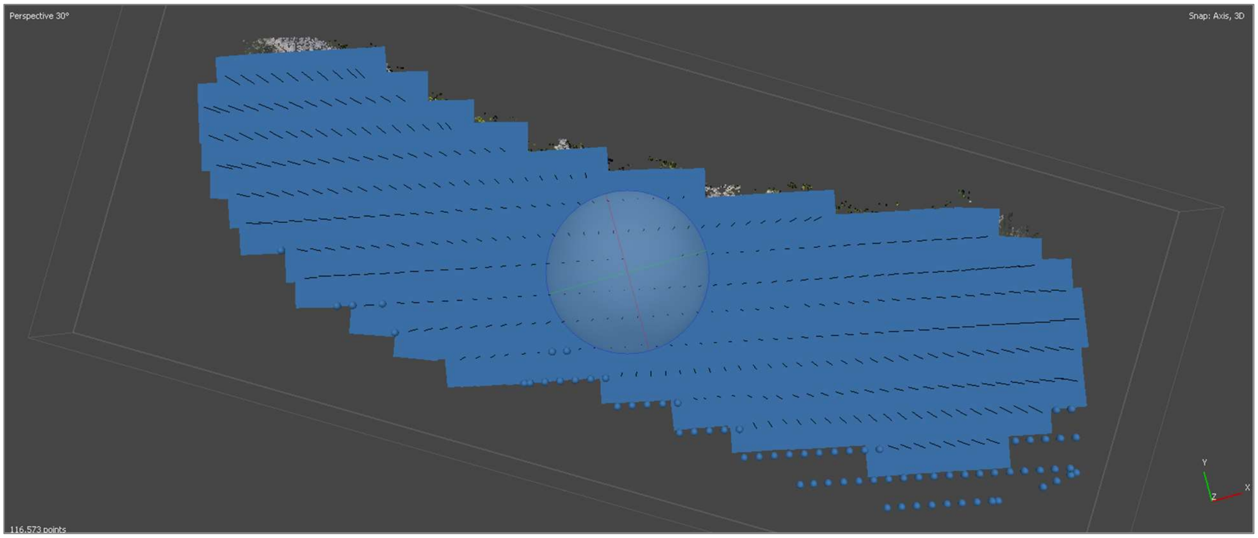
Overcast at start of the survey, slowly clearing throughout. Calm, minimal winds.

Imagery inspection

Inspection of the raw RGB imagery shows that there was:
- Good water clarity and penetration to substrate in and around kelp bed
- Moderate contrast between kelp and water
- Large glare patch dominating ¼ of the images and scattered glare over much of the rest.

Orthomosaic output

Initial photogrammetric results of this survey were mostly successful:
- 411 out of 484 images aligning (0 cameras disabled)
- High degree of fidelity to the regularly spaced survey grid
- Orthomosaic shows minimal distortions but some missing images



Perspective 30°
Snap: Axis, 3D
116,573 points

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Basemap: ESRI, Maxar

Squaxin Island – 7/30/2020

Survey conditions

Survey date	July 30, 2020
Flight time	8:28 – 9:47 am (79 mins)
Area surveyed	16.1 hectares
Tide (predicted)	Start: -0.59 ft | End: -0.80 ft | Low: -1.03 ft @ 9:13 am
Tide (corrected)	Start: -0.20 ft | End: -0.25 ft
Sun altitude angle	Start: 25.1° | End: 38.4°
Altitude | GSD	80 meters | 1.81 cm/pixel

General observations on weather conditions:

Overall a clear and calm day. Small amount of scattered clouds that cleared throughout the survey. There appeared to be a steady current for most of the survey, perhaps starting to reverse towards the end.

Imagery inspection

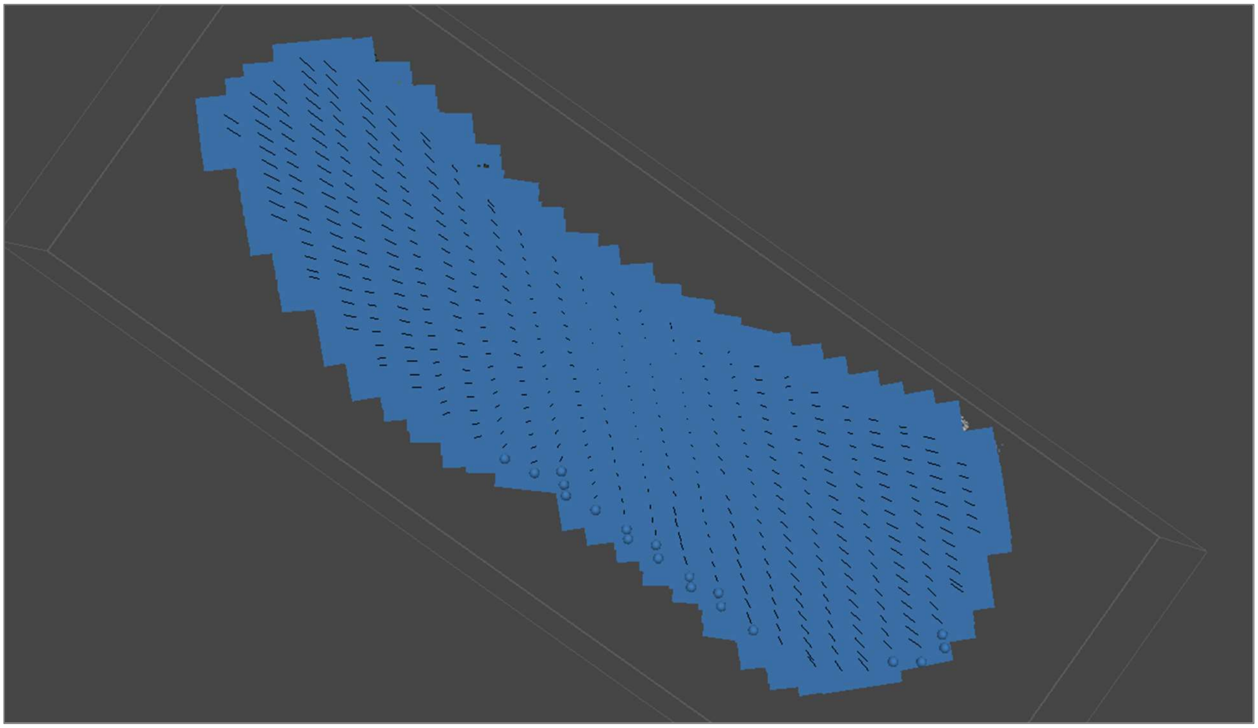
Inspection of the raw RGB imagery shows that there was:

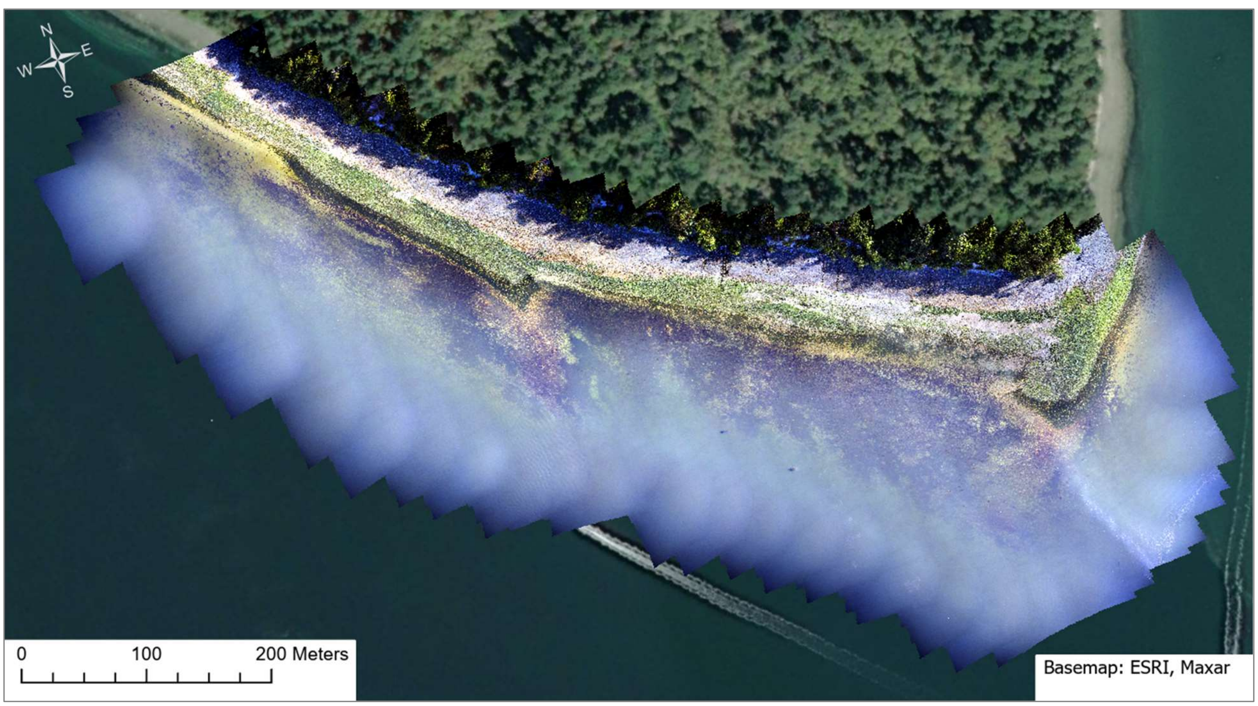
- Moderate water clarity, some penetration to substrate in and around kelp bed, less at deeper edge
- Fair contrast between kelp and water
- No patch of glare, more of a general haze in the imagery

Orthomosaic output

Initial photogrammetric results of this survey were very good:

- 489 out of 508 images aligning (0 cameras disabled)
- High degree of fidelity to the regularly spaced survey grid
- Orthomosaic shows minimal distortions and no missing images

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Basemap: ESRI, Maxar

Squaxin Island – 8/28/2020

Survey conditions

Survey date	August 28, 2020
Flight time	9:42 – 11:14 am (92 mins)
Area surveyed	19.8 hectares
Tide (predicted)	Start: 0.01 ft | End: 3.21 ft | Low: -0.56 ft @ 8:47 am
Tide (corrected)	Start: 0.32 ft | End: 3.41 ft
Sun altitude angle	Start: 31.8° | End: 44.6°
Altitude | GSD	60 meters | 1.36 cm/pixel

General observations on weather conditions:

Heavy fog prevented starting the survey at the preplanned time. Lifted approximately an hour after low and survey was started then. Mostly clear by the end of the survey. Light wind.




Imagery inspection

Inspection of the raw RGB imagery shows that there was:

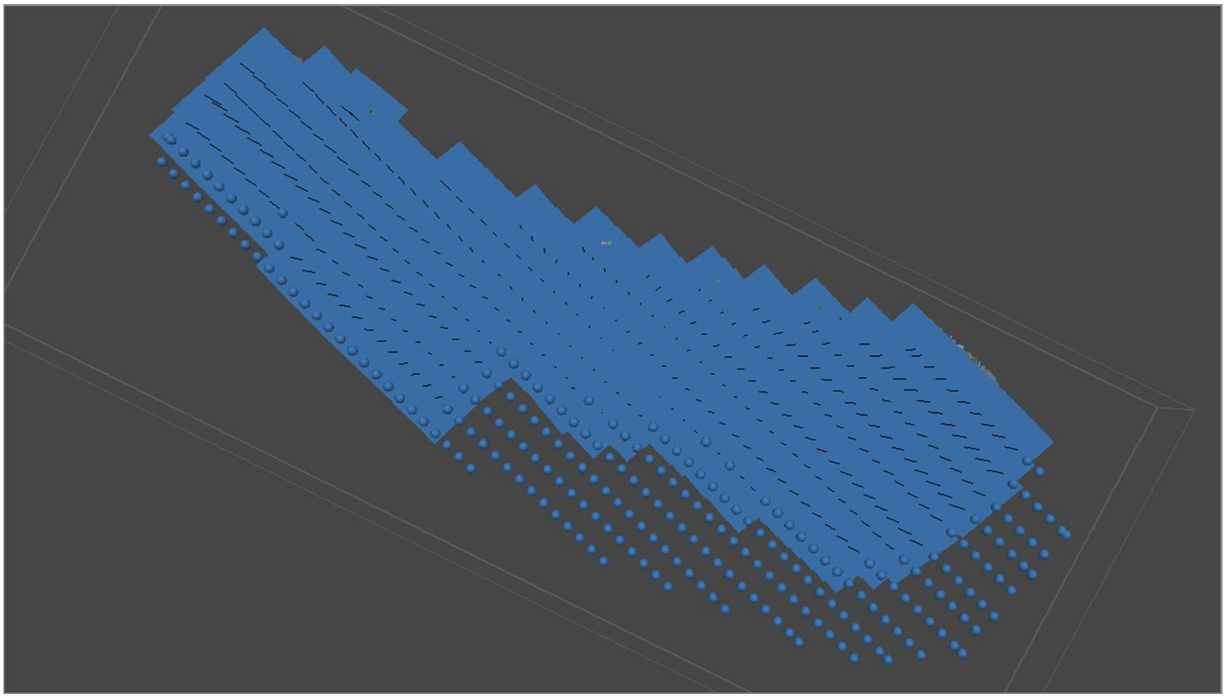
- Moderate to low water clarity, some penetration to substrate in and around kelp bed
- Poor contrast between kelp and water

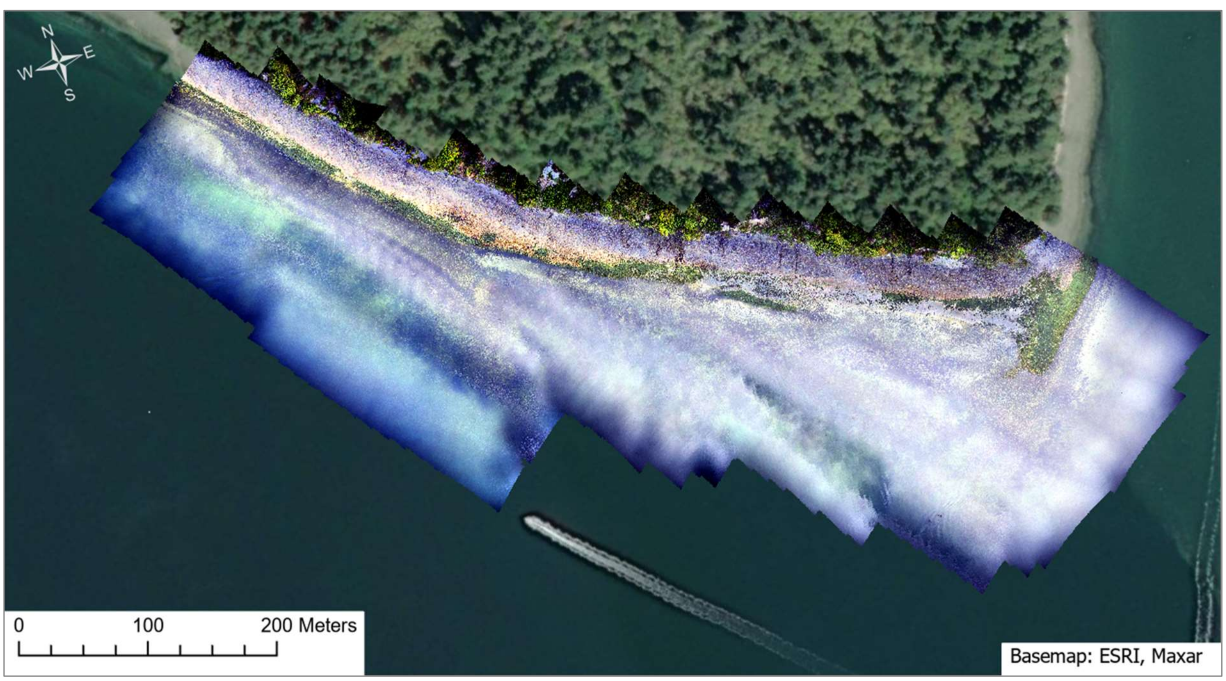
- Generalized reflection of cloud layer throughout imagery

Orthomosaic output

Initial photogrammetric results of this survey were mixed:

- 326 out of 550 images aligning (0 cameras disabled)
- Moderate degree of fidelity to the regularly spaced survey grid
- Orthomosaic shows minimal distortion but significant banding and missing images





Lincoln Park – 7/31/2020

Survey conditions

Survey date	July 31, 2020
Flight time	8:59 – 9:55 am (56 mins)
Area surveyed	12.03 hectares
Tide (predicted)	Start: -1.61 ft | End: -1.25 ft | Low: -1.62 ft @ 9:10 am
Tide (corrected)	Start: -1.25 ft | End: -0.82 ft
Sun altitude angle	Start: 30.5° | End: 39.7°
Altitude | GSD	80 meters | 1.81 cm/pixel

General observations on weather conditions:

Scattered clouds upon arrival, clearing up as the morning progressed. The beach area was heavily shaded from above south bluff with shadows impacting kelp canopy some.




Imagery inspection

Inspection of the raw RGB imagery shows that there was:

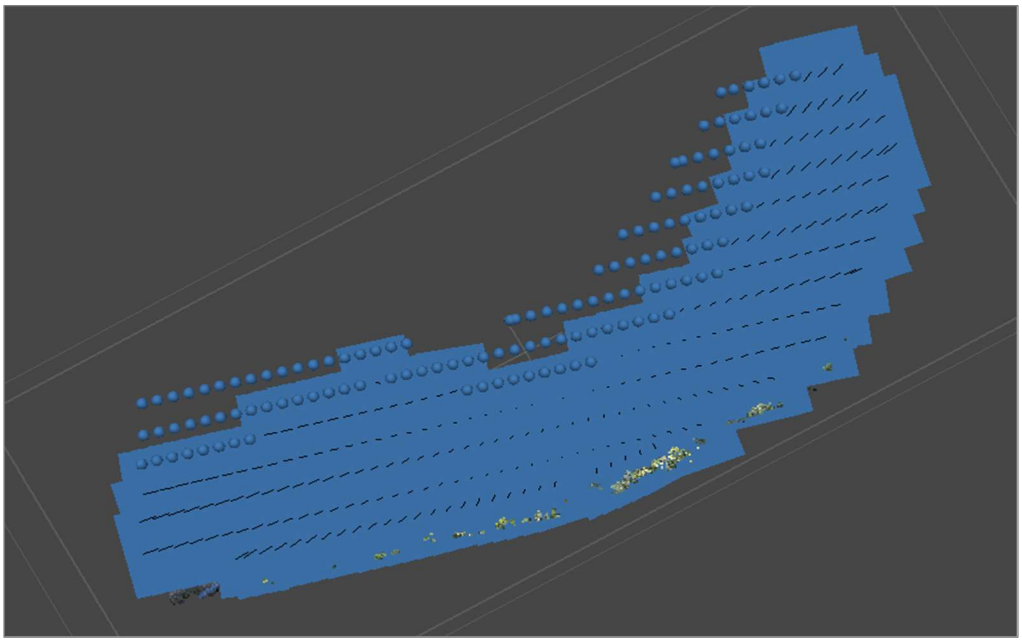
- Moderate water clarity and penetration to substrate in and around kelp bed
- Moderate contrast between kelp and water

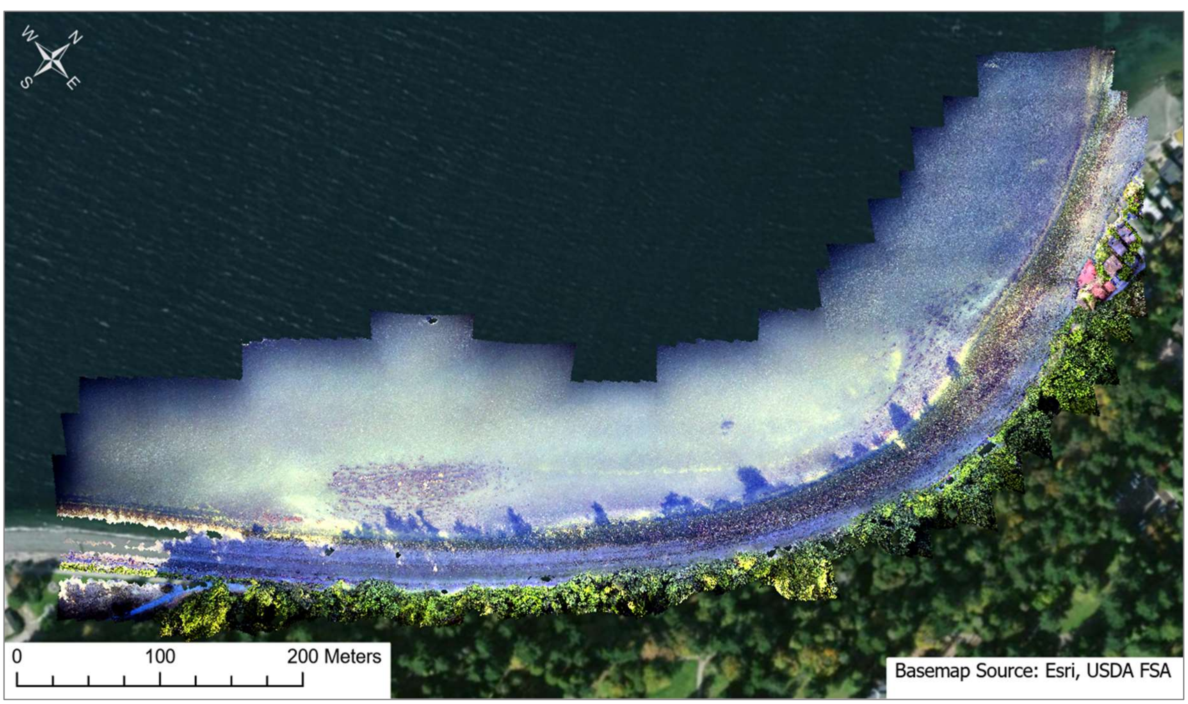
- Some diffuse glare in the SE corner of the imagery. Also long shadows cast by trees on ridge above the site.

Orthomosaic output

Initial photogrammetric results of this survey were mostly successful:

- 250 out of 379 images aligning (0 cameras disabled)
- High degree of fidelity to the regularly spaced survey grid
- Orthomosaic shows minimal distortions and missing images confined to area beyond kelp canopy





Lincoln Park – 8/7/2020 – Survey 1

Survey conditions

Survey date	August 7, 2020
Flight time	1:35 – 2:10 pm (35 mins)
Area surveyed	10.27 hectares
Tide (predicted)	Start: 0.78 ft | End: 0.71 ft | Low: 0.68 ft @ 2:00 pm
Tide (corrected)	Start: 0.61 ft | End: 0.57 ft
Sun altitude angle	Start: 58.3° | End: 56.6°
Altitude | GSD	80 meters | 1.81 cm/pixel

General observations on weather conditions:

Sky was mostly clear, and site was generally calm throughout the survey.

Imagery inspection

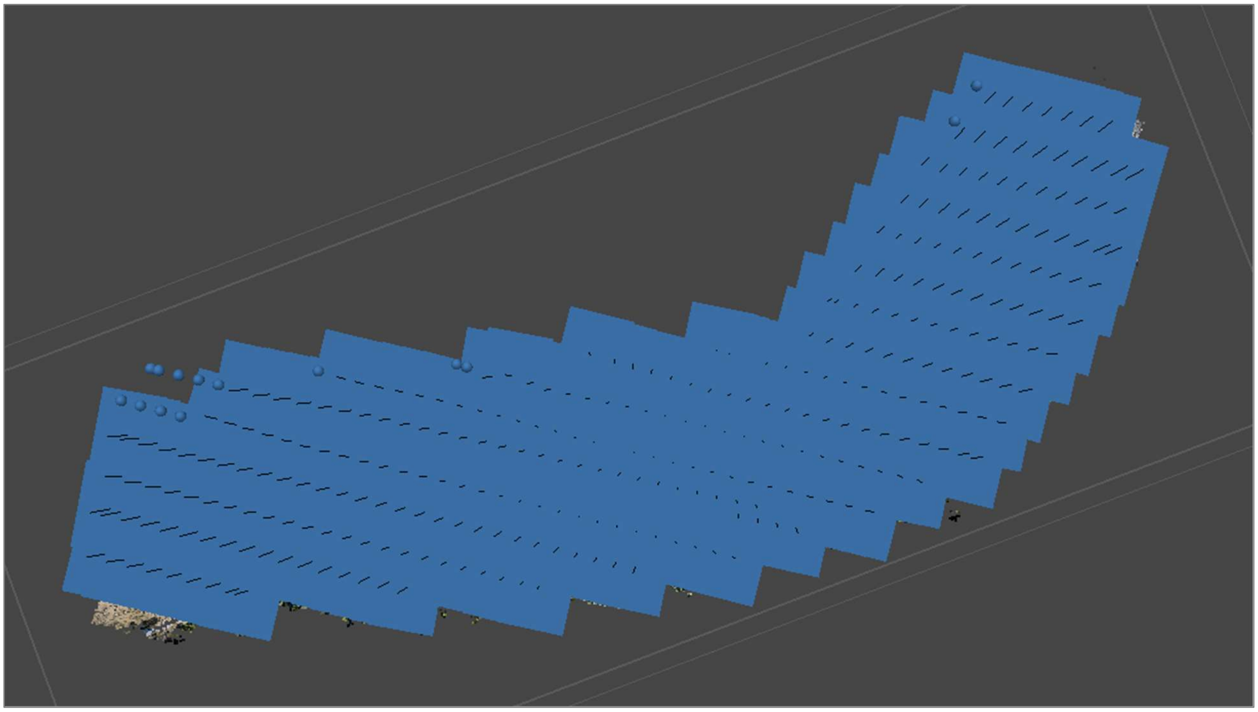
Inspection of the raw RGB imagery shows that there was:

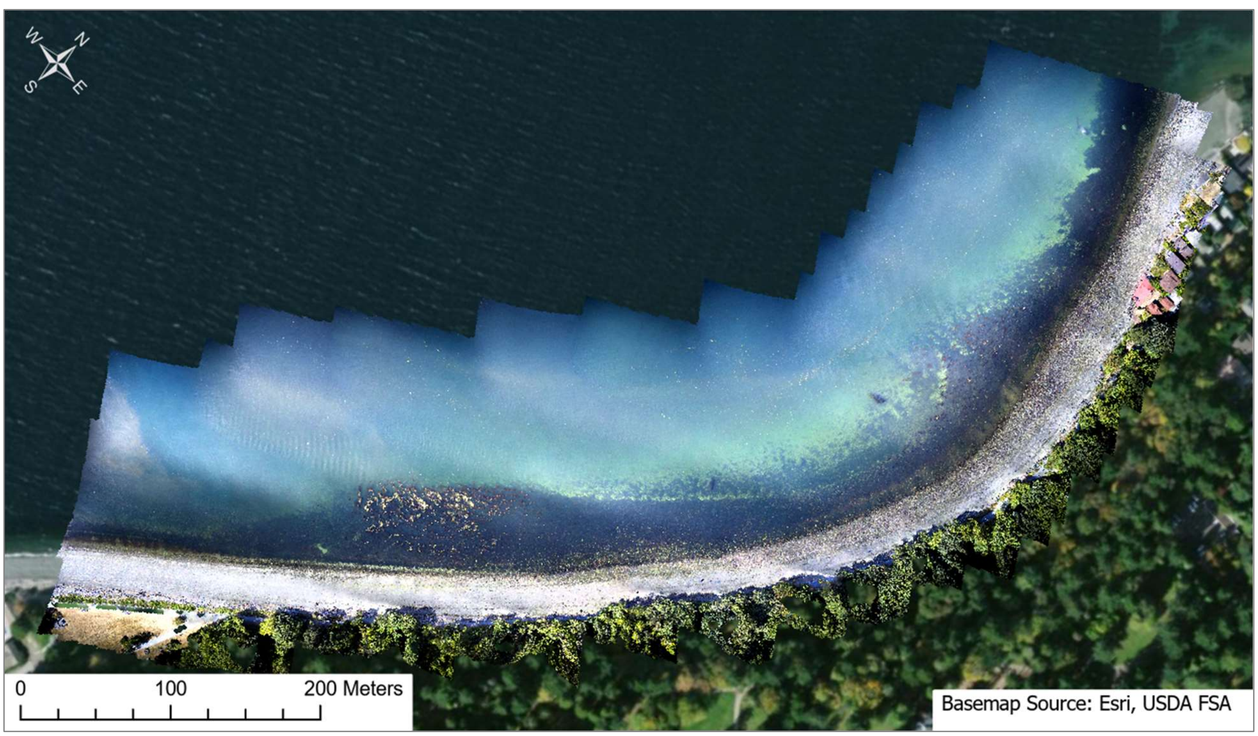
- Good water clarity, penetration to substrate in and around kelp bed
- Good contrast between kelp and water
- Large patch of glare in the SW corner of imagery but compact/confined, does not impact more than about 1/4 image

Orthomosaic output

Initial photogrammetric results of this survey were very successful:

- 313 out of 327 images aligning (0 cameras disabled)
- high degree of fidelity to the regularly spaced survey grid
- Orthomosaic shows minimal distortions and no missing images

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Basemap Source: Esri, USDA FSA

Lincoln Park – 8/7/2020 – Survey 2

Survey conditions

Survey date	August 7, 2020
Flight time	2:27 – 3:05 pm (38 mins)
Area surveyed	10.27 hectares
Tide (predicted)	Start: 0.80 ft | End: 1.43 ft | Low: 0.68 ft @ 2:00 pm
Tide (corrected)	Start: 0.70 ft | End: 1.36 ft
Sun altitude angle	Start: 55.3° | End: 51.3°
Altitude | GSD	80 meters | 1.81 cm/pixel

General observations on weather conditions:

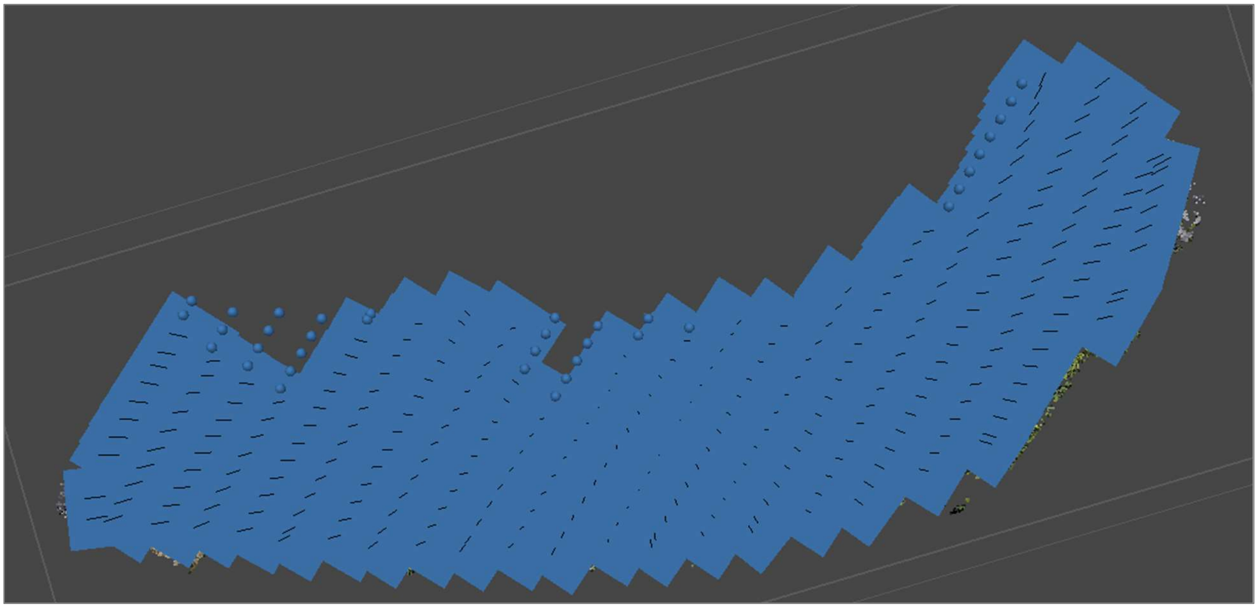
Some scattered clouds began encroaching on the site but otherwise conditions remained the same as previous survey earlier in the day: clear and calm.

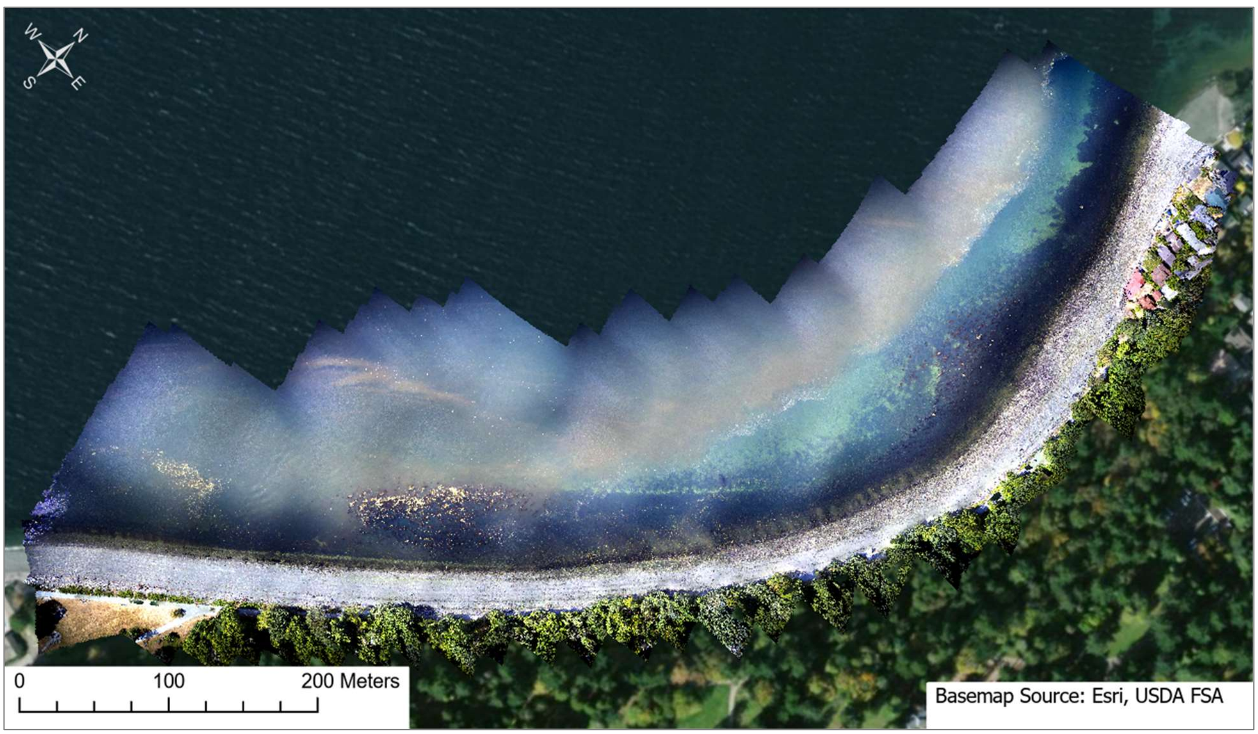
Imagery inspection

Inspection of the raw RGB imagery shows that there was:
- Good water clarity in nearshore, penetration to substrate in and around kelp bed
- Large turbid plume is pushing in to the site from the north as tide comes in. It is hitting the kelp bed to the SW of the site
- Good contrast between kelp and water overall
- Larger patch of glare in the SW corner of imagery but still compact/confined

Orthomosaic output

Initial photogrammetric results of this survey were very good:
- 297 out of 333 images aligned (0 cameras disabled)
- High degree of fidelity to the regularly spaced survey grid
- Orthomosaic shows minimal distortions and very few missing images

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Basemap Source: Esri, USDA FSA

Hansville – 8/3/2020

Survey conditions

Survey date	August 3, 2020
Flight time	10:13 – 11:07 am (54 mins)
Area surveyed	12.98 hectares
Tide (predicted)	Start: -1.15 ft | End: -1.94 ft | Low: -1.96 ft @ 11:16 am
Tide (corrected)	Start: -0.81 ft | End: -1.63 ft
Sun altitude angle	Start: 41.8° | End: 49.5°
Altitude | GSD	80 meters | 1.81 cm/pixel

General observations on weather conditions:
Site was overcast with somewhat patchy clouds at the beginning of the survey. Cleared significantly by the end. Light wind, no gusts.



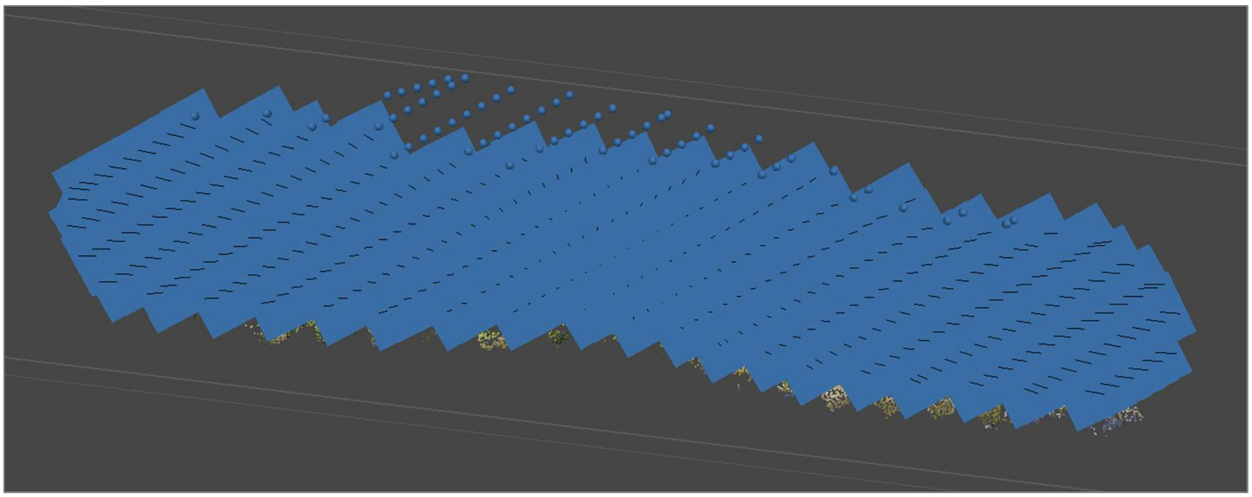

Imagery inspection

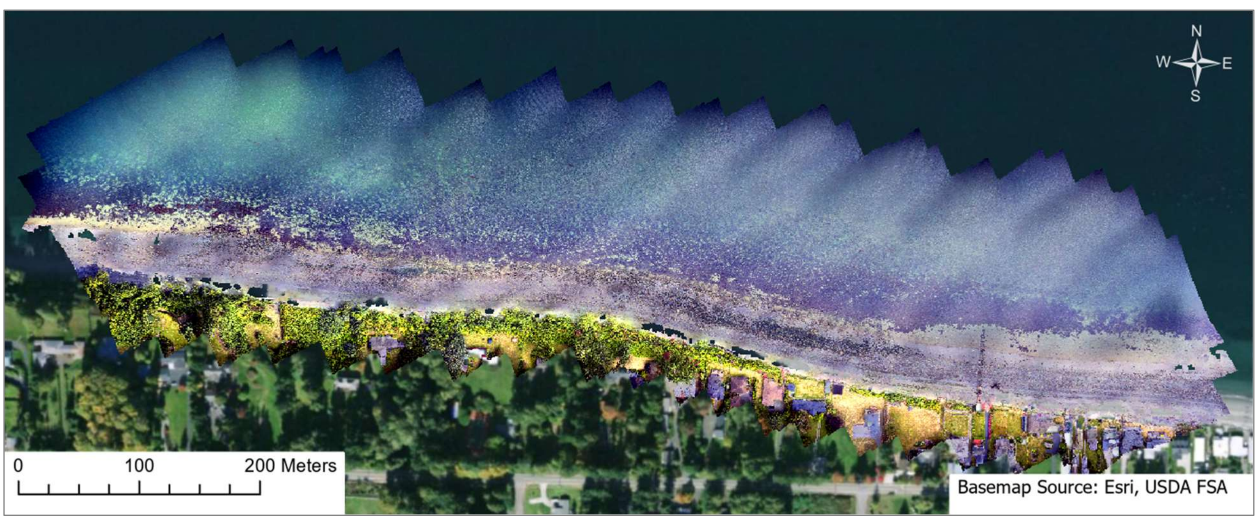
Inspection of the raw RGB imagery shows that there was:

- Good water clarity, moderate penetration to substrate in and around kelp bed
- Moderate contrast between kelp and water overall
- Diffuse glare throughout imagery, affecting at least half of each image

Orthomosaic output

Initial photogrammetric results of this survey were mostly successful:
- 348 out of 414 images aligned (0 cameras disabled)
- High degree of fidelity to the regularly spaced survey grid
- Orthomosaic shows minimal distortions, some missing images at outer edge





Hansville – 8/17/2020

Survey conditions

Survey date	August 17, 2020
Flight time	8:59 – 9:39 am (40 mins)
Area surveyed	12.4 hectares
Tide (predicted)	Start: -0.80 ft | End: -1.50 ft | Low: -1.67 ft @ 10:10 am
Tide (corrected)	Start: -0.23 ft | End: -0.83 ft
Sun altitude angle	Start: 27.2° | End: 33.7°
Altitude | GSD	80 meters | 1.81 cm/pixel

General observations on weather conditions:

Day was generally calm and clear. Minimal wind and no cloud cover. Tide did appear to change during survey.

Imagery inspection

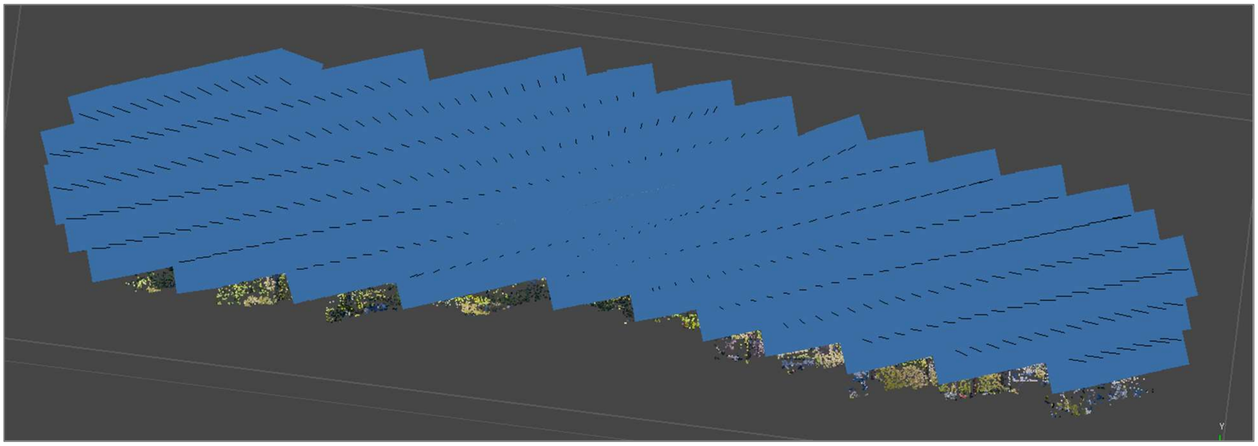
Inspection of the raw RGB imagery shows that there was:

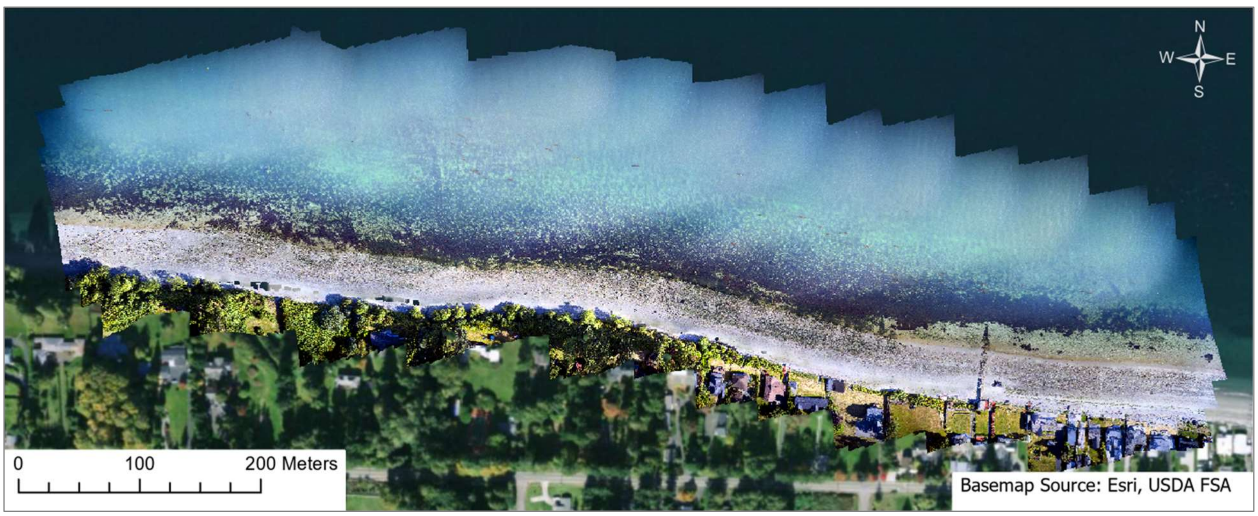
- Very good water clarity and penetration to substrate in and around kelp bed. Some glow effect within water column, possibly due to clear conditions
- High contrast between kelp and water in deeper water, less so in shallow
- Small amount of glare in the corner of imagery starting to encroach late in survey

Orthomosaic output

Initial photogrammetric results of this survey were very successful:

- 383 out of 383 images aligning (0 cameras disabled)
- High degree of fidelity to the regularly spaced survey grid (one survey line drifted off course, not immediately clear why)
- Orthomosaic shows minimal distortions and no missing images

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Basemap Source: Esri, USDA FSA

Vashon Island – 8/15/2020

Survey conditions

Survey date	August 15, 2020
Flight time	9:00 – 10:05 am (65 mins)
Area surveyed	26.4 hectares
Tide (predicted)	Start: -0.31 ft | End: 0.56 ft | Low: -0.33 ft @ 8:47 am
Tide (corrected)	Start: -0.51 ft | End: 0.37 ft
Sun altitude angle	Start: 27.9° | End: 38.4°
Altitude | GSD	100 meters | 2.26 cm/pixel

General observations on weather conditions:

Day was very calm and clear. Minimal wind.

Imagery inspection

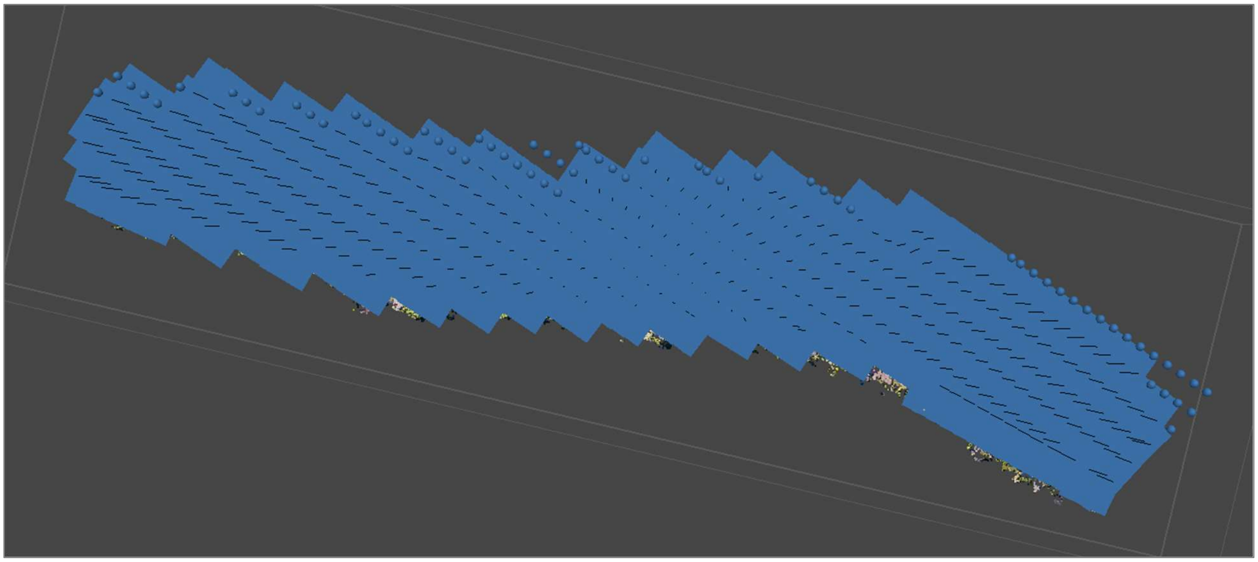
Inspection of the raw RGB imagery shows that there was:

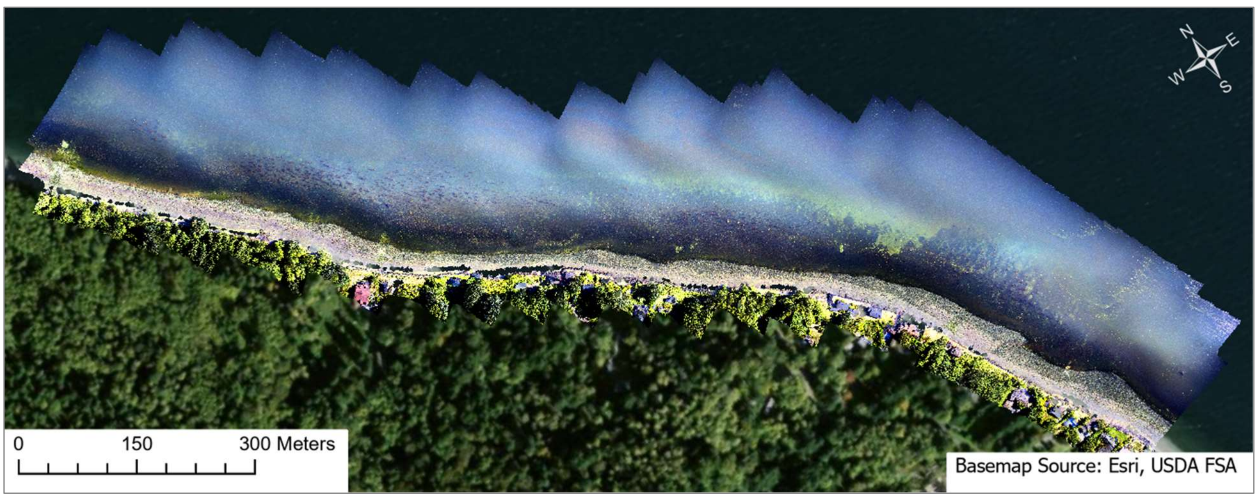
- Excellent water clarity and penetration to substrate in and around kelp bed
- High contrast between kelp and water
- Some glare in the SE corner of imagery, impact confined to less than ¼ of images
- Significant streaks in water column, possibly of algae. Algal bloom visible on surface

Orthomosaic output

Initial photogrammetric results of this survey were very successful:

- 363 out of 430 images aligning (0 cameras disabled)
- High degree of fidelity to the regularly spaced survey grid
- Orthomosaic shows minimal distortions, missing images confined to outer edge beyond kelp

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Basemap Source: Esri, USDA FSA