

**UNOCCUPIED AIRCRAFT SYSTEM APPLICATIONS FOR SALT MARSH SHORELINES:
A HANDBOOK**

By

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Chapter 1 | Introduction

1.1 | Salt Marshes: Benefits and Habitat Status

Salt marshes are coastal wetlands comprised of halophytic, or salt-tolerant grasses that are regularly inundated by tides. An estimated 3.8 million acres of intertidal wetlands were present in the contiguous United States as of 2009, where 66.7% of these wetlands were salt marsh found in the southeastern and gulf coastlines (Dahl, 2009). Salt marshes provide many services, including but not limited to: shoreline protection (Currin, Chappell, & Deaton, 2009), water filtration (Pennings & Bertness, 1999), habitat and refuge for coastal fauna (Boesch & Turner, 1984; Lefcheck et al., 2019; Stedman & Hanson, 2000; Withers, 2002), carbon storage (Chmura, Anisfeld, Cahoon, & Lynch, 2003), and tourism revenue (Wall, 1998). In North Carolina, salt marshes provide an annual \$27.5¹ billion storm protection value by preventing coastal erosion from severe weather (NCDEQ, 2015). During rain events stormwater runoff is filtered by salt marshes, removing excess nutrients and trapping sediment before it reaches the ocean (NCDEQ, 2015; Pennings & Bertness, 1999). Salt marshes are critical for commercial fishery production; for example, 90% of North Carolina's commercial fisheries and 75% of Louisiana's commercial fisheries depend upon wetlands for food and larval protection (Louisiana Sea Grant, n.d.; NCDEQ, 2015). Additionally, salt marshes provide habitat to many coastal species including invertebrates, fish, and shorebirds (Deegan, Hughes, & Rountree, 2002; Gittman et al., 2016; Withers, 2002), making these environs an ideal tourism destination for recreational fishers and birders (Wall, 1998).

Between 2004 and 2009 there was a 2.8% decrease (111,500 acres) in estuarine wetlands in the U.S. (Dahl, 2009). This decrease is primarily due to the increased severity and frequency of storms which exacerbates erosion rates due to wave action (Currin, Davis, Baron, Malhotra, & Mark, 2015; Dahl, 2009). These impacts are regionally more pronounced as salt marshes rely upon a steady supply of sediment and seasonal die-off to keep up with sea level rise (Dahl, 2009). Without an influx of sediment, erosion occurs, and marsh plants become submerged more often or permanently, ultimately drowning the plants. Once these plants drown, marshes die off;

¹ Value adjusted from 2014 (US\$25.6 billion) to 2019 (US\$27.5 billion)

without the plants' roots to keep sediment in place, erosion is exacerbated, and more marsh area is lost. Regions like the northern Gulf of Mexico are particularly vulnerable to these impacts due to changes in the Mississippi River flow from levees and canals (Dahl, 2009).

1.2 | Salt Marshes: Monitoring Practices

Salt marsh monitoring is labor intensive and monitoring costs vary widely by region (Berger, 1997; Currin, Delano, & Valdes-Weaver, 2008). Cost variability originates from the level of monitoring, duration, frequency, and number of reports required for each site, as well as site accessibility and size. The level of monitoring is defined by the number of variables collected during the monitoring process, such as biomass, stem density, biodiversity, sediment composition, and soil elevation (Berger, 1997). Stem height and stem density may be transformed into an above ground biomass equivalent using region-specific conversion curves of dried biomass to stem density and height ratios (Davis, Currin, O'Brien, Raffenburg, & Davis, 2015). Soil elevation table (SET) measurements over time reveal whether a marsh is accreting sediment or eroding, though installing these tables may not be feasible in all locations. Additionally, monitoring frequency varies based upon project goals; for example, biomass data may be collected once a month during peak growing season (Berger, 1997). A site may require multiple reports depending upon project deliverable requirements, further adding to the monitoring cost. In 1997, the median marsh monitoring cost across the Northeast US was \$3,293.43 per acre² (Berger, 1997). Due to costs associated with these practices, some monitoring has been expanded to include a citizen science component, increasing the number of monitoring hours that can be conducted (Currin et al., 2008).

While *in situ* monitoring provides critical health assessment data, it can also be destructive to the marsh. The level of impact varies by sampling procedure; most sampling methods require individuals to walk through the marsh, trampling grasses and scarring sediment by leaving deep shoe prints in the marsh mud. Further, coring for sediment sampling results in deep holes throughout the marsh, as multiple cores may be taken in each marsh zones. Many of these sites may function as long-term research locations; while long term monitoring improves

² 1997 median cost of monitoring was US\$2,100 per acre (Table 3.1), adjusted to USD 2019

understanding of ecosystem function and resiliency to natural disasters, repeated exposure results in sediment scarring (Figure 1). Some long-term sites have implemented walking aids, such as wooden boardwalks or lightweight mobile platforms, to reduce the cumulative impacts on the marsh.

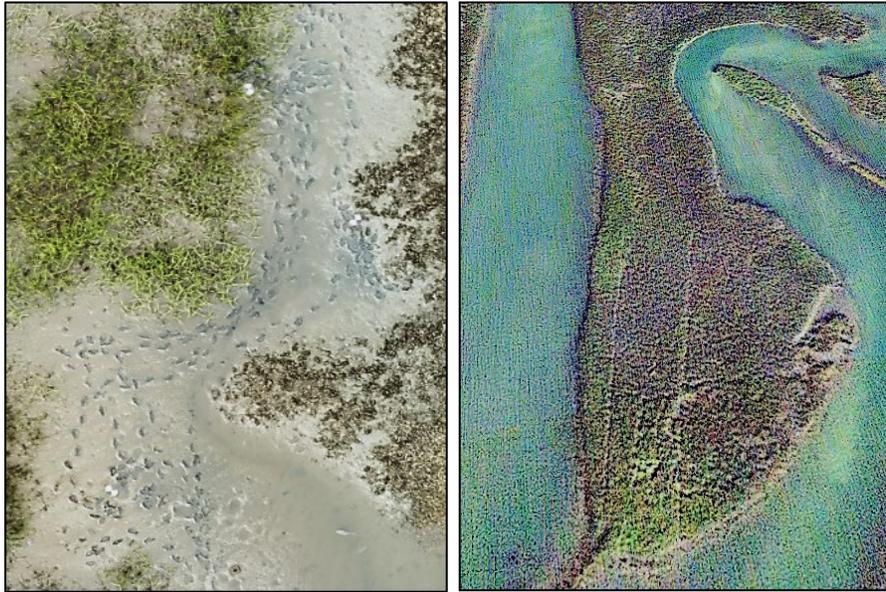


Figure 1. (Left): Physical impacts to the salt marsh while conducting field work (boot prints). (Right): Over time, these monitoring practices may result in scarring from walking the same transect lines (Middle Marsh, NC).

1.3 | Remote Sensing and Salt Marshes

Remote sensing offers insight into large and fine scale changes in wetland habitats (Pettorelli, Schulte to Buhne, Shapiro, & Glover-Kapfer, 2018); organizations such as U.S. Fish and Wildlife Service have used these techniques for the last 30 years (Dahl, 2006). Much of salt marsh remote sensing is conducted using high altitude aerial photography or satellite imagery (Dahl, 2006). Medium resolution satellite imagery such as the Landsat Thematic Mapper (30-m resolution) permits analysis of coastal marsh changes over large areas, such as within the Chesapeake Bay Watershed (Klema, 2014). Light Detection and Ranging (LIDAR) can provide a 3D image by sending radar pulses to the marsh in question, returning a signal representing the canopy profile and ground returns, allowing the creation of a digital surface model (Klema, 2014). When paired with indices derived from multispectral remote sensing data, such as the Normalized Difference Vegetation Index (NDVI), a biomass equivalent can be evaluated.

Indices such as NDVI can be used to determine plant health, a critical component of overall marsh health. NDVI calculates the difference between near-infrared (NIR) and red reflectance, as plants reflect NIR while absorbing red wavelengths (Pettorelli et al., 2018). The healthier the vegetation, the more NIR is reflected. It is important to note that NDVI may be unreliable in tidal systems, as well as within specific salt marsh plant densities (Byrd, O'Connell, Di Tommaso, & Kelly, 2013; Kearney, Stutzer, Turpie, & Stevenson, 2018); relying on other indices may be more reliable depending on the salt marsh in question. The Enhanced Vegetation Index (EVI) is derived from NDVI, though it corrects for some atmospheric disturbance (Huete et al., 2002). Leaf Area Index (LAI) can also be calculated with remote sensing techniques, which is the ratio of leaf area to ground area; this method can be used as an indicator of plant stress (Zheng & Moskal, 2009). Spectral index libraries are being developed in order to improve remote mapping of coastal wetlands based upon vegetation expected in a given region (Zomer, Trabucco, & Ustin, 2009).

While these methods allow for large-scale monitoring and reduce monitoring time, they may come at a high cost. Cost varies significantly depending upon the image provider; some satellite data is open-access while others cost upwards of US\$20 per scene (Pettorelli et al., 2018). Each scene varies in size, depending on the swath of the satellite that captured the image. For example, a scene from Sentinel 2 level 1C would capture 100km x 100km (Pettorelli et al., 2018). Furthermore, these images may not capture the spatial and temporal data necessary to monitor cases such as local salt marsh changes after a natural disaster (Gray et al., 2018). While combining satellite imagery with ultra-high resolution data (e.g. unoccupied aircraft imagery with <5cm resolution), details can be extracted for specific significant regions (Gray et al., 2018). Additionally, when looking to uncover critical information that determines whether a salt marsh will keep up with sea level rise, such as canopy height and marsh elevation, satellite imagery will not provide the necessary resolution to determine this information.

1.4 | The Case for Unoccupied Aircraft Systems

Unoccupied aircraft systems (UAS), AKA drones, have become a prominent tool in the field of coastal management. The term UAS encompasses not only the aircraft itself (Unoccupied Aircraft Vehicle or UAV), but also the sensors, ground control station, and communication units (e.g. controller). New advances enable researchers and managers to enhance resource management

through improved data quality, data collection efficiency, safety, immediacy, and reduced cost (Johnston et al., *in prep*).

Platforms

Developing project goals and establishing data requirements of the project are necessary to ensure the correct platform, or drone, is selected to achieve these project goals. Drone platforms include both fixed-wing and multirotor, providing different survey benefits (Figure 2a-d).

Fixed-Wing Platforms

Fixed-wing drones function and are configured similarly to airplanes, though are often launched by hand and land autonomously (Figure 2c) (Johnston, 2019). Fixed-wing platforms are designed for high altitude and larger survey areas, permit longer flight times (i.e. hours of flight on one battery charge), and generate lower resolution imagery than multirotor platforms (Johnston, 2019; Joyce, Duce, Leahy, Leon, & Maier, 2018). However, the resolution captured with fixed-wing platforms is still an order of magnitude better than the best satellite imaging available, as they collect imagery on a centimeter-level resolution opposed to decimeter-level of satellites. Many fixed-wing platforms are comprised of light weight foam, making these platforms easy to disassemble and move between sites, though require more space for takeoff and landing (Joyce et al., 2018). Some fixed-wing platforms may have attached landing gear (i.e. wheels) and require a runway to use, and some are amphibious and can tolerate water landings. Further, some transitional fixed-wing aircraft have vertical takeoff and landing (VTOL) abilities which allow these platforms to take-off and land in confined areas (Johnston, 2019).

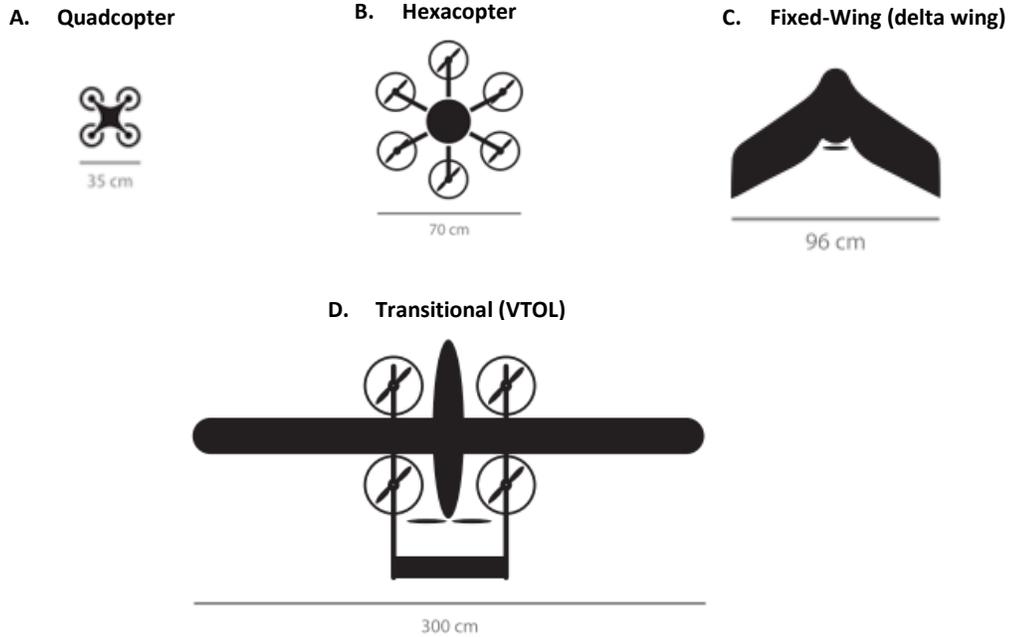


Figure 2. Schematics of typical unoccupied aircraft systems (adapted from Johnston 2019).

Multicopter Platforms

Multicopter (or multicopter) platforms are designed to survey smaller flight areas, have a shorter battery life, but enable pilots to fly safely at lower altitudes at slower velocities, resulting in higher resolution data (Figure 2a-b) (Johnston, 2019; Joyce et al., 2018). Multicopter drones are typically comprised of between four (quadcopter) and eight (octocopter) propellers, which provide security in case of an emergency but also result in less efficient energy use (Johnston, 2019). Multicopter drones are typically made of plastic or carbon fiber; larger multicopters can often be folded for easy transport (Figure 3a-c) (Johnston, 2019). Further, these platforms are typically not as expensive as fixed-wing platforms and can be launched and recovered by hand.



Figure 3. Example of medium-sized hexacopter folded for transport: a) hexacopter folded for storage and transport to site, b & c) quick expansion and setup upon arriving at surveying site. Adapted from Johnston et al. (in prep).

Sensors

Depending upon project goals, different sensors may be required to collect appropriate data. Many consumer-grade drones come equipped with a single optical sensor, such as a GoPro HERO camera (Johnston, 2019). Both consumer and commercial-grade drones may be altered to use sensors including but not limited to: thermal, near infrared (NIR), specialized multispectral sensors (e.g. MicaSense RedEdge), light detection and ranging (LIDAR), and higher resolution color (RGB) optical sensors. Sensor choice is also dependent upon project goals; for example, a multispectral sensor is necessary to conduct vegetation health assessments. Sensors may be purchased and added to stock drone models, such as a multispectral sensor to a DJI Phantom Pro 4, increasing the number of projects a single drone may be applicable for.

Quality

Data quality may exceed that of traditional sampling methods, depending upon the chosen platform, sensor, and ground sampling distance (GSD). The quality of collected imagery may be pre-checked in the field through the ground control station, using the drone's software. The GSD is the distance between center points of each sample taken on the ground; in the case of drone imagery, it is the size of each pixel on the ground. The GSD will change depending upon the sensor and altitude of each flight (Thomson, 2016). UASs provide higher resolution data than satellite imagery, enabling fine-scale temporal and spatial changes to be detected. With high-resolution sampling it is possible to visually distinguish changes in marsh plant species, which may aid in marsh delineation. The imagery is used in Structure from Motion (SfM) software, which creates

a 3D structure from 2D images taken at different positions and angles. This can then be used to create digital surface models (DSMs) and digital terrain models (DTMs). A DSM is the 3D structure of an entire surface, such as a marsh canopy, while a DTM is a 3D representation of the ground surface (e.g. marsh sediment). These products are quite accurate in coastal environments; a comparison between a UAS derived DSM and a terrestrial laser scan (TLS) of the same beach site was different by an average of 4.2cm (Seymour et al., 2018). Further, the systematic process of preprogramming flights and image processing software templates creates a repeatable method to survey salt marsh environments, reducing human error which may occur during traditional ground sampling methods. Consumer off the shelf (COTS) platforms may provide submeter accuracy, and with the use of ground control points (GCPs), that accuracy will improve to sub-decimeter levels.

Currently, GCPs are used to improve the accuracy of captured imagery. These are spaced throughout the survey site and designed to have high contrast, such as an iron cross design (Figure 4). Ground control point locations are collected with a GPS to reference overlapping images, which aids in creating accurate mosaics in the chosen software.

Chapter 2.2 | Ground Control Point (GCP) Placement further describes how GCPs may be optimally placed for improved survey accuracy.



Figure 4. Example of a ground control point (GCP) with an iron cross pattern deployed in the field.

Efficiency

While UASs cannot cover the same area as occupied aircraft, UASs cover larger areas than *in situ* measurements. Less preparation is required to survey with UASs compared to both occupied aircraft and *in situ* field measurements; a pre-flight check for a UASs is less intensive than for an occupied aircraft and requires less equipment than *in situ* field work. Comparisons using UAS

and a terrestrial laser scanner (TLS) to monitor coastal morphology demonstrate it is less expensive and less resource intensive to monitor a larger area with UAS than TLS with the same number of personnel (Seymour et al., 2018). Furthermore, traditional ground measurement methods may drastically limit the potential survey area due to limited resources. For example, traditional oyster reef monitoring methods require manual GPS point collection (Baggett et al., 2015), which is both time and resource intensive. Using a UAS, the survey area may increase three-fold, as seen in (Windle, Poulin, Johnston, & Ridge, *in review*), while decreasing the time required to survey the area. Flight times for each UAS system vary based upon environmental conditions, payload, and battery usage (Table 1).

Table 1. Examples of advertised maximum flight time for different UAS.

Platform	Maximum Flight Time (minutes)
SenseFly ebee Classic ³	50
Parrot Bebop 2 ⁴	25
DJI Phantom 4 Pro ⁵	30
DJI S900 ⁶	18

Safety

Traditionally, occupied aircraft have been used to perform aerial surveys, placing the occupants at risk of injury or death (Butler, Connor, & Lincoln, 2015). UAS do require human involvement, however, risk is reduced when this technology is used properly as the human element is limited. Flight plans may be pre-programmed for both fixed-wing and multirotor platforms; therefore, the potential interaction period is reduced to launching and landing the drone. Programmed flight plans may be interrupted by the pilot at any time to avoid collision with other objects, such as wildlife or other aircraft. Drone operations also require fewer personnel than other operations, reducing the potential of injury during field surveys.

³ Accessed April 21, 2019: <https://www.sensefly.com/drone/ebee-mapping-drone/>

⁴ Accessed April 21, 2019: <https://www.parrot.com/us/drones/parrot-bebop-2#technicals>

⁵ Accessed April 21, 2019: <https://www.dji.com/phantom-4-pro>

⁶ Accessed April 21, 2019: <https://www.dji.com/spreading-wings-s900>

Immediacy

Surveying intertidal salt marshes is tide dependent, and the use of UAS allows data collection to occur at the optimal tide phase, opposed to collecting data at arbitrary tidal phases, as may be required with traditional survey methods. Small UASs enable surveys to be conducted rapidly as additional survey opportunities arise. Time sensitive surveys, such as after a natural disaster, can deploy immediately and collect data more swiftly than traditional remote sensing methods. Traditional methods may be unreliable due to cloud cover or high tides captured with satellite imagery, and occupied aircraft experience greater restrictions when planning a survey mission. The ease and rapidity of data collection also permits resampling if data quality standards were not met, such as glare from the solar angle or shadows during imagery collection (Joyce et al., 2018).

Cost

Small consumer-grade drones with high-resolution cameras may range from a few hundred dollars to \$1,500 (Johnston, 2019). The cost of a platform will increase as the capabilities of the sensor improves. For example, the addition of a multispectral MicaSense RedEdge 5-sensor unit may increase the total system cost by \$5,500.⁷ Many of these systems are consumer-grade but operate with professional capabilities and are known as prosumer drones. Some commercial platforms may require a sensor to be purchased separately, though discounts on these purchases may be available based on user sector (e.g. educator). Additionally, to operate UASs commercially within the United States, the Federal Aviation Administration (FAA) requires pilots to register their platforms and receive their Part 107 certification to ensure safe operation of the aircraft.

Maintaining the aircraft incurs additional costs; pilots should expect to replace propellers, wings, and batteries. Losing an aircraft or damage beyond repair is also possible (e.g. water damage), resulting in necessary purchase of a new platform and sensors.

For autopilot functions, a ground control station (GCS) is necessary in the field (e.g. eMotion from senseFly). A GCS may be comprised of a laptop, telemetry link (usually included with drone), and

⁷ Accessed March 15, 2019: <https://www.micasense.com/rededge-mx/>

the drone’s processing software, which can be preprogrammed with the intended flight path, maximizing survey potential (Johnston, 2019). Many drones are also compatible to operate from a mobile device with a drone-specific application, which may reduce costs.

Furthermore, processing the data collected by these UASs requires purchasing software such as Agisoft, Pix4D, or Drone2Map to create usable end-products. Software fees may be incurred annually, depending upon the selected software package.

Table 2. Cost range associated with different components of UAS-based surveys. Cost range determined from leading providers.

Item	Cost Range (USD)
Consumer-grade UAS (multirotor)	\$100 – 1,500
Commercial-grade UAS (multirotor)	\$1,500 - \$5,000
Consumer-grade UAS (fixed-wing)	\$80 - \$500
Commercial-grade UAS (fixed-wing)	\$ 1,500 – \$25,000
FAA Part 107 Certification	\$150
Processing Software	\$179 - \$5,000
Ground Control Station (Tablet/Laptop)	\$500-\$1,000/\$1,500 – \$2,300
Ground Control Points	\$20-50 per GCP

Caveats

It is important to keep in mind that UASs are new technology and may reveal some technical problems as they are used. Before investing in this technology, the costs and benefits associated with purchasing platforms and training pilots should be considered. There is high variability in the cost associated with UASs; therefore, UASs should be selected that meet minimum requirements of the intended survey, as they can be upgraded and adapted if needed (e.g. NDVI sensor upgrade for DJI Phantom 4 Pro). It may be more feasible to partner with another organization, such as an academic institution, to conduct surveys if there is not a stable source of funding to ensure UAS maintenance and pilot recertification fees can be covered.

While UASs can be rapidly deployed, they are highly weather dependent – wind, rain, and extreme temperatures must all be considered when preparing flight plans. These considerations may reduce the data quality or impede operations altogether.

Survey area must be considered as well, as UASs cannot cover as much ground as other occupied aircraft or remote sensing technology (e.g. satellite imagery). However, the use of multiple UASs or deploying UASs during optimal conditions over the course of multiple days reduces this concern.

1.5 | Handbook Target Audience

This handbook is intended for audiences looking to improve or supplement their current salt marsh monitoring practices, as well as organizations looking to start their first salt marsh monitoring program. From researchers to restoration project managers, this handbook will guide users through aerial data collection, ground truthing, and data processing. It is recommended that a collaborative network is used for those new to salt marsh monitoring, in order to ensure data is accurately collected and processed. Furthermore, establishing these networks may reduce initial investment costs as resources may be shared between partners.

1.6 | Handbook Limitations

This handbook was designed to guide aerial monitoring practices for both natural and restored salt marshes. However, these practices were designed while monitoring living shorelines dominated by *Spartina*; therefore, it is possible these methods may not be ideal for all marsh habitats. Furthermore, the methods used in this handbook are limited to specific processing software, though processing may be achieved using different software such as those mentioned in the **Cost** section of **1.4 | The Case for Unoccupied Aircraft Systems**.

Chapter 2 | Monitoring Overview

2.1 | Site Selection

Site selection should be based upon the user's monitoring goals, with requirements of the drone in mind (e.g. flying within controlled airspace).⁸ Additionally, site selection and platform selection are linked; site access points will need to allow for the launch and recover needs of the UAS platform selected (**2.3 | Platform Selection**). For biomass and areal extent calculations, aerial surveys should be conducted at peak growing season. To determine seasonal marsh die-off, surveys should be conducted both before the growing season begins and at the peak of growing season.

2.2 | Ground Control Point (GCP) Placement

Ground control points, or GCPs, are points on the ground with known locations, used to enhance position accuracy when generating products. These targets should not be something naturally within the survey site, as their location may change relative to other objects over time (e.g. driftwood). For example, a recognizable target may be an iron cross type target supported by a PVC pole (Figure 4). Spacing these points strategically is critical; if they are placed too close together, the GCPs may be mistaken for one another in photos and result in processing errors, and may not provide appropriate spatial corrections. Similarly, if they are spaced too far apart or not enough are implemented in the survey site, they cannot provide the intended benefits.

GCPs should be placed throughout the survey site at different elevations and in different regions of the marsh (e.g. water, mud flat), and its location collected with a survey-grade GPS unit. This improves GCP spacing and improves processing accuracy, as groundtruthed elevations have been captured throughout the marsh to cross check with elevations the drone captures. Depending on site acreage, 10-20 GCPs are recommended (Clapuyt, Vanacker, & Oost, 2016; Tonkin & Midgley, 2016), and should be dispersed throughout the site. GCP dispersal also establishes where the data will be most accurate; beyond the extent of the GCPs data accuracy will decline. Placing GCPs in a five dice pattern is useful to establish a boxed site extent with one or many GCPs

⁸ Learning airspace restrictions are a part of obtaining the U.S. FAA Part 107 License.

distributed throughout the center of the survey site, depending on site size. When feasible, it may be useful to install permanent GCPs that can be resurveyed when needed (e.g. GPS location of each post-storm) to reduce the impact to the marsh.

2.3 | Platform Selection

Choosing the right platform for a project requires attention to cost, project goals, and potential future projects. Cost is the most limiting factor in selecting the platform, however these costs are decreasing every day due to improvements in technology and increased demand. While consumer-grade platforms may be perceived as 'lower-quality', with the right sensors they can meet the demands of a technical project. For example, a DJI Phantom 4 Pro can be equipped with an additional multispectral sensor, transforming a high-end consumer-grade, or prosumer, platform into a commercial-grade rival.

Project goals should be evaluated to determine which platform will meet project requirements. If large-scale area mapping is the goal, a fixed-wing platform would be preferable. If both large areas and higher resolution data are desired, it may be most effective to purchase two platforms in order to maximize survey ability. Furthermore, consider starting with smaller, consumer-grade platforms to gain pilot experience and reduce potential accidents.

2.4 | UAS Flights

As mentioned in **1.4 | The Case for Unoccupied Aircraft Systems**, flight plans may be pre-programmed using the platform's mapping software (e.g. senseFly's eMOTION software, DJI Ground Control Station, etc.). While planning the flight path, it's important to incorporate image overlap to ensure keypoints are identifiable by the processing software. Wherever possible, it is recommended to use between 80-90% front overlap and 70-80% side overlap.

Fixed-wing platforms usually require higher altitude flight paths than multirotor platforms; with higher altitude there is an increase in area covered, however, the ground sampling distance (GSD) increases and the resolution decreases. Depending on project goals, a multirotor platform may be better suited to capture the desired resolution. The GSD can be calculated by downloading a

GSD calculator tool and filling in the necessary parameters based upon the selected sensors.⁹ For example, at an altitude of 100m using a Sony Alpha 6000 and MicaSense RedEdge-MX, a GSD of 2 cm/pixel and 7 cm/pixel are achieved, respectively. Further, GCS software may automatically calculate GSD once sensor information (e.g. camera parameters) is provided.

Flight planning should also account for sun angle and tide, as these will alter the accuracy of spectral indices. It is recommended to fly at low tide in order to have the sediment bed fully exposed to collect a more accurate DTM, as well as to reduce impacts on NDVI accuracy (Bierlich et al., *in prep*; Byrd et al., 2013; Kearney et al., 2018). Additionally, planning flights where low-tide coincides with mid-day is ideal to decrease shadowing from low angle sunlight. To reduce the impacts of clouds and sun angle, multispectral sensors may incorporate radiometric calibration and downwelling light sensors. The former simply involves taking a picture of the calibration card before and after the flight to be incorporated into the photograph processing software. The latter is installed with the multispectral sensor and provides incoming light levels to calibrate reflectance detected.

2.5 | Ground Truthing

While the purpose of implementing drone technology is in part to reduce physical impacts to the marsh, collecting groundtruth data is recommended when initially surveying a marsh. This is to ensure the methods outlined in this handbook are appropriate for the marsh in question. For example, methods may need to be altered when surveying marshes dominated by *Salicornia* or *Phragmites*.

Collecting aerial data from sites with long-term monitoring may be advantageous, as these sites may have additional information as to how the site has changed over time. Furthermore, if a site is already being monitored using traditional ground truthing methods, the addition of a drone is a way to rapidly expand the area surveyed.

⁹ Accessed March 1, 2019: <https://support.pix4d.com/hc/en-us/articles/202560249-TOOLS-GSD-calculator>

Practical Example: Ground Truthing Living Shoreline

To assess the reliability of UAS data, ground truthing is conducted from the upland marsh to the low marsh and samples should be collected approximately every 5m. A 1mx1m PVC quadrat (referenced quadrat from here on) should be placed to the left of the meter tape at 0m and stepping on the left side of the tape should be avoided to prevent impacting the marsh plants that will be measured. A total of 10 stem heights should be collected from within this quadrat, chosen by measuring stems along the two midlines of the quadrat until a total of 10 are measured and recorded (Figure 5). Within this quadrat, a 0.25mx0.25m quadrat (quarter-meter quadrat from here on) should be placed in the landward right corner, containing marsh plants within it (Figure 5 *popout*).

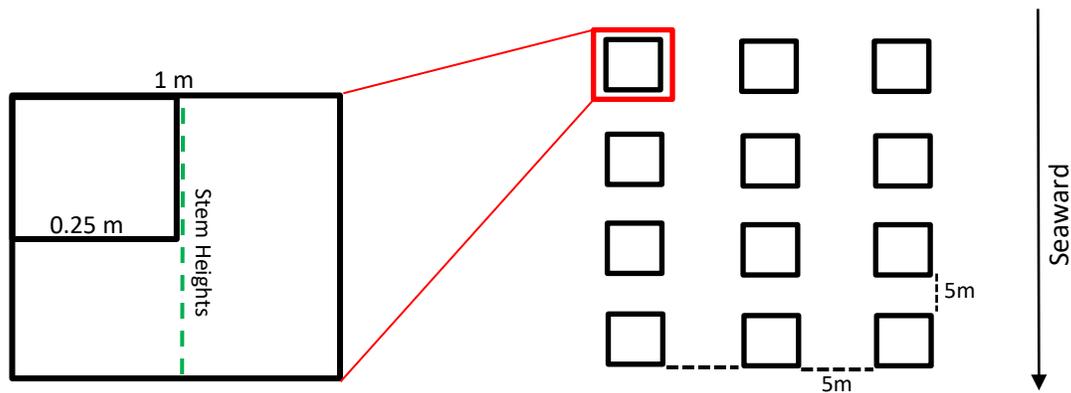


Figure 5. Stem height and density ground truthing protocol schematic. Samples should be collected from upland to lowland marsh (adapted from NOAA vegetation protocols).

Within this quarter-meter quadrat, plant stem density should be obtained by counting each live stem present. The two quadrats should be moved seaward to the 5m mark and the stem height and stem density measurements should be repeated for this transect until the width of the marsh is reached. Depending upon the size of the site, transects should be spaced approximately 5m apart (moving parallel to shore) to ensure a good stem height and stem density sample is obtained. If the site is not a living shoreline or a non-fringing marsh, the upland reference location should be noted (Figure 6).

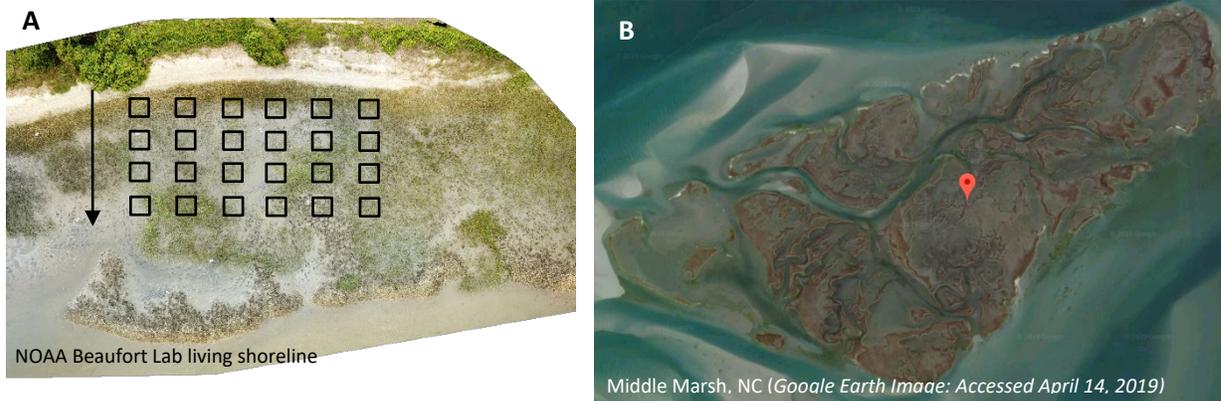


Figure 6. Example of A) living shoreline with clear upland location; arrow denotes movement from upland to lowland surveys and B) non-fringing marsh, requiring a set transect starting location.

2.6 | Visual Data Processing

Image processing may be done through software such as Pix4D, Agisoft, and Drone2Map. While the software interface is different, the desired product is generally the same. Different processing steps are required for optical and multispectral images. It is recommended that new users reference their chosen software's online help resources for processing guidance, as steps may differ by software and sensor. Prior to processing, all photos must have correct location coordinates within their metadata. If no coordinates were saved from the platform's onboard GPS, after following the chosen software's processing steps, photos can be georectified using GCPs or within a Geographic Information System (GIS). Each processing step should be run individually to assess quality reports and ensure no errors are being carried through each step. A point cloud will be generated during processing; this can be used to create a digital surface model (DSM) or a digital terrain model (DTM) using different interpolation methods, depending upon what is selected in the processing software.

Practical Example: Visual Processing in Pix4D

If processing in Pix4D, Optical (RGB) processing may be done using the 3D Maps processing template. Once the initial processing is complete and the quality report is checked, GCP data should be imported and set to the correct coordinate system. Each GCP should be identified and registered in three different images in order to improve georectification accuracy; the project should be reoptimized to ensure the imported GCP locations and the computed locations are

accurate within approximately 2cm. The point cloud mesh can be generated at low, optimal, or high density with a set number of point matches (e.g. 4 matches), and an XYZ or LAS file can be exported for further analysis (Figure 7). Finally, an orthomosaic can be generated as well as a digital surface model (DSM).

Extra steps are required for processing multispectral imagery as each band has a different spectral value. In Pix4D, the Agricultural Multispectral processing template can be used which will guide the user through processing. For example, if using the MicaSense RedEdge sensor, a total of five bands are referenced throughout processing. Each spectral band will have its own folder of photos that were captured with that spectral band and should be imported into the processing software. When registering GCPs, three (3) GCPs should be registered for each spectral band (e.g. 3 photos for each of the 5 bands totaling 15 registered GCPs). Processing should still be completed one step at a time to check the quality report and ensure no errors are being carried through the processing. Exporting the final multispectral reflectance values data allows for further processing, as noted in **Chapter 4 | Canopy Height Model**.

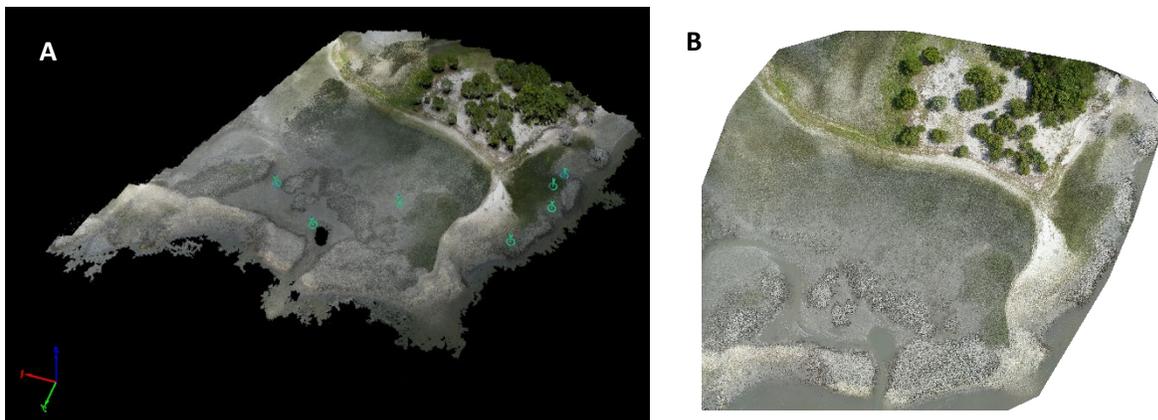


Figure 7. A) 3D UAS point cloud of Bird Shoal site generated using Pix4D software with GCPs indicated by green targets and B) the resulting orthomosaic of the same flight.

Practical Example: Vertical Accuracy Assessment

The accuracy of capturing the height of marsh plants using UAS was tested by modifying methods developed by Lemein, Cox, Albert, & Mori, 2015 and Neumeier, 2005. A 150cm mirror was mounted to a PVC frame placed at a 45° angle 25cm in front of a total of 32 0.25m² plots within a *Spartina alterniflora* dominated salt marsh. A digital camera was mounted to the top of the mirror frame, centered over the mirror and supported by a PVC frame in order to optically capture true heights (Figure 8).

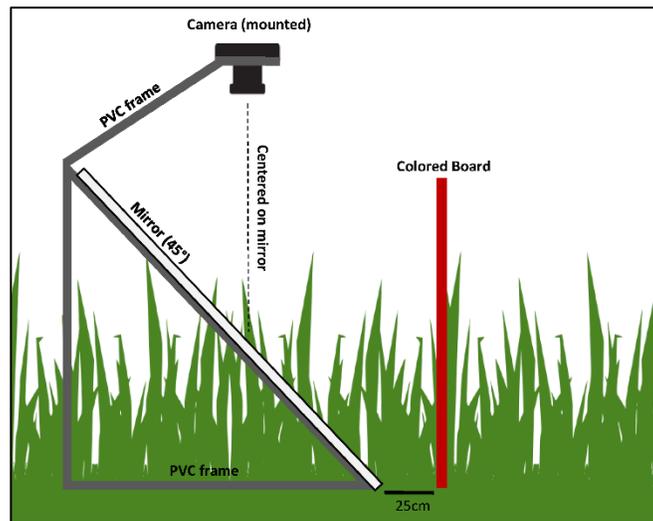


Figure 8. Vertical accuracy apparatus schema (adapted from Neumeier 2005). The 150cm mirror is placed at a 45° angle and the camera is mounted directly above the mirror's center.

Further, 16 of the 32 plots had the top ~15cm painted with red non-toxic, washable paint in attempt to increase contrast between the plant stem tops and neighboring plant stem bases (red plots) (Figure 9). Control plots (16 with no paint) had a red background placed behind the layer of marsh grass for maximum contrast between a row of grasses and background. The red plots had a white background to eliminate the chance for red painted marsh tops to blend in with a red background during image processing. Image analysis using global and adaptive thresholding demonstrated 22 pixels represent one centimeter, allowing for comparison to both groundtruthed heights and UAS generated plant heights.

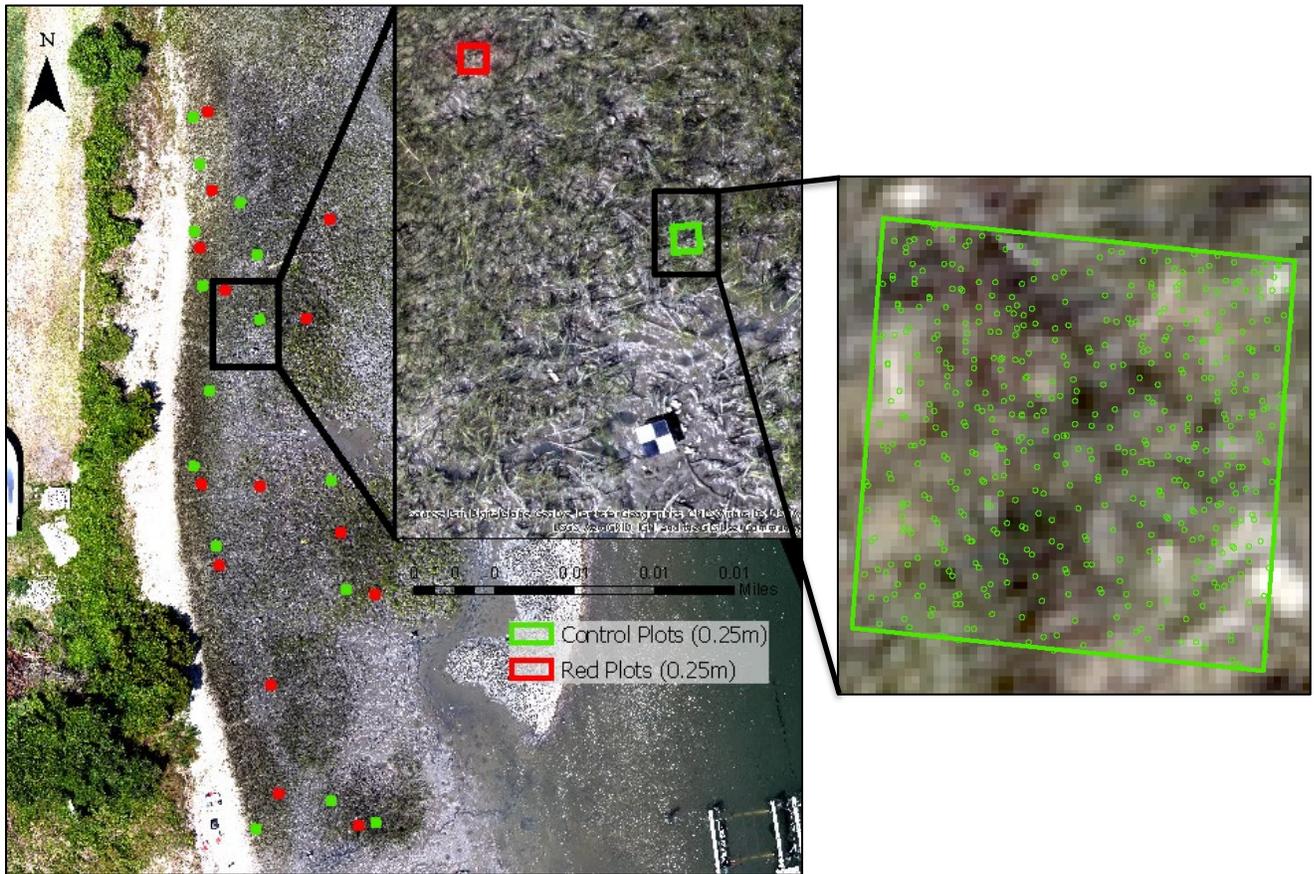


Figure 9. Control (green) and painted (red) plot location (NOAA Beaufort Lab living shoreline, Beaufort, NC). Filtered point cloud points from a control plot demonstrated in right-most extent.

Chapter 3 | Salt Marsh Area and Habitat Classification

Calculating salt marsh area with UAS imagery can be done using traditional remote sensing habitat classification methods (Adam, Mutanga, & Rugege, 2010; Dronova, 2015). However, due to the very high resolution achieved with some UAS sensors (e.g. Sony Alpha 6000 or MicaSense RedEdge), object-based image analysis (OBIA) will yield classification with higher accuracy (Pettorelli et al., 2018).

With programs like ArcGIS, it is also possible to create classification schemes using a classification wizard.¹⁰ Once the classification is complete and compared with ground-truthing data (See above), it is possible to extract total habitat area based on these classifications. Due to the ease of surveying with UAS, it is possible to rapidly assess changes in habitat extent over time to improve management and restoration project timeliness.

Further, UAS data can be used to create habitat classifications and may be more accurate than satellite-derived classifications (Gray et al., 2018). Further, it is possible to use high-resolution UAS data to train satellite imagery to generate a better classification scheme across a larger area (Gray et al., 2018). Though classification is often done to establish general regions within the coastal zone (e.g. oyster reef, salt marsh, upland shrub), it is also possible to determine species diversity from spectral signatures. Multispectral imagery can be used to determine species type due to differences in NIR reflectance values of plants; this may allow for identification of invasive species such as *Phragmites* (Artigas & Yang, 2006). Using UAS data may enable more rapid assessments of species diversity to determine how quickly invasive species are spreading throughout an area.

Practical Example: Pivers Island Living Shoreline Classification

The Image Classification Wizard in ArcGIS Pro¹¹ enables new users to create a classification scheme from a raster image. Due to the high-resolution imagery (~7cm GSD), supervised -based classification was used (Figure 10). The composite band image was generated by compiling all

¹⁰ Accessed March 2, 2019: <https://pro.arcgis.com/en/pro-app/help/analysis/image-analyst/the-image-classification-wizard.htm>

¹¹ Accessed March 2, 2019: <https://pro.arcgis.com/en/pro-app/help/analysis/image-analyst/the-image-classification-wizard.htm>

five RedEdge sensor bands through the Composite Bands tool in ArcGIS Pro.¹² Training samples were created by generating polygons on the composite band image in ArcGIS that represented the classes present at this site (e.g. emergent wetland and upland vegetation) and imported into the Wizard. Due to the nature of this living shoreline, five habitat classes were defined (Figure 10). After classifying the habitat, it is possible to extract the area covered by each of the classes from the resulting table generated in ArcGIS.

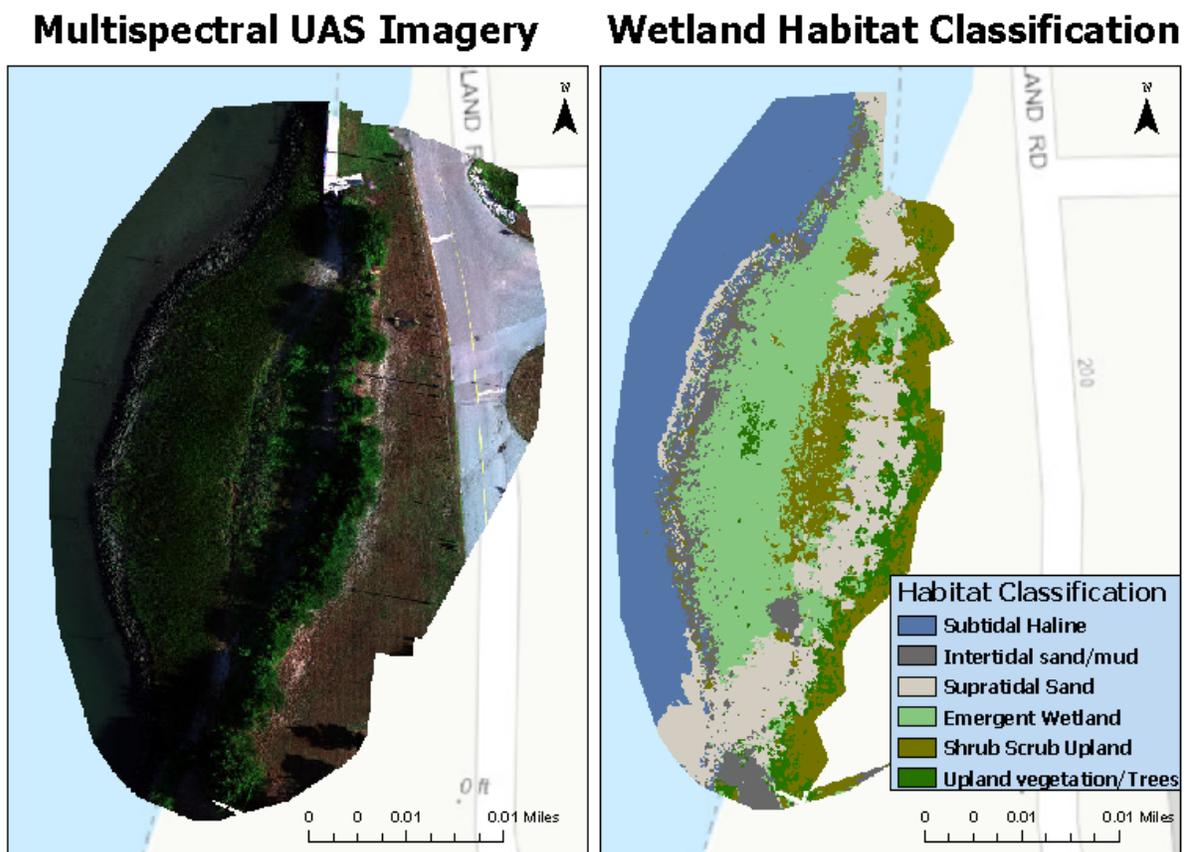


Figure 10. (Left): High resolution multispectral composite band mosaic image collected by UAS of the southern Pivers Island living shoreline located at the Duke University Marine Lab (Beaufort, NC). (Right): Habitat classification map generated from the orthomosaic (~7cm GSD).

¹² Accessed March 2, 2019: <https://pro.arcgis.com/en/pro-app/tool-reference/data-management/composite-bands.htm>

Chapter 4 | Canopy Height Model

The greatest threat to salt marshes is rising sea levels and determining soil elevation changes is a critical step in salt marsh management. Current elevation monitoring methods involve soil elevation tables (SETs), which documents soil elevation changes over time (National Park Service, 2015). Accessing these stationary tools impacts the marsh and does not necessarily represent the elevation of the whole marsh. Using UAS-derived point cloud data, canopy height and terrain can be modeled with limited impact to the marsh. While there are multiple methods available, using a difference method by determining canopy height based upon a digital terrain model (DTM) is the most accurate method (Grenzdörffer, 2014). If a DTM does not currently exist for the salt marsh in question, ground points may be collected with an RTK-GPS to establish a baseline to be used, or the most recent set of LIDAR data if available.

Practical Example: Digital Terrain Model and Digital Surface Model from UAS LAS Data

Initially, UAS data must be processed using a software such as those mentioned in **2.6 | Visual Data Processing**; the resulting point cloud should be exported as a LAS file. This file was filtered by NDVI vegetation and ground values. NDVI values above the calculated threshold represent vegetation, while values below this threshold represent the ground. Converting these rasters to polygons generates a mask that can be used to extract LAS data for both the surface (vegetation) and terrain (ground).

A tessellation grid was created for both the surface and terrain, and the number of points per grid was calculated to remove any grids that have no points, avoiding processing errors. The mean and standard deviation of LAS points in each tessellation grid was calculated, and the top 5% of vegetation Z-values and bottom 5% of ground Z-values were calculated. These values were used to interpolate a vegetation surface and ground surface using Kriging. Subtracting the DTM from the DSM will result in the final canopy height model, allowing managers to understand how healthy the marsh canopy is as well as whether the sediment is accreting or eroding over time (Figure 11 and Figure 12).

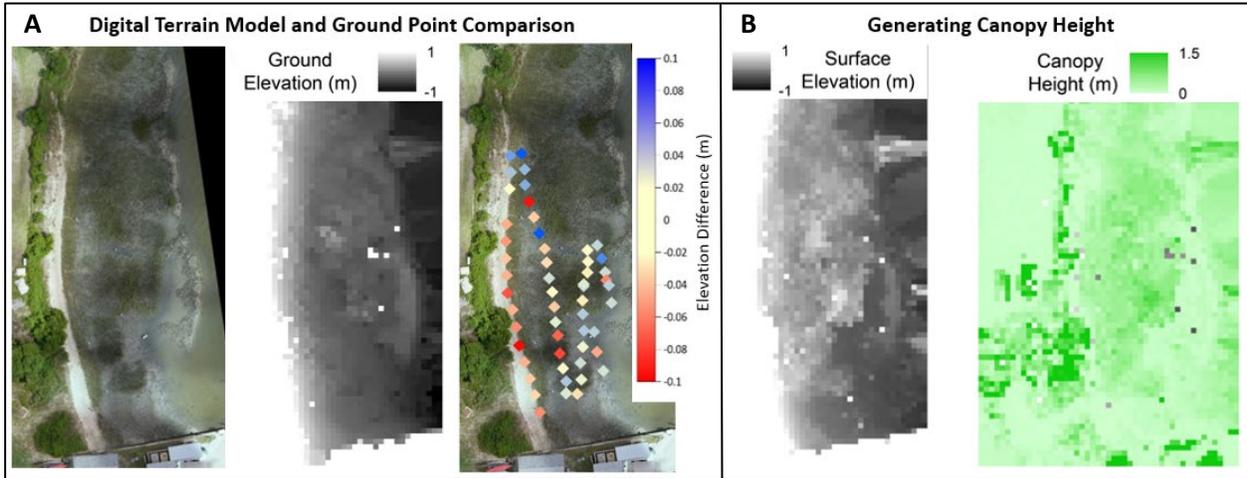


Figure 11. A) Difference between ground points (ground elevation taken with a GPS) and UAS calculated DTM. Mean error between Z-values of ground points and UAS generated DTM was 4.4cm. B) UAS multispectral point cloud used to filter vegetation points using ArcGIS LAS tool, followed by generating a DSM. The difference between the DSM and DTM is the canopy height.

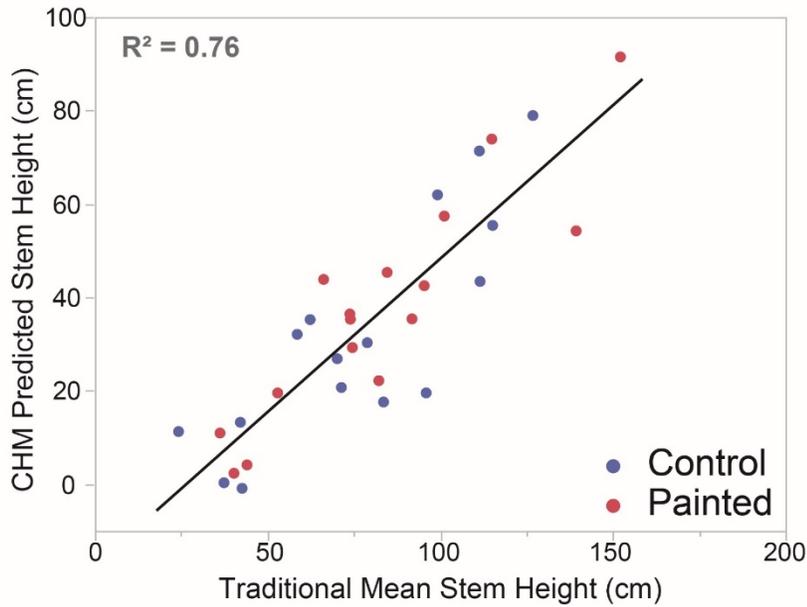


Figure 12. Canopy height determination from UAS data (LAS form) compared to groundtruthed plant heights. Control and painted plots are referenced in Practical Example: Vertical Accuracy Assessment.

Chapter 5 | Aboveground Biomass and Density

Due to the difficulty of assessing total biomass (i.e. shoots and roots), the focus is placed on assessing aboveground biomass (AGB), an indicator of salt marsh health (Klemas, 2014). Traditional AGB methods require destruction of some marsh plants and lab processing (Klemas, 2014). Remote sensing methods have also been used to quantify AGB from satellite imagery (Byrd et al., 2013), though some interference may occur from tidal influence on NDVI values and leaf litter (Kearney et al., 2018). Further difficulties may arise as some vegetation grows to different heights based on environmental variables (e.g. *S. alterniflora*), which may influence NDVI values (Kearney et al., 2018). Using traditional methods, a region-specific regression for AGB may be generated (e.g. Davis et al., 2015) and used with high resolution UAS point cloud data to generate an AGB proxy. This will ultimately reduce impact to the marsh and provide an alternative way to estimate biomass, an indicator of marsh health.

Practical Example: UAS Point Cloud AGB Proxy

Using the following regression developed by Davis *et al.* 2015:

$$y = 0.00005x^3 + 0.0003x^2 + 0.0008x$$

where y stem dry weight (g) and x is average stem height (cm), the average point cloud stem height in each tessellation grid (see **Chapter 4 | Canopy Height Model**) can be used to calculate dry stem weight and determine approximate AGB (g/m²).

Further, stem density estimates can be made once an initial ground truthing comparison is made based on the sensors used. When initially surveying a site, using traditional groundtruthing methods described in ***Practical Example: Ground Truthing Living Shoreline1.2 | Salt Marshes: Monitoring Practices*** may establish the relationship between UAS points and marsh plant density that can be used for future surveys. However, it is important to keep in mind that variations in vegetation growth during UAS surveys and traditional sampling (i.e. peak growing season) may alter the strength of the relationship.

Chapter 6 | Caveats

UAS Systems

The UAS platforms used to test these methods were resources available from the Marine Robotics and Remote Sensing Laboratory. It is possible other platforms and sensors are better designed to monitor salt marshes, and more will become available as technology advances.

Methods

It is important to consider that the methods outlined in this handbook may apply to some, but not all salt marsh habitats. These methods were tested on two living shorelines and two fringing marshes, however, all were located in the same region (Beaufort, NC, USA), and the dominant species was *Spartina alterniflora*. The selected sites were each <0.5 acre, though these methods were developed with monitoring large sites in mind.

Additionally, data were only processed using ArcGIS Pro and Pix4D due to available resources. Therefore, it is possible that processing may be done more feasibly with less expensive software as suggested in Chapter **2.6 | Visual Data Processing**. Furthermore, as technology develops there may be cheaper options for UAS further reducing costs associated with these methods.

These monitoring methods will continue to be refined as processing methods continue to be developed. These methods are intended to be expanded upon and redeveloped to ensure they meet the needs of coastal managers.

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