Master of Environmental Studies

The Evergreen State College
Graduate Program on the Environment
Thesis Prospectus

Name Tyler Cowdrey **ID Number** A00415406

Mailing Address 1919 Evergreen Park Dr SW Apt 89

Olympia, WA 98502

Telephone (847) 338 - 6753

E-mail cowtyl04@evergreen.edu

STUDENT AGREEMENT:

SIGNATURE: ______________ **DATE** 12/18/2020

FACULTY READER APPROVAL:

SIGNATURE: ______________ **DATE** ______________

MES DIRECTOR APPROVAL:

SIGNATURE: ______________ **DATE** ______________

1) Provide the working title of your thesis.

Mapping and characterizing the floating bull kelp (*Nereocystis luetkeana*) forests of Puget Sound using consumer-level unmanned aerial vehicle (UAV) based imaging platforms.

2) In 250 words or less, summarize the key background information needed to understand your research problem and question.

Bull kelp (*Nereocystis luetkeana*), a species of floating brown macroalgae, is an important primary producer in Puget Sound that serves a central role in local marine ecosystems. Among kelp's essential functions are the growth of vegetative tissues that provide a food source for a variety of grazers, the dampening of wave energy and slowing of coastal erosion, and the annual growth of "kelp forests" that serve as three-dimensional habitat for diverse species of fish, invertebrates, and marine mammals. Prior to the early 1990s there had been relatively few demographic or quantitative studies of the timing of recruitment, reproduction, and mortality of bull kelp within Puget Sound (Maxell and Miller, 1996), though in the decades since more research has been conducted on local populations (Duggins et al., 2001; Dobkowski et al., 2019; Weigel and Pfister, 2019)

The Washington Department of Natural Resources (DNR) Nearshore Habitat Program first conducted an inventory of floating kelp beds on the outer coast and in the Strait of Juan de Fuca using plane-based imagery in 1989 (Berry et al., 2005). These aerial inventories have been conducted annually in the years since, but do not extend south of the San Juan Islands (Van Wagenen, 2015). Recently, there have been growing concerns that bull kelp is declining in Puget Sound and DNR Nearshore has expanded its scope. Surveys of beds in South Puget Sound since 2013 have validated these concerns as significant decreases have been documented and a number of beds have disappeared altogether (Berry, 2017; Berry et al., 2019). Many gaps remain in the data on kelp distribution in Puget Sound.

3) State your research question(s).

Primary:

- Can imagery captured by consumer-level UAVs be processed to reliably generate geospatially accurate maps of floating bull kelp forests of Puget Sound? If so, with what environmental limitations/constraints?

Secondary:

- Is there a significant difference between the size and density estimates of bull kelp beds generated from orthoimages collected in the visible spectrum with an inexpensive Mavic 2 Pro compared to that collected in visible and near-infrared using a considerably more expensive Matrice 200 model carrying a Parrot Sequoia multispectral camera?
- What is the impact of the tidal height on the estimated size of bull kelp canopies generated from classified UAV orthoimagery? Does the magnitude of the impact depend on morphological characteristics of the kelp bed being surveyed? Can seasonal trends be isolated using time-series of variable tide-level surveys?
- Can a correlation be found between density estimates generated using orthoimage analysis and density estimates from WADNR's boat-based field collections?

4) Situate your research problem within the relevant literature. What is the theoretical and/or practical framework of your research problem?

Species of large brown macroalgae of the order Laminariales, also known as kelps, are important primary producers that inhabit temperate coastal ecosystems around the world. Forests of canopy-forming floating kelp provide many important functions to those ecosystems including the fixing of nutrients directly in vegetative tissues that serve as food for herbivores, the driving of secondary production as these tissues decompose (sometimes on an annual cycle), the dampening of coastal wave energy and tidal currents, the alteration of local seawater chemistry, and the formation of complex three-dimensional biogenic habitats for microbial communities, sessile animals, finfish, and marine mammals (Mann, 1973; Eckman et al., 1989; Steneck et al., 2002; Teagle et al., 2017; Pfister et al., 2019; Weigel and Pfister, 2019; Shaffer et al, 2020). Within the greater Puget Sound, floating kelp forests are abundant and composed of both giant kelp (*Macrocystis pyrifera*) and bull kelp (*Nereocystis leutkeana*), with the former being present exclusively in the Strait of Juan de Fuca and outer coast and the latter being present throughout the region including Puget Sound proper (Thom and Hallum, 1990; Mumford, 2007; Van Wagenen, 2015; Pfister et al., 2017).

Historically, there has been a recognition that kelp forests around the world occupy a narrow niche in nearshore coastal ecosystems and that they are vulnerable to deforestation due to disease, overabundance of herbivores, and oceanographic anomalies in temperature, salinity, or nutrient loading (Steneck et al., 2002). At the local region scale, Thom and Hallum (1990) completed a review of all historical data on bull kelp beds within Puget Sound dating back to

1912 and found that while there was a significant increase in forest extent overall (53% increase in shoreline length coverage in 1977 as compared to 1912), many small subregions had experienced substantial losses. Among the many possible causes of the variability in the kelp coverage the authors provided were changes in survey methodology and motivation, changes to the coastline and eutrophication from anthropogenic activity, competition with invasive species of marine vegetation, and inter-annual variation in kelp productivity. On the latter point, they (Thom and Hallum, 1990) note that surveys conducted in the Strait of Juan de Fuca by the Washington Department of Wildlife and Washington Coastal Kelp Resource map project in 1978 and 1989 respectively found a 42% difference in distribution, which likely was a combination of natural variation and differences in methodology. In addition, recent studies have shown that kelps may be vulnerable to the effects of climate change (Schiel et al., 2004; Harley et al., 2012; Krumhansl et al., 2016) and there have been multiple high profile cases of kelp forests experiencing dramatic mass mortality events due to ocean warming (Wernberg et al., 2016; Rogers-Bennet and Catton, 2019; Thomsen et al., 2019).

As discussed in question #2 above, the Washington Department of Natural Resources has had a program monitoring coastal kelp forests since 1989 using aerial photography, though these surveys only cover the Strait of Juan de Fuca and on the outer WA coast (Van Wagenen, 2015; Pfister et al., 2017). In order to assess the health of bull kelp beds within Puget Sound, WADNR has recently begun sub-regional scale studies of canopy area, density, and vegetation health via boat-based survey. These studies have revealed a worrisome trend of bed area reduction and multiple complete bed losses in southern Puget Sound (Berry, 2017; Berry et al., 2019). Between 2013 and 2018, four kelp bed sites ranging from less than a hectare to over eight hectares in South Puget Sound were surveyed (Squaxin Island, Brisco Point, Devil's Head, and Fox Island), and three of the four completely died off. Only Squaxin Island still remains and occupies about a third of its previous area. In total more than eight hectares of kelp canopy were lost in the five year span. These efforts are now expanding to Central Puget Sound and should yield results in the coming years. Paired with the evidence of the potential negative long-term impacts on kelp forests caused by climate change, these results provide a clear and urgent mandate to conduct annual monitoring of kelp beds throughout Puget Sound not only for the sake of scientific inquiry but also to better inform conservation efforts. This assessment is shared in the recently published *Puget Sound Kelp Conservation and Recovery Plan* (2020) – a collaborative effort by the Northwest Straits Initiative, NOAA's National Marine Fisheries Service, and WA DNR among others – which cites the current lack of a regionwide inventory of kelp forests as an impediment to efforts to conserve and recover bull kelp populations in the Sound.

Airplane-based aerial photography has long been an established method for obtaining monitoring data for marine vegetation (e.g. area, density, biomass, etc.) (Foreman, 1984; Deysher, 1993; Stekoll et al., 2006; Pfister et al, 2017; Orth et al, 2019). These methods provide high resolution data and can cover large geographic areas; they are also limited by the cost and expertise necessary to fly aerial surveys. As a result, a great deal of interest has grown in recent years around the idea of analyzing satellite data as an alternative method for regional long-term monitoring of coastal marine ecosystems. Recent studies comparing the latest advances in satellite data analysis with conventional methods of surveying kelp forests have yielded promising results (Cavanaugh et al., 2010; Cavanaugh et al., 2011; Bell et al., 2020; Friedlander et al., 2020; Mora-Soto et al., 2020), including multiple that focused on bull kelp in particular (Nijland et al., 2019; Schroeder et al., 2019; Hamilton et al., 2020). Despite these advances, limitations with satellite data remain namely the tradeoff between cost and resolution, and availability of imagery that meets necessary collection criteria (e.g. cloud cover, sun angle, etc.), and even the highest resolution satellites still can miss kelp beds that are very sparse and/or too close to shore (Schroeder et al., 2019).

Another alternative method that may complement the limitations of satellite imagery is the use of unmanned aerial vehicles (UAVs), commonly known as drones, to collect aerial survey data. The field of using UAVs for environmental monitoring is still a relatively new one, with significant improvements in the technology having been achieved in just the past ten years (Anderson and Gaston, 2013; Klemas, 2015; Turner et al., 2016; Colefax et al., 2017; Manfreda et al., 2018). UAV surveys have recently been implemented in a variety of coastal marine environmental monitoring applications related to seagrasses (Duffy et al., 2017; Ventura et al., 2018; Nahirnick et al., 2019), coastal wetlands (Zhou et al., 2018; Doughty and Cavanaugh, 2019), intertidal reefs (Murfitt et al., 2017; Collin et al., 2019), and algae blooms (Kislik et al., 2018; Taddia et al., 2019). In addition, multiple recent UAV-based studies have targeted species of brown macroalgae (Tait et al., 2019; Thomsen et al., 2019; Rossiter et al., 2020), including floating *Macrocystis pyrifera* giant kelp canopies specifically (Cavanaugh, 2020). To date, there appear to have been no published studies mapping the floating canopies of *Nereocystis leutkeana* using a UAV that this author was able to locate. However, the proliferation of recent UAV studies above strongly suggests that similar methods could be used to successfully survey bull kelp in Puget Sound. Given the urgent nature of the monitoring and conservation of the local bull kelp population, this tool could be an instrumental component in establishing ecological baselines and trends in the coming years.

5) Explain the significance of this research problem. Why is this research important? What are the potential contributions of your work? How might your work advance scholarship?

As can be seen in the section above, the field of UAV-based aerial monitoring of marine ecosystems is a nascent and evolving field of study. The promise of inexpensive (relative to manned flights) and easily deployable monitoring platforms is immense given recent advancements in UAV technology that enable precise flight planning, data acquisition in multiple spectral bands, and reliable structure-from-motion orthomosaic creation. All indications are that significant improvements in these technologies will continue to be made in coming years, for example with the price of hardware continuing to decline, machine-learning being implemented into post-processing software, etc., and the fields where UAV-based data collection could complement existing methodologies is ever-expanding.

Per the *Puget Sound Kelp Conservation and Recovery Plan* (2020), local populations of kelps are beginning to decline and at risk of much greater decline due to the impacts of climate change and anthropogenic development. The report lays out six critical modes of action that need to be taken including the creation and maintenance of a database of robust distributional and trend data on kelp populations, of which very little information is currently recorded. While there have been notable recent studies in the Northeast Pacific region investigating the monitoring *Nereocystis leutkeana* kelp using both satellite based data (Schroeder et al., 2019; Hamilton et al., 2020) and oblique on-shore photography (Britton-Simmons et al., 2008), as well as studies assessing the efficacy of UAVs in mapping *Zostera marina* eelgrass (Nahirnick et al., 2018) and *Macrocystis pyrifera* kelp canopies (Cavanaugh, 2020), there have so far been no published studies that this author could find marrying UAV imaging and bull kelp. This research could therefore serve as a foundational study in the use of UAVs to monitor bull kelp forests in Puget Sound and beyond.

In addition, this project could serve as an important benchmark in assessing the capabilities of inexpensive consumer-level UAVs as compared to their more expensive contractor-level counterparts. The agencies responsible for monitoring marine resources often have budgetary constraints on equipment purchasing that can inhibit their ability to fulfill their mandate. Quantifying the extent to which less expensive UAVs are able to achieve similar results could be useful to those working to enact programs that would monitor resources on a broader scale, say via the hiring of many seasonal workers to cover as large an area as little time as possible.

6) Summarize your study design. If applicable, identify the key variables in your study. What is their relationship to each other? For example, which variables are you considering as independent (explanatory) and dependent (response)?

<u>With regard to survey scheduling this summer:</u>
This study design encompasses a number of different research questions identified above. My sense of the ability to evaluate these questions within the time and resource constraints of the 2020 summer field season was a matter of constant discussion with the DNR Nearshore folks and informed when and where surveys were conducted. Given the novel territory we all were operating in, it was impossible to know whether any one question was the "most" answerable, or even the most pertinent to kelp monitoring via remote sensing imagery. For example, surveying the same site every day for a week straight *might* yield valuable data on the impact of tides beyond just surveying the same site at different tides throughout the summer, but it also might be an exercise in redundancy. Compounding on this uncertainty was the reality that there are precious few days in a given summer tide series that meet target conditions for both tidal height and sun angle (not to mention weather), so choosing to survey at one location was also necessarily a choice *not to* survey at another.

Over the course of the summer, the decision when and where to survey during each tide series was often made at the end of the previous one (a week or so out) based on the quality of data collected, the accessibility of the site, the characteristics of the kelp bed (some of these were being surveyed by DNR for the first time ever), travel logistics, etc. *Overall*, surveys were conducted in order to collect as much high quality data at each site as possible, and at a subset of about three to four sites enough times over the course of the summer to assess additional questions about tides and seasonality (among others). So, what I outline below is a breakdown of those various questions that I believe all of the data I collected will hopefully be up to the task of addressing.

<u>Proof of concept:</u>
The first question of my project is simply what *Nereocystis leutkeana* kelp bed canopy area and density estimates can be generated from the survey methodology I developed. In that regard, this research project is first and foremost a proof-of-concept that the methods employed in other UAV monitoring studies are applicable to the mapping of bull kelp canopies in Puget Sound. Initial efforts to apply photogrammetry software (detailed more in question 8) to my imagery appear promising and generated useable orthomosaics that can be analyzed. This step is currently the biggest hurdle to widespread use of UAV surveying technologies so if I can develop a reliable workflow this question will largely be answered. Image classification (again see question 8) is the final phase of the process and is a much more developed field, so while there will still need to be some investigation as to what index best separates kelp and water pixels in what conditions, whether it can be done at all is not really as much of a question.

Assuming this part of the project goes well, the imagery that I collect and analyze will become part of the record used by DNR staff to inform management decisions related to the nearshore environment and will hopefully serve as a basis for future UAV monitoring efforts.

Secondary questions:

If my methods work and useable data can be acquired pertaining to bull kelp canopy area and density using my UAV-based imagery, I am hopeful that the data I generate can be analyzed to begin to address a number of other as of yet unanswered research questions.

Comparison of RGB and NIR imagery:

On two occasions surveys were conducted concurrently in both RGB (red green blue) and NIR (near infrared) multispectral imagery. This was achieved by surveying in RGB with the Mavic 2 Pro (consistent with surveying procedures at other times/locations), and simultaneously surveying in NIR using WADNR's Matrice 200 carrying a Parrot Sequoia multispectral camera. To produce similar pixel resolutions in the data sets, the Matrice was flown at an altitude of only 50 m (as compared to 80 m with the Mavic), which had the added benefit of preventing mid-air collisions. Evidence of the simultaneous flights can be seen in a number of photos captured by the Mavic that show the Matrice flying below. Most of the studies I have come across thus far have employed only one or the other, so I will be interested in doing a comparison between the data generated by each given the same inputs. The amount of data to do this comparison is likely not enough for a statistical comparison, however a qualitative assessment could still be interesting.

Impact of tides:

The first additional question I'm interested in assessing is the impact that tide height (**independent**) has on apparent canopy area (**dependent**). It is well established that tidal current is lowest – a period known as slack tide – in the time immediately before and after the lower low tide in a semidiurnal tide cycle (Britton-Simmons et al., 2008; Berry et al., 2019; NOAA Tides & Currents). In addition, the level of said low tide varies on a daily basis, with differences ranging from 0.1 – 1.0 feet from one day to the next during a summer low tide series in Puget Sound (NOAA Tides & Currents). Therefore, one should be able to roughly isolate the impact of tide height on canopy area in the absence of tidal current by conducting surveys at the lower low tide on different days at a given site.

For a given low tide series, there will be on average ~10 days that meet the criteria of having a low tide that is less than the +1.0 m threshold identified by DNR in past monitoring efforts by at least 0.5 m (Pfister et al., 2017; NOAA Tides and Currents). Based on that pattern it should be feasible to visit multiple sites multiple times per tide series, however to hit the extreme low tide for each site that number is limited to two. As I outlined above, this summer I opted to visit multiple sites per tide series rather than the same site multiple days in a row. I am still hopeful that tide impacts can be assessed though perhaps not with as many other variables controlled as if I visited the same site multiple days in a row. One candidate site for answering this question is Lincoln Park, located near the Fauntleroy ferry terminal. This site was surveyed on 7/31 and 8/7 at tidal heights of -0.5 m and +0.25 m respectively. Over this short time window one would not expect significant seasonal variation so any differences should be attributable to tidal action.

Seasonal trend:

In an effort to assess seasonal trends in canopy area, multiple sites were surveyed during multiple low tide series from July through September. The pattern of low tides changes throughout the year, so surveys were initially expected to be conducted early in the summer that correspond to a similar low tide late in the season. For example, the extreme low tide at the Tacoma Narrows from September 20-29 was only approximately -0.23 m, whereas the series low on July 21 was -0.85 m. To survey at a comparable tide to the ones in Sep. during that July series, one would therefore need to survey three days before or after the extreme low. In theory, to evaluate canopy area or density (**dependent**) as a function of season change (**independent**), these tidal heights should be matched as closely as possible at time periods that are far enough so that a physical difference in growth would occur.

As the summer field season began it immediately became apparent that this level of control and planning was simply not possible while also trying to line up my surveys with DNR's kayak survey dates, and allowing for days when the weather did not cooperate (fog, wind, cloudy, etc.). That being said, five of the survey sites were visited multiple times during different tide series, and two of the other sites were surveyed at least a month apart. One example of a site with many seasonal observations is North Beach Park, which was surveyed five times from mid-July to late September). Of those, the surveys on 7/18, 8/16, and 8/30 all occurred at a tidal height of roughly -0.25 m, which could serve as a potential time series to assess seasonal change.

Other environmental factors:
There are a few of other factors I collected data on including wind speed, cloud cover, and turbidity. The collection methods for the first three are outlined more in the next section. These data were collected concurrently with UAV surveys in an effort to identify their impact on the quality of data generated. At this time there are no plans to attempt to correlate bed area with any of these parameters as tide height seasonality are predicted to be more significant, but other research has shown that things like sun glint and cloud reflection can complicate orthomosaic creation and image classification from UAV images (Nahirnick et al., 2018; Cavanaugh, 2020).

7) **Describe the data that will be the foundation of your thesis. Will you use existing data, or gather new data (or both)? Describe the process of acquiring or collecting data.**

The data I will be using for my project will be almost entirely new data in the form of aerial imagery of *Nereocystis leutkeana* kelp beds in Puget Sound. This data was acquired from July to September of 2020 by flying drone surveys over kelp beds that were selected in consultation with the DNR Nearshore Habitat Program and Aquatics GIS Unit, as well as the Northwest Straits Commission (which is involved in community monitoring of kelp beds in the northern Puget Sound and Strait of Juan de Fuca). From a list of potential sites, eight were selected based on airspace restrictions, accessibility, planning logistics, and characteristics of the beds.

The primary equipment I used to collect aerial imagery data for this study was my personal DJI Mavic 2 Pro, a quadcopter UAV that carries a Hasselblad L1D-20c camera with a 1" CMOS sensor capable of capturing 20MP RGB images. I also worked with DNR colleagues to fly concurrent surveys with their DJI Matrice 200 series carrying a Parrot Sequoia multispectral sensor on two occasions. I would have liked to have more surveys to compare the two data collection methodologies but there were limitations on equipment and personnel availability that prevented it.

Flight planning was done in a pair of flight planning applications. MapPilot was the primary application used in the Mavic surveys because of the many customization features it has that the competitors do not (linear flight planning, RAW image capturing, custom KML coordinate importing). DroneDeploy and Pix4D are also well-established options that were considered and tested but ultimately were deemed less suited for the purposes of this study. For the pair of flights utilizing the Matrice 200, DroneDeploy was used because it is the software my DNR colleague was most comfortable with. Every effort was made to ensure that the parameters of each matched prior to flying. Flight parameters that can impact the quality of data such as flight speed, altitude, image overlap, and custom camera settings were all set based on examples given in the literature above, with the intention of minimizing blur and maximizing coverage given battery constraints.

Other data that will be important to my analysis include tide height, sun angle, wind speed, cloud cover, and turbidity. The first two are available in public databases maintained by NOAA for the corresponding time and date of survey, and estimated tide height was also recorded on site using a mobile app for reference. Wind speed was collected in situ with a Vernier ANM-BTA Anemometer that was supplied by the Evergreen State College Science Support Center. Cloud cover will be estimated on an "okta" scale using photos of the sky that were taken in situ with my personal Nikon D5200 DSLR camera using a fisheye lens. Turbidity was collected by DNR Nearshore staff when they were conducting kayak surveys (for those dates they were present) using a standard sized marine Secchi disc, which is lowered into the water until it is no longer visible. This data is not available for all of the survey dates, so may not be used.

Finally, collecting data on water current was explored at the beginning of the summer. Britton-Simmons et al. (2008) identified rapid changes in current as being more significant than tide height in demining the canopy area seen from shore in the San Juan Islands, which gives impetus to the desire to conduct a like study. This unfortunately did not come to fruition. I was in contact with multiple companies that manufacture current meters (both acoustic doppler and analog impeller models) but they were too expensive for DNR to be able to purchase and deploy on such short notice.

8) Summarize your methods of data analysis. If applicable, discuss specific techniques that you will use to understand the relationships between variables (e.g., interview coding, cost-benefit analysis, specific statistical analyses, spatial analysis) and the steps and tools (e.g., lab equipment, software) that you will take to complete your analyses.

Analysis of the aerial imagery I collect can be broken into three rough categories: post-processing, image classification, and statistical analysis.

Post-processing:
The critical step in this process is the "stitching" of a single continuous orthorectified image from the 100s of individual images I collect during a survey. The current best practice for UAV image stitching is a photogrammetric technique called "surface from motion" (SfM). This method takes the position and orientation of images and pastes them together using tie points that are transformed into a dense point cloud. There are many companies that currently provide software capable of running SfM either on the cloud or on local machines including DroneDeploy, Pix4D Mapper, and ESRI's Drone 2 Map. The software that DNR has a license to is called Agisoft Metashape and runs on a high-end processing computer located at the Natural Resources Building. As part of my project I have been granted permission to use this license. There are many intricacies of using Metashape related to various input parameters, so I have been spending a great deal of time over the past couple months just learning to use it. I am anticipating that there is a great deal still to learn that I will be encountering as I process my imagery.

There are additional post-processing steps that can be run prior to or after SfM (e.g. spectral reflectance calibration, masking problematic pixels such as sun glint, etc.) that are too technical to detail here (and frankly I don't fully understand yet). There are many examples of these additional processes in the literature sources above that I will be mining for techniques in the near future.

Image classification:
This category of analysis deals with how pixels are differentiated from each other and classified into categories such as kelp, open water, rocks, etc. There are a myriad of ways to conduct this analysis in terms of both the spectral indices and classification algorithms used. Examples of different indices that have shown promise in marine vegetation classification are: normalized difference vegetation index, floating algae index, green NDVI, normalized difference red-edge blue, NIR/Blue, and many more. There are similarly many classification algorithms that have been employed: supervised classification, object based image analysis, threshold classification, multiple endmember spectral mixture analysis, etc. As with the additional post-processing steps, it is impossible to know now which of both of these methods will be most appropriate at this time, however given the depth of analysis using different methods in the available literature I am confident that there are many candidates that would likely yield good results.

Statistical analysis:
Once the UAV images have been processed, orthorectified, and classified, what I should end up with are maps of each survey showing pixels that were kelp, and those that were not. Using the resolution of the original images (or those used for processing if they are resampled) will allow me to turn that pixel ratio into estimates of both canopy area and canopy density over a certain range. These values can then be used in regression analysis with tide level and seasonality to determine how much variance each describes. T-tests and/or ANOVA can be run on the range of density values between different sites to determine if there is significant difference in their variance (my hypothesis would be that there is). Other analyses such as mixed effect models may be employed as well if there appears to be correlations with multiple parameters.

9) Address the ethical issues raised by your thesis work. Include issues such as risks to anyone involved in the research, as well as specific people or groups that might benefit from or be harmed by your thesis work, perhaps depending on your results. List any specific reviews you must complete first (e.g., Human Subjects Review or Animal Use Protocol Form).

Overall, I do not see many ethical issues raised by my project. It is an objective data driven investigation of the efficacy of using UAVs to map marine vegetation for the sake of well-informed future resource management efforts. There are a couple areas where ethics should be considered:

Transparency/public availability of results:
Since I am conducting this study in collaboration with the Washington Department of Natural Resources I have an obligation to the people of the State of Washington to make my results transparent and publicly available (given DNR channels) with regard to the portions of my research that relied on public resources.

Tribal sovereignty:
One of the kelp beds that is a candidate for my study is located just off shore at Squaxin Island, an island that is part of the territory of the sovereign Squaxin Island Tribe. DNR has conducted surveys at this location in the past so I relied on my colleagues there to determine the proper channels to seek approval to fly there. Overall, we were able to survey the site on three separate occasions, which was a great success. If the leadership and/or member of the Squaxin Island Tribe were interested in seeing my results or giving a presentation at some

point in the future I would certainly oblige.

Public nuisance:
The flying of UAVs in public areas has sometimes been a contentious issue with people feeling that they constitute a public nuisance and/or an invasion of privacy. From a legal perspective, the flying of a UAV in a public area where there are no airspace restrictions prohibiting flights is perfectly within the law so long as all other FAA regulations are followed. However, as someone representing the Evergreen State College and DNR, it was in my interest to minimize confrontations with disgruntled members of the public. Most of the kelp beds being considered for survey are somewhat remote so this helped to minimize contact. Some members of the public did make their displeasure known to me this summer, but for the most part the response from people I encountered was curiosity and excitement.

10) **List specific research permits or permissions you need to obtain before you begin collecting data (e.g. landowner permissions, agency permits).**

The primary license I needed to acquire was the FAA Part 107 Remote Pilot Certificate, which allowed me to fly in areas with advisory flight restrictions using the LAANC system. Getting this license requires taking a 60-question multiple choice test at a certified testing center. A couple of my sites had additional flight restrictions which necessitated giving advanced notice to air traffic control towers for local airports/airstrips, including the kelp beds near the Tacoma Narrows. I successfully passed my FAA exam in July prior to conducting my surveys.

Also, in order to survey the Squaxin Island bed I needed to be granted advanced permission by the Squaxin Island Tribe. My DNR colleagues have worked with them in the past so I relied on their past experience to inform how to go about this. This did turn out to be a limitation, and we were not able to visit the site as often as I had hoped. However, we were able to survey there on 3 separate occasions so I am very excited about that.

11) **Reflect on how your positionality as a researcher could affect your results and how you will account for this in the research process.**

This is something I need to spend more time considering in general. My initial reaction is that my project is driven by the collection of physical data, and that my results will speak for themselves in terms of the potential of the technology to be used as a long-term monitoring tool.

That being said, in a broader sense my positionality is that of a researcher who believes in the power of technology to tell us objective truths about the physical world that can then be harnessed to affect positive change in our relation to our environment. This perspective has driven me to pour myself into this project and to be hopeful of its potential results, but someone who holds a different worldview may not agree with my guiding premise.

12) **Provide at least a rough estimate of the costs associated with conducting your research. Provide details about each budget item so that the breakdown of the final cost is clear.**

This summer I spent ~$3,500 of my own money on this project. This included the cost of the drone and extra batteries (~$2k), various drone accessories including a hard case ($500), and iPad mini ($435), data storage media ($350), my FAA test ($160), and a fisheye camera lens ($135).

Not included in the above estimate is fuel/transportation costs. I estimate that I drove roughly 1,880 miles for my project this summer. At WA State's rate of $0.575 / mile, this works out to $1,083, that I am hoping to be reimbursed for (at least in part).

In addition to the costs I have already incurred, there is one additional item I am planning on applying for thesis funds to cover. This is the educational license of Agisoft Metashape which costs $549. I have access through this software through my colleagues at DNR but must travel to the Natural Resources Building to use it. Under normal circumstances this would be just inconvenient, but with COVID safety protocols in place it has actually been a pretty big impediment to me processing data faster (I must notify and get confirmation each time I want to travel there).

13) Provide a detailed working outline of your thesis.

I. Title
    Mapping and characterizing the bull kelp (*Nereocystis luetkeana*) forests of Puget Sound using consumer-level UAV imaging platforms.
II. Abstract
III. Table of Contents
IV. List of Figures
V. List of Tables
VI. Acknowledgements
    a. Erin Martin
    b. Helen Berry, WADNR Nearshore, WADNR AQR GIS folks
    c. Mike Ruth
VII. Introduction
    a. Kelps are a vital source of biogenic habitat around the world
    b. Bull kelp in Puget Sound is beginning to decline and at risk from climate change and human development. This creates a need for robust long term data collection on distribution and trends
    c. UAV technology is an exciting new frontier in image acquisition and presents many benefits over existing survey methodologies
    d. This project investigates the use of UAVs to map and characterize bull kelp beds in Puget Sound
VIII. Literature Review
    a. Bull kelp biology & ecology
        i. Life cycle, seasonal variation
        ii. Role as biogenic habitat creator
        iii. Other ecosystem services
    b. Climate change and anthropogenic impacts on kelps
        i. Known stressors that will be affected by climate change
        ii. Mass-mortality events
    c. Bull kelp in Puget Sound
        i. Historical distribution knowledge
        ii. WADNR aerial survey efforts
        iii. WADNR boat-based work
        iv. Conservation and Restoration Plan
    d. Remote sensing of marine vegetation
        i. Airplane-based
        ii. Satellite
    e. UAV imaging applications

i. Other marine vegetation: eelgrass, salt marshes, mangroves
ii. Kelps
f. Oceanographic characteristics and trends in Puget Sound
i. Behavior of tides in Salish Sea
ii. Seasonal changes in temperature, salinity, nutrients

IX. Methods
a. Field Location
i. Introduce the sites, describe why they were chosen
b. Field surveys
i. Equipment selection and setup procedures
ii. Flight planning applications
iii. Selecting tide and sun angle windows to fly
iv. Data management best practices
c. Photogrammetry and orthomosaic creation
i. Pre-processing / sun glint masking
ii. Software parameters
iii. Manual photo alignment
iv. Orthomosaic generation
d. Image classification
i. Choice of method (object-based, threshold analysis, etc.)
ii. Choice of spectral index
iii. Manual/supervised classifcation
e. Statistical analyses

X. Results
a. Efficacy of mapping bull kelp forests with UAV imagery
i. Conditions under which useable orthomosaics were able/not able to be generated reliably
ii. Distortions/artifacts due to surveying over water
iii. Other technical hurdles
b. Canopy area and density estimates for each site generated by UAV survey methodology
c. Differences between the characteristics of the different kelp sites (likely to be qualitative comparisons only)
i. Trends moving north to south in Puget Sound
ii. Implications for creating baselines at different sites
d. Comparisons of RGB and NIR imagery results
e. Impacts of tide height on canopy area estimates
f. Seasonal variation in individual kelp beds
g. Comparisons of density results from UAV survey to those from WADNR kayak surveys

XI. Discussion
a. Determine conditions that are most conducive to collecting high quality UAV imagery
b. Cost – benefit (like) analysis of UAV technology of different cost and sophistication for the purpose of collecting survey imagery
c. Assess the viability of establishing a widespread survey protocol for kelp forests around Puget Sound in order to create baseline and temporal datasets for conservation and restorations

XII. Conclusion

XIII. References

XIV. Appendices

14) Provide a specific work plan and a timeline for each of the major tasks in the work plan. Be as realistic as you can, even though you will probably need to alter this schedule as you complete the tasks. Remember that faculty readers take time to return your drafts and that the final polishing and formatting of your thesis for binding will take longer than you ever imagined.

Please see attached Gantt chart.

15) Who, beyond your MES faculty reader, will support your thesis? Indicate support both within and outside of Evergreen. Be specific about who they are and in what capacity they will support your thesis. If you are working with an outside agency or expert, be specific about their expectations for your data analysis or publication of results.

I am working closely with the WADNR Nearshore Habitat Program on my project. This team is headed up by Helen Berry. Her and the other members of her team provided invaluable support and insight earlier this year as I was refining the scope of my project and planning my surveys. I will continue to correspond with them as I work through the image processing phase of my project to determine which surveys to prioritize, and will likely work with them closely again when I begin analyzing potential correlations between my results and those of the kayak surveys they conducted.

Based on numerous discussions with Helen and her staff, the expectation they have of me is that my data and results will be available to them, and that I may assist in the drafting of a report of our combined efforts this past summer (if time/energy allows). We have an understanding that completing my project and graduating is the top priority, and have a good working relationship such that I don't foresee any issues working through what kind of products I can help them create later into my work.

I also have been working with Mike Ruth throughout the development and execution of my project. This has largely been due to our working relationship as I am the current GIS TA for his sequence. I anticipate continuing to rely on his expertise and feedback as I move through the image processing and classification phases of my project, though in an informal way. He does not have any expectations of me beyond continuing to act in my capacity as GIS TA and to be a fellow GIS nerd to discuss ideas with.

16) List the 3-5 most important references you have used to identify the specific questions and context of your topic, help with issues of research design and analysis, and/or provide a basis for interpretation. For each annotated reference, explain how your project specifically connects to the source by extending, challenging, or responding to the conclusions, methods, or implications. For any other sources cited in this document provide a complete bibliographic citation.

Berry, H., Calloway, M., & Ledbetter, J. (2019). *Bull Kelp Monitoring in South Puget Sound in 2017 and 2018.* Olympia, WA: Nearshore Habitat Program, Washington State Department of Natural Resources.

This report summarizes the findings of the WA Department of Natural Resources Nearshore Habitat Program in their study of the bull kelp beds in South Puget Sound over the past few years. Their findings show that a number of beds have declined precipitously or disappeared outright, and point to environmental factors such as water temperature, excess nutrient loading, and water current as potential sources for the declines. The authors of this report

conclude that much more research is needed to characterize the kelp forests of Puget Sound and monitor them for similar declines in order to prevent total extirpation in the future due to climate change and anthropogenic development. This research is the basis for my project existing at all and I have been working closely with the authors of this report on my project since about April/May of this year. They have been invaluable colleagues in helping me to select which kelp beds to survey and in designing my survey grids, among many other aspects of my project.

Britton-Simmons, K., Eckman, J.E., & Duggins, D.O. (2008). Effect of tidal currents and tidal stage on estimates of bed size in the kelp *Nereocystis leutkeana*. *Marine Ecology Progress Series, 355,* 95-105.

In this study, the authors investigated the impact that tidal height and currents had on the apparent size of bull kelp canopies at sites located around the San Juan Islands. To achieve this, they set up stationary cameras on shore that would capture oblique photos of the floating kelp beds at predetermined intervals, and also deployed acoustic doppler current profilers (ADCPs) on the sea floor in their vicinity. The resulting photos were classified using a manual threshold system where the technician would move a slider on a gray-scale spectral distribution until just kelp canopy was selected. Canopy area was then extrapolated from this. Overall, the authors found that tidal height had an insignificant impact compared to current, which impacted canopy area with changes as little as 0.1m/s. This study was important to the development of my project in that it is the only non-plane-based study of bull kelp canopies in Puget Sound using imagery I could find, and also a widely cited source on the impacts of currents on kelp canopies. Despite this, there are significant limitations to their study design (such as not being able to see below the surface) that suggested research questions I could explore.

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

This research conducted by members of the Spectral Lab at the University of Victoria, investigated the use of satellite imagery to map bull kelp forests in the nearshore environment surrounding Vancouver Island. The authors meticulously assess a wide variety of image classification methodologies and spectral indices against ground truth kayak survey data to determine which is the most effective. Their results showed that a combination of NDVI, green-NDVI, and principal component indices used in ISODATA unsupervised classification performed the best. This study is actually the one that first sent me down this path and provided a lot of the fodder that went into my initial brainstorming. Contained in it is a plethora of information about the optical properties of kelp, the tradeoffs of different image collection technologies, different ways of doing image classification, and citations to all sorts of other papers involving kelps and remote sensing, which proved (and continue to be) extremely valuable as I work through my project.

Cavanaugh, K.C. (2020). *Effect of Tides and Currents on UAV-Based Detection of Giant Kelp Canopy*. [Thesis, University of California Los Angeles]. UCLA Electronic Theses and Dissertations.

This Master's thesis is the work of Katherine Cavanaugh at UCLA to assess the effect of tides and currents on the mapping of giant kelp (*Macrocystis pyrifera*) using UAV-based imagery. To accomplish this task, she flew a DJI Matrice 100 carrying a MicaSense RedEdge multispectral sensor at a giant kelp forest site located near Santa Barbara, stitched the imagery together using photogrammetry software, and classified the imagery using a variety

of different indices. Overall, she found that there was a significant impact on canopy area due to tidal height, but that currents did not change enough during the study period to have an impact. This is perhaps the closest thing I have found thus far to the study I am conducting, albeit for giant kelp rather than bull kelp. In many ways it represents the study I would have liked to have conducted with (a lot) more funding for a higher quality drone and camera, as well as current and tide sensors to deploy. There is a significant amount of math presented here with regard to image processing that I will likely try to employ on my imagery as well.

References

Anderson, K., & Gaston, K.J. (2013). Lightweight unmanned aerial vehicles will revolutionize spatial ecology. *Frontiers in Ecology and the Environment, 11*(3), 138-146.

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

Berry, H. (2017). *Assessment of Bull Kelp at Squaxin Island in 2013, 2014 and 2016.* Olympia, WA: Nearshore Habitat Program, Washington State Department of Natural Resources.

Berry, H., Calloway, M., & Ledbetter, J. (2019). *Bull Kelp Monitoring in South Puget Sound in 2017 and 2018.* Olympia, WA: Nearshore Habitat Program, Washington State Department of Natural Resources.

Berry, H., Mumford, T.F., & Dowty, P. (2005). *Using Historical Data to Estimate Changes in Floating Kelp (Nereocystis luetkeana and Macrocystis integrifolia) in Puget Sound, Washington*. Olympia, WA: Nearshore Habitat Program, Washington State Department of Natural Resources.

Britton-Simmons, K., Eckman, J.E., & Duggins, D.O. (2008). Effect of tidal currents and tidal stage on estimates of bed size in the kelp *Nereocystis leutkeana*. *Marine Ecology Progress Series, 355,* 95-105.

Calloway, M., Oster, D., Berry, H., Mumford, T., Naar, N., Peabody, B., …, and Toft, J. (2020). *Puget Sound Kelp Conservation and Recovery Plan*. Prepared for NOAA-NMFS: Seattle, WA.

Cavanaugh, K.C. (2020). *Effect of Tides and Currents on UAV-Based Detection of Giant Kelp Canopy*. [Thesis, University of California Los Angeles]. UCLA Electronic Theses and Dissertations.

Cavanaugh, K.C., Siegel, D.A., Kinland, B.P., & Reed, D.C. (2010). Scaling giant kelp field measurements to regional scales using satellite observations. *Marine Ecology Progress Series, 403,* 13-27.

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

Colefax, A.P., Butcher, P.A., & Kelaher, B.P. (2017). The potential for unmanned aerial vehicles (UAVs) to conduct marine fauna surveys in place of manned aircraft. *ICES Journal of Marine Science, 75*(1), 1-8.

Collin, A., Dubois, S., James, D., & Houet, T. (2019). Improving Intertidal Reef Mapping Using UAV Surface, Red Edge, and Near-Infrared Data. *Drones, 3*(67), 12pp.

Deysher, L.E. Evaluation of remote sensing techniques for monitoring giant kelp populations. *Hydrobiologia, 260/261,* 307-312.

Dobkowski, K.A., Flanaga, K.D., & Nordstrom, J.R. (2019). Factors Influencing Recruitment and Appearance of Bull Kelp *Nereocystis Luetkeana* (Phylum Ochrophyta). *Journal of Phycology, 55*, 236-244.

Doughty, C.L., & Cavanaugh, K.C. (2019). Mapping Coastal Wetland Biomass from High Resolution

Unmanned Aerial Vehicle (UAV) Imagery. *Remote Sensing, 11*(540), 16pp.

Duffy, J.P., Pratt, L., Anderson, K., Land, P.E., & Shutler, J.D. (2017). Spatial assessment of intertidal seagrass meadows using optical imaging systems and a lightweight drone. *Estuarine, Coastal and Shelf Science, 200,* 169-180.

Duggins, D., Eckman, J.E., Siddon, C.E., & Klinger, T. (2001). Interactive roles of mesograzers and current flow in survival of kelps. *Marine Ecology Progress Series, 223,* 143-155.

Eckman, J.E., Duggins, D.O., & Sewell, A.T. (1989). Ecology of understory kelp environments. I. Effects of kelps on flow and particle transport near the bottom. *Journal of Experimental Marine Biology and Ecology, 129,* 173-187.

Foreman, R.E. (1984). Studies on *Nereocystis* growth in British Columbia, Canada. *Hydrobiologia, Vol. 166/117,* 325-332.

Friedlander, A.L., Ballesteros, E., Bell, T.W., Casell, J.E., Campagna, C., Goodell, W., … , Dayton, P.K. (2020). Kelp forests at the end of the earth: 45 years later. *PLoS ONE, 15*(3), 23pp.

Hamilton, S.L., Bell, T.W., Watson, J.R., Grorud-Colvert, K.A., & Menge, B.A. (2020). Remote sensing: generation of long-term kelp bed data sets for evaluation of impacts of climatic variation. *Ecology,* Advanced online publication.

Harley, C.D., Anderson, K.M., Demes, K.W., Jorve, J.P., Kordas, R.L., Coyle, T.A., & Graham, M.H. (2012). Effects of Climate Change on Global Seaweed Communites. *Journal of Phycology, 48,* 1064-1078.

Kislik, C., Dronova, I., & Kelly, M. (2018). UAVs in Support of Algal Bloom Research: A Review of Current Applications and Future Opportunities. *Drones, 2*(35), 14pp.

Klemas, V.V. (2015). Coastal and Environmental Remote Sensing from Unmanned Aerial Vehicles: An Overview. *Journal of Coastal Research, 31*(5), 1260-1267.

Krumhansl, K.A., Okamoto, D.K., Rassweiler, A., Novak, M., Bolton, J.J., Cavanaugh, K.C., … , & Byrnes, J.E.K. (2016). Global patterns of kelp forest change over the past half-century. *Proceedings of the National Academy of Sciences of the United State of America, 133*(48), 13785-13790.

Manfreda, S., McCabe, M.F., Miller, P.E., Lucas, R., Madrigal, V.P., Mallinis, G., … , Toth, B. (2018). On the Use of Unmanned Aerial Systems for Environmental Monitoring. *Remote Sensing, 10*(4), 28pp.

Mann, K.H. (1973). Seaweeds: Their Productivity and Strategy for Growth. *Science, 182*(*4116*), 975-981.

Maxell, B.A., & Miller, K.A. (1996). Demographic Studies of the Annual Kelps *Nereocystis luetkeana* and *Costaria costata* (Laminariales, Phaeophyta) in Puget Sound, Washington. *Botanica Marina, 39*, 479-489.

Mora-Soto, A., Palacios, M., Macaya, E.C., Gomez, I., Huovinen, P., Perez-Matus, A., … , Macias-Fauria, M. A High-Resolution Global Map of Giant Kelp (*Macrocystis pyrifera*) Forests and Intertidal Green Algae (*Ulvophyceae*) with Sentinel-2 Imagery. *Remote Sensing, 12, 694,* 20pp.

Mumford, Jr., T.F. (2007). *Kelp and Eelgrass in Puget Sound.* Olympia, WA: Puget Sound Nearshore

Partnership.

Murfitt, S.L., Allan, B.M., Bellgrove, A., Rattray, A., Young, M.A., & Ierodiaconou, D. (2017). Applications of unmanned aerial vehicles in intertidal reef monitoring. *Scientific Reports, 7*(10259), 11pp.

Nahirnick, N.K., Reshitnyk, L., Campbell, M., Hessing-Lewis, M., Costa, M., Yakimishyn, J., & Lee, L. (2018). Mapping with confidence; delineating seagrass habitats using Unoccupied Aerial Systems (UAS). *Remote Sensing in Ecology and Conservation, 5*(2), 121-135.

Nijland, W., Reshitnyk, L., & Rubidge, E. (2019). Satellite remote sensing of canopy-forming kelp on a complex coastline: A novel procedure using the Landsat image archive. *Remote Sensing of Environment, 220*, 41-50.

Orth, R.J., Dennison, W.C., Gurbisz, C., Hannam, M., Keisman, J., Landry, J.B., … , Batiuk, R.A. (2019). Long-term Annual Aerial Surveys of Submersed Aquatic Vegetation (SAV) Support Science, Management, and Restoration. *Estuaries and Coasts,* 16pp.

Pfister, C.A., Altabet, M.A., & Weigel, B.L. (2019). Kelp beds and their local effects on seawater chemistry, productivity, and microbial communities. *Ecology, 100*(10), 15pp.

Pfister, C.A., Berry, H.D., & Mumford, T. (2017). The dynamics of Kelp Forests in the Northeast Pacific Ocean and the relationship with environmental drivers. *Journal of Ecology, 106,* 1520-1533.

Rogers-Bennett, L., & Catton, C.A. (2019). Marine heat wave and multiple stressors tip bull kelp forest to sea urchin barrens. *Scientific Reports, 9*(15050), 10pp.

Rossiter, T., Furey, T., McCarthy, T., & Stengel, D.B. (2020). UAV-mounted hyperspectral mapping of intertidal macroalgae. *Estuarine, Coastal and Shelf Science.* Advanced online publication.

Schiel, D.R., Steinbeck, J.R., & Foster, M.S. (2004). Ten Years of Induced Ocean Warming Causes Comprehensive Changes in Marine Benthic Communities. *Ecology, 85*(7), 1833-1839

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

Shaffer, J.A., Munsch, S.H., & Cordell, J.R. (2020). Kelp Forest Zooplankton, Forage Fishes, and Juvenile Salmonids of the Northeast Pacific Nearshore. *Marine and Coastal Fisheries, 12*, 4-20.

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

Steneck, R.S., Graham, M.H., Bourque, B.J., Corbett, D., Erlandson, J.M., Estes, J.A., & Tegner M.J. (2002). Kelp forest ecosystems: biodiversity, stability, resilience and future. *Environmental Conservation, 29*(4), 436-459.

Taddia, Y., Russo, P., Lovo, S., & Pellegrinelli, A. (2019). Multispectral UAV monitoring of submerged seaweed in shallow water. *Applied Geomatics, 12,* 19-34.

Tait, L., Bind, J., Charan-Dixon, H., Hawes, I., Pirker, J., & Schiel, D. (2019). Unmanned Aerial Vehicles (UAVs) for Monitoring Macroalgal Biodiversity: Comparison of RGB and Multispectral Imaging

Sensors for Biodiversity Assessments. *Remote Sensing, 11*(2332), 18pp.

Teagle, H., Hawkins, S.J., Moore, P.J., & Smale, D.A. (2017). The role of kelp species as biogenic habitat formers in coastal marine ecosystems. *Journal of Experimental Biology and Ecology, 492*, 81-98.

Thom, R.M., & Hallum, L. (1990). *Long-Term Changes in the Areal Extent of Tidal Marshes, Eelgrass Meadows and Kelp Forests of Puget Sound* (EPA Report No. 910/9-91-005). Seattle, WA: Wetland Ecosystem Team, Fisheries Research Institute, University of Washington.

Thomsen, M.S., Mondardini, L., Alestra, T., Gerrity, S., Tait, L., South, P.M., Lilley, S.A., & Schiel, D.R. (2019). Local Extinction of Bull Kelp (*Durvillaea* spp.) Due to a Marine Heatwave. *Frontiers in Marine Science, 6*(84), 10pp.

Turner, I.L., Harley, M.D., & Drummond, C.D. (2016). UAVs for coastal surveying. *Coastal Engineering, 114*, 19-24.

Van Wagenen, R.F. (2015). *Washington Coastal Kelp Resources: Port Townsend to the Columbia River. Summer 2014.* Olympia, WA: Nearshore Habitat Program, Washington State Department of Natural Resources.

Ventura, D., Bonifazi, A., Gravina, M.F., Belluscio, A., & Ardizzone, G. (2018). Mapping and Classification of Ecologically Sensitive Marine Habitats Using Unmanned Aerial Vehicle (UAV) Imagery and Object-Based Image Analysis (OBIA). *Remote Sensing, 10*(1331), 23pp.

Weigel, B.L., & Pfister, C.A. (2019). Successional Dynamics and Seascape-Level Patterns of Microbial Communities on the Canopy-Forming Kelps *Nereocystis luetkeana* and *Macrocystis pyrifera*. *Frontiers in Microbiology, 10*(346), 17pp.

Wernberg, T., Bennett, S., Babcock, R.C., de Bettignies, T., Cure, K., Depczynski, M., … , & Wilson, S. (2016). Climate-driven regime shift of a temperate marine ecosystem. *Science, 353*(6295), 169-172.

Zhou, Z., Yang, Y., & Chen, B. (2018). Estimating *Spartina alterniflora* fractional vegetation cover and aboveground biomass in a coastal wetland using SPOT6 satellite and UAV data. *Aquatic Botany, 144*, 38-45.