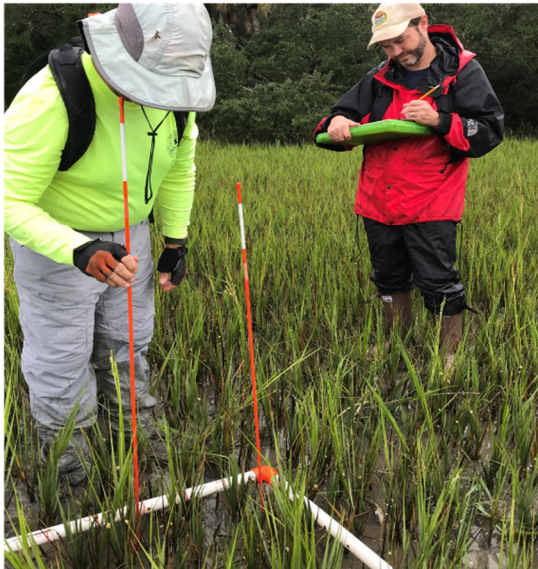


A protocol for monitoring coastal wetlands with drones: image acquisition, processing, and analysis workflows



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A Protocol for Monitoring Coastal Wetlands with Drones: Image Acquisition, Processing, and Analysis Workflows

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Suggested citation: Puckett, B., C. Falvo, C. Deaton, B. Morse, E. Smith, J. Ridge. 2022. A protocol for monitoring coastal wetlands with drones: image acquisition, processing, and analysis workflows. National Estuarine Research Reserve System Science Collaborative. 73pp.

1. Introduction and Objectives

Monitoring plays a central role in detecting climate and anthropogenic impacts on coastal ecosystems. Tidal wetlands exhibit high spatial complexity and temporal variability. Monitoring programs to measure the impacts of stressors and, ultimately, inform management must be designed accordingly. Many modern-day monitoring programs combine ground-based measurements and remotely sensed (e.g., satellite) observations for describing change associated with small- and large-scale spatiotemporal processes. The NERRS System-Wide Monitoring Program (SWMP) uses a similar approach designed, in part, to assess changes in the ecological characteristics and aerial extent of vegetated habitats as an indicator of health and vitality of coastal ecosystems.

To date, a huge investment has been made across the NERRS to assess changes in tidal wetland vegetation through SWMP biotic and sentinel site monitoring, as well as habitat mapping. Biotic and sentinel site monitoring are conducted at spatial scales of meter square permanent plots every 1-3 years. Habitat mapping is conducted at reserve-wide, watershed scales via imagery from satellites or manned flights with 1-30 m pixel resolution every 5-10 years. While both approaches have strengths, important processes at intermediate spatial (i.e., marsh platform) and finer temporal (i.e., storm events) scales may be missed. For instance, permanent plots may miss important spatial heterogeneity such as marsh die-offs. Moreover, repeated ground-based sampling along permanent transects can result in substantial damage to vegetation from trampling. Satellite-derived imagery reduces flexibility in timing (e.g., seasonally, tide stage), can have obstructions from cloud cover, or have insufficient resolution to delineate and detect changes occurring at important ecotones.

Bridging the spatial and temporal scales that limit current monitoring programs is key to improving our understanding of the drivers of change in tidal wetlands. In this context, Unmanned Aerial Systems (UAS, i.e., drones) have considerable potential to radically improve tidal wetland monitoring programs, including SWMP. UAS-mounted sensors offer an extraordinary opportunity to bridge the existing gap between ground-based observations and traditional remote sensing, by providing high spatial detail over relatively large areas in a cost effective way, with customizable sensors, all at an entirely new, user-defined temporal capacity. However, the published research using UAS rarely documents the methodology, workflow, and practical information in sufficient detail to allow others, with little remote pilot and image analysis experience, to replicate them or to learn from their mistakes. A major challenge in the utilization of UAS is that operational standards and data-collection techniques are developed independently, which is neither efficient nor optimal for large-scale data archiving, sharing and the reproducibility of measurements, which are all critical pillars of SWMP.

The objectives for this project were to conduct a regionally coordinated effort, working in salt marshes and mangroves within six National Estuarine Research Reserves in the Southeast and Caribbean to develop, assess and collaboratively refine a UAS-based tidal wetlands monitoring protocol that details image acquisition, post-processing, and analysis workflows. End users have indicated that barriers to the use of UAS technology for applications such as tidal wetlands monitoring span the entire data collection workflow from flight planning best practices, to image analysis procedures, to metadata standards. To address these barriers and to ensure consistent and coordinated acquisition, analysis, and management of data, this document is comprised of three distinct, yet interrelated protocols:

- 1) Operational protocol covering image acquisition and ground-based vegetation surveys.

- 2) Image processing protocol covering post-processing of imagery following acquisition. Post-processing details are provided for Pix4D and Drone2Map photogrammetry software.
- 3) Image analysis protocol covering canopy height estimation, ecotone delineation, total and species-specific percent cover estimation, and NDVI-based estimates of above-ground biomass.

This document is targeted at entry-level UAS users with UAS training and required certifications (e.g., FAA Part 107 certificate) that are interested in exploring UAS as a tool for monitoring coastal wetlands. The document does not include UAS operation guidance or airspace rules and regulations.

2. Operational Protocol

2.1. Image Acquisition

The image acquisition protocol is targeted at users that have UAS training and required certifications (e.g., FAA Part 107 certificate) and, therefore, will not include UAS operation guidance or airspace rules and regulations. All users must ensure all required federal, state and local certifications have been acquired prior to conducting UAS flights. The protocol is written for image acquisition with RGB (Red-Green-Blue spectrum) and multispectral sensors to generate and analyze orthomosaics, digital elevation models, and reflectance-based indices.

Conduct UAS flights to obtain imagery prior to in-situ vegetation monitoring, delineation of ecotones, or harvesting of aboveground biomass. Flight planning parameters (Table 1) are based on project team consensus of general best practices. Use a pre-flight checklist to ensure best results and equipment longevity (Table 2). If using a multispectral sensor with a calibration card, take photos of the reflectance panel before and after each flight (as well as before and after battery swaps), ensuring that the entire reflectance panel is included in the image. Depending on the sensor setup, collection of these additional near infrared and red-edge bands can occur concurrently with RGB sensor collection or with a follow-up flight (i.e., within 30 minutes). A flight log datasheet (S1 in supplementary documents) should be completed in concurrence with the flight to capture relevant metadata. The numbered 'flights' in the log (in time of day, airframe, etc) are meant to capture each paired take-off and landing (i.e., battery swaps or sensor swaps).

Table 1. Mission Planning Parameters

Parameter	Decision
Altitude	50 m altitude; preferably over an area covering ≥ 3 vegetation transects used for ground-based validation surveys.
Time of day	After 7:00 am, before 10:00 am. Generally too much reflection from the marsh platform in the middle of the day; low light too early or too late in day; often windier later in day. If shading is a problem at your site (e.g., upland trees), consider later in the window. Make sure to avoid shadowing on reflectance panels used for multispectral sensor calibration.
Tide	Low tide - greatest exposure of ground; can probably fly c. 1 hr on each side of low tide
Wind conditions	Must be < than 15mph, preferably lower than 10mph. Less movement of vegetation will result in better image processing results.
Cloud conditions	If cloudy, lower wind speed is important. Clouds can help reduce shadowing. If clouds are patchy make sure to use reflectance panels for calibration before and after each takeoff-landing.
Flight Lines	Set up flight lines to be parallel to creeks and perpendicular to elevation gradient; on rising tide, plan flights to begin at water, moving up the elevation gradient, vise versa on falling tides. Check that there are at least 3 transects of photos being captured on the smallest dimension of the mission box and that flight lines extend beyond the area of interest.
Ground control and checkpoints	One ground control point (GCP) per hectare is a reasonable goal (2 GCPs per hectare is ~ optimal). Spread GCPs fairly evenly across the area being flown. While surveying GCPs, take ~50 RTK ground

	checkpoints haphazardly distributed throughout the flight area (spaced from transects and GCPs to avoid redundancy).
Image overlap	75% front and side overlap.
Flight speed	Auto adjust speed on mid setting (recommend 15 mph (6.7m/s) or under), slower if cloudy (under 10 mph (4.4m/s)).
Camera settings	Users can set camera settings if comfortable doing so, but use of auto settings, which is often optimized for mapping, is generally sufficient. Tips for improving image quality if the user is adjusting the camera settings available for DroneDeploy and Pix4DCapture .
Image file	JPEG

2.1.1. Ground Control Points (GCPs)

A minimum of 3 GCP's are required in an image set for photogrammetry software to include them in image processing. A minimum of 5 GCP's is recommended in order to see a significant increase in the absolute accuracy of the project. Having at least 5 GCP's minimizes the measurement inaccuracies and helps to detect mistakes that may occur when inserting the points. Strive for 1 GCP per hectare, but 2 per hectare is preferable. Distribution should be uniform, not linear or clumped distribution. Best results are typically obtained when adhering to a quincunx pattern (i.e., how dots are arranged on the 5-side of a die) for GCP distribution to capture corners and center of the landscape (see the red squares in [Figure 1](#)).

Table 2. Preflight Checklist

Preflight Checklist	✓	NA
Check area of operation for obstructions, people, and property		
Create takeoff/landing exclusion if necessary (signage in public areas)		
Check airframe for signs of damage		
Check aircraft motor bearings spin freely without unusual noise or resistance. Check props for damage, cracks, and tightness		
Install SD Card with sufficient space available		
Remove lens cap/gimbal protection		
Clean lens if necessary		
Power on transmitter. Check transmitter operation and battery level. All switches neutral		
Power up aircraft		
Connect to aircraft		
Check fail safes are appropriate for mission - Return to Home altitude, fence radius, max altitude, minimum battery alert		
Check transmitter/aircraft signal strength		
Check GPS signal		

Check sensor errors/warnings		
Upload appropriate flight plan to UAV		
Calibrate multispectral sensors using radiometric targets (for Micasense sensors)		
Complete flight log upon landing		

When installing GCPs, strive for a relatively stable target. When using PVC poles to support GCPs, the poles should generally be driven c. 1-2 ft into the sediment (and perhaps even deeper in really soft sediment). The height of GCPs above the surface depends on vegetation characteristics--in bare areas, GCPs can be placed directly on the sediment surface. In very dense vegetation, the GCPs will need to be placed at an elevation approximately even with the canopy height. Plan to take various lengths of PVC poles for these different settings. Try not to put all GCPs at the same elevation. GCPs should be 'surveyed-in' by collecting x,y coordinates, as well as elevation by occupying the point of reference (often the center) of the GCP using real-time kinematic (RTK) GPS. Use of virtual reference stations (VRS), as opposed to a base station, should provide sufficient accuracy for our purposes.

See GCP Construction Instructions ([Appendix 1](#)) for guidance on how to construct GCPs.

Quality Note: It is a best practice to QA/QC real-time kinematic (RTK) GPS data by using nearby benchmarks (e.g., surface elevation tables) before and after surveys for assessing the horizontal and vertical position accuracy reported by the instrument during the survey.

Quality Note: If an adequate number of ground control points can not be distributed at a study site, it is recommended that either an UAS equipped with an RTK system is used to improve data collection accuracy or a water level measurement is taken at a marsh site to improve accuracy during post-processing (see [GCP Caveat 2b](#) for details).

2.1.2. Vertical ground-truth points (optional, but recommended):

Vertical ground-truth points, which are referred to as 'checkpoints' in this protocol, provide an additional means to validate and assess the accuracy of the digital elevation models produced from image processing. If time permits, it is IDEAL to collect ~5-10 ground checkpoints per hectare using RTK GPS. The checkpoints should be haphazardly distributed throughout the entire area over which imagery will be collected (see [Figure 1](#)). Checkpoints can be taken during the course of surveying GCPs, but should not all be concentrated by GCPs or permanent plots along transects to avoid redundancy.

Figure 1. GCP, Checkpoint and Vegetation Plot Locations

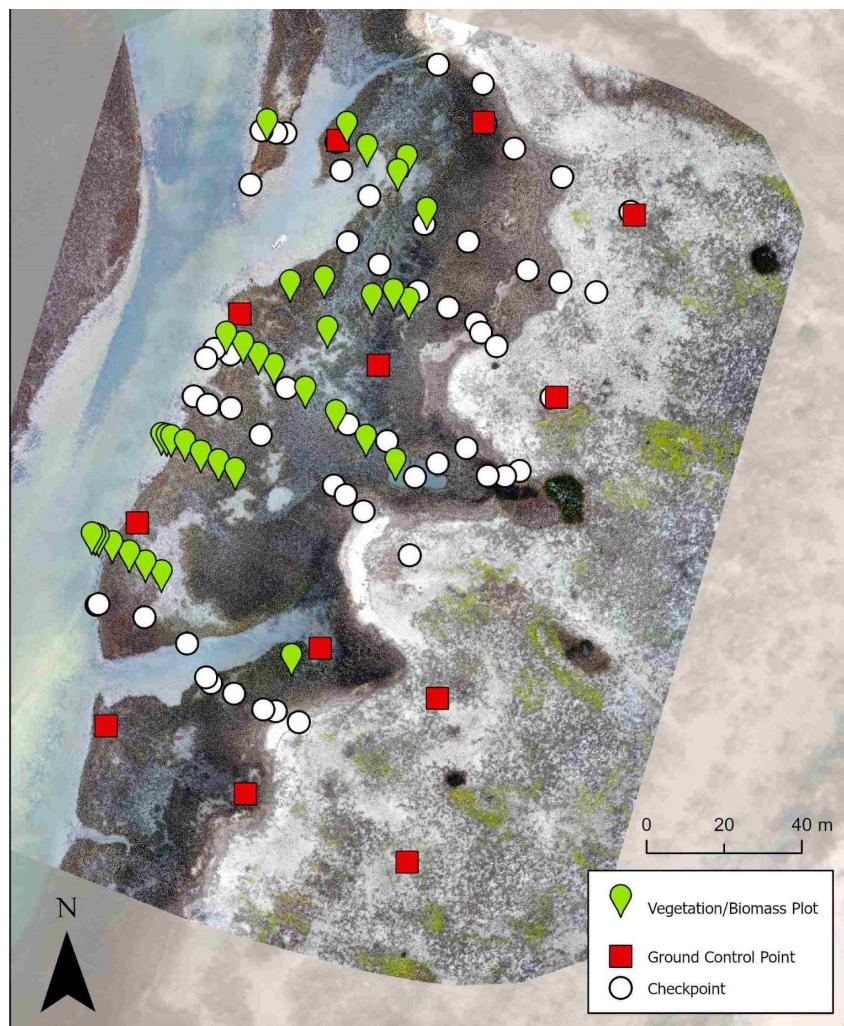


Figure 1. Location of ground control points, checkpoints, and vegetation/biomass plots at NCNERR in February 2021. Notice, checkpoints are distributed throughout the survey area and elevation gradient. Vegetation and biomass plots were also surveyed using RTK GPS, so checkpoints were offset from those plots in many cases to reduce redundancy.

2.1.3. Mission Planning

Mission planning is critical to acquiring quality imagery. A number of parameters must be considered during the mission planning process including, but not limited to, flight altitude, weather conditions, and flight lines. The mission planning parameters agreed on by the project team based on experience and general best practices are provided in [Table 1](#).

2.1.4. Preflight and Equipment Checklists

Begin preparing for image acquisition at least 1-2 days prior to actually conducting the flights (see [Recommended Sampling Schedule](#) below). During this time, it is a good idea to check for software/firmware updates for your specific drone and ensure flight patterns and camera settings are correct for the mission to be conducted. Remember to charge all batteries including: UAS (airframe and controller) batteries, RTK antenna and receiver batteries, ground station (i.e., ipad) batteries. Also

remember to check memory cards and check airspace (NOTAM or LAANC). Be sure to develop an equipment checklist (S2-S5 in supplementary documents includes several examples) to ensure all necessary items are packed for field work. A general preflight checklist to be used while onsite prior to conducting the mission is provided in Table 2. In areas with high humidity, it is often necessary to allow equipment, particularly sensor lenses, to acclimate prior to flights.

2.1.5. Collecting Multispectral Imagery

There are different methods of collecting and calibrating multispectral imagery, the process is dependent upon the sensor used and light sensing equipment available.

Calibration. The use of a radiometric calibration target enables Pix4D to calibrate and correct the images to reflectance according to the values given by the reflectance target. When using reflectance targets, their images must be imported for processing, like regular images, in order to be used for radiometric correction. Calibration images in the field should be stored in a separate subfolder. Sensors that require pre and post-flight calibration images (e.g., most MicaSense sensors) require further separation of calibration images into respective subfolders.

See [MicaSense documentation on calibration](#) and [Pix4D's guidance on Radiometric Calibration Targets](#) for more information.

Targetless workflow. Setups such as the Parrot Sequoia+ provides absolute reflectance measurements without reflectance targets. See [Parrot Sequoia+ and Pix4D Documentation](#) to learn more.

Sunshine sensors. The use of a sunshine sensor improves the overall correction results by including more information about the illumination on the field (sun irradiance and, when supported by the hardware, sun angle). For supported camera models, this information is stored in the image EXIF tags and automatically found by Pix4Dfields.

2.2. Ground-based Vegetation Surveys

Ground-based vegetation surveys serve as a validation of image-based estimates for the parameters of interest (e.g., percent cover). Generally follow the standard SWMP protocols¹ for quantifying total percent cover of vegetation, percent cover by species, and canopy height. The general approach used here consists of sampling permanent plots located along fixed transects. Transects are often oriented across a gradient (e.g., elevation). For the purposes of validating image-based estimates, aim to survey ≥ 30 1m² plots (or sub-plots in the case of mangrove sampling design²).

Quality Note: Vegetation surveys MUST be conducted within 1 week following image acquisition (see [Recommended Sampling Schedule](#) for full timeline).

¹ Moore, K. 2009. NERRS SWMP Bio-Monitoring Protocol: Long-term Monitoring of Estuarine Submersed and Emergent Vegetation Communities. NERRS Technical Report. 14pp.

² Moore, K. 2009.

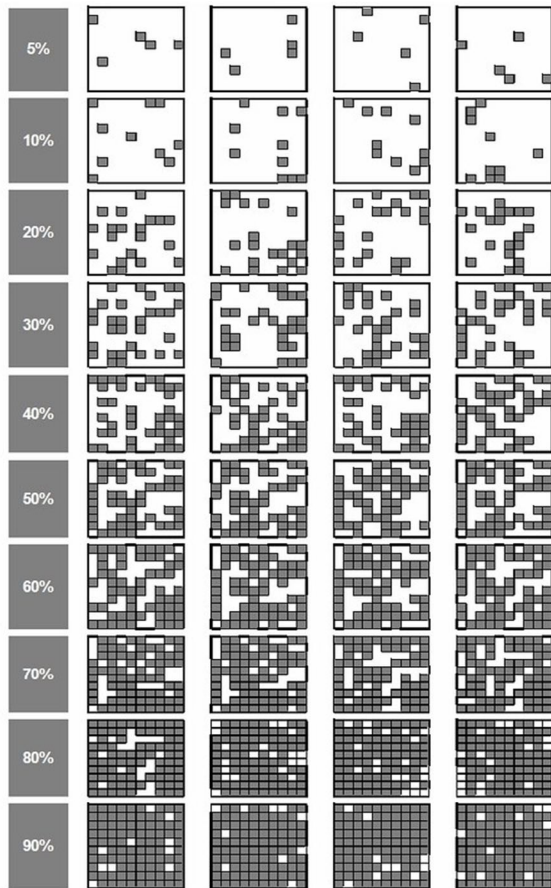
2.2.1. Species-Specific Percent Cover

To quantify species-specific percent cover, each permanent plot (or sub-plot) is sampled non-destructively. Percent cover can be quantified visually or using the point intercept method (visual estimates are required; point intercept is optional).

For **visual percent cover**, cover estimates for species and other cover types should use 10% cover intervals, except at the low end where a 5% interval should be used (see [Figure 2](#) for a reference percent cover guide). For species or cover types that are present, but lower than 5%, indicate their presence by designating a percent cover of 1%.

Quality Note: Include cover estimates for 'dead cover' as well, which will include plants/wrack with no live (green or yellow) plant tissue.

Figure 2. Reference Percent Cover Guide (using 10% intervals)



If also using the **point intercept method**, lower a thin rod perpendicular to the substrate at 50 systematically spaced grid 'nodes' within a 1m² quadrat. Each species or cover type, including unvegetated cover types (e.g., bare ground, oyster shell) that the rod intercepts at each node is recorded as a 'hit'. Multiple species can be present at a given node; record a hit for every species the rod intercepts at each node. Only record bare ground if the rod hits no vegetation or other cover type at all (e.g., oyster shell). After sampling all 50 nodes, the total number of 'hits' for each species and cover type is tallied and multiplied by 2 to give percent cover (0-100%). Be sure to visually inspect the entire

plot and indicate all species and cover types that are present within the plot, but do not intersect a node by designating a percent cover of 1% (vs lowest cover for a hit = 2%).

2.2.2. Canopy Height

Canopy Height should be measured following percent cover sampling. Measure maximum canopy height and average canopy height in each plot or sub-plot. Measure **maximum canopy height** by measuring the height above the sediment surface of the three tallest points in the canopy within each plot. Measure maximum canopy height in two ways: 1) straightening the stems and stretching the leaves (i.e., pulling the plant slightly upwards) of marsh grasses to follow the SWMP guidelines and 2) not straightening stems nor stretching leaves, which is more reflective of what the sensor ‘sees’ and the digital surface model depicts.

To estimate **average canopy height** (marsh vegetation only), measure the height above sediment of ten randomly selected plants of the dominant species in each plot. Again, do this in two ways:

1) straightening the stems and stretching the leaves (i.e., pulling the plant slightly upwards) of marsh grasses to follow the SWMP guidelines and 2) not straightening stems nor stretching leaves.

After quantifying cover and canopy height, obtain latitude, longitude, and elevation at the center of each permanent vegetation plot using RTK GPS. Use of virtual reference stations (VRS) during RTK surveys should provide sufficient accuracy for our purposes. If this sampling is being combined with regularly scheduled SWMP biomonitoring sampling, stem density data should also be collected. This project did not use stem density data.

2.2.3. Above-ground biomass

Harvest salt marsh vegetation to measure above-ground biomass (g/m^2) for two vegetation types: monoculture stands of *S. alterniflora*, and the mixed species vegetation stands that tend to occur at higher elevations in southeastern salt marshes (e.g., short-form *S. alterniflora* mixed with *Distichlis spicata*, *Salicornia* spp., and *Spartina patens*). Harvest biomass in an area proximal to one or more of your transects to ensure representativeness, but far enough removed such that biomass harvesting does not interfere with your long-term monitoring site.

Quality Note: Biomass harvest MUST be conducted within 1 week following image acquisition (see [Recommended Sampling Schedule](#) for full timeline).

Within each vegetation type, collect aboveground biomass within a 0.25m^2 quadrat by clipping all standing vegetation to the soil surface, excluding fallen litter. No need to count or measure plants before clipping. During the target time period (early summer), most biomass should be ‘live’ (i.e., any rooted plant with green or yellow tissue). In the event that there is dead biomass within plots (i.e., no live tissue on plant), it should be clipped, stored, processed, and weighed separately from ‘live’ biomass. Collect a minimum of 12 quadrats, located along the marsh elevation gradient to span a gradient of stem density and plant height for each vegetation type. Aim to get at least three plots for each vegetation type that cover each of the extremes--extremely low biomass and extremely high biomass (leaving c. 6 plots for each vegetation type with ~ average biomass). Store clippings from each plot in separate, labeled bags (e.g., trash bags). Using RTK GPS, obtain the latitude, longitude, and elevation

from the center of each biomass plot to allow direct plot-level comparisons with derived spectral data. Upon returning to the lab, freeze clippings unless samples are planned to be processed within 24 hours.

To process clipped vegetation from each plot, wash plants using $\leq 2\text{mm}$ mesh to remove sediments, but retain plant material. Allow plant material from each plot to air dry in separate trays before bagging in brown paper bags (e.g., grocery bags). Dry at 60°C for 72 h. It is likely that plants will have to be dried in 2-3 batches to avoid overcrowding a single drying oven. Once dried, weigh plant material from each plot to the nearest 0.1 g to calculate grams dry weight per m^2 .

2.2.4. Delineating ecotones

Using RTK GPS, survey the following ecotones: wetland-water edge, low marsh-high marsh, and wetland-upland.

The **wetland-water edge ecotone** is defined as the most landward point where vegetation is absent. Wetland-water edge delineation is not required if doing so will be overly destructive at your site, but please conduct this activity if possible. One option may be to survey this ecotone via boat during high tide and/or using an [offset pole kit](#) to avoid walking near this ecotone.

The **low marsh-high marsh ecotone** will be defined where the dominant species shifts from low marsh species (e.g., *Spartina alterniflora*) to high marsh species (e.g., *S. patens*). This is likely to be a somewhat subjective determination on the fly (no pun intended!), so use your expert knowledge of the site for delineating this boundary as accurately as possible.

The **wetland-upland ecotone** will be defined as the location where wetland species are no longer the dominant species (based on cover). If there are additional ecotones of importance at your sentinel site (e.g., wetland vegetation-salt pannes or wetland vegetation-ponds) delineate those with RTK GPS as well.

Set RTK units to record at 0.5m intervals. To delineate boundaries and ecotones, we will walk parallel to the boundary of interest for at least 50 meters. It will be helpful to mount your RTK receiver on a backpack ([example backpack](#)) for ecotone delineation. We are most concerned with horizontal coordinate accuracy during ecotone delineations, so position the receiver on the side of the backpack closest to the ecotone of interest and do your best to ensure the receiver is directly over the ecotone while walking. The elevation of RTK receivers mounted on backpacks will not be very accurate given points will be recorded at different parts of the surveyor's stride, as we sink in the mud, etc. Accurate elevations are not a priority for ecotone delineations.

2.3. RTK GPS surveys

RTK surveys are conducted to get x,y coordinates and elevation of the following:

- 1) Ground control points
- 2) Ground checkpoints
- 3) Center of permanent plots along transects
- 4) Center of biomass plots
- 5) Along select ecotones (x,y coordinates only)

Quality Note: It is a best practice to QA/QC real-time kinematic (RTK) GPS data by using nearby benchmarks (e.g., surface elevation tables) before and after surveys for assessing the horizontal and vertical position accuracy reported by the instrument during survey.

It is important that RTK surveys be conducted in association with vegetation surveys using the same coordinate system, datum and geoid used to survey GCPs and checkpoints during image acquisition. This information should be included in the readme.txt file (S6 in supplemental docs folder) so that it can be later incorporated into the georeferencing step of the image processing (an example readme.txt file is provided in S6 in supplementary documents). The contents of the readme file should include the following:

1. UAS platform used
2. Sensor(s) used
3. Coordinate system used for RTK surveys of GCPs and checkpoints. Coordinate system can be obtained from GPS controller (Trimble units) or Software/App (Emlid units).
 - a) Coordinate system: e.g., United State/US Continental or US State Plane or UTM
 - b) Zone (if applicable)
 - c) Datum: e.g., WGS 1984 or NAD 1983
 - d) Geoid: e.g., G12AUS
 - e) Units (distance): e.g., meters

General Note: Using an RTK GPS to derive a NAVD88 or other orthometric height requires both an ellipsoid height (referenced to a geometric datum (e.g. NAD 83) and geoid height (referenced to a hybrid geoid model (e.g. GEOID12A)).

2.4. Recommended Sampling Schedule

To maximize efficiency while in the field, an example sampling schedule is provided below. Site specificity will determine if this schedule can work at your site. For instance, at large sites where multiple flights have to be conducted to cover the entire site, it may not be possible to, for example, conduct flights and harvest biomass in the same day. Likewise, if your site consists of multiple transects spaced out over large distances, a single flight day might be required for each transect. However, vegetation surveys and biomass harvest **MUST** be conducted within 1 week following image acquisition in order for UAS imagery to reflect the conditions measured in the ground-based surveys.

The recommended sampling schedule involves conducting all flights and vegetation sampling within the same week, starting with UAS flights, then proceeding with biomass harvesting and other vegetation sampling. Details are as follows:

- a) 1-2 days before field work:
 - i) Check for software/firmware updates for drone, make sure flight patterns and camera settings are correct. Charge UAS and RTK batteries, check memory cards, and check airspace.
- b) Field day 1-2:
 - i) Deploy GCP's and survey with RTK GNSS

- ii) Obtain ~50 randomly distributed checkpoints across the entire site with RTK GNSS
- iii) Perform pre-flight checklist
- iv) Fly sentinel site at 50m
- v) Harvest biomass plots, surveying center of plot with RTK
 - 1) *S. alterniflora* monoculture plots x 12
 - 2) Mixed spp. vegetation plots x 12
- c) Field day 2-3 (MUST be within 1 week of imagery acquisition):
 - i) Permanent plot transect monitoring
 - 1) Species specific percent cover
 - 2) Maximum canopy height
 - 3) Average canopy height
 - ii) Ecotone delineation
 - 1) Wetland-water
 - 2) Low marsh-high marsh
 - 3) Wetland-upland

2.5. Data File Structure and Naming Convention

For data management purposes, it is important that a consistent file structure and naming convention is established to prepare for the image processing phase of the workflow. The data, data products, and metadata are archived using the file naming conventions and file structure below:

Abbreviations used in this naming convention:

- Date = 6 digit date (YYMMDD; e.g., 210914 for September 14, 2022)
- Reserve = 3 letter abbreviation for NERR site (XXX; e.g., SAP for Sapelo Island NERR)
- UAS designation = 1 letter abbreviation for airframe (z; e.g., v - Mavic, t - Matrice, p - Phantom, i - Inspire)
- UAS sensor type = 1 letter abbreviation for sensor type (e.g., m - Multispectral, o - Optical (RGB))

Suggested File Structure:

- Drone_the_SWMP/
 - NERRS_drone_marsh_monitoring_SOP.docx
 - /XXX_Field_and_UAS_Survey_Archive
 - /Field_Vegetation_Survey [contains field survey metadata, collected data, RTK survey data and select documents]
 - FieldMetadata_XXX_YYMMDD.m.docx
 - /field_measurements
 - YYMMDDXXX_permanent_plot_veg_survey.xlsx
 - YYMMDDXXX_above_ground_biomass.xlsx
 - /ecotones
 - YYMMDDXXX_wetland-water_rtk.csv
 - YYMMDDXXX_low-high_rtk.csv
 - YYMMDDXXX_wetland-upland_rtk.csv
 - /field_rtk_data
 - YYMMDDXXX_bio_plots_rtk.csv

- YYYYMMDDXXX_veg_plots_rtk.csv
 - YYYYMMDDXXX_checkpoint_rtk.csv
 - YYYYMMDDXXX_gcp_rtk.csv
- /field_documents
 - YYYYMMDDXXX_readme.txt
 - YYYYMMDDXXX_flight_log.docx
- /UAS_Survey [contains image metadata, raw imagery, image products, and select documents]
 - ImageMetadata_XXX_YYYYMMDD.m.docx
 - /uas_imagery
 - /YYYYMMDDXXXzo
 - /img
 - (raw rgb images (.tif files))
 - /YYYYMMDDXXXzm
 - /img
 - (raw multispectral images (.tif files))
 - /calibration
 - calibration_coefficients.txt
 - /pre-flight
 - (Pre-flight calibration images (.tif files))
 - /post-flight
 - (Post-flight calibration images (.tif files))
 - /uas_products

General Note: Upload the four files associated with each georeferenced TIFF (.tif, .prj, .tfw and .ovr). Use the same naming convention for all files.

Multispectral Note: For multispectral imagery, include all files for each band (e.g., blue, red edge, nir, etc.)

 - /orthomosaic
 - YYYYMMDDXXXzo_ortho.tif
 - YYYYMMDDXXXzo_ortho.prj
 - YYYYMMDDXXXzo_ortho.tfw
 - YYYYMMDDXXXzo_ortho.ovr
 - /elevation_models
 - YYYYMMDDXXXzo_dsm.tif
 - YYYYMMDDXXXzo_dsm.prj
 - YYYYMMDDXXXzo_dsm.tfw
 - YYYYMMDDXXXzo_dsm.ovr
 - YYYYMMDDXXXzo_dtm.tif
 - YYYYMMDDXXXzo_dtm.prj
 - YYYYMMDDXXXzo_dtm.tfw
 - YYYYMMDDXXXzo_dtm.ovr
 - /ndvi
 - YYYYMMDDXXXzm_ndvi.tif
 - YYYYMMDDXXXzm_ndvi.prj

- YYMMDDXXXzm_ndvi.tfw
 - YYMMDDXXXzm_ndvi.ovr
- /uas_documents
 - /flight_plans
 - YYMMDDXXXzo_flight_plan.pdf
 - YYMMDDXXXzm_flight_plan.pdf
 - /quality_reports
 - YYMMDDXXXzo_quality_report.pdf\$
 - YYMMDDXXXzm_quality_report.pdf\$
 - /field_documents
 - YYMMDDXXX_readme.txt
 - YYMMDDXXX_flight_log.docx

3. Image Processing in Pix4D

The image processing protocol for Drone2Map is available in [Appendix 2](#).

3.1. Adding Photos/Camera Calibration

New Project

- Create a new project in a specified file location. Ensure naming convention is clear.

General Note: Once the file name and location has been established, making changes to either will result in Pix4D no longer being able to recognize the project or input images.

Select Images

- Add images using the Add Images... button to add images individually or Add Directories... to add an entire folder of images. If the drone has separate RGB and multispectral sensors, the two imagery sets should be processed independently.
 - If multiple flights were flown to cover one study area, all images from all flights can be imported at the same time, as long as the areas covered by the flights are continuous and there is sufficient overlap between the flights (if this is not the case, the software will not be able to stitch the images together).

Multispectral Note: For multispectral imagery with calibration card images, calibration images should be added along with the flight images. One calibration card image per sensor is required. If multiple calibration images were taken (for example, pre-flight and post-flight images), a set (one image per sensor) must be selected to serve as the calibration images for the project (the image set with lighting conditions most like the majority of the flight conditions should be chosen). If the calibration image set is in its own directory, this directory can be added by clicking Add Directories. If individual calibration images need to be hand selected, this can be done by clicking Add Images. Once added, Pix4D should automatically recognize the QR code in each calibration image and extract the correct reflectance value. Calibration settings should be checked in step 3 before processing final outputs to ensure reflectance values are correctly carried over. (See [Processing Step 3 > Index Calculator](#) options for further instructions).

Image Properties

- Pix4D will read EXIF metadata from images upon loading them in; metadata including camera model information and geolocation information will be displayed in the Image Properties window.
- Pix4D uses the image geolocation information to position the cameras correctly relative to the modeled surface; it is recommended that the automatically recognized image geolocation coordinate system is left as is.
- Click the Next button to proceed to the next step where the GCP and output coordinate systems can be selected.

Output Coordinate System

There are different coordinate system setting options that vary based on whether image geolocation and GCPs were used during image acquisition. See Pix4D's guidance on [Selecting Coordinate Systems](#) for more information. The following steps are written for a process that uses both image geolocation and GCPs.

General Note: It is not necessary, but recommended that the output coordinate system be designated the same as the GCP coordinate system. Establishing the desired output coordinate system at this stage avoids having to adjust, reoptimize and reprocess outputs in later stages. It is possible, however, for both the horizontal and vertical coordinate systems to be edited at later stages, see Pix4D's documentation on [how to access editing options](#) for image geolocation, GCPs and output coordinate system information.

- The image geolocation coordinate system recognized in the previous step will be displayed as the Selected Coordinate System in the Select Output Coordinate System window.
- If the automatically detected coordinate system (the image geolocation coordinate system) is not the desired output coordinate system, both horizontal coordinate systems can be adjusted at this stage.
 - The horizontal coordinate system can be specified by selecting Known Coordinate System and typing its name. It can also be selected from a list or inputted from a PRJ file by checking the Advanced Coordinate Options box and choosing one of the search options.
 - The vertical coordinate system can be specified by selecting the Advanced Coordinate Options box.
 - If the desired vertical output coordinate system is based on one of the MSL (mean sea level) geoids listed in the first option, one of these can be selected.
 - If the desired coordinate system is not one of the listed MSL geoids, but has a known height above the GRS 1980 ellipsoid (based off of NAD83(2011)), that height can be manually inputted by clicking the second option. [NOAA's online vertical datum transformation \(VDATUM\) tool](#) is a useful means of determining the offset between a common coordinate system or datum (e.g., NAVD88) and NAD83(2011) (the datum the GRS 1980 ellipsoid is based off of).
 - If none of the geoids in the first option match the desired vertical coordinate system, and the height above the GRS 1980 ellipsoid is not known, the Arbitrary option can be selected, which will result in no adjustments being made to the inputted Z values. An arbitrary vertical coordinate system will display as (2D) in the coordinate system name.

General Note: Due to the limited options Pix4D provides for vertical coordinate systems, most projects require designating the vertical coordinate system as arbitrary and then doing a manual adjustment of GCP height. This workaround comes into play after [GCPs are imported](#). The full workaround is documented in the GCP caveat #1 section of this protocol ([Appendix 3](#)).

Processing Options Template

- Select the appropriate template for the type of imagery being processed. The 3D Maps template is standard for processing RGB imagery, while the Ag Multispectral template is standard for processing multispectral imagery. The outputs used to conduct analyses in this protocol are orthomosaic, digital terrain model, digital surface model, and normalized difference vegetation index (NDVI; multispectral sensors only) rasters. Note that specific sensors may have Pix4D templates available online to import (e.g. the sentera double 4k sensor).
 - To learn more about which outputs each template produces, refer to [Pix4D's documentation](#).

Quality Note: Ensure that Start Processing Now is NOT selected in the bottom, right corner. If it is, the project will begin processing all 3 steps immediately. Settings should be adjusted prior to processing. Click Finish to proceed to Processing Options.

3.2. Photo Alignment and Optimization

Set up the initial processing of the project (Step 1) by navigating to Process > Processing Options. The default settings for this step are recommended, however each option for both RGB and MS (multispectral) imagery is explained below. Read more about what happens in the initial processing step in [Pix4D's documentation on Step 1](#).

3.2.1. Processing Step 1: Initial Processing

General

- Keypoints Image Scale: *The Keypoint Image Scale defines the image size at which keypoints are extracted, with Full using the full image scale and Rapid using a reduced image scale for faster processing.*
 - RGB and MS default: **Full**
- Quality Report Orthomosaic: *A preview of the orthomosaic can be displayed in the quality report, a record that outputs processing details and results.*
 - RGB and MS default: **Checked box**

Matching

- Matching Image Pairs: *Matching Image Pairs allows the user to optimize the processing for flights flown in an aerial grid (Option: Aerial Grid or Corridor), free-flown (Option: Free Flight or Terrestrial), or with other specific parameters (Option: Custom).*
 - RGB and MS default: **Aerial Grid or Corridor**
- Matching Strategy: *Geometrically Verified Matching is more computationally expensive, but can be more rigorous by excluding geometrically inconsistent matches.*
 - RGB default: **UNchecked box**
 - MS default: **Checked box**

Quality Note: Although Geometrically Verified Matching is not a default option for RGB imagery, this is one of Pix4D's recommendations for fixing a project that doesn't get enough matches after the first processing step (this can occur in study sites with homogeneous features like dense canopies or grass fields). See Camera Optimization section of Quality Check Table for more details ([Appendix 4](#)).

Calibration

- Targeted Number of Keypoints: *Keypoints are distinguishable features used to tie overlapping images together.*
 - RGB default: **Automatic**
 - MS default: **Custom (10,000)**
- Calibration:
 - Calibration Method: *Standard calibration, the default in most processing templates; Alternative calibration, recommended for aerial nadir images with accurate geolocation, low texture content, and relatively flat terrain (Alternative is the default setting when using the Ag multispectral template); and Accurate Geolocation and Orientation is recommended for projects with very accurate geolocation and orientation information attached to all images.*
 - RGB default: **Standard**
 - MS default: **Alternative**
 - Internal Camera Optimization:

- RGB and MS default: **All**

Quality Note: Selecting All Prior and reprocessing output can help with camera optimization quality if the quality report indicates a greater than 5% relative difference in internal camera parameter optimization. The setting forces the internal parameters to be closer to the initial values. See Camera Optimization section of Quality Check Table for details ([Appendix 4](#)).

- External Camera Optimization:
 - RGB and MS default: **All**
- Rematch:
 - RGB default: **Automatic**
 - MS default: **Custom** (Rematch box **checked**)

Quality Note: The Rematch option can be used to improve reconstruction if a project has an error in the Dataset section of the quality report. See Dataset section of the Quality Check Table for further details ([Appendix 4](#)).

- Pre-Processing:
 - RGB and MS default: **not used** except with Parrot Bebop images
- Export:
 - RGB and MS default:
 - Camera Internals and Externals, AAT, BBA box **checked**
 - Undistorted Images box **UNchecked**

Running Step 1 and Checking Outputs

It is recommended that Step 1 is run first on its own and the [Initial Quality Check](#) (below) is done prior to running steps 2 and 3 to ensure best results.

- Run Step 1 by checking the 1. Initial Processing box, unchecking boxes for steps 2 and 3, and clicking Start.

Initial Quality Check

Once the initial processing step is complete, a rayCloud view becomes available (visible when rayCloud icon is selected along the left sidebar) and can be used to visualize and spot check the generated point surface (shown as a broken surface of points floating in space) as well as initial and computed camera positions (shown as blue and green circles). These features can be visualized or hidden by checking or unchecking boxes within the left sidebar Layers menu. The rayCloud view can be navigated and adjusted by selecting the different View and Navigation options in the top icon bar (see Pix4D's guidance on [How to Navigate 3D View](#)).

A quality report will also be generated at this stage and will provide processing details and accuracy measures for each output. The quality report can be accessed either by selecting the checkmark icon in the Process top icon bar or navigating to Process > Quality Report. (If quality report is not a selectable option, navigate to Process > Generate Quality Report).

Quality Note: If any settings were adjusted following the initial quality check, the project should be Reoptimized OR Rematched and Optimized. Any disabled or uncalibrated images will not be taken into account in either of these reconstruction options. See below for specifications on which option to use:

- **Reoptimize:** (Process > Reoptimize) This reoptimizes the camera positions and internal camera parameters. Does not compute more matches between the images, therefore it is a 'fast step' that improves the accuracy of the project.
 - When to Use:
 - After adding GCP's, MTP's, and/or Checkpoints
 - After changing the coordinate systems
 - After disabling Images
- **Rematch and Optimize:** (Process > Rematch and Reoptimize) This computes more matches between the images, thus creating more Automatic Tie Points, and reoptimizes the internal and external camera parameters. This option is more time consuming but can improve the percentage of camera calibration and the reconstruction of the model. Using this feature for large projects (500+ images) will significantly increase the processing time.
 - When to Use:
 - After manually calibrating cameras that were not initially calibrated
 - For difficult projects where few matches were initially found
 - To merge individual projects that do not share common images
 - To optimize Step 1. Initial Processing by rematching images.

General Note: If Step 2. Point Cloud and Mesh and Step 3. DSM, Orthomosaic and Index have been processed, their result files will be deleted. These files should either be saved in a different folder/file location or the steps should be repeated as necessary.

3.2.2. GCP Registration

Importing GCPs

After Step 1 is complete, ground control points (GCPs) can be imported and incorporated into the project. Refer to the See Pix4D's documentation to learn more about [GCPs](#).

- Navigate to the GTP/MTP Manager icon in the Project toolbar.
- Ensure that the GCP coordinate system is correct. Click Edit... to adjust the horizontal and/or vertical coordinate system.
- Import an existing spreadsheet (CSV or TXT file) containing GCP locations (X, Y and Z) using the Import GCPs... button in the GCP manager.

Quality Note: The imported spreadsheet should contain only longitude/easting (X), latitude/northing (Y), and altitude (Z) values (the units should match that of the coordinate system being used, e.g., decimal degrees for WGS84). Also note that GCPs can also be imported manually at this stage. Refer to Pix4D's documentation on [Importing GCPs](#) for more information.

- Once GCPs are imported into the GCP manager, click OK to proceed to GCP registration.
- GCP icons will display in rayCloud view as blue circles with vertical lines coming out of the center of them. Each GCP will be listed in the left sidebar, in the Layers menu nested under the Tie Points > GCPs / MTPs drop downs.

Quality Note: Correctly positioned GCP icons allow Pix4D to triangulate and identify the actual GCP targets in the aerial imagery, which is necessary for GCP registration. If GCPs are positioned too high above the surface (i.e., above the camera positions), no images will show up in the right sidebar upon

selecting a GCP in the left layer menu. If this is the case, the GCP height should be manually adjusted in order to proceed with GCP registration. See [GCP Caveat # 1](#) for further instructions.

- Upon selecting one of the GCPs from the Layers menu on the left, both Selection (GCP location and other metadata) and Images (images in which Pix4D has found the GCP target) information should be shown in the right hand sidebar.

Registering GCPs

The following process should be followed for each registration image, for each GCP:

- With GCP selected (either in the Layers sidebar menu on the left or by clicking on the GCP icon in the rayCloud view), hover mouse over an image displayed in the Images window in the right sidebar.
- Zoom out (either by using the mouse or the zoom buttons in the Images window) until the GCP target (usually a black and white cross) becomes visible in the image. Once the GCP is visible, zoom closer to it by centering the mouse over it and zooming in. Zoom in until the center of the target can be confidently identified with a single mouse click.

Quality Note: The higher the zoom level on the GCP, the higher confidence Pix4D assigns to the location of that GCP and the more it is taken into account when modeling the surface. The size of the yellow circle reflects the zoom and confidence level.

- Once at the desired zoom level, click once in the center of the target. A yellow cross centered in a yellow circle will appear in the image and the Number of Marked Images (in the Selection window) will increase by one. An image can be clicked more than once to adjust the cross's position.

Quality Note: It is recommended that at least 5 images are registered for each GCP.

Multispectral Note: When processing multispectral imagery, it is important that images from a variety of 'image sets' are registered. In the file naming system, an image set is usually the number before the file extension (e.g., in file 'DJI_0713.JPG', 0713 is the image set number). An image set number represents a unique camera position above the ground. When capturing multispectral imagery, each lens of a camera will snap an image at each camera position. Each GCP must be registered in images from different image sets/camera positions in order for Pix4D to be able to triangulate the GCP locations. One band from each image set can be registered and counted in the minimum of 5 registered GCP images, it does not matter which band is registered. Also note that thermal imagery is often not visually sharp enough to identify GCP target centers, so thermal images can be ignored in this process.

- Once this process is repeated for enough images (varies for each project, but usually after 2-3 images have been registered), Pix4D will begin to automatically recognize the location of the GCP target in the other images (Pix4D's estimate of the center of the GCP target is indicated by a green cross). For best results, continue registering images (i.e., clicking the visible center of the GCP target, thereby adjusting Pix4D's estimate) until the green cross appears as close to the center of the GCP targets as possible.

Quality Note: If there is a thumbnail image where the GCP target is not visible (e.g., the image was taken near the GCP but the target was not captured in the image), do not click in the image, simply ignore it and move onto another image.

- Once enough images have been registered, click Apply in the Selection window in the right sidebar to apply changes. A green GCP icon should appear, representing an adjusted GCP location based on the registration.
- Repeat the registration process for each GCP.

Quality Note: If a registration process was completed after manually adjusting GCP height ([see GCP Caveat #1](#)), the vertical GCP coordinate system must be set back to Arbitrary before reoptimizing.

- Once all GCPs are registered and GCP coordinate system is set appropriately, the project can be reoptimized by selecting Process > Reoptimize. A message will pop up saying that by overwriting the results from the first step (the tie point cloud) will be regenerated. This is expected and desired, as the registered GCPs should increase the accuracy of the tie point positions. Click OK.

Output Quality Check

Once the tie point cloud has been reoptimized, examine the outputted surface, camera positions and GCP icons in the rayCloud view.

- The point surface should match the general topography of the study site (e.g., flat or hilly).
 - Altitudes can be spot checked by clicking on individual tie points on the modeled surface, and reading the Z value reported in the Computed Position output (in the right sidebar under the Selection dropdown).

Quality Note: If the point surface does not reflect the expected topography of the study site, this may be due to an insufficient number and/or distribution of GCPs (e.g., having three total GCPs for a site arranged in a line, resulting in accurate tie point elevations for a strip of the study site but inaccurate elevations in the rest of the site). If this is the case, manual GCPs should be added. See the [GCP Caveat #2](#) for full details.

- The camera position icons should be positioned above the point surface at roughly the same altitude as the drone was flown (e.g., if images were collected via a 50m flight, seeing that point surface is ~.5 m and computed camera position is ~51 m is a good indication that cameras are positioned correctly relative to surface).
 - Camera position altitudes can be spot checked by clicking either the green (computed) or blue (initial) camera position icons in the rayCloud view and reading the Z value reported in the Computed Position output (in the right sidebar under the Selection dropdown).
- The GCP icons should be positioned on top of the point surface at their expected altitudes.
 - GCP icon altitudes can be spot checked by selecting a GCP from the left Layers menu or a GCP icon in the rayCloud view, and reading the Z value reported in the Computed Position output (in the right sidebar under the Selection dropdown).
- Once the point cloud has been spot checked, the georeferencing section of the Quality Check Table ([Appendix 4](#)) in the Quality Report should be checked to ensure there is no significant GCP error.

3.3. Creating Densified Point Cloud, Orthomosaic and Elevation Models

3.3.1. Processing Step 2. Point Cloud and Mesh

Processing Step 2 increases the density of the points of the 3D model created in step 1, which leads to higher accuracy of both the DSM and orthomosaic. Processing options allow the user to define parameters for the point cloud densification, classify, and export the point cloud. Most of the default settings are recommended for Processing Step 2. However, alternate settings may be desired and are

briefly described below. See Pix4D's documentation on [Processing Step 2. Point Cloud and Mesh](#) for further details.

Point Cloud

- Point Cloud Densification
 - Image Scale: *The Image Scale defines the image scale at which dense cloud points are generated. The multiscale option computes additional 3D points on multiple image scales; this option is useful for computing additional points in vegetated areas.*
 - RGB and MS default: **½ (Half image size)**, Multiscale **box checked**
 - Point Density: *The Point Density describes the desired density of the point cloud, higher density being more computationally expensive.*
 - RGB default: **Optimal**
 - MS default: **Low (Fast)**
 - Minimum Number of Matches:
 - RGB and MS default: **3**
- Point Cloud Classification: *Point cloud classification is recommended when generating a Digital Terrain Model (DTM). Classifying the point cloud will classify each point into the following categories: Ground, Road Surface, High Vegetation, Building, Human Made Object.*
 - RGB and MS recommendation for generating DTM: Classify Point Cloud **box checked**
- Export: *The point cloud can be exported to various formats based on user preferences, the analysis conducted for this protocol doesn't use any of the outputs listed at this step. See Pix4D's documentation on [Point Cloud Export Options](#) for further details on the options.*
 - RGB and MS default: **none selected**

3D Textured Mesh

- Generation: *A 3D textured mesh can be optionally generated. See Pix4D's documentation on [3D Textured Mesh](#) for further details.*
 - RGB and MS default: Generate 3D Textured Mesh **box UNchecked**
- Settings:
 - RGB and MS default: **Medium Resolution**
- Export:
 - RGB and MS default: **none used**

Advanced

- Point Cloud Densification:
 - RGB and MS default: **7x7 pixels**
- Image Groups:
 - RGB and MS default: dependent on band structure, Pix4D automatically populates this
- Point Cloud Filters:
 - RGB and MS default:
 - Use Processing Area box **checked**
 - Use Annotations box **checked**

- Limit Camera Depth Automatically **box UNchecked**
- 3D Textured Mesh Settings:
 - RGB and MS default: Sample Density Divider = 1

Running Step 2 and Checking Outputs

Run step 2 by checking the 2. Point Cloud and Mesh box and clicking Start to generate Densified Point Cloud.

Point Deletion

Point deletion is an optional process that allows the user to remove unwanted features and/or noise from the point cloud surface. If point deletion is desired, use the Edit Densified Point Cloud button in the upper menu bar and change the class to Disabled. A processing area can also be set (rayCloud > New Processing Area) to select only a given area for further processing. See Pix4D documentation on [How to Edit the Point Cloud](#) for more details.

3.3.2. Processing Step 3. DSM, Orthomosaic and Index

Processing Step 3 creates the final outputs of the project (orthomosaic, DSM, DTM, reflectance maps and vegetation indices). See Pix4D's documentation on [Processing Step 3. DSM, Orthomosaic and Index](#) for further details on project outputs.

Different outputs are better suited for RGB vs multispectral imagery. If only one type of imagery (either RGB or multispectral) was collected at a study site, options are available to generate appropriate outputs for analyses. See [Table 3](#) below for breakdown of how to generate each output for each equipment scenario:

Table 3. Deriving Outputs from Different Sensors (RGB vs. Multispectral (MS))

Equipment Scenario	Elevation Model Generation (DSM, DTM)	Orthomosaic Generation	Reflectance Map and Vegetation Index Generation (NDVI, individual band reflectance, etc.)
Both RGB and MS Imagery	Process outputs in step 3 using RGB imagery	Process output in step 3 using RGB imagery	Process outputs in step 3 using MS imagery
RGB only	Process outputs in step 3 using RGB imagery	Process output in step 3 using RGB imagery	Create custom indices using alternative veg index process (documented in Appendix 5)
MS only	Process outputs in step 3 using MS imagery Quality Note: The resolutions of MS-generated elevation models are not as fine as those generated with RGB imagery	Create custom orthomosaic using multiband raster process (documented in Appendix 6)	Process outputs in step 3 using MS imagery

DSM and Orthomosaic

- Resolution: A standard GSD of 1 is used unless downsampling is desired, in which case the Custom box can be used to input a custom GSD size.
 - RGB and MS default: **Automatic (GSD = 1)**

- DSM Filters: *Noise filtering and surface smoothing will remove artifacts and noise from the DSM surface.*
 - RGB and MS defaults:
 - Use Noise Filtering **box checked**
 - Use Surface Smoothing **box checked**
 - Type: **Sharp**
- Raster DSM: *The Raster DSM options allow the user to generate the DSM using an Inverse Distance Weighting (slower and recommended for a lot of elevation change) or Triangulation (faster and recommended for flatter surfaces) interpolation method.*
 - RGB defaults:
 - GeoTIFF **box checked**
 - Method = **Inverse Distance Weighting**
 - Merge Tiles **box checked**
 - MS defaults:
 - GeoTIFF **box UNchecked**
- Orthomosaic
 - RGB defaults:
 - GeoTIFF **box checked**
 - Merge Tiles **box checked**
 - GeoTIFF without Transparency **box UNchecked**
 - Google Maps Tiles and KML **box UNchecked**
 - MS defaults:
 - GeoTIFF **box UNchecked**

Additional Outputs

- Grid DSM:
 - RGB and MS default: **none used**
- Raster DTM:
 - RGB and MS (settings when generating DTM):
 - GeoTIFF **box checked**
 - Merge Tiles **box checked**
- Raster DTM Resolution:
 - RGB and MS (settings when generating DTM): **Automatic (GSD = 5)**
- Contour Lines
 - RGB and MS default: **none used**

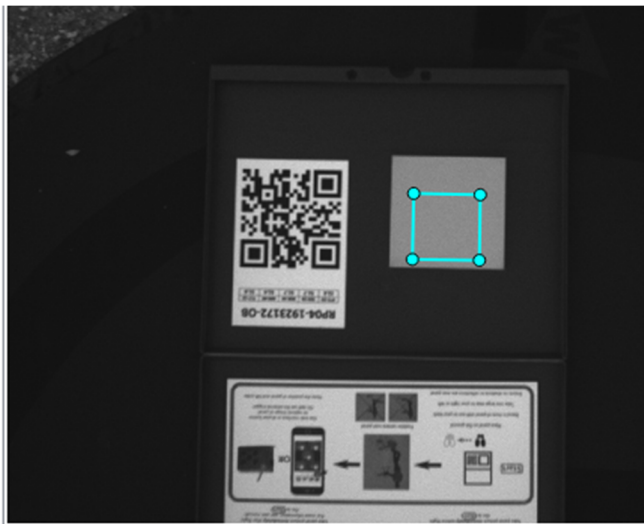
Index Calculator

Multispectral vs RGB Note: If multispectral imagery is being processed in addition to RGB imagery, no index calculator settings need to be adjusted for the RGB project. If only RGB imagery is available, the multispectral settings listed below for Radiometric Processing, Resolution, Reflectance Map, Indices and Export sections can be inputted into the RGB project. Note that NDVI will not (and cannot) be generated from R, G and B bands. See alternative veg index process ([Appendix 5](#)) for instructions on how to use these three bands to create other vegetation indices.

- **Radiometric Processing and Calibration:** *Correct Correction Type and Calibration values should be verified before proceeding. Pix4D usually correctly recognizes and populates this information, but errors sometimes occur.*
 - Correction Type options vary based on the calibration equipment used (i.e., reflectance panel, sunshine sensor, etc.). See [Pix4D's documentation on Radiometric Corrections](#) for more information on each of the options.
 - No Correction: no radiometric correction will be performed.
 - Camera Only: require image EXIF metadata
 - Camera and Sun Irradiance: require sun irradiance sensor, image XMP tags and EXIF metadata (light sensor data is most effective in overcast, completely cloudy conditions)
 - Camera, Sun Irradiance, and Sun Angle: requires known geometry of sensor and camera to be embedded in EXIF, along with XMP tags and EXIF metadata (this option should only be selected for flights that were performed in clear sky conditions)
 - Camera, Sun Irradiance and Sun Angle using DLS IMU: requires an IMU embedded in the sun sensor and the orientation to be tagged in XMP (this option should only be used for flights that were performed in clear sky conditions)

Quality Note: If the Correction Type is highlighted red in the dropdown menu (in Processing Options > Step 3 > Index Calculator > Radiometric Processing and Calibration), that means Pix4D could not find any EXIF/XMP metadata written in the project and that option cannot be used for processing. To fix this, click the Calibrate... box and import the image of the calibration panel corresponding to the band that was selected. Click and drag to draw a box around the gray square in the calibration card image (see [Figure 3](#)). The correct reflectance value for the particular band should be inputted into the Reflectance Factor box. Reflectance values should be between 0 and 1.0. The sensor company can be contacted for the correct reflectance values if they are not known.

Figure 3. Radiometric Calibration Card



- Use the coefficient for that band associated with the type of sensor. If the coefficient is unknown, contact the sensor company for panel coefficients.

- Resolution
 - MS default: **Automatic (GSD =1)**
- Reflectance Map
 - MS default:
 - GeoTIFF **box checked**
 - Merge Tiles **box checked**
- Indices
 - MS recommendation: selecting boxes for all bands and indices available
- Export
 - MS default:
 - Index Values as Point Shapefiles **box UNchecked**
 - Index Values and Rates as Polygon Shapefiles **box checked**

3.3.3. Running Step 3 and Generating Outputs

Run Step 3 by checking the 3. DSM, Orthomosaic and Index box and clicking Start. Outputs will be generated (usually over multiple hours) and the quality report will be updated with additional information on outputs.

Exporting Products

Pix4D will store outputs within the home project folder using the following file structure:

- 1_initial/ → Quality Report
- 2_densification/ → Point Cloud (creates outputs only if specified in settings)
- 3_dsm_ortho/ → Orthomosaic, DSM, DTM (plus other extras if specified in settings)
- 4_index/ → Indices, Reflectance Maps, Project Data (additional info about GSD, etc.)

General Note: Both Reflectance and Indices output folders contain rasters (one for each respective band/index); pixel values for both of these raster outputs represent reflectance values. The difference between the two types of outputs is that the index rasters are able to be visualized in Pix4D's index calculator interface, when opening files in ArcGIS or other programs files are redundant. Only outputs from the Indices folder will be used for this analysis.

4. Post Processing and Analysis

The analysis sections below provide instructions for analyzing drone imagery outputs with the goal of estimating four ground-based measurements traditionally measured in many wetland monitoring programs, including two parameters that are measured as part of the emergent vegetation biomonitoring component of the NERR System Wide Monitoring Program (Moore 2009): canopy height, percent cover, ecotones and above-ground biomass. The analyses for this project were written such that for each parameter, drone imagery-based measurements are compared to ground-based measurements for accuracy assessment. All analyses were done in ArcGIS (see software specific notes below):

Software specific notes:

- In *ArcGIS Pro*, all tools and toolboxes referenced here can be accessed via the Geoprocessing pane, accessed by clicking the Tools button under the Analysis ribbon tab. For the percent cover analysis, the Spatial Analyst license is required to complete the process (license can be checked by going to the Project menu, selecting Licensing and inspecting the Esri Extensions box).
- In *ArcGIS Desktop*, all tools and toolboxes referenced here can be accessed via the ArcToolbox (under the Geoprocessing menu). For the percent cover analysis, be sure to enable the Spatial Analyst toolbox by checking the appropriate box in the Customize>Extensions menu.
- For those new to ArcGIS, it is typically faster to find tools by using the search function (in the Geoprocessing pane in *ArcGIS Pro* and in the Search pane in *ArcGIS Desktop*) than by manually going through the toolbox menus.

Coordinate System Standardization:

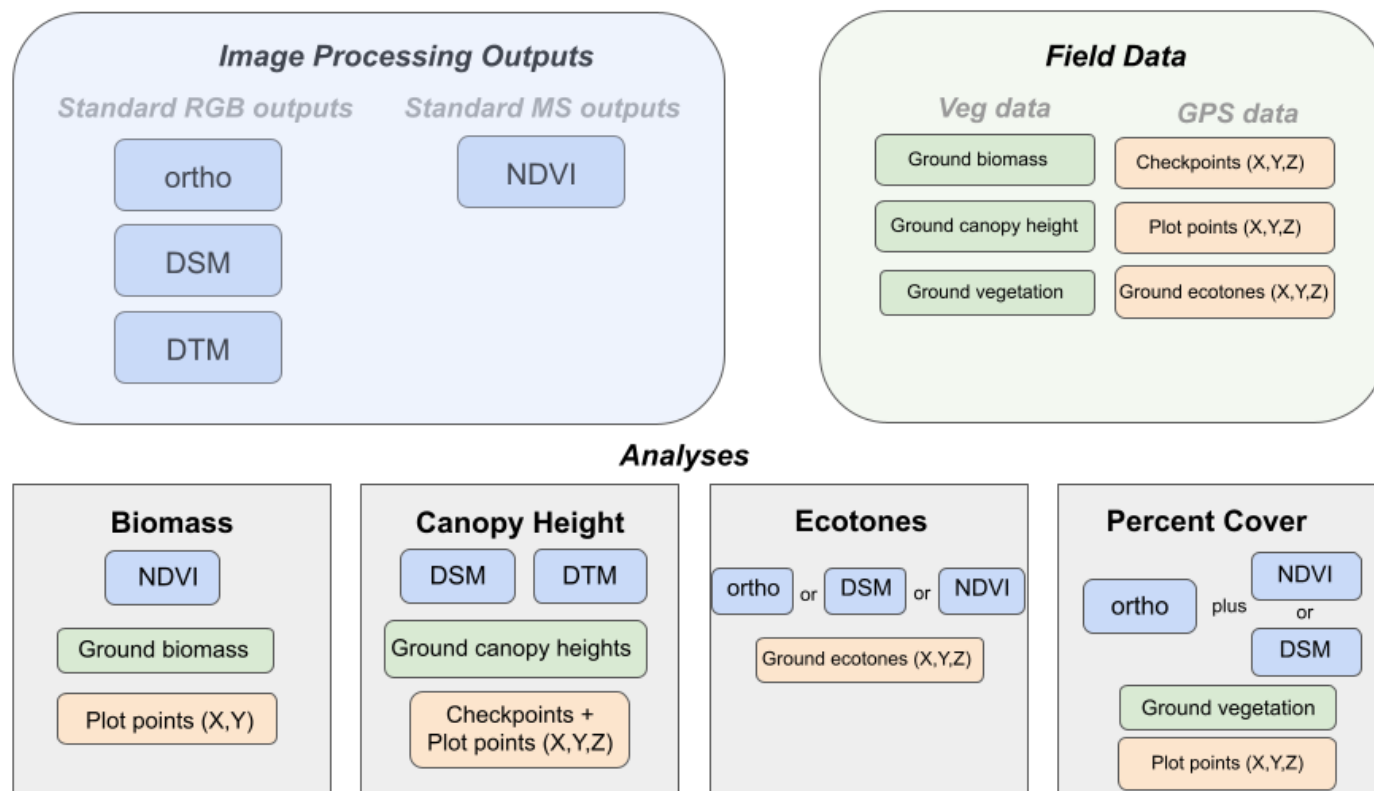
It is important for the quality of results that all data used for analysis is in the same coordinate system (both horizontal and vertical) to ensure consistency among comparisons. The coordinate systems of the image processing outputs should match those of the field data for each comparison. The horizontal coordinate system varies by region/field GPS system used; a standard vertical coordinate system used in this project is NAVD88.

- Horizontal CS - If the output coordinate systems were set consistently in image processing, all outputs should already be in the same coordinate system (and should match the coordinate system used for field data collection). If not, they can be reprojected in ArcGIS.
 - To check the coordinate system of an output, bring the file into an ArcGIS map, right click on the layer in the Contents pane and select Properties > Source > Spatial Reference.
 - To change the coordinate system of a layer, choose the Project tool (for shapefiles) or the Project Raster tool (for rasters) and enter the input data and output coordinate system accordingly.
- Vertical CS - All outputs should be projected to NAVD88, for consistency.
 - To set all layers in map to the same vertical coordinate system, right click the name of the map in the Contents pane, then select Properties > Coordinate Systems > Current Z. NAVD88 is located under Vertical Coordinate Systems > Gravity Related > North America.

Data to Analysis Workflow:

[Figure 4](#) shows which image processing outputs and field data feed into each of the four analyses. Remember that the sensor(s) and resultant imagery for a study site will dictate how the Image Processing Outputs are derived (the standard RGB and Multispectral output breakdown shown can be used when a study site has both RGB and MS imagery). Refer to [Table 3](#) for guidance on how to derive outputs when using only an RGB, only a multispectral sensor or a combination of the two.

Figure 4. Data to Analysis Flowchart



4.1 Assessing Accuracy of Elevation Models and Efficacy for Estimating Canopy Height

Caveat

At the time this protocol was written, the image processing softwares we used (Pix4D and Drone2Map) were not able to produce surface models (DSMs and DTMs) of tidal wetland landscapes with the accuracy needed to measure canopy height. We still have provided our process for checking the accuracy of the DSM and DTM rasters individually and estimating canopy height for the purposes of documenting the methods used in this effort.

The following data are used in the canopy height analysis (also see [Figure 4](#)):

- Digital Surface Model (DSM) raster (modeled surface (vegetation, exposed ground) elevations, generated during image processing)

- Digital Terrain Model (DTM) raster (modeled terrain (ground) elevations, generated during image processing)
- Canopy Height Values (measured maximum and average stem heights, acquired in the field)
- Checkpoint, Vegetation and Biomass Plot Elevation Values (Z values at each X,Y plot location, acquired in the field)

General Note: The DSM and DTM accuracy check processes described below are not required for obtaining an estimate of canopy height; the purpose of the accuracy checks are to get a sense of the error associated with the DSM and DTM separately.

Check Accuracy of DSM

The field-based canopy height measurements taken at vegetation plots can be used as ‘true values’ to compare the modeled surface (DSM) elevation values against. The difference between average DSM elevation and canopy elevation (field-based canopy height + ground elevation at each plot) can be taken at each available plot to give a sense of DSM error.

- Import plot number, ground-measured canopy height values for each plot, along with plot X, Y, Z data into ArcGIS Pro and convert to a canopy elevation shapefile. The canopy elevation shapefile should contain the four canopy height measurements collected at each plot: average canopy height with leaf/stem straightening, max canopy height with leaf/stem straightening, and average and max canopy heights without leaf/stem straightening). Create a CSV file pulling the necessary data from the permanent plot vegetation survey data. For plots without vegetation enter a canopy height of 0. Create a new column labeled for each variation on canopy height measurement (e.g., ‘canopy_elevation_avg_straight’, ‘canopy_elev_max_straight’, etc.) and add the plot elevation (the Z value of each plot location) to the canopy height for each column.
 - To create the canopy elevation shapefile, feed the CSV into the XY Table to Point tool (designate the longitude column as the X Field, the latitude column as the Y Field, and the Coordinate System used to collect the coordinates in the field).
- The DSM TIFF file derived from image processing should be used to extract DSM elevation values at each vegetation plot to create the mean, min and max DSM table (the table should contain plot number and mean, min, and max DSM elevation for each vegetation plot).
 - [Create a shapefile with the square footprints](#) of the vegetation plot locations
 - Use the Buffer tool (found in the Analysis Toolbox) to create a circular buffer around the center points in the canopy elevation shapefile, input 0.5 meters Distance for a 1 x 1 meter vegetation quadrat. Leave the Method and Dissolve Type inputs at their default (Planar and No Dissolve).
 - Use the Minimum Bounding Geometry tool from the Data Management toolbox to turn the circle buffers into squares. Use the circular buffers as the input feature, and set the Geometry Type to Rectangle by Area and Group Option to None.
 - To create the DSM table, use the Zonal Statistics as Table tool (in Image Analyst Toolbox) to extract the DSM value at each plot (designate the vegetation plot quadrat footprint shapefile as the feature zone data, designate the plot number column as the zone field, designate the DSM raster as the input value raster, choose a name and

location for the output table and designate the statistics type as Minimum, Maximum, and Mean).

- The canopy elevation data and the DSM elevation data should be added to the same table in order to quantify error and assess accuracy.
 - To join the DSM data table to the canopy elevation shapefile attribute table, use the Join Field tool (in Data Management Toolbox) (designate the canopy elevation shapefile as the input table, the plot number as the input join field, the DSM table as the join table, the plot number as the join table field, and the min, max, and mean DSM value field as the transfer fields). Note, the DSM values will be added to the attribute table of the designated input table (e.g., canopy elevation shapefile).
 - Open the canopy elevation shapefile attribute table, right click on the newly added MIN column, select fields, and update the alias for MIN, MAX and MEAN (e.g., dsm_min, dsm_max) so the naming convention is clear.
 - The resulting values are the differences between average DSM elevation and field-based canopy height at each plot.

Check Accuracy of DTM

The field-based elevation measurements taken at checkpoints, vegetation plots, and biomass plots (all referred to as checkpoints for the DTM accuracy exercise) can be used as True Values to compare the modeled terrain (DTM) elevation values against. The difference between average DTM elevation and field-based ground elevations can be taken at each available point to get a sense of DTM error.

- Ground-measured checkpoints acquired in the field should be inputted into a CSV file, imported into ArcGIS Pro and converted to a checkpoints shapefile (the checkpoints shapefile should contain unique checkpoint ID, longitude, latitude and elevation values for each point).
 - To create checkpoints shapefile, feed the CSV into the XY Table to Point tool (designate the longitude column as the X Field, the latitude column as the Y Field, and the Coordinate System used to collect the coordinates in the field).
- The DTM TIFF file derived from image processing should be imported into ArcGIS Pro as a raster. Average DTM values should be extracted at each checkpoint plot to create the mean DTM table (the mean DTM table should contain checkpoint plot id and mean DTM value for each checkpoint location).
 - To create the mean DTM table, use the Zonal Statistics as Table tool to extract the mean DTM value at each checkpoint location (designate the checkpoint plot shapefile as the feature zone data, designate the checkpoint ID column as the zone field, designate the DTM raster as the input value raster, choose a name and location for the output table, and designate the statistics type as mean).
- The checkpoint elevation data and the mean DTM data at each checkpoint should be added to the same table in order to quantify error and assess accuracy.
 - To join the mean DTM data table to the checkpoint shapefile attribute table, use the Join Field tool to add the mean DTM column to the checkpoint shapefile attribute table (designate the checkpoint shapefile as the input table, the plot number as the input join field, the mean DTM table as the join table, the checkpoint ID as the join table field, and the mean DTM value field as the transfer field). Note, the mean DTM values will be

added to the attribute table of the designated input table (e.g., checkpoint shapefile attribute table).

- The DTM values should be subtracted from the checkpoint elevation values for each point in order to obtain height differences for each point that can then be used to quantify error.
 - To quantify differences between mean DTM and checkpoint elevation values at each point in ArcGIS Pro, open Fields View within the attribute table of the checkpoint shapefile attribute table (right click on a column header and select Fields).
 - In Fields View, add a new numeric field (named DIFF or something distinguishable), save changes and exit field view.
 - In the checkpoint shapefile attribute table, right click the new field and select calculate field. Enter an expression that subtracts the values in the mean DTM field from the checkpoint elevation values field. In the Fields box, double click the field representing the checkpoint elevation values, then click the subtraction sign, and then click the field representing DTM mean elevation values. Click OK.
 - Repeat this same exercise for vegetation plots and biomass plots if ground-based RTK elevations were also taken at these plots.
 - The resulting values are the differences between average DTM elevations and ground-based elevations at each measured point.

Calculate Estimated Canopy Height

The difference between DTM elevation and DSM elevations at each vegetation plot can be used to estimate canopy height (with the caveat described [above](#) in mind).

- It is recommended that the DSM and DTM values be compared at the resolution of the DSM raster (the DSM resolution is equal to the ground sampling distance (GSD) of the drone, while the DTM resolution is more coarse).
 - Use the Resample tool to align the two rasters and ensure they have the same cell size. Designate the DTM raster as the Input Raster, and the DSM raster as both the Snap Raster (Environment Setting) and the Output Cell Size (set the Snap Raster Environment Setting first, then the Output Cell Size setting).
- Quality Note:** The resolution of the output raster should be checked before proceeding to the next step (right click the raster and select Properties > Source > Raster Information to ensure Cell Size X and Y are as expected). Note that running the Resample tool within an ArcGIS Pro geoprocessing model has shown to be problematic; the tool can be run outside the model if errors occur.
- Once the DTM raster is resampled and aligned with the DSM raster, use the Raster Calculator to subtract the DTM raster from the DSM raster. The result will be a difference raster referred to as 'DSM-DTM raster' going forward.
- Use the DSM-DTM raster to extract estimated canopy height at each vegetation plot (The square quadrat footprints should be used here, not the veg plot points). The canopy height table should contain plot number and mean, min, and max canopy height values within each 1 m² vegetation plot.

- To create the mean DSM-DTM table, use the Zonal Statistics as Table tool to extract the canopy height value at each plot (designate the veg plot quadrat footprint shapefile as the feature zone data, designate the plot number column as the zone field, designate the DSM-DTM raster as the input value raster, choose a name and location for the output table and designate the statistics type as Minimum, Maximum, and Mean).
- The resulting values represent an estimation of canopy height at each plot.

4.2 Ecotone Delineation

The following data are used in the ecotone analysis (also see [Figure 4](#)):

- Orthomosaic raster (true color image, acquired in the field)
- Digital Surface Model (DSM) raster (modeled surface (vegetation, exposed ground) elevations, generated during image processing)
- NDVI raster (Normalized Difference Vegetation Index, generated in image processing)
- Field ecotones (X,Y locations of each ecotone line, acquired in the field)

To start

- Add the RGB orthomosaic to a new map. Select the Measure tool in the Map ribbon tab in the Inquiry group (called the Measure tool in ArcGIS Desktop, accessed from the Tools toolbar). Use the defaults--planar measurements in metric units. Zoom in on the orthomosaic on an ecotone of interest, start clicking to add a multi-point line. With each click, the tool will populate a list of the distance between each point. Continue clicking along any line or boundary, aiming to get the distance between each point to approximately one meter. This exercise is simply to calibrate point-clicking to a fairly consistent distance, so continue until points can be reliably added at roughly one-meter intervals.

Manually delineating ecotones

- Boundaries will need to be delineated for (1) the water-wetland edge, (2) the low marsh-high marsh edge, and (3) the wetland-upland edge (see [Delineating Field Ecotones section](#) for descriptions of ecotones). To avoid a biased interpretation, do not view the field-delineated ecotone shapefiles prior to manually delineating ecotones.
- In the Catalog pane, navigate to the folder or geodatabase that will contain the boundary files, right-click, and under the New pop-out, select Shapefile (if working in a folder) or Feature Class (if working in a geodatabase). Follow through the prompts, selecting Line/Polyline as the geometry type, and being sure to choose the same projection as the other files in the project.
- Using the Create Features pane (under the Edit ribbon tab in the Features group in *ArcGIS Pro*; right-click the layer and select Start Editing in *ArcGIS Desktop*), select the feature class you just created under the Templates menu, select the Line/Polyline tool, and digitize one of the ecotones, aiming for roughly one meter in between points to match the sampling interval of ground-based RTK delineations. Try to begin and end the line for each ecotone at the approximate location the field surveys of each ecotone started and ended.
 - Use the arrow keys on the keyboard to navigate along the orthomosaic while using the Create tool, or hold the 'C' key while clicking to temporarily switch back to using the cursor to navigate the map.
 - In *ArcGIS Pro*, click Save in the Edit tab in the Manage Edits group to save the edits.

- In *ArcGIS Desktop*, click Save Edits from the Editor menu in the pop-up toolbar, then click Stop Editing.
- Repeat these steps with all three of the ecotones of interest, creating a new Shapefile/Feature Class file for each ecotone.
- Be sure to save all edits regularly.

Compare the hand-delineated boundary to field-measured boundary

- Run the Near tool from the Analysis toolbox, using the field-measured RTK delineation of the ecotone (a point shapefile of the GPS points from the ecotone) as the Input Features, and using the digitally delineated ecotone (the Line/Polyline feature class) as the Near Features. Set the Method to Geodesic, and update the field names to e.g., NEAR_FID_RGB and NEAR_DIST_RGB (change these to _NDVI and _DSM when using NDVI and DSM rasters to delineate ecotones) and leave the other options at their defaults.
 - This modifies the input point shapefile by adding two new columns. There is nothing wrong with that, but if preserving the original file in an unmodified format is preferable, then make a copy of the point shapefile and use that as the Input Features. Additionally, ArcGIS Pro has an Enable Undo option for the tool (next to the Run button) that enables an edit session, which can be very useful, but be sure to save the edits before proceeding.
- Open the attribute table of the now-modified GPS points that were used as the Input Features in the previous step. Right-click on the NEAR_DIST column and select statistics. This will open a new panel that contains the mean and standard deviation (among other statistics), which serve as a metric of how close the field-measured boundaries and digitally delineated boundaries are to each other.
 - Repeat this process for each ecotone.
- Repeat all steps using the NDVI raster instead of the RGB orthomosaic to delineate the ecotones.

Extracting ecotones from classified rasters

- To extract ecotones from species-specific classified rasters, first complete the percent cover analyses ([below](#)).
- The following steps were written to extract the low marsh-high marsh ecotone, but should work just as well for the water-wetland and wetland-upland ecotones (or the border of any species/zone in the species specific classified raster).
 - First, run the Reclassify tool to reclassify the species-specific classified raster into just two classes, using classvalue as the Reclass field (it may be necessary to press the Unique button to repopulate the table). Set the unvegetated and low marsh species to 0, and set all of the high marsh species to 1, adjusting the classes for different ecotones.
 - Use the reclassified raster as input for the Resample tool, and set the sampling technique option to Majority. The cell size strongly affects the shape of the final ecotone - coarser resolutions create simpler ecotones with fewer patches, while finer resolutions create more complex ecotones with more patches. A cell size of 0.25m x 0.25m generally provides good results, with resolutions of 0.1m x 0.1m and 1m x 1m providing less and more linear ecotones, respectively.

- Use the resampled raster as input for the Boundary Clean tool, leaving the default settings. If desired, the Sort Type option can be changed to Descending to preferentially shrink and dissolve habitat patches, or to Ascending to preferentially expand and connect habitat patches.
- Use the output raster from Boundary Clean as input to the Contour List tool. Specify the numeric identity of the first class from the reclassified raster (i.e. 0) as the Contour Value.
- Optional: to create a smoother, potentially more realistic ecotone, take the output contour shapefile and use it as input to the Smooth Line tool. Set Smoothing Tolerance to 5 meters, and leave all other options as defaults. Changing the Smoothing Tolerance results in a line that conforms more or less sharply to the hard edges of the initial contour shapefile.
- It should be possible to modify this process to create multiple ecotones at once, for instance obtaining the wetland-upland boundary at the same time by including an 'upland' category in the Reclass table in the Reclassify tool, and providing the Contour List tool with multiple values. The process presented here only extracts a single ecotone for simplicity.

Quality Note: If comparing the extracted ecotone to a field-measured ecotone or one delineated by hand in ArcGIS, the cell size used in the Resample tool should be carefully considered. Smaller cell sizes (finer resolutions) tend to result in more patches of habitat, as opposed to a single block, so if an ecotone with many circular patches is being compared to a single linear ecotone (e.g. with the Near tool), its accuracy may be artificially inflated by the presence of the patches. The cell size in the Resample tool can be used to change the number of resulting habitat patches, and the Sort Type option in the Boundary Clean tool can be used to dictate whether those patches are preferentially removed or expanded, depending on the preference of the user.

4.3 Percent Cover Analysis

4.3.1 Total percent cover (vegetated vs unvegetated classification)

The following data are used in the percent cover analysis (also see [Figure 4](#)):

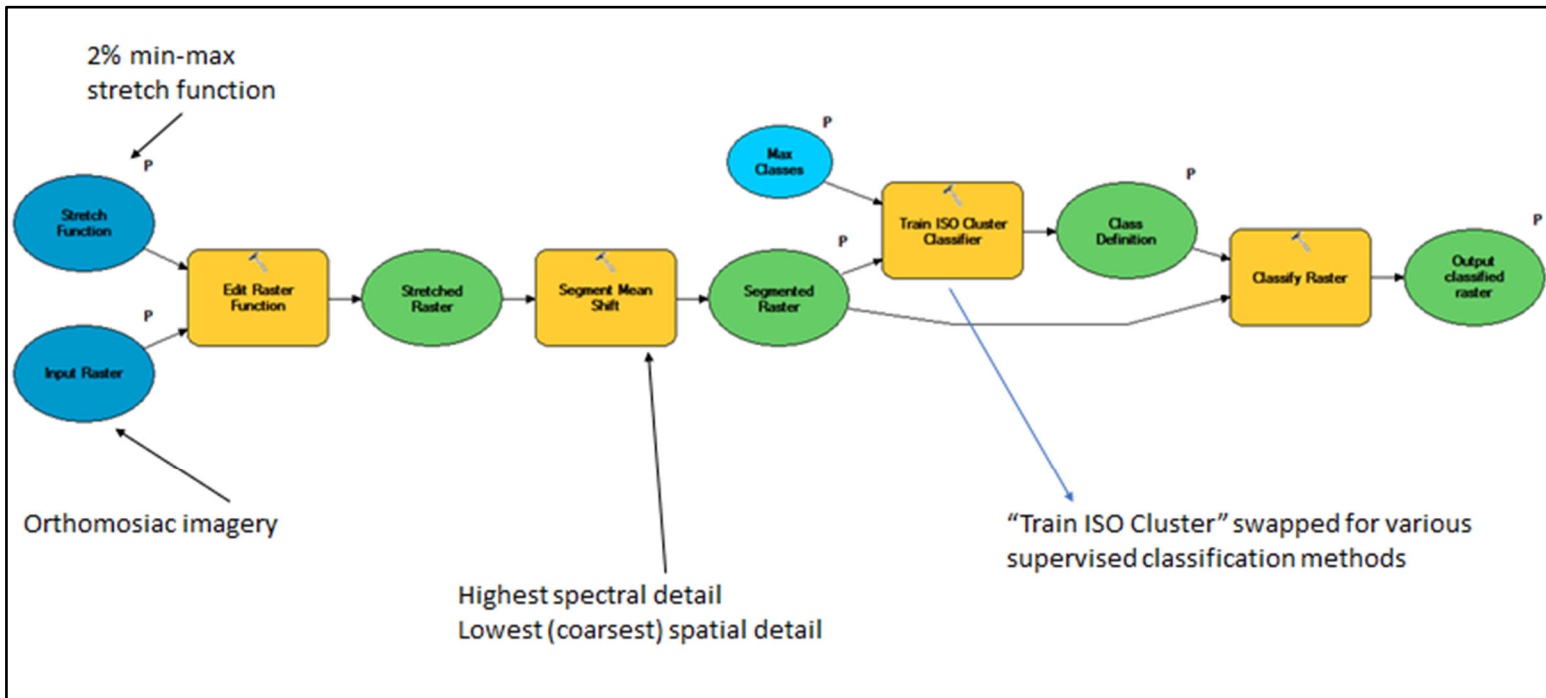
- Orthomosaic raster (true color image, generated from image processing)
- Digital Surface Model (DSM) raster (modeled surface (vegetation, exposed ground) elevations, generated from image processing)
- NDVI raster (Normalized Difference Vegetation Index, generated from image processing)
- Ground vegetation data (per plot percent cover estimates, acquired in the field)
- Ground vegetation plot locations (X, Y and Z locations of vegetation plots, acquired in the field)

This process requires a Spatial Analyst license in both ArcGIS Pro and Desktop. See ArcGIS Pro's documentation on [Image Analysis](#) for an in-depth overview of the classification process. See Gray et al. 2018 for an example of this technique as used in the NC NERR³.

³ P. C. Gray, J. T. Ridge, S. K. Poulin, A. C. Seymour, A. M. Schwantes, J. J. Swenson, and D. W. Johnston, "Integrating drone imagery into high resolution satellite remote sensing assessments of estuarine environments," *Remote. Sens.* 10, 1257 (2018).

There will be six output rasters from this analysis. The first three output rasters will be the total percent cover raster derived from the RGB orthoimagery alone, from the RGB orthomosaic plus the NDVI raster, and from the RGB orthomosaic plus the DSM raster. The second three output rasters will be derived from the same imagery/raster inputs, but will be multi-species percent cover rasters. The general classification workflow necessary to estimate percent cover is provided in [Figure 5](#).

Figure 5. Segmented Classification Workflow



Clip the imagery to just the wetland area

Quality Note: This step is not strictly necessary; all of the Percent Cover Analysis can be conducted on the full orthomosaic, but following this step significantly improves the accuracy of the classification, and cuts down on processing times.

- In the Catalog pane, navigate to the folder or geodatabase that will contain the boundary files, right-click, and under the New pop-out, select Shapefile (if working in a folder) or Feature Class (if working in a geodatabase). Follow through the prompts, selecting Polygon as the geometry type, and being sure to choose the same projection as the other files in the project.
- Using the Create Features pane (under the Edit ribbon tab in the Features group in *ArcGIS Pro*; right-click the layer and select Start Editing in *ArcGIS Desktop*), select the feature class you just created under the Templates menu, select the Polygon tool, and digitize a polygon surrounding the wetland area, from the wetland-upland ecotone to the wetland-water ecotone. This polygon will be used to clip out any area of the image that isn't wetland (i.e. remove water and upland areas), so aim to make the boundaries conform as closely as possible to the extent of wetland vegetation.
 - Be sure to include all of the percent cover plots inside the polygon, even if they fall beyond the water-wetland or wetland-upland ecotones.

- Those who completed the Ecotone Delineation section ([above](#)) can use the Trace tool in the Create Features pane to follow their previously delineated ecotones, switching to the Polygon tool when necessary to connect ecotones and fill in gaps.
- If the upland-wetland boundary is more of a transition zone than a clean divide, some upland vegetation may be included in the boundary - just be sure to add an extra class for the upland vegetation in the Training Samples step later on.
- If the wetland area is not contiguous, it will be necessary to create separate features (in the same shapefile/feature class) and then merge them together into a single feature.
 - To merge the features in *ArcGIS Pro*, select all of the features, open the Modify Features pane (from the Edit tab in the ribbon), and select Merge from the Construct section
 - To merge the features in *ArcGIS Desktop*, select all of the features, and under the Editor menu in the pop-up toolbar, select Merge
- Save all edits.
 - In *ArcGIS Pro*, click Save in the Edit tab in the Manage Edits group to save the edits.
 - In *ArcGIS Desktop*, click Save Edits from the Editor menu in the pop-up toolbar, then click Stop Editing.
- Run the Extract by Mask tool from the Spatial Analyst toolbox, using the RGB orthomosaic for the Input Raster option, and using the wetland boundary polygon for the Input Raster or Feature Mask Data option.
 - The output of this step will be the input for the following section.

Stretch raster function - increases contrast between features of interest

- *ArcGIS Pro*: select the layer to be classified from the contents pane (the one created by the extract by mask tool above), navigate to the Imagery tab in the top ribbon, and select Raster Functions. In the pane that appears, expand the Appearance section, and select Stretch.
- *ArcGIS Desktop*: Under the Window menu, open the Image Analysis window, and select the imagery raster. In the Processing section, select Add Function. In the window that pops up, right-click the raster name, and select Stretch Function from the Insert Function pop-out.
- In the tool inputs, make sure the correct input raster is selected, change Type to PercentMinMax, leave the Output Minimum and Maximum at their defaults (0 and 255), and change the Percent Clip Minimum and Maximum each to 2.
 - Gamma: affects appearance of mid-level brightness. Gamma values less than 1 increase contrast in lighter areas of the image, while gamma values greater than 1 increase contrast in darker areas of the image. At first, it is recommended to leave it untouched and accept the default, but if the end-product classified raster is struggling to distinguish features in darker or lighter areas, come back and change gamma, making sure that the Use Gamma box is checked. A gamma value of 0.2 was used (in first three entries = the rgb bands) for analyzing the NC imagery, where the low marsh appeared brighter due to reflection off of the wet mud, so enhancing contrast among the lighter areas in the image enhanced the ability of the classifier to distinguish *Spartina alterniflora* from unvegetated mud.

- When setting Gamma, it is recommended to set bands to the same gamma value (unless there is a reason to do otherwise). ArcGIS Pro will automatically add an extra band if the gamma for all bands is modified - this can be ignored.

General Note: Raster functions, including Stretch, create a new layer in the active ArcGIS project/map, but do not save a new raster file, so if the entire project is not saved when closed, the layer will be lost. This generally is not an issue, but if desired, it can be avoided altogether by saving the layer as a separate file. To do so, right click on the layer in the Contents pane, and under Data, select Export Raster.

[Segmentation](#) - breaks image up into objects or 'segments' by combining adjacent pixels based on their similarity

- *ArcGIS Pro:* select the layer to be classified from the contents pane (the one created by the stretch raster function above), navigate to the Imagery tab in the top ribbon, and under Classification Tools, select Segmentation.
- *ArcGIS Desktop:* Use the Segment Mean Shift tool from the Spatial Analyst toolbox.
- In the tool inputs, increase Spectral Detail to the maximum (20), decrease Spatial Detail to the minimum (1), and leave the minimum segment size at its default (20).

Quality Note: The above settings for spectral and spatial detail consistently yield the best results. Minimum segment size can be increased if the classified output imagery appears noisy and overfitted, but it should not be decreased below 20. For instance, at North Inlet-Winyah Bay NERR trial and error suggested that a minimum segment size of 75 provided the best result.

- Change the Output Dataset name for clarity if desired.

[Training Samples](#) - the distribution of the training sample selection strongly affects the quality of the output classified image, so this step requires detailed attention.

- Ensure the segmented output from the previous step is selected in the contents pane, click the classification tools dropdown (from imagery tab, image classification group) and select Training Samples Manager.
- When opening the Training Samples Manager, schemas (which define the classes that training samples may belong to) are displayed in the upper pane, and training samples are displayed in the lower pane.
- Start by creating a new schema (the icon that looks like a list on paper), then add 'vegetated' and 'unvegetated' classes by right clicking on New Schema that was just created, and selecting Add New Class. For each new class, specify a unique value for the required Value field (e.g. 0 for unvegetated and 1 for vegetated). Vegetated and unvegetated classes will be sufficient for estimating Total Percent cover of vegetation - estimating species-specific percent cover will be discussed below. Once the schema is complete with all desired classes, save the schema.
 - Any area not covered by live vegetation should be considered unvegetated, including areas covered by water, wrack, or debris (see [Percent Cover Ground-based vegetation surveys](#) subsection for more details).
- To start adding training samples, select one of the classes in the schema pane, then select a drawing tool (rectangle, circle, polygon, or freehand) from above the schema pane, and start

drawing training samples on the image that are good representatives of the selected class. The polygon and freehand tools take more time, but could theoretically make better/more precise training samples. Generally, using the rectangle tool has produced satisfactory results. Save these training samples regularly. If you make a training sample that overlaps with another class, you can delete it using the red 'x'.

Quality Note: Capturing representative training samples is very important! Make sure to select areas of the image that represent the full range of colors and brightness of each class across the image. For instance, vegetation may appear green on clean growth, but may also appear grayish, purplish, or brownish if it is muddy or reflecting sunlight (be sure to use training samples from monospecific stands, short form, tall form, mixed-species stands, etc.). Likewise, bare ground may appear brown, light gray, dark gray, or purplish depending on soil moisture and sunlight reflection, bright white if covered by wrack, or black when shadowed by vegetation. It is important to capture all colors present for each class, or the classifier will struggle to interpret the imagery. Try to provide training samples for each class that span the geography and the elevation gradient.

- Aim for ~ 100 training samples each for vegetated and unvegetated classes.
 - For reference, the wetland area of the North Carolina NERR covered 14,000 m², and used 187 training samples (73 vegetated and 114 unvegetated). Training samples were rectangular, varied greatly in size, and in some instances included non-conforming objects (e.g. a small bare patch in a vegetated area, or a couple of *Spartina alterniflora* stems on a mudflat).
- Once the training samples have been saved, they can be added into the map, as with any shapefile (when saving the Schema, add '.ecs' to the end of your file name; when saving the training samples add '.shp'. If you are unable to locate the saved data, save it in a separate folder that is not a geodatabase). Once added to the map, right-click on the layer in the Contents pane, and select Attribute Table. This allows the user to more easily obtain a count of the number of samples within each class, or to reassign classes if needed (by changing by the 'Classname' and 'Classvalue' fields for an entry).

[Classification](#) - can be supervised or unsupervised, though this protocol uses only supervised methods. There are three desired products from this section - one classification derived from the RGB orthomosaic alone, one from the RGB orthomosaic in combination with the NDVI raster, and one from the RGB orthomosaic in combination with the Digital Surface Model (DSM).

- ArcGIS has three supervised classifiers available: random trees, support vector machine, and maximum likelihood.

Quality Note: The Random Trees classifier provided the most accurate classification at North Carolina NERR, so it is recommended to start with Random Trees, then try the Maximum Likelihood or Support Vector Machine classifiers if the classification from Random Trees is unsatisfactory.

- Run the Train ____ Classifier from the Spatial Analyst toolbox (it is recommended to start with Random Trees). Use output from the Segmentation step above as the Input Raster and the

saved training samples shapefile as input training sample file. Leave The Dimension Value Field blank, and leave all other inputs as their defaults, except for Additional Input Raster.

- When naming the output file, be sure to indicate which classifier was used by adding ‘_RT’ or ‘_SVM’ or ‘_ML’ for the Random Trees, Support Vector Machine, or Maximum Likelihood classifiers, respectively.
- In both the Train Classifier and Classify Raster tools, there is an option to provide a secondary raster. Classification results will be significantly improved by providing the corresponding NDVI or DSM raster.
 - It will be necessary to run this step three times, once with no additional input raster, once with the NDVI raster, and once with the DSM raster.
- Next, run the Classify Raster tool, using the output from the Segmentation step above for the Input Raster and each output of the Train ____ Classifier tool as the input classifier definition.
 - The Additional Input Raster input should match the same additional raster (NDVI, DSM, or none) that was used in the Train ____ Classifier tool.
 - Be sure to indicate which inputs were used in the output file name by adding ‘_RGB’ or ‘_withDSM’ or ‘_withNDVI’ to the end of the file name.
- Conduct a visual inspection of the classified output raster. Toggle between the RGB orthomosaic and the classified raster, taking mental note if the classified raster appears to be fairly accurate, or if it has consistent, obvious, and significant errors. Be sure to inspect different areas of the image, e.g. high marsh, low marsh, transition zones, darker and lighter areas, etc.
- If the classified raster visually appears to be fairly accurate (relative to site knowledge and the site orthomosaic), proceed to the next section (accuracy assessment). If the classified raster appears to be deficient, try running a different classifier (one of the Train ____ Classifier tools) to see if that provides a more accurate result before proceeding.

Quality Note: If the output classified image from all three classifiers has low accuracy, it may help to add more training samples and then run the classifiers again.

Quality Note: The output raster will sometimes create extraneous rectangular blocks outside of the imagery. If this happens, run the Extract By Mask tool to clip the classified raster to just the area of interest, as at the beginning of this section.

Accuracy assessment

The following quantitative accuracy assessment should be done following a visual inspection of the classified rasters. This method of accuracy assessment creates random points across a classified image, which will be compared to the class those points should belong to (which will be manually identified from the segmented raster). Repeat this for each of the three classified rasters from the previous section.

- Run the [Create Accuracy Assessment Points](#) tool from the Spatial Analyst toolbox, with the classified raster as the input. Select Stratified Random or Equalized Stratified Random for the Sampling Strategy option, and specify at least 100 points in the Number of Random Points option.

- Stratified random sampling distributes the points proportionally to the area of each class, while equalized stratified random sampling distributes the random points evenly between each class. Stratified random sampling is generally recommended, unless there are concerns about the accuracy of classes that cover relatively little area (as may be the case with a multiple-species classification), in which case equalized random sampling is recommended.
- A greater number of random points increases confidence in the accuracy estimates, but increases the amount of work required. Where possible, use 50 points per category.
- Visually inspect the generated points on the map to ensure that the points are not clustered together on a per-class basis. If they are, run the tool again, switching between Sampling Strategy options if necessary.
- Identify the correct class for each accuracy point by manually editing the entry in the 'Grndtruth' column of the accuracy point shapefile, being sure to save edits.
 - The quickest way to do this is to right-click on an entry in the attribute table, select 'zoom to,' and identify what segment in the segmented raster that point overlays in the RGB imagery raster. Be sure to right click on the 'Classified' column header and select Hide so as to not bias your classifications in the 'GrndTruth' column (to un-hide right click a column header, select fields, and add a check under visible for the hidden field).
- Run the [Compute Confusion Matrix](#) tool from the Spatial Analyst toolbox with the fully updated accuracy point shapefile as the input.
 - The output table provides a matrix of which points were classified as each class, and which classes they should have been assigned to. The diagonal of the matrix is the number of points that were correctly classified, and the off-diagonal cells represent misclassified points.
 - The 'P_accuracy' row (producer's accuracy) represents the proportion of the area for each class in the classified raster that was correctly classified (e.g. "80% of the area classified as vegetation was actually vegetation")
 - The 'U_accuracy' column (user's accuracy) represents the proportion of the actual area of each class that was classified correctly (e.g. "80 percent of vegetated area was correctly identified as vegetation by the classifier")
 - The cell at the intersection of the 'P_accuracy' row and the 'U_accuracy' column represents the overall accuracy of the classified map.
 - Ideally, the error will be randomly distributed (producer's and user's accuracies are both consistently similar across all classes), and the overall accuracy will be greater than 75%. If this is not the case, then return to the previous section to try to create a more accurate classification.
 - If it isn't possible to achieve these conditions after multiple attempts, it is fine to proceed to the next section, comparing the classified imagery to field-measured percent cover - but it is unlikely that the relationship will be particularly good.
- Repeat the accuracy assessment for each of the output classified rasters (RGB alone, RGB+DSM, and RGB+NDVI). This will eventually result in a total of 6 confusion matrix tables - three for the Total Percent Cover analysis, and another three for the Multi-Species Percent Cover analysis.

Comparison Between Drone vs. Field-based Total Percent Cover Estimation

After confirming that the accuracy assessment from the previous section yielded an overall accuracy of 75% or better (or that achieving such accuracy is unrealistic for a site), proceed to comparing the classified imagery to field-measured percent cover. This process compares total percent cover of all vegetation estimated from 1m² quadrats in the field to the coverage from the classified image in the footprint of the quadrats. This should be the same process with both ArcGIS Pro and Desktop. Repeat this for each of the three classified rasters from the classification section.

- [Create a shapefile with the footprints](#) of the square quadrat locations
 - Load the center points of the quadrat locations into ArcGIS as a new point shapefile
 - Use the Buffer tool (found in the Analysis Toolbox) to create a circular buffer around the center points in the canopy elevation shapefile, input 0.5 meters Distance for a 1 x 1 meter vegetation quadrat. Leave the Method and Dissolve Type inputs at their default (Planar and No Dissolve).
 - Use the Minimum Bounding Geometry tool from the Data Management toolbox to turn the circle buffers into squares. Use the circular buffers as the input feature, and set the Geometry Type to Rectangle by Area and Group Option to None.
- Use the Tabulate Area tool from the Spatial Analyst toolbox to calculate vegetated/unvegetated coverage. Use the squared quadrat locations (output from Minimum Bounding Geometry) as the 'Input raster or feature zone data,' and use the classified raster as the 'Input raster or feature class data.' If they don't come up as the defaults, set the 'Zone' field to 'Point_name' (or whatever field identifies the individual quadrat locations), and set the 'Class field' to 'Class_name.' The processing cell size should default to the same as the classified raster.

Quality Note: The Tabulate Area tool can be buggy. It may need to be run twice to get an appropriate output if the first output is blank or missing data.

- Right-click on the output table, and under Data, select Export Table. Specify the output location (*not* in a geodatabase) and name it with '.csv' to specify a CSV output file.
- If the quadrat size was 1 m², the data in the output table represent fractional coverage (multiply by 100 to get percent coverage). If the quadrat size was not 1 m², then the output data (areal coverage) will need to be divided by the quadrat size to calculate percent coverage.

4.3.2 Species-specific Percent Cover Analysis (multiple vegetation species classification)

The only difference for attempting to distinguish different vegetation species (instead of just vegetated vs. unvegetated, as above) is the need to create a new classification schema that contains classes for each different species to be identified, being sure to create enough training samples within that class for the classifier to reliably pick out the species. Err on the side of having an excess amount of training samples rather than too few, but it won't be necessary (or maybe even possible) to get 100 training samples (as suggested above) for some of the less prominent species.

Larger species, especially those that form dense monospecific stands (e.g. *Juncus roemarianus*, *Spartina alterniflora*), will be easier for the supervised classifiers to distinguish. Mixed-species stands are unlikely to be accurately classified into their individual species, so a 'mixed species' training class made up of similar-looking/co-occurring species can be useful to improve output quality. Small, sparsely distributed understory species (e.g. *Limonium carolinianum* or *Salicornia* spp. mixed with *S. alterniflora*) are unlikely to be reliably detected and should not be assigned classes unless good training samples can be provided. At the North Carolina site, the following classes were specified: unvegetated, *Spartina alterniflora*, *Borrchia frutescens*, and *Spartina patens* + *Distichlis spicata* together (since they co-occur and are barely distinguishable when estimating percent cover in the field). While vegetative wrack was treated as unvegetated area in the total percent cover analysis above, here it can be assigned its own class and training samples.

General Note: The training samples from the vegetated-unvegetated classification can be modified for reuse, with new classes added. To do so, navigate to the location of the previously used training samples in the Catalog pane, right-click, select Copy, then right-click again and select Paste. Rename the new shapefile, and add it to the map. Inspect the samples on the map, and delete any of the 'vegetated' samples that are not exclusively the dominant species (e.g. *Spartina alterniflora*), leaving the shapefile with only samples representing the dominant species and unvegetated area (In *ArcGIS Desktop*, be sure to click Start Editing first). Save the edits, then open the shapefile with the Training Sample Manager. Add new classes that represent the other species present, then begin populating each class with training samples.

As with the vegetated-unvegetated classification, when running the Train ____ Classifier and Classify Raster tools, run each tool using as inputs the RGB orthoimagery with the NDVI raster, RGB orthoimagery with the DSM raster, and RGB orthoimagery alone. This will again yield three separate output rasters.

If analyzing the entire vegetated area of the image produces poor results when classifying for multiple species, then it may be worth extracting just the multi-species area of the imagery (with the Extract by Mask tool) and analyzing just that area of the imagery.

Quality Note: For quantifying the accuracy of the classification, it may only be possible to use the method outlined in the [Accuracy Assessment section](#) above, unless the site has a significant number of field measurements (10 or more plots) that are representative of the areas containing multiple species, in which case the regression method of comparing to field-measured percent cover should also be used (the [Comparison Between Drone vs. Field-based Total Percent Cover Estimation section](#) above). Accuracy assessment will again need to be completed for each of the three classified rasters.

4.4 Assessing Efficacy of Vegetation Indices to Estimate Above-ground Plant Biomass

This biomass analysis was conducted to assess how well drone-collected vegetation indices (NDVI) correlated with ground-based biomass measurements.

The following data are used in the above-ground biomass analysis:

- NDVI raster (Normalized Difference Vegetation Index, generated in image processing)
- Total biomass CSV (clipped biomass measurements (g/m^2), acquired in the field)
- Biomass plot shapefile (X,Y locations of biomass plots, acquired in the field)

Extract mean NDVI value at each Biomass Plot

- Ground-measured biomass plot locations and measurements should be organized into a CSV, imported into ArcGIS Pro and converted to a biomass shapefile (the biomass shapefile should contain plot number, longitude, latitude and field-derived biomass values).
 - To create the biomass shapefile, feed the CSV into the XY Table to Point tool (designate the longitude column as the X Field, the latitude column as the Y Field, and the Coordinate System used to collect the coordinates in the field).
- The points in the biomass shapefile should be buffered and bounded to create plots that emulate the 0.25 m^2 square plots where biomass measurements were taken in the field. To [Create a shapefile with the footprints](#) of the square quadrat locations:
 - Load the center points of the quadrat locations into ArcGIS as a new point shapefile
 - Use the Buffer tool to create a circular buffer around the center points (0.25 meters for a $.25 \text{ m}^2$ biomass quadrat). Leave the Method and Dissolve Type inputs at their default (Planar and No Dissolve).
 - Use the Minimum Bounding Geometry tool from the Data Management toolbox to turn the circle buffers into squares. Use the circular buffers as the input feature, and set the Geometry Type to Rectangle by Area and Group Option to None.
- The NDVI TIFF file created in processing step 3 of Pix4D should be imported into ArcGIS Pro as a raster. Average NDVI values should be extracted at each biomass plot to create the mean NDVI table (the mean NDVI table should contain plot number and mean NDVI value for each plot).
 - To create the mean NDVI table, use the Zonal Statistics as Table tool to extract the mean NDVI value at each biomass plot (designate the square buffer output from the previous step as the feature zone data, designate the plot number as the zone field, designate the NDVI TIFF as the input value raster, choose a name and location for the output table, and designate mean as the statistics type). Running this should output a table containing a mean NDVI value associated with each 0.25 m^2 biomass plot.

Explore Correlation Between NDVI and Ground Biomass

- By plotting the data from the NDVI table (mean NDVI value at each biomass plot) against the data from the ground-based biomass table (ground-measured biomass at each biomass plot), the correlation between NDVI and ground biomass can be explored.
 - Join the NDVI data to the ground biomass data using the plot numbers as the join key. The resulting CSV should have an average NDVI value and a measure of biomass (total biomass (live + dead) was used in this analysis) for each plot.
 - Perform a linear regression analysis to model the relationship between ground biomass and NDVI.

Appendices

Appendix 1. Ground control point construction instructions.

Ground control Points (GCPs) can be constructed in many ways, two examples are as follows:

- A relatively cheap option is to paint 5-gallon bucket lids and install mounting hardware for attachment to PVC poles (full Bucket Lid GCP construction instructions are documented below)
- A more expensive GCP option that provides increased durability and a target with sharper edges for improved accuracy during image processing. Guidance is as follows:
 - Construct GCPs by fastening (screws or heat annealing) black and white [starboard](#) together using precut 12" white and 6" black squares (at least ¼" thick).
 - Mounting hardware ([part 1](#) [screwed to GCP] and [part 2](#) [part 2 is glued to the PVC pole]) can also be installed on starboard GCPs for attachment of GCP to PVC poles.

Bucket Lid ground control points (GCPs) Construction Instructions

Supplies needed:

- Standard, 5-gallon white or blue bucket lids (one for each GCP)
- Drill with wire brush OR angle grinder with wire brush OR sanding sponge
- Spray paint (black for white bucket lids or white for blue bucket lids). Use paints that are specifically formulated to adhere to plastics. There are several available on the market such as **Krylon Fusion All-in-one**, **Valspar Plastic Spray Paint**, and **Rust-Oleum Specialty Paint for Plastic Spray**. Rustoleum appliance epoxy spray paint works well also.
- thin cardboard (from a soda box)
- scissors
- 1 [PVC floor flange](#) per GCP
- 1 PVC [adapter](#) fitting per GCP
- 2 stainless steel bolts per GCP (we probably used 3/8" x 1.5")
- drill bit (match to bolt diameter)
- 4 stainless steel washers per GCP
- 2 stainless steel lock nuts per GCP
- 1/2" PVC poles—we cut poles at varying lengths to provide flexibility in application (c. 24", 36" and 48")
- PVC cutter OR Miter saw or Sawzall
- 2-4 [landscape stakes](#) per GCP (if you anticipate putting any GCPs directly on the ground). They clip nicely on the edge of the bucket lids to keep lids from moving.

- 1) Use drill w/ brush (angle grinder or sanding sponge) to scuff and rough-up bottom side of lid to improve adherence of spray paint. FYI, metal brushes are going to work better and faster than sanding sponge. See picture below for how we 'scuffed' bucket lids.



- 2) Cutout cardboard triangles to mask $\sim 1/2$ of the bucket lid as shown in the picture below. You may need to add tape around the edges of the cutout to provide reinforcement for repeated spray paintings.



- 3) Spray paint the parts of the bucket lid not covered by cardboard masks. We had the best luck weighing down the two triangle masks with a couple rocks and spraying quickly. We also tried using a variety of tape (including painters tape), but were unable to get straight edges because the spray paint bled under the tape due to the roughing (step 1). Allow the lid to dry.
- 4) Attach PVC pole mounting hardware. We used a [PVC floor flange](#), which has 4 holes for bolting through (we only used two holes in the flange; using all 4 seemed unnecessary). Put the flat side of the flange in the middle of the non-painted side of the bucket lid (see picture below). Mark location for drilling two holes (opposite each other) ensuring that the holes and washers will not cover up important color-change edges on the GCP. Drill holes through bucket lid. Put the washer on each side of the bucket lid (picture 1 and 3) and tighten the lock nut. Thread PVC [adapter](#) fitting on flange (see picture below). Insert PVC pole into PVC adapter.



Appendix 2. Image Processing in Drone2Map version 2.3

General Note: Drone2Map software should be updated to version 2.3 or beyond. Some of the steps and functionality detailed below are not available in earlier versions.

Basic workflow for 2D processing (used to process Nadir images): Add Imagery and Source Data → Define Processing Options → Add Ground Control → Process Image Collection → Generate Output Products (e.g., orthomosaics, elevation models).

1. Adding Imagery

1.1. New Project

- Select project template. For wetland monitoring, select 2D Full.
 - Name the project and specify the file path. Ensure naming convention is clear (e.g., 2Dfull_rgb_ncnerr_05062021).

General Note: Once the file name and location has been established, they should remain constant. If changed, Drone2Map will no longer recognize the project and it can result in having to reprocess the images.

1.2. Select Images

- Add images using the Add Images... button to add images individually or Add Folder to add an entire folder of images.
 - If your drone has separate RGB and multispectral sensors, the two imagery sets should be processed separately. Create the project.
 - If multiple flights were flown to cover one study area, all images from all flights can be imported at the same time, as long as the areas covered by the flights are continuous and there is sufficient overlap between the flights (if this is not the case, the software will not be able to stitch the images together).

General Note: Drone2Map will NOT import images with the same filename. Some sensors start over on image naming after each battery change. You must rename images with the same name prior to importing into Drone2Map.

- To rename a batch of images quickly in Windows, hold Shift and right-click in open space in the File Explorer window where the image files to be renamed are located, select Open PowerShell Window Here. In the resulting window use the following statement: `ls | Rename-Item -NewName {"I" + $_.name}`, which adds the letter I in front of each filename.
 - The ls command is passing its output (list of files in that directory) to the Rename-Item command, where the name structure is specified in the braces {}. In PowerShell \$_ is a placeholder for whatever object is currently being processed, in this case each file. In this way we can quickly and easily prepend any string to the filename. This command will make this change to all files contained in this folder.

General Note: Drone2Map v2.3 is unable to process calibration card images used for calibrating multispectral sensors.

1.3. Image Properties

Drone2Map will read EXIF metadata from images upon loading them in; metadata including altitude and geolocation information will be displayed in the Image Attribute Table (right click Images in the Contents pane, then select Attribute Table to view).

Drone2Map uses the image geolocation information to position the cameras correctly relative to the modeled surface; it is recommended that the automatically recognized image geolocation coordinate system is left as is.

2. Defining Processing Options

Processing options can be adjusted in Drone2Map. Steps can be run independently, minimizing the time required to generate the desired products; however, the initial step must be run at least once.

Use the Processing Options window to configure which steps will run, the settings for each step, and which products will be created. To view image processing options, click Options on the Home tab in the Processing group. The default settings for this step are generally recommended, with some notable exceptions (detailed below). For more information on all options, see [Drone2Map's documentation](#).

2.1. 2D Products tab

Make sure Create Orthomosaic, Create Digital Surface Model, and Create Digital Terrain Model are all selected.

- *Create orthomosaic:* Automatic Resolution should be selected. Resolution defines the spatial resolution used to generate the orthomosaic and DSM. Automatic = 1 x ground sampling distance.
- *Create Digital Surface Model:* Select **Triangulation** Method as the method used for the raster DSM generation. The method affects the processing time and the quality of the results. The triangulation algorithm is recommended for flat areas (agriculture fields) and stockpiles.
- *Create Digital Terrain Model:* Select Automatic Resolution (5 x GSD)

2.2. 3D Products tab

We do not need to select the desired output formats for the point cloud or set the parameters to be used for mesh generation, so none of the boxes in the Create Point Clouds and Create Textured Meshes should be checked.

- *General 3D Options:* make sure **Classify Point Clouds** is checked. This enables the generation of the point cloud classification and, when used for the DTM generation, it significantly improves the DTM. Make sure **Merge LAS Tiles** is checked. This option produces a single file with all the points.

2.3. Initial tab

Initial processing options change the way Drone2Map calculates keypoints and matching image pairs.

- *Run Initial:* Enables the Initial Processing step. Make sure this is checked.
- *Keypoints Image Scale:* The Keypoint Image Scale defines the image size at which keypoints are extracted, with Full using the full image scale and Rapid using a reduced image scale for faster processing. Full requires longer processing time, but is best when creating GIS-ready products. Make sure **Full** is selected.

- *Matching Image Pairs*: allows the user to optimize the processing for flights flown in an aerial grid (Option: Aerial Grid or Corridor), free-flown (Option: Free Flight or Terrestrial), or with other specific parameters (Option: Custom). We will use **Aerial Grid or Corridor**.
- *Matching Strategy*: Geometry Verified Matching is more computationally expensive, but can be more rigorous by excluding geometrically inconsistent matches. **Geometrically Verified Matching** is recommended for applications like ours with repeated features (e.g. dense mangrove canopy, homogeneous field).
- *Targeted Number of Keypoints*: select **Automatic** for the number of keypoints to be extracted. For multispectral imagery, select **Custom** and enter 10,000 keypoints. The Calibration Method determines how the camera's internal and external parameters are optimized. Select **Alternative** from the drop-down, which is optimized for aerial nadir images with accurate geolocation and low texture content and for relatively flat terrain.
- *Camera Optimization*: The internal camera parameters can be optimized in the following ways:
 - All (recommended for UAS)
 - None (recommended for using large cameras already calibrated)
 - Leading (optimizes the most important internal parameters)
 - All Prior (forcing the internal parameters to be close to the initial values)

Quality Note: Toggling **All Prior** and reprocessing output can help with camera optimization quality if the quality report indicates a greater than 5% relative difference in internal camera parameter optimization. See Quality Check Table for more details ([Appendix 4](#)).

 - The External Camera Parameters can be optimized in the following ways:
 - All (optimizes the rotation and position of the cameras)
 - None (no optimization)
 - Orientation (optimizes the orientation only; It is recommended only when the camera position is known and very accurate, and the camera orientation is not as accurate as the camera position)
- *Rematch*: make sure **Automatic** is selected if <500 images in the project. Select **Custom** if > 500 images.
 - Select the **Rematch** option to allow for rematching after the first part of the initial processing which may improve the reconstruction (see [Drone2Map Quality Check Table](#) below for further details).

2.4. Dense tab

This step increases the density of the points of the Point Cloud, which leads to higher accuracy of both the DSM and orthomosaic. Processing options allow the user to define parameters for the point cloud densification.

- Check the **Run Dense** box. This option increases processing times, but improves the accuracy of the output orthomosaic.
- *Image Scale*: use the default (Half Image Size), but make sure **Multiscale** is checked. When this option is used, additional 3D points are computed on multiple image scales, starting with the chosen scale from the Image Scale drop-down list and going to the 1/8 scale (eighth image size, tolerant). For example, if 1/2 (half image size, default) is selected, the additional 3D points are computed on images with half, quarter, and eighth image size. This is useful for computing additional 3D points on vegetation areas as well as keeping details about areas without vegetation.

- Toggle off **Limit Camera Depth Automatically**: Prevents the reconstruction of background objects. When toggled on this is useful for oblique/terrestrial projects around objects.

2.5. Coordinate Systems tab

This step defines the horizontal and vertical coordinate system for the images and the project outputs.

- *Image Coordinate System*: The default horizontal coordinate system for images is WGS84. Drone2Map should pull this from the imagery EXIF header. Drone GPS settings should be checked to confirm this is carried over correctly. To change the image horizontal coordinate system, click the globe button and select the appropriate coordinate system. The default vertical reference is EGM96 for images (most image heights are referenced to the EGM96 geoid).
- *Project Coordinate System*: This can only be modified if ground control points are NOT included in the project. Since we used GCP's, do not worry about changing the Project Coordinate System at this step. If GCP's are not used, the coordinate system and vertical reference model are determined by the coordinate system and vertical reference of the images themselves.

2.6. Resources tab

Ensure the project location, image location and location of Log File are correct. Adjust amount of CPU threads (computer resources) being used during image processing. The more CPU threads, the faster the processing (recommended if the computer is not going to be simultaneously used for other tasks). Use CUDA uses the computers graphics processing unit during processing (recommended).

2.7. Processing multispectral imagery

While most camera models are well defined in the camera database, other camera models, such as those that store each band as an individual image (e.g., Micasense Altum), need additional information defined to process correctly.

When a camera stores each band as an individual image, it may be necessary to assign group names. Drone2Map uses group names to correctly assign each drone image to its correct single band orthomosaic, which will be composited into a multiband orthomosaic during post processing. To select images and group them into logical single orthomosaics that are ready for compositing during post processing, complete the following steps: (see [Drone2Map documentation](#) for more details):

1. Make a note of the group names that need to be defined. For example band 1 through band 6 on the Micasense Altum are Blue, Green, Red, Red edge, NIR, and LWIR, respectively. Use these names for each group name.
2. For each group, you'll select images and assign a name.
3. On the Flight Data tab, open the Images Table.
4. Find the unique image names and determine how to select all images in one group. This is typically done by filtering by character strings in the file names or file paths. Using the Altum as an examples, images within an image set are named IMG_0000_1.tif, IMG_0000_2.tif, IMG_0000_3.tif, IMG_0000_4.tif, IMG_0000_5.tif, IMG_0000_6.tif; one image for each band. Use the Select by Attributes tool (Flight Data tab, Selection group). In the Select by Attributes window (in the right panel of Drone2Map), click Add Clause and a query such as Where -- File -- ends with -- _1.tif to select all the Blue band images. Click Select.
5. Verify that your query selected the desired images in the Images Table. Then use the Group Names tool on the Flight Data tab to enter the new group name (e.g., Blue).
6. Clear the previous selection (using Clear on Image Table). Repeat the above steps until all images are assigned to the correct group.

3. Add Ground Control

Drone2Map obtains GPS information from images or an external geolocation file during project setup. Where projects require better accuracy than the GPS can provide, you can add controls to your project. Control refers to points on the earth's surface with a known location that can be used to georeference your images to the correct position. Drone2Map provides the capability to import control from a file or manually add control from the map. Drone2Map documentation on managing control is [here](#).

Quality Note: At least 3 control points, but preferably 5+ must be included for them to be taken into account during image processing. For each control point, a minimum of two image links are required, but 5+ links are recommended.

3.1. Import Control

To import control points from a file, click the Control dropdown in the Control group within the Home Tab. Select Import Control → Import from CSV or text file.

- *Import Control From:* Click browse to select the pathname from your control file. Make sure Data Contains Headers is checked, and Comma Delimiter is selected if importing a .csv file.
 - Make sure there are no letters included at the end of the coordinates in .csv file (e.g., N for latitude North or W for longitude West). Make sure coordinates are negative when appropriate. For instance, GCP surveys using WGS84 as the horizontal coordinate system will need to report longitudes as negative (in US).
- *Control Coordinate System:* If necessary, update the Horizontal Coordinate System. This should match the coordinate system used for RTK GNSS surveys (#3 on readme.txt file you submitted with your data). If the updated horizontal coordinate system is one you anticipate using frequently for other GCP surveys, right click the coordinate system and select add to favorites.
 - *Vertical Reference:* The vertical reference indicates the vertical model to which your Ground Control elevation values refer. Note that the vertical reference choice may be different for images than it is for control points. You have the following vertical

reference

Options:asdf

- EGM 84—For altitudes based on the EGM84 geoid.
- EGM 96—For altitudes based on the EGM96 geoid.
- EGM 2008—For altitudes based on the EGM2008 geoid.
- Ellipsoid—For altitudes based on the ellipsoid specified in the horizontal coordinate system.
- Height Above Ellipsoid—For altitudes based on the ellipsoid specified in the horizontal coordinate system; it allows you to provide a height above the applicable ellipsoid.

The default is the EGM96 geoid, but it is common to conduct RTK surveys of control points (and vegetation plots) using the NAVD88 geoid. If this is the case, you will need to select Height Above Ellipsoid as your vertical reference. NOAA's online [vertical datum transformation \(VDATUM\) tool](#) is a useful means of determining the offset between the NAVD88 orthometric height you reported in your GCP file and the ellipsoid you used for the horizontal coordinate system.

at For instance, at NCNERR, we used the NAD83(2011) ellipsoid for our horizontal coordinate system and NAVD88 Geoid12A model for estimating orthometric height of our ground control points. The vertical offset between the ellipsoid and geoid we used our site is -37.343m (i.e., the NAVD88 geoid12A model is 37.343m below the NAD83(2011) ellipsoid).

Use VDATUM to calculate the vertical offset. Select the appropriate Region. In the Vertical Information section, enter the source reference frame based on the vertical reference your ground control points are reported in (for NCNERR example, this is NAVD88). The Target Reference Frame is the ellipsoid used in the horizontal coordinate system (for NCNERR example, this is NAD83(2011)). Choose the appropriate units. Select Height. Check GEOID model and select the model used for the source data (for NCNERR example, this is GEOID12A). Repeat for Target GEOID model. Scroll down to the map and click where your study site is located to populate the latitude and longitude inputs (for NCNERR example, this is 34.168226, -77.828171). Enter a Height of 0. Click Convert. At the bottom of the Ellipsoidal Transformation Epoch Inputs, select month-day-year, and enter the date of your ground control surveys and specify the reference data of the output positions (for NCNERR example, this is 5,6,2021 for both). Click OK. The value reported in the Height Output cell is the offset between the orthometric elevation of your control points and the ellipsoid (for NCNERR example, this is -37.343m).

In Drone2Map, enter this number (-37.343) in the Geoid Height Field in the Import Control Window. Make sure the vertical units are set correctly.

- *Control Photos*: Provides an option to import your GCP photos. Skip this option.
- *Control Field Information*: Make sure the appropriate fields within your GCP .csv file are selected for Lat (Y), Long (X), Elevation (Z), and Label. Click Enter Accuracy Values Manually next to the Accuracy Horizontal field (it should default to 0.02m, which is fine for RTK) unless accuracy values are included in the .csv file. Click OK. GCPs should be visible on the map (green + sign) and should be located within the footprint of your flight lines (orange lines) and images (blue circles).

Revisit the Options window (Home Tab → Processing group), select coordinates and make sure the project coordinate system (both horizontal coordinate system and vertical reference) match what you selected above the Control Coordinate System.

Export the selected processing options as a template by selecting Export Template (bottom left of options window), then browse to and designate the output location for your template, and click Save. When you create your next project to process wetland imagery, choose your exported template, and these settings and options are loaded into Drone2Map.

3.2. Control Manager

The control manager is located in the Home tab in the control group. The control manager displays information about the placed control points and provides quick access to common control operations.

3.3. Image Links Editor

To apply control, links are created between each control point and corresponding images. Links can be created either manually or computer assisted. Manually linking control points to images is the preferred method when processing projects unattended, such as overnight processing, in which there is no intervention by the user throughout processing. Assisted linking of control points requires initial

processing to be run, and significantly reduces the amount of time required to link control points to images. The steps below are for creating manual links.

Click the Image Links Editor button in the control manager (left icon or via the Home tab in the Control group). The image links editor opens and displays information about the selected control point (Lat, Long, Elevation), Control Point name, Control Point Type and a list of the images on the left. The list of images is ordered by distance from the GCP. Note, not all the images listed will contain the GCP.

General Note: Control can be set as a Ground Control Point (GCP) or Check Point.

Ground control points (GCPs) are used to georeference the model. If there are more GCPs in a project than necessary to accurately scale, rotate, and locate, some of the GCPs can be used as checkpoints to assess the accuracy of the project. GCPs improve the relative and the absolute accuracy of the model.

Checkpoints (CPs) are used to assess the absolute accuracy of the model. For our purposes, we will specify controls as Ground Control Points.

From the image list, select an image to which control should be linked. The selected image will appear in the preview window. Either the built-in map controls or mouse can be used to navigate the image (zoom and pan).

- 1) Zoom in on the GCP and place the crosshairs of the pointer in the image that corresponds to the location on the GCP where the RTK was placed for surveying (often at the center of the target). Click to create the link. A yellow X marks the point on the image. To redo the link, click another location. To remove the link, click Remove Link (right hand corner above the image). Repeat this process for at least 5 images for each GCP. It is a best practice to NOT link the first 5 images listed to a single GCP. Rather, try to spread the links among images that are not directly in sequence (i.e., rather than linking GCP to images 190, 191, 192, 193..., link to a set of random numbers).

Multispectral Note: When processing multispectral imagery, it is important that images from a variety of image sets are registered. In the file naming system, an image set is usually the number before the file extension (e.g., in file DJI_0713.JPG, 0713 is the image set number). An image set number represents a unique camera position above the ground. When capturing multispectral imagery, you will have an image within each image set for every band captured on the multispectral sensor. Each GCP must be registered in images from different image sets/camera positions in order for Drone2Map to be able to triangulate the GCP locations (i.e., do not link DJI_071_1, DJI_071_2, DJI_071_3, rather link DJI_071_1, DJI_045_2, DJI_88_3, etc). One band from each image set can be registered and counted in the minimum of 5 registered GCP images, it does not matter which band is registered. Also note that thermal imagery is often not visually sharp enough to identify GCP target centers, so thermal images can be ignored in this process.

- 2) To move to the next control point, click the dropdown in the Control Point list. Repeat step 1 for each control point. If two GCPs appear in a single image, make sure the image is being linked to the correct GCP.

3.4. Export Control

The Export Control tool allows you to save your control and associated linked images as an external file. This way, you can reuse them in future projects. To export your control, use the Select tool to select the control points you want to export (or you can select GCPs by clicking on the left most column of the

control manager, holding shift and clicking on the last row to select all GCPs for export). On the Home tab, click the Control drop-down list → Export Control. Choose a location to save the .zip file. Click Save.

3.5. Start Processing

Click the Start button on the Home Tab in the Processing Group to begin processing the imagery. Depending on the number of images, homogeneity of the landscape, your CPU specs and the CPU resources you allotted in the Options window, this will likely take hours.

3.6. Troubleshooting

3.6.1. Fixing a distorted orthomosaic or DSM

If the output orthomosaic and/or DSM is spatially distorted (compressed, stretched, etc), this may be because the GCPs were in a poor configuration. To remedy this, open the Control Manager and delete one of the GCPs. More than one GCP can be deleted here, but each GCP removed reduces accuracy, so it is recommended to start by only removing one GCP. Start processing again, and the resulting products will hopefully not be distorted.

After running processing without the full set of GCPs, it is important to inspect the DSM for ‘doming’, where the elevation of the DSM appears to form a dome, with the remaining GCPs at the center. This may also appear as ‘banding’ if the remaining GCPs are in a linear arrangement, where the DSM is steeply sloped and the colors in the DSM appear as a rainbow. If this occurs, refer to the following section to add additional GCPs using water level as a reference to improve the georeferencing of the surface. When re-processing with the additional GCPs, be sure to re-enable any GCPs that were removed.

3.6.2. Creating new GCPs to improve georeferencing of surface using water level as a reference

This method is used when there is a need for additional GCPs but there is no ground-checked reference available (e.g., another GCP or checkpoint), but there is at least one area in the study site that contains a distinguishable feature at or very close to water level. Manual tie points can be created at these locations using water level as the assumed elevation value. These manual tie points can then be transformed into 3D GCPs and used to georeference the modeled surface.

Quality Note: Ideally the points created will be evenly distributed across the study site surface (points arranged in a quincunx pattern (i.e., how dots are arranged on the 5-side of a die) results in much higher quality georeferencing as compared to points arranged in a straight line).

Quality Note: It is ideal that a water level measurement is taken in the field at the time imagery was captured. Alternatively, a water level estimate can be extrapolated from initial DSM. If this alternate method is used, note that points in open water have variable elevation values, so it is ideal to identify a point at the edge of land and water to serve as the water level reference. This method is done under the assumption that all points in areas considered at water level (i.e., tide pools, mouths of tributaries, etc.) are at the same or close to the same elevation (the height of the water).

- Run processing as normal with all available GCPs.
 - If the distribution of GCPs is causing distortion in the orthomosaic and/or DSM, and it is necessary to remove some GCPs, be sure to leave a GCP adjacent to the water enabled.
- Once processing is completed, toggle between viewing the DSM and the orthomosaic, and click around on points as close to the water’s edge as is possible near whichever GCP is closest to the water. Try a few different points around the water’s edge and try to estimate an average elevation. This value will be used as the water level elevation.

- Once the water level elevation is established, use the Add From Map option from the Control dropdown to create at least two manual GCPs that are selected in spots that correspond to the water level elevation estimated (i.e. at the water's edge). Place them on a memorable feature that can be picked out later (e.g. a clump of oysters, a piece of debris, a hole in the mud).
- It is recommended to zoom in on each new GCP and take a screenshot to refer back to when linking images to each new GCP because there won't be a physical GCP in the image to link to.
- The new GCPs will appear in the Control Manager, and the X, Y, and Z coordinates can be viewed in the Image Links Editor; however, those coordinates are derived from the current (inaccurate) DSM.
 - It is currently not possible to edit those coordinates in Drone2Map (as of version 2.3.2), so it will be necessary to manually edit the CSV file that the initial GCPs were imported from. Open that CSV file, and add new entries for each new GCP, copying the Latitude and Longitude from the Image links Editor (but not elevation), and enter the 'water level' elevation as each new GCP's elevation.
 - If the CSV file does not already have columns for horizontal accuracy and vertical accuracy, add them. For the GCPs that were surveyed in the field, assign horizontal and vertical accuracy values of 0.02m. For the newly created GCPs, assign horizontal and vertical accuracies of 0.1m so that Drone2Map doesn't assign too much weight to this GCP location, as the elevation value is not exact.
- Save the CSV file.
- Once the CSV file has been edited and saved, remove the new GCPs from the Control Manager (they currently have inaccurate elevations).
- Follow the steps from the [Import Control](#) section above to re-import the CSV file containing the GCPs (including the newly created GCPs).
- In the Control Manager remove all duplicates (each of the original GCPs should appear twice now - remove the ones that are not already linked to images to save time).
- Using the Image Links Editor, link the new GCPs to 5 to 8 drone images, referring back to the screenshot to make sure that they're being linked to the same feature every time.
- Once all GCPs are linked to enough images, press the Start Processing button again. The resulting DSM should have much better accuracy.

Quality Note: After re-processing, make sure to refer to the [Drone2Map Quality Check Table](#) to ensure there are no georeferencing errors.

4. Products

Drone2Map will store outputs within the home project folder specified when initiating the project. The following file structure will be used:

- .gdb (geodatabase)
- Products
 - 2D
 - DEM
 - Ortho
 - 3D
- Project
 - Data
 - Logs
 - process
- Report
 - Quality Report (see [Drone2Map Processing Report](#) below for details)
- .d2mx (Drone2Map project file)
- .tbx (ArcGIS Toolbox)

4.1. Indices

- After processing is completed, generate multispectral indices by selecting Indices in the Analysis tab in the Tools group. Click the drop-down menu and select NDVI (normalized difference vegetation index). Feel free to explore the other indices, but for our purposes, we will only use NDVI for analyses.
 - NDVI is a standardized index allowing you to generate an orthomosaic displaying greenness, also known as relative biomass. This index takes advantage of the contrast of characteristics between two bands from a multispectral raster dataset—the chlorophyll pigment absorption in the red band and the high reflectivity of plant material in the near-infrared (NIR) band.

The documented and default NDVI equation is as follows:

$$\text{NDVI} = ((\text{NIR} - \text{Red}) / (\text{NIR} + \text{Red}))$$

- NIR = pixel values from the near-infrared band
- Red = pixel values from the red band

This index outputs values between -1.0 and 1.0.

- Export the NDVI as a raster by right clicking on the NDVI layer in the Contents pane → Data → Export Raster. The Export Raster window will open. Make sure the file path of the output raster dataset is correct. The Coordinate System is automatically populated with the coordinate system of the source raster layer that is being exported. Use the default values for the other options (for details, see the [Drone2Map documentation](#)).

General Note: Drone2Map does not allow any coefficients to be applied to specific bands which is necessary for sensors such as the Sentera d4k ndvi + ndre to generate sensical index values. For instance, the Red and NIR bands for the Sentera d4k sensor are calculated as follows:

$$\text{Red} = -0.966 * \text{DNblue} + 1.000 * \text{DNred}$$

$$\text{NIR} = 4.350 * \text{DNblue} - 0.286 * \text{DNred}$$




- Application of band specific corrections for calculating indices can be done in ArcGIS Pro. Using the Catalog Pane in ArcGIS Pro, add the raster to be corrected to a new map. In the case of the NDVI generated from Sentera d4k ndvi + ndre, you should see red, green, and blue (NIR) bands. Use the Raster Functions tool (Imagery tab, Analysis group). In Raster Functions, click on the Math dropdown and select [Band Arithmetic](#). Select the Raster to be corrected in the Raster dropdown. For Method, select User Defined (top of list). Enter the sensor-specific formula in the Band Indexes field. For instance, for the Sentera d4k sensor Band 3 (B3) is the NIR band and Band 1 (B1) is the Red band. Substitute the band equations above into the NDVI formula: $((4.350 * B3 - 0.286 * B1) - (-0.966 * B3 + 1.000 * B1)) / ((4.350 * B3 - 0.286 * B1) + (-0.966 * B3 + 1.000 * B1))$.
- Create a new layer. To save the new layer, right click the new layer in the contents pane, select Data → Export Raster.
- To bound the NDVI index between 1 and -1, use the following equation in the raster calculator in ArcGIS Pro (image analyst tools):
 - $\text{Con}(\text{"raster.tif"} < -1, -1, \text{"raster.tif"})$ where "raster.tif" is the name of your NDVI raster. Repeat with $\text{Con}(\text{"raster.tif"} > 1, 1, \text{"raster.tif"})$ to bound values to 1.

5. Drone2Map Processing Report

Every ArcGIS Drone2Map project includes a detailed processing report that displays the results. To access the report once the initial processing step is completed, on the Home tab, in the Processing section, click Report. You can also access the processing report at any time in the project folder in PDF and HTML format.

5.1 Drone2Map Quality Check Table

The following table provides guidance for using the Quality Check table on page 1 of the quality report. For additional guidance, see Drone2Maps [documentation on quality reports](#).

Quality Check Item	Definitions and Conceptual Framework	Quality Report Value Check 	Visual Quality Check	Troubleshooting  
Images	<p>Median number of keypoints per image.</p> <p>Keypoints are points of interest (high contrast, interesting texture) on the images that can be easily distinguished. The number of keypoints identified depends on the size of the images and the visual content.</p> <p>Drone2Map's ability to reconstruct an accurate 3D surface depends on the amount of keypoints that can be identified in multiple, overlapping images (aka matched keypoints).</p>	At least 10,000 keypoints extracted per image is recommended for optimal quality.	<p><u>Quality Report:</u> 2D keypoint matches can be visualized in figure 5 of the quality report.</p> <p><u>Images:</u> Image quality can be viewed by scanning through the images and checking for appropriate exposure levels and lighting, crispness, etc.</p>	<p>Not having enough keypoints per image can be the result of repetitive visual content (e.g., a uniform area of grass or water), lack of image overlap, poor image quality and/or too many changes in the scene during image acquisition.</p> <p>These issues can be addressed in the following ways:</p> <ul style="list-style-type: none"> ● Increase image overlap during image acquisition ● Adjust camera settings ● Increasing image size
Dataset	<p>Number of enabled images that have been calibrated.</p> <p>Calibrated images are images that contain adequate numbers of keypoints to be used for surface reconstruction. In order for an image to calibrate, it needs to have a minimum number of 25 keypoint matches.</p>	At least 95% of images calibrated in one block is recommended for optimal quality.	<u>Quality Report:</u> Image overlap can be visualized in figures 4 and 5 of the Quality Report. The distribution of project blocks can be visualized in figure 3 of the Quality Report. The Uncertainty Ellipses describe how	<p>Not having enough images calibrated can be the result of an image calibration error and/or an instance of multiple blocks. The presence of uncalibrated images in a project can be resolved in the following ways:</p> <ul style="list-style-type: none"> ● Increase image overlap during image acquisition

	<p>Enabled images are incorporated into the project, while disabled images are recognized as not useful to surface reconstruction; this could happen automatically (e.g., Drone2Map recognizing calibration card images) or manually by the user.</p> <p>A block is a set of images that are calibrated together. Ideally, all or most of the images are calibrated in one block. Having multiple blocks indicates that there were not enough matches between blocks to provide global optimization.</p>		<p>precisely each image is located with respect to the other images by means of the Manual and Automatic Tie Points. Ideally, the ellipses in the center of the project are smaller than at the outside, as these images have more matches that bind them to the surrounding images. Large ellipses in parts of the project may indicate problems calibrating these parts and typically correspond to areas with few matches.</p>	<ul style="list-style-type: none"> ● Process project with lower keypoint image scale ● Adjust camera parameters to improve image quality
Camera Optimization	<p>Percentage representing the difference between the initial camera model and the optimized camera model.</p> <p>When using a perspective lens, the camera optimization value is the percentage difference between the initial and optimal focal lengths.</p> <p>The focal length transformation parameters are a property of the camera's sensor and optics and vary with temperature, shocks, altitude and time. The calibration process starts from an initial camera model and optimizes the parameters.</p>	<p>Less than 5% difference between initial and optimized camera model value is recommended for optimal quality.</p>		<p>A large difference between the initial and optimized camera models can be due to flat or homogeneous areas not capturing enough visual information, images having significant rolling shutter distortion, and/or wrong initial internal camera parameters. A project with homogenous or flat areas not capturing enough visual information can be resolved in the following ways:</p> <ul style="list-style-type: none"> ● Process with lower keypoints image scale ● Enable geometrically verified matching ● Set internal calibration parameters to All Prior

Matching	<p>Common keypoints identified in multiple images. This information is used to correctly orient and stitch individual images together. Higher numbers of matches will increase the processing time and the quality of the results.</p>	<p>More than 1,000 matches computed per calibrated image (for keypoint image scale $> \frac{1}{4}$) and 100 matches per calibrated image (for keypoint image scale $< \frac{1}{8}$) is recommended for optimal quality.</p>	<p><u>Quality Report</u>: Figure 5 in the quality report is useful for assessing the strength and quality of matches.</p>	<p>A low number of matches suggests the results may be unreliable. This is often related to low overlap between images, but can also be attributed to initial camera model parameters.</p> <p>Address this issue by doing the following:</p> <ul style="list-style-type: none"> ● See the Dataset Quality Check section (above) to improve the results. ● Restart the calibration a few times with different settings (camera model, Manual Tie Points) to get more matches. ● Increase image overlap.
Georeferencing	<p>Information about how the project was georeferenced and what error is associated with the GCPs.</p> <p>Ground Sampling Distance (GSD) is the distance between two consecutive pixel centers measured on the ground. A higher GSD value translates to a lower spatial and image resolution.</p> <p>The Root Mean Square error in each direction (X, Y, Z) This error calculation will take into account the systematic error. If Mean error is equal to 0 (zero), the RMS error will be equal to the Sigma Z error. The comparison of the RMS error and Sigma error, indicates a</p>	<p>Optimal accuracy is obtained when 5-10 GCPs are distributed evenly across the study site.</p> <p>Ideally, the GCP error is less than 2 times the average GSD.</p>		<p>A GCP error greater than 4 times the GSD could indicate a severe issue with the dataset or an error with marking or specifying the GCPs.</p> <p>In a project where GCPs are used, georeferencing errors can be addressed in the following ways:</p> <ul style="list-style-type: none"> ● Adding additional GCPs ● Adjusting GCP accuracy values ● Remarking images <p>In a project where no GCPs were used, the project is</p>

	<p>systematic error. Of the 3 indicators, the RMS Error is the most representative of the error in the project since it takes into account both the mean error and variance.</p>			<p>georeferenced using the position of the computed image positions. Error could be a result of a GPS device used to geolocate the original images suffering from global shift.</p> <p>There could also be cases where GCPs are discarded by the software due to errors in the GCPs.</p>
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Appendix 3. GCP Caveats

1. Manually Adjusting GCP Height to Facilitate Registration Process

If GCP icons are visible above the camera positions, or too high off the point surface for GCPs to be identified in any imagery, follow the steps below to manually adjust the height of the GCPs so they are close to the modeled surface:

- Navigate to GCP/MTP Manager and click Edit... to open GCP coordinate system options.
- Check the Advanced Coordinate Options box to expand the vertical coordinate system options.
 - Select the Geoid Height Above GRS 1980 Ellipsoid [m] option and input an altitude that will adjust the GCPs to be close to the level of the tie point cloud (e.g., if the altitudes of the tie points are around -80 m, and the altitude of the GCP is 1.5 m, input a height of -80 into the box to bring the GCP icons down to just above the point surface).
- Click OK in the coordinate system options box, the vertical GCP coordinate system (the information in parentheses) will update to reflect the change. Click OK in the GTP Manager window and the following message will display: Reoptimize the project in the new output coordinate system for higher accuracy. Click OK.
- The GCP icons will have adjusted based on the height above the ellipsoid that was inputted. Select one of the GCPs either by clicking on the icon in the rayCloud view or by selecting one in the Layers menu list.
 - If image thumbnails appear in the right sidebar, proceed to next steps. If no images appear, repeat the previous step to adjust the height until the GCP icons are as close to the height of the point surface as possible.
- Once images appear in the right sidebar, the standard [GCP Registration](#) steps can be completed. However, because the vertical GCP coordinate system was adjusted to facilitate the registration process, once all GCPs are registered, the vertical GCP coordinate system must be set back to Arbitrary (in the GCP Manager > Advanced Options) before reoptimizing.

2. Creating New GCPs to Improve Georeferencing of Surface

There are various instances that necessitate manually creating GCPs. Two instances are described in the steps below.

Manual tie points must be created and then transformed into 3D GCPs. See Pix4D's documentation about the different types of [Tie Points](#) to learn more.

A. Creating New GCPs Using Original GCP as Reference

This method is used when something goes wrong with an original GCP (e.g., nearby GCP #4 target was accidentally tagged as GCP #5, eliciting a Georeferencing error in the quality report). The following

process explains how to create a fresh GCP in the rayCloud, populate it with the original GCP information, and delete the original/erroneous GCP.

- In the rayCloud view, select a tie point very close to the erroneous GCP.
- Upon selecting a tie point in the proximity of the GCP, both Selection information and Images should be shown in the right sidebar.
- Hover mouse over the first image displayed and zoom out until the GCP target is visible in the image. Once the desired zoom (confidence) level has been reached, select the New Tie Point icon (the leftmost icon in the Images icon bar), then click once in the center of the GCP target to establish the tie point.
- Continue registering this GCP following the [Registering GCPs](#) instructions.
- In the Selection section of the right sidebar, change the Type from Manual Tie Point to 3D GCP. Change the Label to something distinguishable if desired.
- Populate the Selection information (X, Y, Z, Horizontal and Vertical Accuracy) by copying and pasting the values from the original GCP Selection information.
- Once GCP is established and Selection information is entered, click Apply to save changes. A new GCP icon should appear in the rayCloud view and the name of the new GCP should appear in the Layers menu list.
- Now that a new GCP (essentially a copy of the original) has been created, the original/erroneous GCP can be deleted by right clicking it in the Layers menu list and selecting Remove.

B. Creating New GCPs Using Water Level as Reference

This method is used when there is a need for additional GCPs but there is no ground-checked reference available (e.g., another GCP or checkpoint), but there is at least one area in the study site that contains a distinguishable feature at or very close to ‘water level’. Manual tie points can be created at these locations using ‘water level’ as the assumed elevation value. These manual tie points can then be transformed into 3D GCPs and used to georeference the modeled surface.

Quality Note: Ideally the points created will be evenly distributed across the study site surface (points arranged in a quincunx pattern (i.e., how dots are arranged on the 5-side of a die) results in much higher quality georeferencing as compared to points arranged in a straight line).

Quality Note: It is ideal that a water level measurement is taken in the field at the time imagery was captured. Alternatively, a water level estimate can be extrapolated from the point cloud. If this alternate method is used, note that tie points in open water have variable elevation values, so it is ideal to identify a point at the edge of land and water to serve as the water level reference. This method is done under the assumption that all points in areas considered at ‘water level’ (i.e., tide pools, mouths of tributaries, etc.) are at the same or close to the same elevation (the height of the water).

- Run step 2 and generate the densified point cloud before starting the GCP creation process. By running step 2 and generating the densified point cloud, points closer to the water’s edge can be selected in order to determine the most accurate elevation value for water level at this site when the images were taken.




- Once the densified point cloud is generated, turn it on in the rayCloud view (check the Point Cloud box in the left Layers menu) and select a point near the boat that's as close to the water's edge as is possible. Try a few different points around the water's edge and see if an 'average' elevation is discernible. This value will be used as the 'water level' elevation.
- Once water level elevation is established, create at least two manual tie points (that will become GCPs) that are selected in spots with enough water to be considered 'water level' (in this case, one at the edge of the tidepool on the east side of the site and the other at the edge of the tributary in the northwest corner of the map).
- To create manual tie points:
 - Select a point in the point cloud surface where the new tie point/GCP will be placed.
 - A series of thumbnail images will pop up in the right sidebar under the Images dropdown.
 - In the first image, zoom out until a distinguishable feature becomes visible (e.g., a sharp angle in the shoreline, a cluster of oysters at the water's edge) then zoom in on this feature. Ideally, the feature is distinguishable and as close to the water's edge as possible.
 - Once the distinguishable feature is visually located in one image, ensure that the feature can be located in multiple images.
 - Once the feature has been visually located in multiple images, return to the first image and zoom in on the feature (the higher the zoom level, the more confidence Pix4D will interpret in its location). Once at the appropriate zoom level, select the New Tie Point button (the leftmost icon in the Images icon bar), then click once on the feature in the image to establish the tie point.
 - Repeat this zooming and clicking process in multiple images (as explained in the [GCP Registration Process](#)). Register at least 5 images, or as many as it takes for Pix4D to automatically place the green cross in the correct position in unregistered images.
 - In the Selection section of the right sidebar, change the Type from Manual Tie Point to 3D GCP. Change the Label to something distinguishable if desired.
 - Input the established water level elevation value derived from the previous step into the Z value. The X and Y values should auto populate after changes are saved.
 - Change both Horizontal and Vertical Accuracy to .1 so that Pix4D doesn't assign too much 'weight' to this GCP location, as the elevation value is not exact.
 - Click Apply. This will save the changes and the GCP will show up in the GCP list under the Layers menu and as a GCP icon in the rayCloud view. Any GCP can be removed by right clicking its name in the Layer menu and clicking Remove.
 - Repeat this process for all manual tie points / new GCPs.
- Once all manual tie points are created and designated as 3D GCPs, the project should be reoptimized and existing outputs should be reprocessed to incorporate changes.

Quality Note: After reoptimization, make sure to refer to the [Output Quality Check](#) step and the Quality Check Tables (for [Pix4D](#) or [Drone2Map](#), respectively) to ensure there are no georeferencing errors.

Appendix 4. Pix4D Output Quality check table

The following table provides guidance for using the Quality Check table on page 1 of the quality report. For additional guidance, see Pix4D's documentation on quality reports:

- [Basic guidance](#) on analyzing the quality report
- [Specifications](#) of quality check table terms, symbols and quality report figures
- [Comprehensive guidance](#) on understanding and troubleshooting using the quality report

Quality Check Item	Definitions and Conceptual Framework	Quality Report Value Check 	Visual Quality Check	Troubleshooting  
Images	<p>Median number of keypoints per image.</p> <p>Keypoints are points of interest (high contrast, interesting texture) on the images that can be easily distinguished. The number of keypoints identified depends on the size of the images and the visual content.</p> <p>Pix4D's ability to reconstruct an accurate 3D surface depends on the amount of keypoints that can be identified in multiple, overlapping images (aka matched keypoints).</p>	At least 10,000 keypoints extracted per image is recommended for optimal quality.	<p><u>Quality Report</u>: 2D keypoint matches can be visualized in figure 5 of the quality report.</p> <p><u>Images</u>: Image quality can be viewed by scanning through the images and checking for appropriate exposure levels and lighting, crispness, etc.</p>	<p>Not having enough keypoints per image can be the result of repetitive visual content (e.g., a uniform area of grass or water), lack of image overlap, poor image quality and/or too many changes in the scene during image acquisition.</p> <p>These issues can be addressed in the following ways:</p> <ul style="list-style-type: none"> • Increase image overlap during image acquisition • Adjust camera settings • Increasing image size
Dataset	<p>Number of enabled images that have been calibrated.</p> <p>Calibrated images are images</p>	At least 95% of images calibrated in one block is recommended for optimal quality.	<u>rayCloud</u> : Uncalibrated images are displayed as red camera position icons in the rayCloud. Uncalibrated images are not used for processing	Not having enough images calibrated can be the result of an image calibration error

	<p>that contain adequate numbers of keypoints to be used for surface reconstruction. In order for an image to calibrate, it needs to have a minimum number of 25 keypoint matches.</p> <p>Enabled images are incorporated into the project, while disabled images are recognized as not useful to surface reconstruction; this could happen automatically (e.g., Pix4D recognizing calibration card images) or manually by the user. Uncalibrated images display in the rayCloud as red icons.</p> <p>A block is a set of images that are calibrated together. Ideally, all or most of the images are calibrated in one block. Having multiple blocks indicates that there were not enough matches between blocks to provide global optimization.</p>		<p>and can arise from a variety of causes.</p> <p><u>Quality Report</u>: Image overlap can be visualized in figures 4 and 5 of the Quality Report. The distribution of project blocks can be visualized in figure 3 of the Quality Report. The Uncertainty Ellipses describe how precisely each image is located with respect to the other images by means of the Manual and Automatic Tie Points. Ideally, the ellipses in the center of the project are smaller than at the outside, as these images have more matches that bind them to the surrounding images. Large ellipses in parts of the project may indicate problems calibrating these parts and typically correspond to areas with few matches.</p>	<p>and/or an instance of multiple blocks.</p> <p>The presence of uncalibrated images in a project can be resolved in the following ways:</p> <ul style="list-style-type: none"> • Increase image overlap during image acquisition • Process project with lower keypoint image scale • Adjust camera parameters to improve image quality <p>A project with multiple blocks can be resolved in the following ways:</p> <ul style="list-style-type: none"> • Enabling the 'Rematch' option • Adding Manual Tie Points between blocks
Camera Optimization	<p>Percentage representing the difference between the initial camera model and the optimized camera model.</p> <p>When using a perspective lens, the camera optimization value is the percentage difference between the initial and optimal</p>	<p>Less than 5% difference between initial and optimized camera model value is recommended for optimal quality.</p>	<p><u>rayCloud</u>: By viewing the rayCloud from the side, the shape of the point cloud surface can be inspected. A relatively level surface is expected for marsh landscapes; a dome-like shape may be due to poor camera optimization quality.</p>	<p>A large difference between the initial and optimized camera models can be due to flat or homogeneous areas not capturing enough visual information, images having significant rolling shutter</p>

	<p>focal lengths. When using a fisheye lens, the value is the percentage difference between the initial and optimized affine transformation parameters C and F.</p> <p>The focal length/affine transformation parameters are a property of the camera's sensor and optics and vary with temperature, shocks, altitude and time. The calibration process starts from an initial camera model and optimizes the parameters.</p>		<p><u>rayCloud</u>: By viewing the rayCloud from above, the camera optimization quality can be visualized. The closer the blue (initial) and green (computed or optimized) camera position icons are to each other, the better the camera optimization quality. A 'doming effect' in the point cloud surface can be attributed to poor camera optimization quality if a pattern of better camera optimization is observed in the center of the surface compared to the periphery (i.e., the camera position icons forming a green circle with a blue ring around it from above).</p>	<p>distortion, and/or wrong initial internal camera parameters.</p> <p>A project with homogenous or flat areas not capturing enough visual information can be resolved in the following ways:</p> <ul style="list-style-type: none"> • Set internal calibration parameters to All Prior • Process with lower keypoints image scale • Enable geometrically verified matching <p>Images with rolling shutter distortion can be corrected in the following ways:</p> <ul style="list-style-type: none"> • Calculate the Vertical Pixel Displacement and enable linear shutter optimization in the Image Properties Editor if needed. <p>Incorrect initial internal camera parameters can be resolved in the following ways:</p> <ul style="list-style-type: none"> • Edit camera model • Generate parameter values for perspective lens or fisheye lens
Matching	Common keypoints identified in multiple images.	More than 1,000 matches computed per calibrated image is	<u>Quality Report</u> : Figure 5 in the quality report is useful for assessing the strength and quality of matches.	A low number of matches suggests the results may be unreliable. This is often related

	<p>Pix4D uses a SIFT algorithm to identify the same unique pixel clusters (keypoints) in multiple images; this information is used to correctly orient and stitch individual images together. Higher numbers of matches will increase the processing time and the quality of the results.</p>	recommended for optimal quality.		<p>to low overlap between images, but can also be attributed to initial camera model parameters.</p> <p>Address this issue by doing the following:</p> <ul style="list-style-type: none"> ● Increase image overlap during image acquisition
<p>Georeferencing</p> <p>Quality Note: Initial information will be displayed in the Georeferencing section of the quality check table of the quality report after step 1 has been processed, but user should make sure to check the updated georeferencing information in the quality check table after GCPs have been registered</p>	<p>Information about how the project was georeferenced and what error is associated with the GCPs.</p> <p>Ground Sampling Distance (GSD) is the distance between two consecutive pixel centers measured on the ground. A higher GSD value translates to a lower spatial and image resolution.</p> <p>The Root Mean Square error in each direction (X, Y, Z) This error calculation will take into account the systematic error. If Mean error is equal to 0 (zero), the RMS error will be equal to the Sigma Z error. The comparison of the RMS error and Sigma error, indicates a systematic error. Of the 3 indicators, the RMS Error is the most representative of the error in the project since it</p>	<p>Optimal accuracy is obtained when 5-10 GCPs are distributed evenly across the study site.</p> <p>Ideally, the GCP error is less than 2 times the average GSD.</p>		<p>A GCP error greater than 4 times the GSD could indicate a severe issue with the dataset or an error with marking or specifying the GCPs.</p> <p>In a project where GCPs are used, georeferencing errors can be addressed in the following ways:</p> <ul style="list-style-type: none"> ● Adding additional GCPs ● Adjusting GCP accuracy values ● Remarking images <p>In a project where no GCPs were used, the project is georeferenced using the position of the computed image positions. Error could be a result of a GPS device used to geolocate the original images suffering from global shift.</p> <p>There could also be cases where GCPs are discarded by</p>

(See GCP Registration section)	takes into account both the mean error and variance.			the software due to errors in the GCPs. Read more about Ground Control Points for more information.
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Appendix 5. Create Alternative Vegetation Indices with RGB Imagery in ArcGIS Pro

Process for creating alternate vegetation indices using RGB imagery:

1. Once multispectral imagery has been processed and outputs have been created, create a new ArcGIS Pro project.
2. Search for and open the Raster Calculator geoprocessing tool (under Analysis > Tools) and use the following steps to generate each vegetation index:
 - a. For the Rasters input field, use the browse icon to navigate to the Pix4D project output folder called Indices (located in 'Project Folder Name' > 4_index > indices). From here, each of the .tif files within the Red, Green and Blue index folders can be selected, which will add them to the Rasters list in the tool.
 - b. Once the three rasters are listed in the Rasters list, create the equation for each vegetation index by selecting the appropriate operators from the Tools list, using the keyboard and double clicking raster files from the list. Each index can be created using the following equations:
 - i. **Excess Green (ExG)** = $2 * \text{Green} - \text{Red} - \text{Blue}$
 - ii. **Vegetative Index Green (Vlg)** = $(\text{Green} - \text{Red}) / (\text{Green} + \text{Red})$
 - c. Once an equation is inputted into the tool's equation box, choose an output location for the vegetation index raster being created (it is best practice to store rasters in a fresh folder, rather than a geodatabase) and name the output appropriately.
 - d. The Environment settings can be left as they are.
 - e. Repeat and run this process for each vegetation index raster.
3. Search for and open the Composite Bands geoprocessing tool (under Analysis > Tools) and input the following:
 - a. For the Input Rasters field, use the browse icon to navigate to the Pix4D project output folder called Indices (located in 'Project Folder Name' > 4_index > indices). From within the indices folder, navigate to the .tif file within each of the Blue, Red, and Green folders. The blue, green and red .tif files are the inputs that will be combined into one, multiband raster.
 - b. For the Output Raster field, select an output file location (make sure it is not inside a geodatabase) and name the output appropriately.
 - c. The Environment settings can be left as they are.
4. Once the raster is created, verify the output is as desired by right clicking on the raster and examining bands (in symbology) and raster information (in properties).

Appendix 6. Creating RGB Orthomosaic from Multispectral Imagery in ArcGIS Pro

1. Once multispectral imagery has been processed and outputs have been created, create a new ArcGIS Pro project.
2. Search for and open the Composite Bands geoprocessing tool (under Analysis > Tools) and use the following steps to generate the RGB orthomosaic:
 - a. For the Input Rasters field, use the browse icon to navigate to the Pix4D project output folder called Indices (located in 'Project Folder Name' > 4_index > indices). From within the indices folder, navigate to the .tif file within each of the Red, Green and Blue folders. The red, green and blue .tif files are the inputs that will be combined into one multiband raster.
 - b. For the Output Raster field, select an output file location (make sure it is not inside a geodatabase) and name the output appropriately.
 - c. The Environment settings can be left as they are.
3. Once the raster is created, verify that the bands are in the desired order by right clicking the composite raster and selecting Symbology. The RGB option should be selected and the red, green and blue bands should be designated as band 1, 2 and 3, respectively.