# The Coastal Ecosystem Mapping and Media Viability Project

A project by

**AGEDI**
مبادرة أبوظبي العالمية للبيانات البيئية
Abu Dhabi Global Environmental Data Initiative

In partnership with

**G·R·I·D ARENDAL**
*A Centre Collaborating with UNEP*

**Five Oceans**
Environmental Services LLC

Supported by

**blue forests**
www.gefblueforests.com

**DUBAI MUNICIPALITY**
بلدية دبي

# Table of Contents

# The Coastal Ecosystem Mapping and Media Viability Project

## 1. Project Description:

The Coastal Ecosystem Mapping and Media Utility project applied advanced and pioneering unmanned aerial vehicle technology with companion software and mobile app to explore the viability of an innovative communications tool. It further evaluated the feasibility of mapping and assessing the geographic extent of coastal blue carbon ecosystems in a low cost and quantitative way.

- The project examined the tools and methodologies implemented to assist the assessment of blue carbon ecosystems through the following activities:
- Assessing the viability of using volume calculations derived from unmanned aerial vehicle footage to calculate biomass and Blue Carbon storage capacity.
- Assessing the viability of using video and photo footage from unmanned aerial as communications and outreach tools to promote international blue carbon efforts.
- The testing of the unmanned aerial vehicle mapping utility and assessing test sites, relevant to the ground-truthing of carbon and ecosystem assessments.
- Developing a methodology for replication in other test sites round the world.
- Promoting the outcomes and potential of the project at an international event to raise awareness of international Blue Carbon efforts and the feasibility of using lower cost technology in the collection of viable defendable scientific data.
- Creating multiple communication and outreach tools to promote the outputs of this project and the organisations associated with it.

The Coastal Ecosystem Mapping and Media Utility project contributes to enable international exposure of the United Arab Emirates (UAE) Blue Carbon efforts and linkages to other International Blue Carbon efforts and projects such as the Global Environment Facility (GEF) Blue Forests Project. The project seeks to potentially add a component to international Blue Carbon projects that is currently not included; an ecosystem mapping and media function that can contribute to the carbon assessment and communications activities of multiple Blue Carbon activities.

## 2. Acknowledgments

Finally we would like to thank the GEF Blue Forests Project for Supporting Levi Westerveld to attend the fieldwork, enabling rapid analysis of the data in the field.

# 3.    Background

## I.    What is Blue Carbon?

**Blue carbon** is the carbon captured by the world's oceans and coastal ecosystems. The carbon captured by living organisms in oceans is stored in the form of biomass and sediments from mangroves, salt marshes and seagrasses.[1]

## II.    Relevance of Blue Carbon

The rates of blue carbon sequestration and storage capacities in aquatic ecosystems are comparable to (and often higher than) those in carbon-rich terrestrial ecosystems such as tropical rainforests or peatlands. Unlike most terrestrial ecosystems, which reach soil carbon equilibrium within decades, deposition of carbon dioxide in coastal ecosystem sediment can continue over millennia. However, when these coastal ecosystems are degraded or destroyed they can become carbon dioxide sources due to the oxidization of biomass and organic soil.[2]

Because coastal ecosystems do contain substantial amounts of carbon, and because this carbon is in danger of being released, they are important in mitigating climate change. However, the rate of loss of mangroves, sea grasses and salt marshes (driven mostly by human activities) is estimated to be among the highest of any ecosystem on the planet, prompting international interest in managing them more effectively for their carbon benefits.[3]

These ecosystems are highly valuable not only for their contribution to climate change mitigation on a global scale, but also for the many valuable services they provide locally.[4]

## III.    Major Findings from the Blue Carbon Demonstration Project (2014)

Abu Dhabi's Blue Carbon ecosystems store significant amounts of carbon that would be emitted upon their degradation. Across the range of ecosystems studied, algal mats showed the highest combined above and below ground carbon stocks per hectare. Average total carbon stock in planted mangroves of different ages was lower than that of natural mangroves. Blue Carbon stocks are estimated to be highest in seagrass, due to the large extent of the ecosystem.

Overall, Blue Carbon ecosystems in Abu Dhabi are calculated to store over an estimated 41 million tonnes of $CO_2$ equivalent within the soil and biomass, more than the Emirate's annual emissions from the oil and gas (26,4 million tonnes) or water and electricity (30,9 million tonnes) sectors.

The combined value of Blue Carbon ecosystem services, including carbon sequestration and storage, coastline protection, habitat provision and water purification, was estimated to exceed 2 billion AED

---

[1] Nellemann, Christian et al. (2009): Blue Carbon. The Role of Healthy Oceans in Binding Carbon. A Rapid Response Assessment. Arendal, Norway: UNEP/GRID-Arendal
[2] Laffoley, Dan and Grimsditch, Gabriel (2009): The Management of Natural Coastal Carbon Sinks. Gland, Switzerland: IUCN
[3] Murray et al. (2010): Payments for Blue Carbon. Potential for Protecting Threatened Coastal Habitats. Durham, USA: Nicholas Institute for Environmental Policy Solutions
[4] Crooks, Stephen et al. (2011): Mitigating Climate Change through Restoration and Management of Coastal Wetlands and Near-shore Marine Ecosystems: Challenges and Opportunities. Washington D.C., USA: World Bank

per annum. They also have significant cultural and social value. In Abu Dhabi, these ecosystems contribute to maintaining livelihoods, provide food and recreation and reduce vulnerabilities to sea level rise, storm events and the spread of disease. These factors merit their inclusion into conservation and management activities and strategies, particularly for future marine spatial planning and financial planning frameworks.[5]

## IV.    Major Findings from the AGEDI National Blue Carbon Project (2015)

- As of 2015, the carbon stocks of 18 mangroves of the UAE have been quantified. This includes four in the Sea of Oman (Kalba) of Sharjah Emirate, six in the Arabian Gulf of the Northern Emirates, and eight in the Abu Dhabi Emirate

- The data suggest that mangroves of the Northern Emirates are generally larger than those of Abu Dhabi Emirate – but this varies:
    - The mean ecosystem carbon stock of the mangroves of the three areas are 389, 229, and 140 Mg C/ha (mega grams of carbon per hectare), respectively.
    - The mean ecosystem carbon stock of all studied sites combined was 293.15 Mg C/ha. The carbon stocks of the Northern and Eastern Emirates were significantly different than the mangroves sampled in Abu Dhabi.

- The greatest differences among sites are in the plant carbon pools and in deeper soil layers:
    - There were few differences in the carbon pools of soils 0-30 cm in depth, however, the plant carbon stocks of the Northern and Eastern Emirates greatly exceeded that of the Abu Dhabi mangroves (i.e. >80 Mg C/ha for the Northern and Eastern Emirates, but <21 Mg C/ha for the sampled Abu Dhabi mangroves)
    - Additional differences were found at greater soil depths; for example, the mean carbon pools of soils >50 cm in depth was 57 Mg C/ha for the Abu Dhabi mangroves but 185 Mg C/ha at the Sharjah sites.

- The carbon stocks of hyper-arid and hyper-saline mangroves of the UAE are at the lower end of carbon stocks, but have some similarities with other parts of the world:
    - Globally mangrove carbon stocks have been reported to be about 1000 Mg C/ha.
    - The size of the UAE's carbon stocks of mangroves of sandy substrates is similar to what has been reported for Madagascar.
    - The very high carbon stocks measured for Kalba South (667 Mg/ha) are similar to productive mangroves in many parts of the world.

## 4.    The need for Unmanned Aerial Vehicle (UAV) or Drone mapping technologies

Small remotely operated and autonomous unmanned aerial vehicles have the potential to collect detailed and quantitative information on blue carbon ecosystems, which can support the assessment and management of both terrestrial and marine ecosystems.

---

[5] AGEDI 2013, Blue Carbon in Abu Dhabi – Protecting our Coastal Heritage: The Abu Dhabi Blue Carbon Demonstration Project, Executive Summary.

The collection of field data has previously been a very manual and complicated task, wherein the strong relationship between field measured tree diameter and/or heights are used as input in allometric equations to calculate above-ground biomass and derive carbon stock estimates (see Kauffman and Donato (2012) for further details).

At the time of this projects implementation (September 2015) the use of drones have never before been used to assess blue carbon ecosystems, nor as a management tool of both terrestrial and marine ecosystems. It has previously been the general consensus that using drones for high quality mapping was to be left to specific drone companies and was thus very expensive.

This project used a low cost unmanned aerial vehicle and companion photogrammetry software at a pilot site to develop a procedure to assess mangrove forest ecosystems and develop innovative communications tools.

The use of drones allows for fully automatic flight at a fixed height, or optionally to fly the unmanned aerial vehicle using a remote control, with the complexity of these actions depending on the complexity of the drone. Photogrammetry companion applications give the possibility to automatically calculate in real time when to optimally acquire images to cover the area as well as to enhance image attributes and characteristics. Once the images are acquired, some software vendors provide mobile/table applications to guide the user on the process of converting them into orthomosaics, point clouds, elevation models, and 3D models. This can also be done using PC software or on the cloud.

## I. Why use unmanned aerial vehicles (Drones) to calculate above ground biomass?

So far utilizing drones to calculate above ground volume of the canopy towards figuring out carbon storage has not been tested, it is this projects goal to assess the viability of using unmanned aerial vehicles as part of any Blue Carbon Ecosystem Field survey.

If successful, this would help field surveys through:

- Identifying priority areas in advance to surveys,
- View hard to reach areas,
- Expand the area of study to a wider area. (See (Error! Reference source not found. for previous method of collecting data from mangroves in the field),
- And lower fieldtrip costs.

The drone imagery can also be used in other capacities, including;

- Producing bilateral studies in parallel as Blue Carbon data collection field studies such as:
- Land Use change,
- Water distribution,
- Payments for Ecosystem Service (PES) assessments,
- State of the Environment (SOE) Assessments,
- And habitat mapping/management.

**Plot layout for carbon stocks measurments of native mangrove stands in Northern and Eastern Emirates, UAE 2014**

Trees > 3 cm dbh measured in 7m radius (A=153.9m²)

Trees < 3 cm dbh measured in 2m radius nested plots(A=12.6m²)(all plots)

Seedlings (<1.3m ht) Counted in the 2m plot

Soil depth measurments and 1 nutrient core (all plots)

Measure pH, Salinity, GPS and total soil depth in each soil core

Plot: 1    2    3    4    5    6

20m    20m

Total transect length 100m

Tree measurements include dbh of mainstem and the crown radius of all plants rooted in plots

Experimental field design to determine forest structure and carbon stocks in natural mangroves of the UAE.

*Figure 1. Graphic taken from National Blue Carbon Decision-Maker Summary – AGEDI 2015 (Note Total plot for one days work is 100 m, sampling 6 x 7m test areas of Above ground Biomass)*

## 5.    Communications & Outreach

GRID-Arendal has 25 years of experience in communicating Environmental Knowledge for Change through innovative communication tools and outreach. AGEDI received positive feedback from the communication and outreach component of the Blue Carbon Demonstration project so when the idea for this project was conceived it became very clear that although we were testing out a new methodology of scientific data collection that communications and outreach would heavily feature in our plans.

If you build it, they will come -- right?

Not necessarily, both AGEDI and GRID-Arendal wanted the availability of this methodology to be widely promoted within the blue carbon community and beyond. The project needed visually striking material that could be used to present the project and its methodology to a wide variety of stakeholders locally and internationally.

In order to serve the "hard-to-reach," it helps to change your thinking. Your goal is to reach the "yet-to-be-reached."

The videos, photos, and 3D maps generated from this project were designed to be one component of a larger program of AGEDI to be a support structure to their main endeavour of facilitating change.

The main outreach materials produced are:

- The methodology document
- A short film detailing the outputs of the fieldwork
- 360 videos produced during the fieldwork

- PowerPoint presentation detailing the project's efforts
- High resolution maps of areas covered during the fieldwork
- High resolution video from the drone
- 3D Fly-through videos of the areas mapped
- Digital terrain Maps of the areas covered during the fieldwork
- A Workshop to present the project
- An information booth at the Eye on Earth Summit 2015

## 6.    Report Purpose

The purpose of this report is to enable others to continue research using unmanned aerial vehicle (Drone) mapping technologies for environmental assessments.  The methodology section of this report focuses on assessing the viability of using volume calculations from drone footage to biomass and Blue Carbon storage capacity estimates. The same methodology and drone imagery has the possibility of being used for a multiple of environmental assessments, below are just a few:

- Land Use change
- Water distribution
- Payments for Ecosystem Service (PES) Assessments
- State of the Environment (SOE) Assessments
- Habitat Mapping / Management

## 7.    Success factors

The project's objective was to test the potential application of using UAVs to calculate volume but also to make all outputs scalable and replicable, especially in developing countries where the vast majority of Blue Carbon ecosystem habitats are located. This was achieved by:

### Using relatively low cost consumer drones:

The home consumer market for drones is increasing exponentially, deciding on the correct drone to use was a key to success. We decided within the test pilot phase to select the DJI Phantom (DJI) as they are easy-to-fly drones, which include aerial photography systems as well as being easily available and lower cost, thus supporting opportunities for replication of the projects methodologies. . Additionally, DJI have developed a Software Developer Kit (SDK), which is available for free for developers enabling the creation of customized mobile app solutions to unlock the full potential of the DJI aerial platform.

### The software used to process the imagery should be available free:

We considered different free and open source software to create orthomosaics (maps from the imagery) and Digital Terrain Models (DTM) (points clouds from drone imagery). We wanted something that was relatively easy to use with an extensive support database. Many of the open source software required plugins to be installed and/or purchased. Cloud based solutions offered similar limitations.

Pix4Dmapper Discovery is free but with a limited number of outputs. For this project, the pro version was purchased by AGEDI but will also render very select partner projects in the future using their

license. Pix4D has also produced a free mobile app to control the drone autonomously making use of the DJI Server Development Kit (SDK), this increases the fieldwork accuracy and production level.

## The project itself should be a capacity building process:

All aspects of the fieldwork from planning to its implementation was done in collaboration with the project team and the municipalities. Before attempting any fieldwork AGEDI, GRID-Arendal and Distant Imaging Services visited the municipalities that was planned to carry fieldwork, to explain what the fieldwork would look like and gave presentations on the possibilities of what ecological work can be done with UAVs.

During the fieldwork notes were taken on what worked and what did not work to help make this methodology report easy to follow. As this was a learning experience for the entire team the first field trip days were spent learning the equipment and tools. The second half of the entire field trip went much faster (to the delight of the very hot team in temperatures above 40°).

During the fieldwork it became apparent that access to imagery obtained from the drones was incredibly important to the managers of the areas on a daily basis. Effort was given to train the local staff in the simple control of the drones so they could possibility use the experience for purchasing their own drones later.

Staff from the Sharjah site have reported since that they have purchased similar drones for accessing the sites from a new perspective giving them better understanding of daily changes and to be aware of any problems.

## The fieldwork should be used as an outreach opportunity:

360° videos were filmed in the field to share visuals of areas the general public cannot access. These immersive 360° videos will enable decision makers and interested members of the public to experience walking through the mangroves encouraging the protection of these unique habitats. This outreach medium also highlights AGEDI and its partners to be seen at the forefront of new technology and ideas for outreach opportunities in coastal ecosystems in other global Blue carbon projects.

This new immersive technology was highlighted at the Eye on Earth Summit 2015 in Abu Dhabi. The team found it a great way to interact with scientists and general pubic alike some of whom had never stepped foot into a mangrove ecosystem even though it is locally located.

## This methodology should be easy to follow:

How easy something is cannot be easily measured as everyone reading this methodology will have different backgrounds. We decided to try and keep the following:

- Technical language kept to a minimum or explained clearly
- Software used should be easily attainable with vast online learning content available
  - Choose software that had accompanying phone/tablet software to assist in collection of data.
- Drones used should not be specialist drone (available from any good stockist)
- Simple information should be very easy to access from data:
  - Plot Size
  - Height flown
  - GPS Position

## Anyone with the correct enthusiasm could replicate the data collection part of this project

In regards to the basic methodology of the data collection and basic image processing, we split the data processing into two segments:

1. Processing achieved with Pix4D
2. Processing achieved with further analysis using GIS software

## 8.    Methodology for calculation of above ground biomass for mangroves

In this project, we used Pix4D software to estimate mangrove tree volumes, and to create datasets for further analysis using GIS software. All imagery and data shown in this methodology were collected September 2015, at the Khor Kalba Site in Sharjah, UAE and Ras Al Khor Wildlife Sanctuary, Dubai, UAE. In the first part of this methodology, we outline the necessary steps to process drone imagery data in Pix4D. In a second section, we describe how GIS software can be used to further analyse raster datasets outputs from Pix4D. We supplement tree volume calculations in Pix4D with calculations using GIS to overcome limitations of the Pix4D software, and for enhanced efficiency and accuracy in our calculations.

The goal of this project was to estimate the feasibility to calculate mangrove tree volume, and transcribe these measurements into mangrove tree biomass and carbon sequestration capabilities estimates.

To estimate above-ground mangrove biomass, the relationship between drone-estimated volume and FAO-defined[6] biomass was explored. Relationships between volume and biomass, such as that outlined by the FAO, estimate above-ground woody biomass (stem, bark, branches; excluding foliage) by multiplying the stem volume of living trees by published wood density values (e.g., Simpson 1996, value for *Avicennia marinia*).

---

## 9. Pre Fieldwork

### Project Planning

In close collaboration with the project partners the test sites were selected before going out to the field. The pilot sites were selected to be as close as possible to previous site locations that were used in fieldwork under the Northern Emirates Blue Carbon Exploration project (Figure 2 previously undertaken by AGEDI and its Partners (Relevance of Blue Carbon). These were chosen also for the purpose of comparability and viability of the project.

Our criteria for choosing the site were as follows:

- They had the most above ground carbon storage of all the sites previously tested (Figure 2),
- They were easy to navigate through (higher canopies and breaks in canopies)
- Regular breaks in canopies (For Ground Control Points)
- There were permissions provided by the municipalities to fly the drones
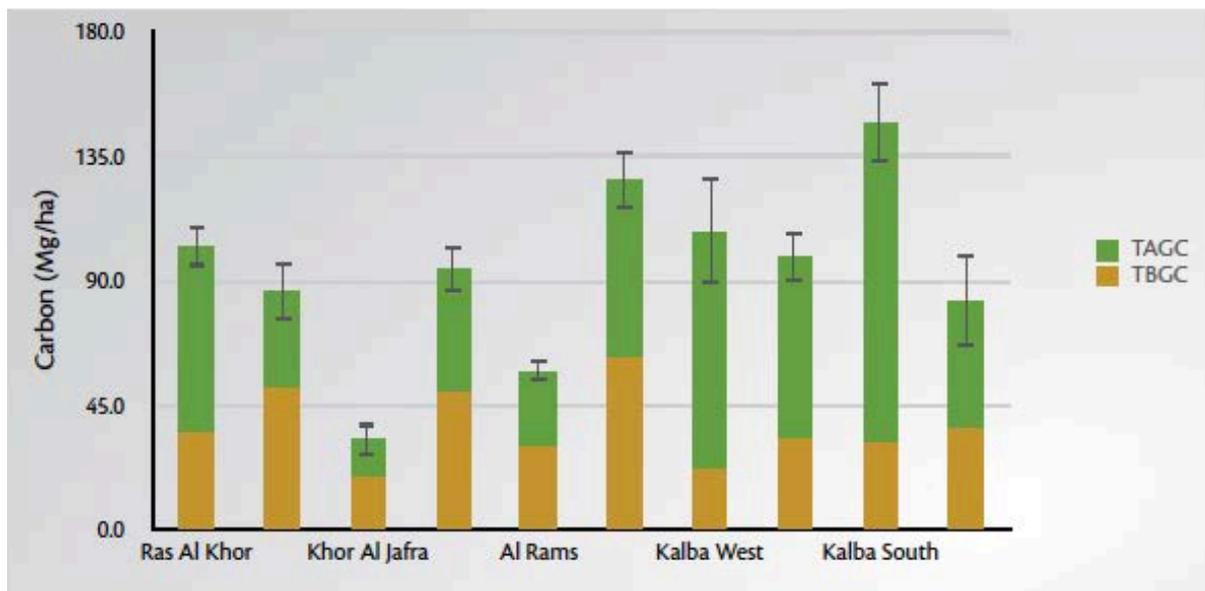


*Figure 2. Total Plant Carbon - Note: Vertical bars represent one standard error. Total carbon pools found in the mangrove trees (aboveground and belowground, Mg/ha) of sampled mangroves of the Northern and Eastern Emirates, UAE. The total carbon pools are broken down by Total aboveground carbon (TAGC) and total belowground carbon (TBGC). TAGC – From National Blue Carbon Decision-Maker Summary – AGEDI 2015.*

*Figure 3. Northern Emirates Blue Carbon Exploration Project Fieldwork sites*



*Figure 4. Locations selected for this project.*

The sites that were selected (Figure 4) were Khor Kalba Site in Fujairah, United Arab Emirates (UAE) and Ras Al Khor Wildlife Sanctuary, Dubai, UAE.

Prior to the start of the project, the team had informal meetings to discuss the following sections:

- 2015  UAE UAV Regulations
- The project had to secure permissions to fly drones in the regions. Recent regulations in Dubai had a direct implication on the planning of the project.
- Drones can fly no higher than 100 meters
- Drones can´t fly within 500 meters of any active airspace (airfields etc.)

GCAA UAV regulations can be found at: https://www.gcaa.gov.ae/en/pages/uas.aspx

- There was no over-head power lines or no-fly zones in regards to airports close to the proposed sites but this was discussed during the planning of the project.

*Tides*

After several tests with the drones prior to traveling to Abu Dhabi it was determined that we had to fly at low tide to capture imagery of bear ground around the mangroves This restriction had to be taken into consideration when planning for the fieldwork.

*Photo 1. Type 1 of the GCP-Sheets used in this project*

*Ground Control Points (GCP)*

Ground Control Points (GCPs) are objects identifiable within Satellite or Airborne imagery that have precise GPS locations that can help remap an image to increase its accuracy. Software such as Pix4D can then be used to create accurate maps. The original photos taken from the drones are typically 10-50 metres off depending on the connected satellites during the photos acquisition.

With the GCPs the accuracies of the images will improve 0.5-2 metres or better depending on the GPS used to locate the GCPs.

*Field Data Collection and Remotely Sensed Ground Control*

There are two ways to ensure that Ground Control Points are accurate. One as used in this project, is to have a person on-site who uses a high grade GPS unit to verify the longitude, latitude, elevation and position (stand in the middle of the GCP and record its location (0). This coupled with post-processing for the purposes of this project has created an accuracy of approximately 2 centimetres.

The other way is through Remotely Sensed Ground Control Points (RSGCP) which can be obtainable through satellite imagery coupled with post-processing done using an archive of confirmed GCPs nearby within the images (telephone masts, military points of interest, etc.)

No RSGCP points were identified in the proposed field sites so the first option was selected. Ideally a mix of the two would be used to give the highest rate of accuracy and reduce the error level of the GPS.

These discussions towards the selection of GCP methodology had a direct impact on the sites that where selected for the work. The denseness of the mangroves and the placement of the GCPs provided challenges when selecting the field sites from satellite imagery.

For best image georectification GCPs should be placed in the corner and centre location of the mission area (Figure 6)
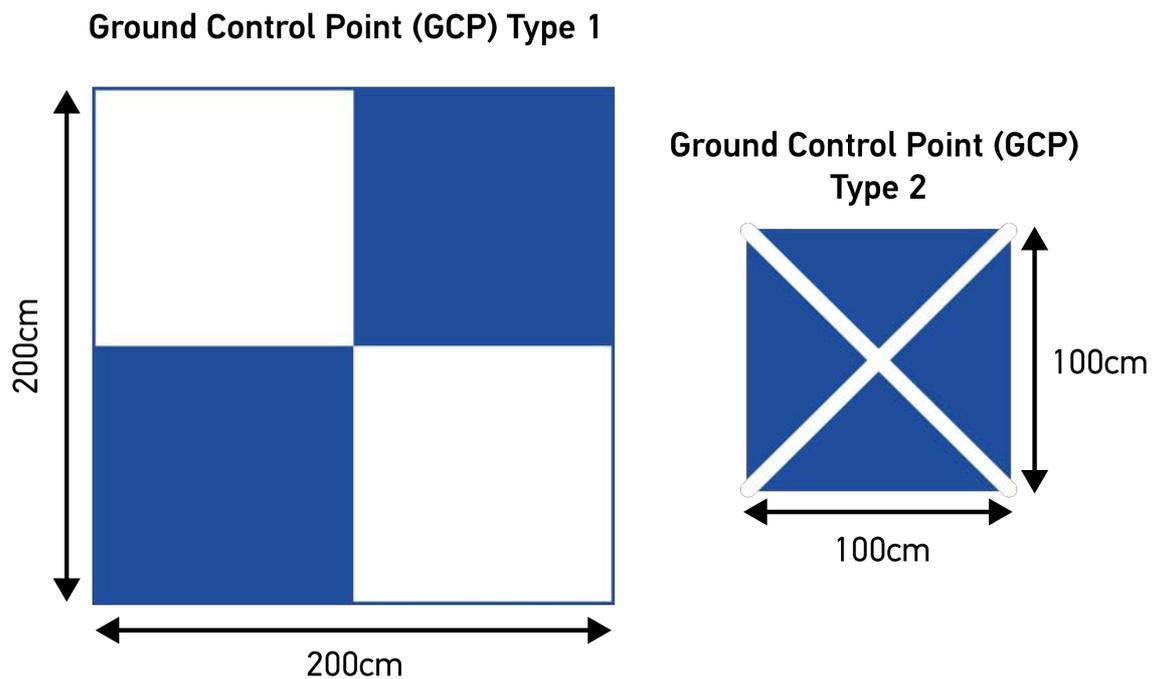


Figure 5. Type 1 and Type 2 – GCP Sheet

## Ideal Placement of The GCPs
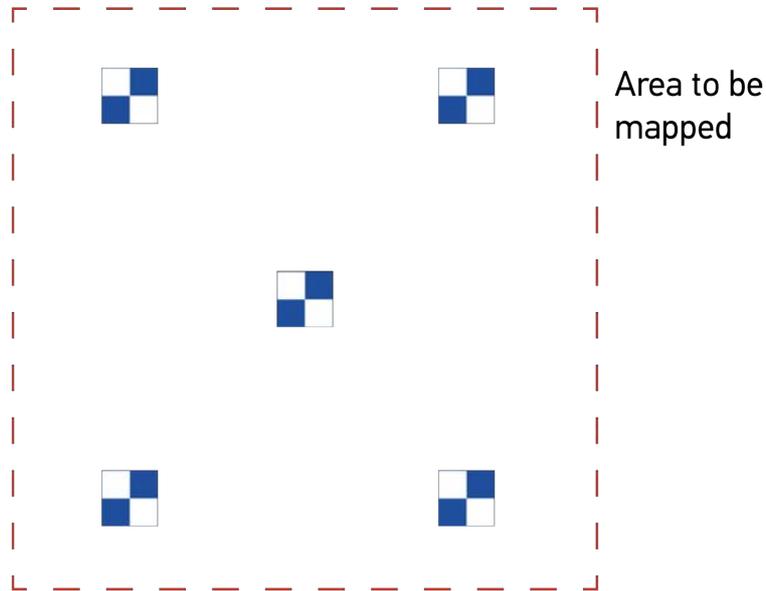


*Figure 6. Placement of the GCPs within a mission area*

For our purposes the project decided to use large plastic sheets that would be identifiable from the drone imagery for the GCP. Prior to going into the field the decision was made to test two different types of sheets for our GCPs.

Although Pix4D recommended using 200 cm x 200 cm sheets as GCPs as this is optimal for being visible at all altitudes, the denseness of the mangrove canopy would restrict access with such a large GCP. A second type of GCP that is 100cm x 100cm was also created to test its effectiveness that would be easier to transport through the dense mangrove.
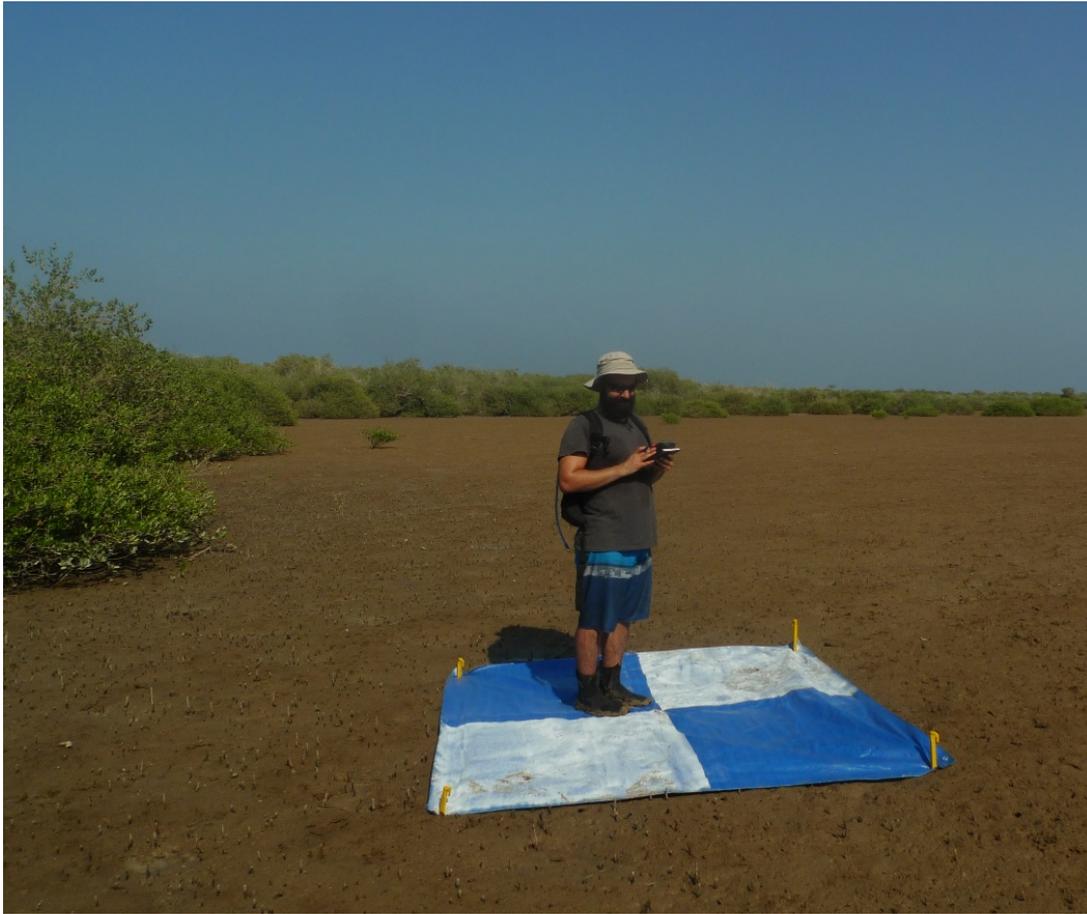
*Photo 2. Kaveh Samimi-Namin standing in the centre of a ground control point (GCP) to take GPS measurements using a survey GPS.*

## 10.    During the Fieldwork

### Pre-flight

A pre-flight checklist was created by Distant Imagery Solutions to ensure the safe flying conditions and that all equipment was in working order.

DJI recommends the operating temperature for the phantom 2/3 to be within -10°C ~ 50°C, and an infrared thermometer was used to check the temperature of the drone to make sure there was no sudden change in temperature in the motors before and after each flight.

Before each drone flight, the height of the flight, the area covered, and the overlap between pictures taken by the drone can be defined in a mission planner application (Figure 8). The location (latitude, longitude, and elevation) at which each image is taken by the drone's camera is also recorded during the flight.

Before all the missions were flown all GCPs were planned, placed and recorded with a GPS. We did so using a combination of discussions from the pre field trip meetings and comparing Google maps imagery within the mission planner app to the physical area during the field mission.

According to recommendations (Figure 6) the placement of the GCPs had to be in ridged configurations, but due to limitations on-site (water, tree placement, obstacles, etc.) this was not always possible, much trial and error went into the mission placement and GCPs placement to find the right balance between mission placement and coverage of the camera (Figure 7).
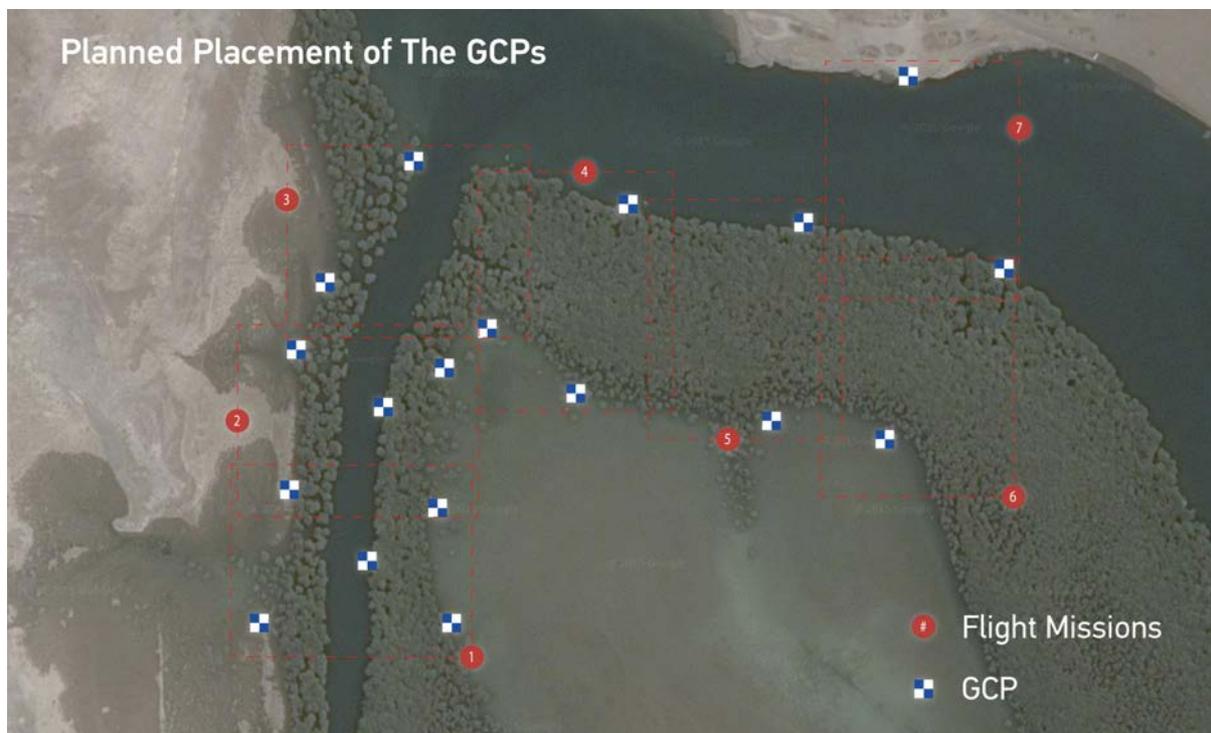


*Figure 7. Onsite planning of missions and GCPs*
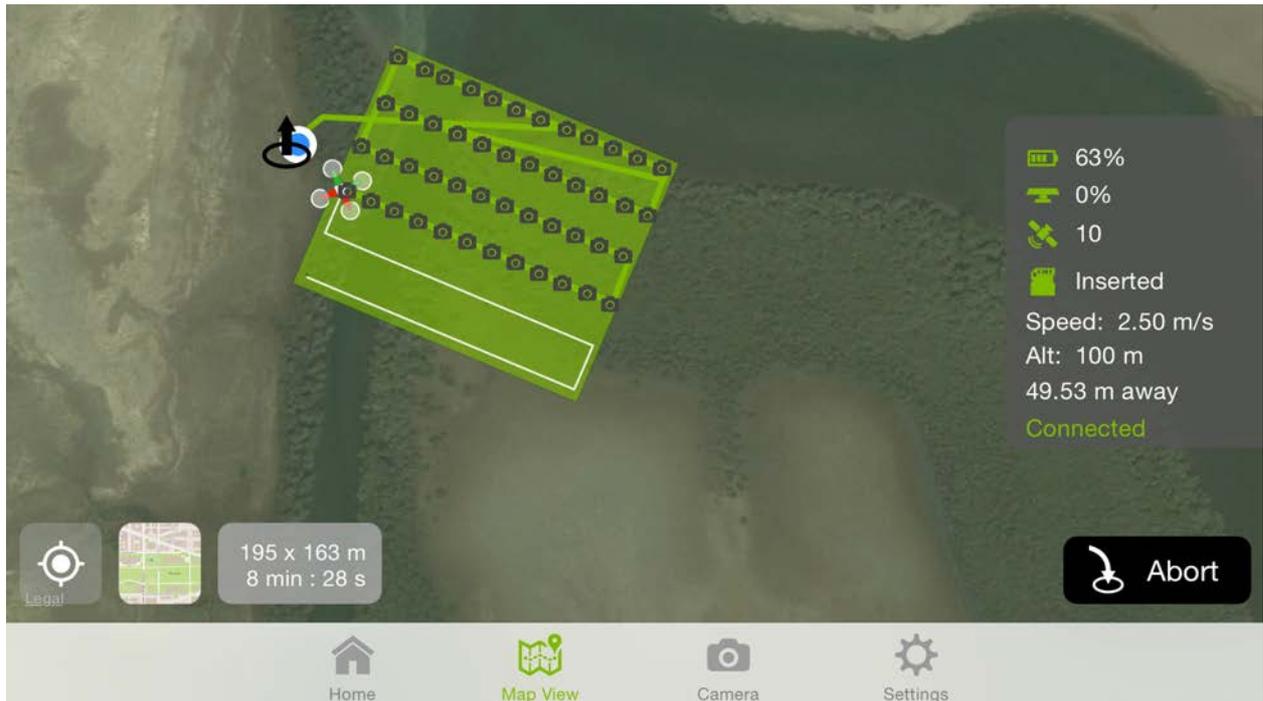
*Figure 8. Screenshot of the Pix4D Capture app.*

After a few tests by looking at the images taken it was discovered that if the drone is flying 70-100 metres high, then the GCPs did not have to all fall inside the mission area as planned (**Figure 6**), as the field of view from the drone camera was bigger than the mission area covered and would capture these GCPs (**Figure 9**).

## Redesigned ideal Placement of The GCPs
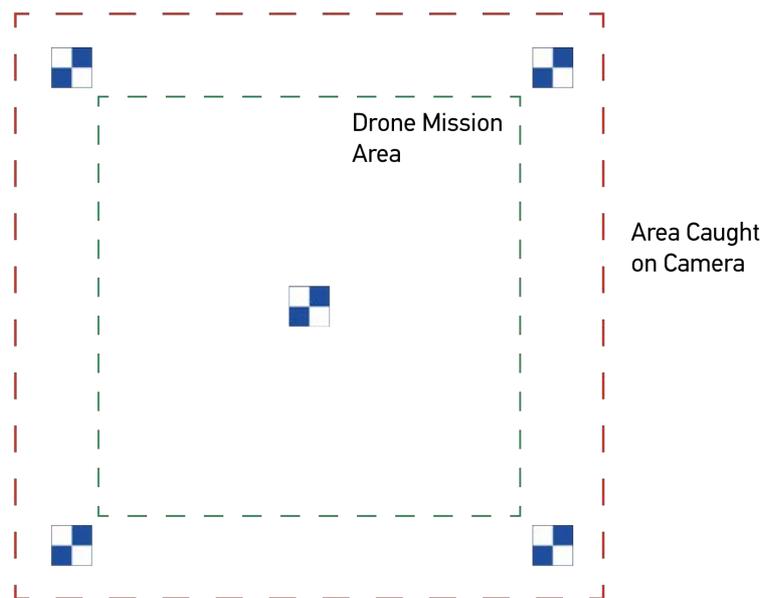


*Figure 9. After a few missions flown it was realised that the GCPs could be further spread out from the flight mission area.*

*Figure 10. Mission plan for the Northern part of Khor Kalba Ramsar Site in Fujairah (three missions shown and Home point H)*

### Home Point

Placement of the drone pilot had a direct impact on the mission area selected for flying (Figure 10), where the furthest point of the missions had to be close enough to the home-point (H) to keep a connection with the pilot. *This will not be as critical in future versions of the mission planner when using a more recent drone with a longer range, but will still have an impact on the overall mission planning.*

### GPS

As long as there was overlap between missions and GCPs visible, for a majority of missions the software was able to auto correct the accuracy of the GPS.

Five Oceans supplied a survey grade GPS unit and an expert to operate it. It was advised that error correction could be done from using RSGCPs or a survey grade base station, and with the replicability in mind it was decided to try and keep the GPS as simple as possible with keeping it as higher grade as possible at low cost in mind.

## Altitude

The drone flying restrictions within the country was the first factor that was used when determining what altitude to fly at. Recommendations from Pix4D and a GIS expert, there will be trade-offs with resolution, horizontal and vertical accuracy of the height of objects that can be detected with different flying heights.

If you imagine the field of view of the drone camera as a cone shape (**Figure 11**), the 3D model can only be created where adjacent cones overlap (Macmillan-Lawler 2015).
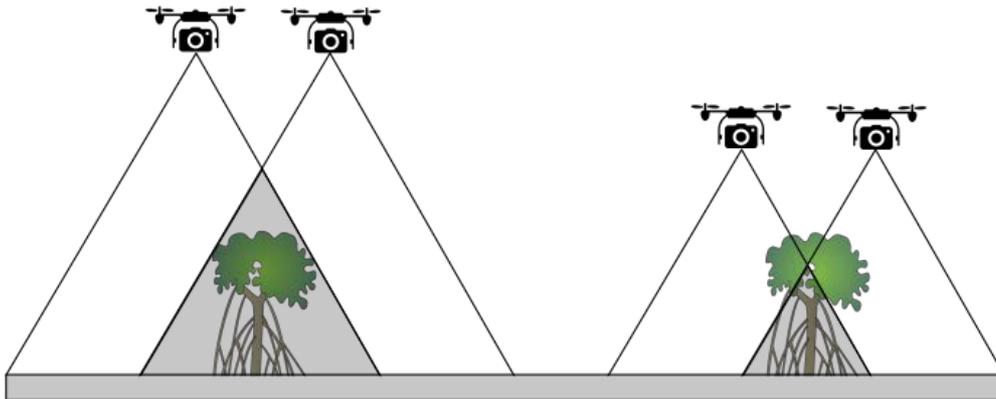


*Figure 11. Flying at a low height will mean images need to be taken closer together to ensure an adequate 3D model size, this results in a loss of vertical measurement accuracy (the further the distance between the cameras, the better the measurement accuracy) flying too low can and also mean that tall objects cannot be measured as they are larger than the model area. Conversely flying too high can result in a loss of resolution, as objects are too small to be detected in the images. This can degrade the accuracy of the 3D model (Macmillan-Lawler 2015).*

During the fieldwork time at the Khor Kalba Site in Fujairah, we decided to fly several missions at several heights to determine the optimal altitude to fly at. As the success criteria of the project was to have multiple outputs from the project including high resolution orthomosaics and 3D video, after reviewing the processed images from the site the optimal altitude was found to be 70 meters which provided both a good resolution imagery as well as enough image overlap necessary to create a 3D model.

## In-flight

We found that even though the flight mission was completely autonomous the pilot had to keep track of the drone in the mapping app to ensure the pre-planned route and speed was being followed and safety assuring the drone could land if there was an error or a break in the connection to the software. Another person was used to be a "spotter" to ensure the drone was on track and still in view.

All photos and data are stored within the on-board SD card on the drone.  At the end of each mission the option is given to synchronize the drone and phone/tablet. This was not always possible due to battery drain or Wi-Fi interference. The time taken to transfer images became a factor in the field as the sun moving across the horizon causes shadows on the images, thus, making it harder to combine the images within the 3D model.  It was decided to complete this task when returning home from the field.

This decision is not without risk as found when one of the drones crashed due to unforeseen technical errors and the SD card was lost, resulting in losing the data collected from that day.



*Photo 3. Take-off for a mission, pilot and spotter*

## 11. After the Fieldwork

### Processing Data in Pix4D

To start to process drone imagery in Pix4D we first create a new project and add all the flight images from a study area to that project. After uploading the images, the correct coordinate system for the study area also needs to be selected. In our case, because we first flew in Fujairah, UAE, we selected the WGS 84 UTM 40N projected coordinate system. Pix4D will automatically select a coordinate system if the images are correctly geolocated. After uploading the images, Pix4D will show an initial map of the study area and the approximate location at which the images were taken. In figure 6, we see where photos were taken from two drone flights in Khor Kalba, Fujiarah.
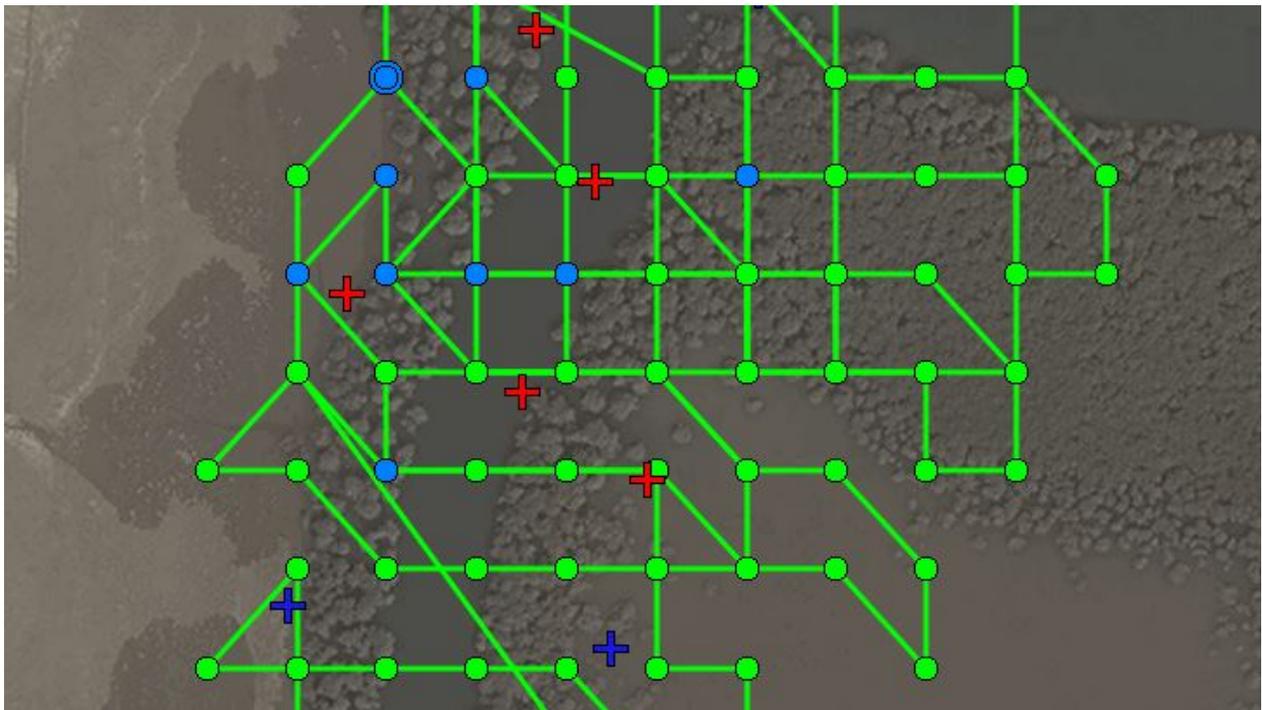


*Figure 12. Pix4D software map showing the location (green and blue dots) at which each uploaded image was taken in our study area after creating new project. The blue and red crosses depict the location of ground control points (GSPs) which are used to georeference the images.*

Figure 1.    **Pix4D software map showing the location (green and blue dots) at which each uploaded image was taken in our study area after creating new project. The blue and red crosses depict the location of ground control points (GSPs) which are used to georeference the images.**

There are three main processing steps in Pix4D; these include: (1) *Initial Processing*, (2) *Point Cloud Mesh,* and (3) *DSM, Orthomosaic and Index* (Process => Local Processing). Below, we outline how to run each processing step and show and describe the outputs created through each step.

After creating a new project in Pix4D, the first step is to run the *Initial Processing* tool (Process => Local Processing). In this process, Pix4D uses photogrammetry to finds points of similar features on different images and locates their position in a 3-dimensional virtual space. At the end of the *Initial Processing*, a rough 3D model of the study area is created (figure 7), as well as a low-resolution

orthomosaic. The 3D model can be used to determine how well a study area was covered by the drone's images.



*Figure 13. Rough 3D model created through the Initial Processing step. Brighter areas in the center of the image have a higher point density and show location with a higher image overlap.*

Figure 2.   **Rough 3D model created through the *Initial Processing* step. Brighter areas in the center of the image have a higher point density and show location with a higher image overlap.**

Before densifying the 3D point cloud model in the *Point Cloud and Mesh* processing step, the 3D output from the *Initial Processing* step is first georeferenced. Georeferencing means locating and scaling an image so that it is positioned accurately in virtual space. To georeference a 3D image, we use the GCPs
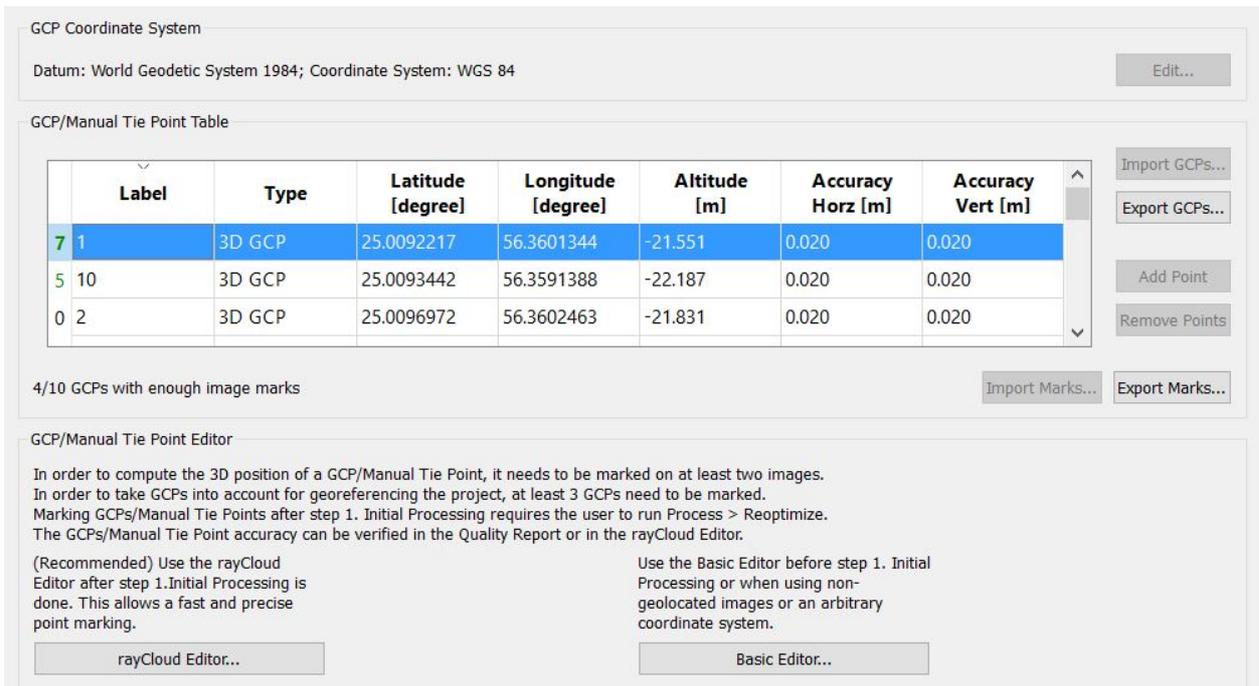
*Figure 14. Image of the GCP/Manual Tie Point Manager control window in Pix4D. This window is used to recreate the GCPs in the Pix4D virtual space using the GPS measurements. The GPS measurements can be entered manually or imported directly in the Tie Point Table.*

Figure 3.    **Image of the *GCP/Manual Tie Point Manager* control window in Pix4D. This window is used to recreate the GCPs in the Pix4D virtual space using the GPS measurements. The GPS measurements can be entered manually or imported directly in the Tie Point Table.**

The *GCP/Manual Tie Point Manager* (Project => GCP/Manual Tie Point Manager) is used in Pix4D to create points that have the GPS latitude, longitude, and elevation information of each tarp (figure 9).
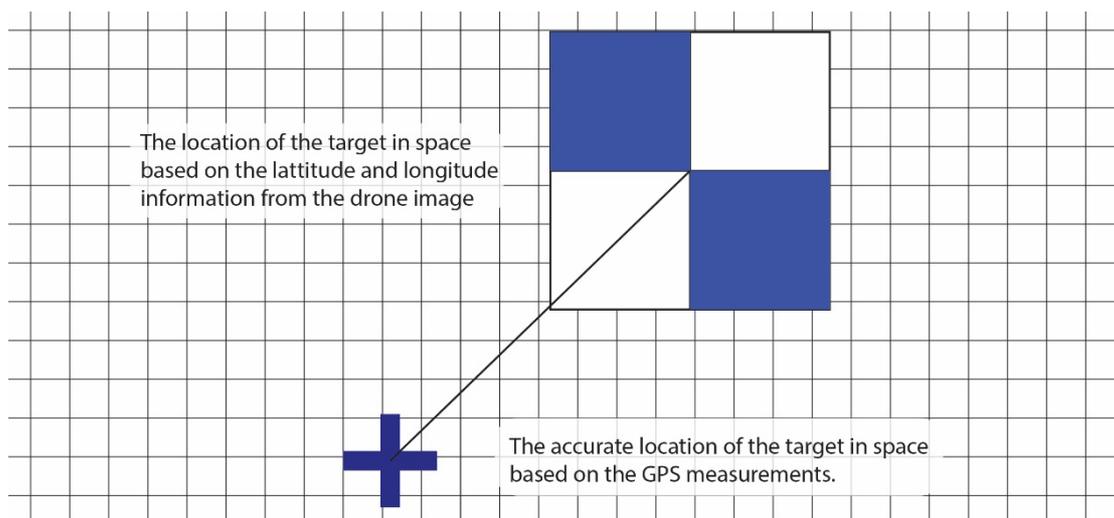


*Figure 15. This figure depicts how the location of GCPs as computed from the drone images and from the GPS measurements differ. The GPS measurements are more precise, and therefore these are used to georeference the drone images in virtual space.*

Figure 4. This figure depicts how the location of GCPs as computed from the drone images and from the GPS measurements differ. The GPS measurements are more precise, and therefore these are used to georeference the drone images in virtual space.

These points can also be created by directly importing the GPS information into Pix4D. After all the points with the GPS location of the GCPs are created in the *GCP/Manual Tie Point Manager*, the *Basic Editor* tool in Pix4D is used to manually tie the GPS points to the center of the tarps on the images taken from the drone (figure 9, figure 10).

| | Label | Type | Latitude [degree] | Longitude [degree] | Altitude [m] | Accuracy Horz [m] | Accuracy Vert [m] |
|---|---|---|---|---|---|---|---|
| 7 | 1 | 3D GCP | 25.0092217 | 56.3601344 | -21.551 | 0.020 | 0.020 |
| 5 | 10 | 3D GCP | 25.0093442 | 56.3591388 | -22.187 | 0.020 | 0.020 |
| 0 | 2 | 3D GCP | 25.0096972 | 56.3602463 | -21.831 | 0.020 | 0.020 |
| 0 | 3 | 3D GCP | 25.0099467 | 56.3598588 | -22.718 | 0.020 | 0.020 |
| 0 | 4 | 3D GCP | 25.0105384 | 56.3600877 | -22.453 | 0.020 | 0.020 |
| 5 | 5 | 3D GCP | 25.0110803 | 56.3605879 | -21.937 | 0.020 | 0.020 |



*Figure 16. The Basic Editor tool used to tag each GPS point back to the GCPs on images taken by the drone. At least 3 GCPs need to be tagged to georeference an image. The GCPs should be placed in the corners and centre of the study area for the best georeferencing results.*

Figure 5. The Basic Editor tool used to tag each GPS point back to the GCPs on images taken by the drone. At least 3 GCPs need to be tagged to georeference an image. The GCPs should be placed in the corners and center of the study area for the best georeferencing results.

After each GPS point is correctly linked to the drone's images, the Pix4D software accurately relocates and scales the 3D image (figure 11) (Process => Reoptimize).

*Figure 17. 3D image of the study area with ground control points represented in blue. These points were used to georeferenced the 3D model in space to its accurate x, y, and z position.*

Figure 6.     **3D image of the study area with ground control points represented in blue. These points were used to georeferenced the 3D model in space to its accurate x, y, and z position.**

After the 3D model is correctly georeferenced, the *Point Cloud Mesh* tool (Process => Point Cloud Mesh) is used to densify the 3D model computed in step 1 (figure 12).

*Figure 18. Densified point cloud output from the Point Cloud Mesh tool. Dark areas show lower point density because of low image overlap in that section of our study area.*

Figure 7.   Densified point cloud output from the *Point Cloud Mesh* tool. Dark areas show lower point density because of low image overlap in that section of our study area.

The point density value of the point cloud can be changed in the tool's options. A higher point density will increase the resolution of the 3D model, as well as other outputs derived from the point cloud such as the DSM or the orthomosaic, but it will also increase the processing time as more points are identified and located in 3-dimensional space.

The *DSM, Orthomosaic and Index* (Process => DSM, Orthomosaic and Index) is the last tool that is used to output raster datasets that can be further processed in GIS software such as ArcGIS. Although many different files can be created in Pix4D, we only need to produce an orthomosaic and a DSM from our study area to calculate mangrove tree volume (figure 13, figure 14).
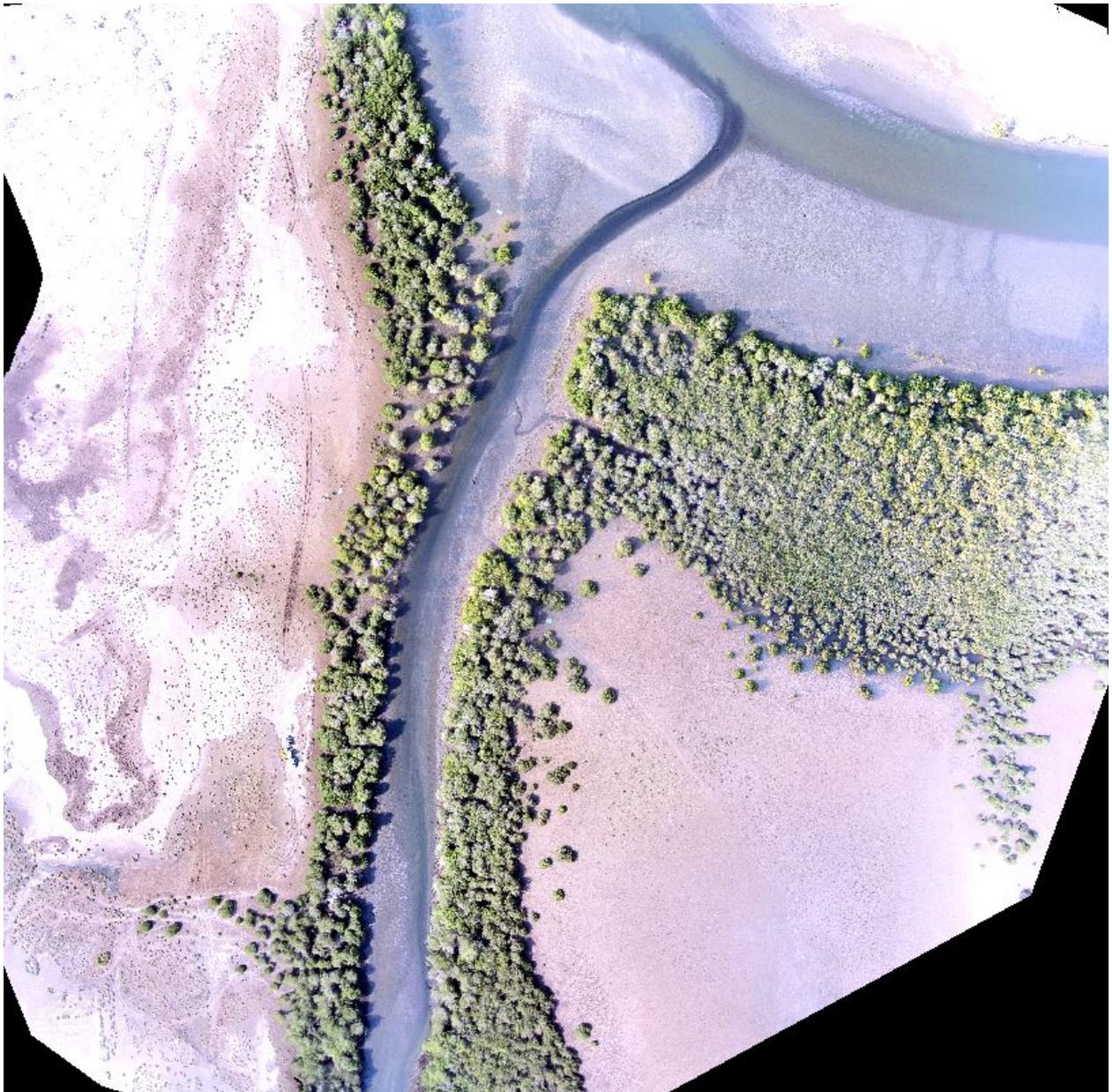
*Figure 19. 5cm resolution 4-bands (red, green, blue, and grayscale) orthomosaic image output created from the drone images in Pix4D.*

Figure 8.    5cm resolution 4-bands (red, green, blue, and grayscale) orthomosaic image output created from the drone images in Pix4D.
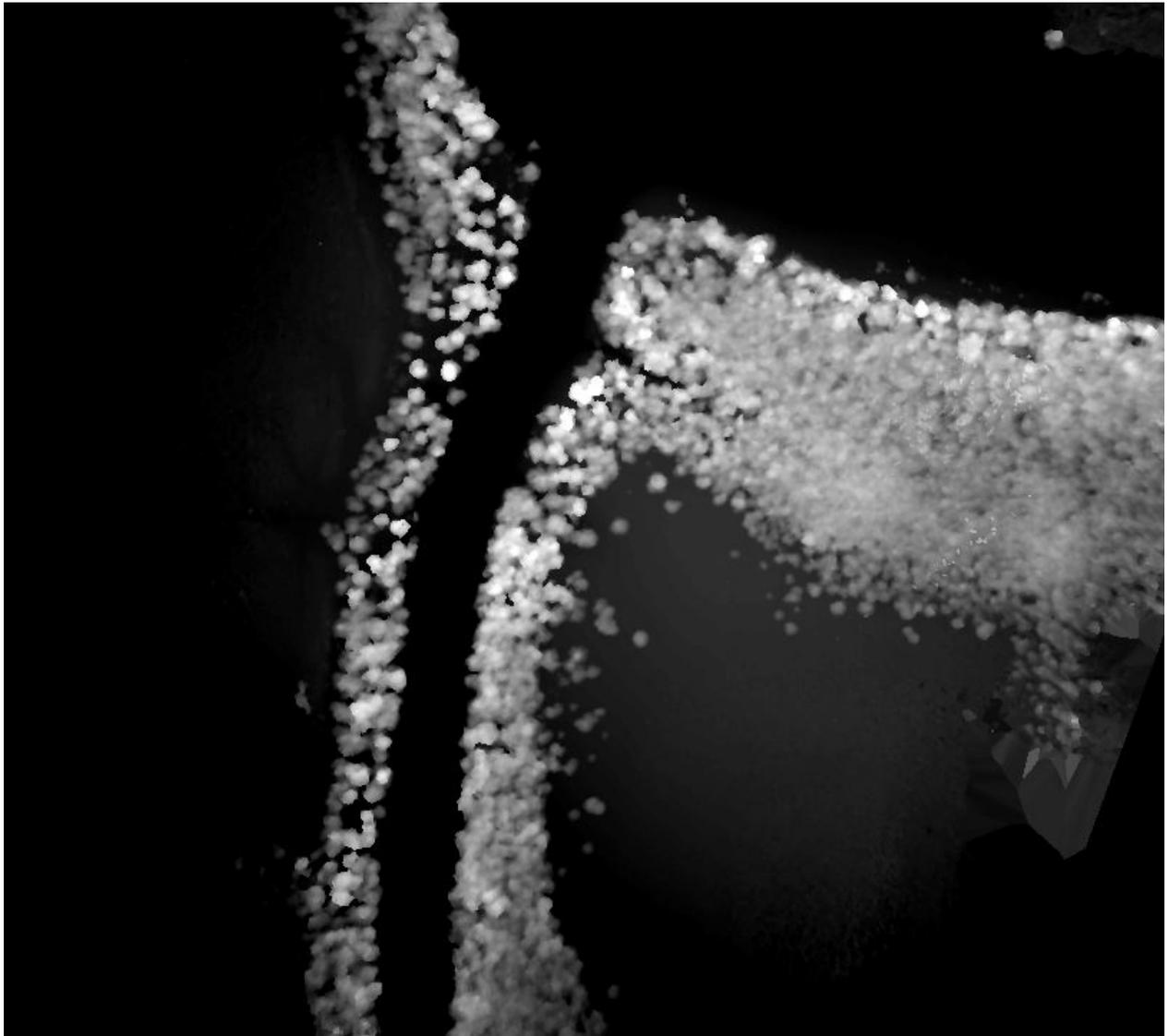


*Figure 20. 5cm resolution 1-band (elevation) Digital Surface Model (DSM) output created from the drone images and the 3D point cloud in Pix4D.*

Figure 9.    5cm resolution 1-band (elevation) Digital Surface Model (DSM) output created from the drone images and the 3D point cloud in Pix4D.

In the options of the tool, the cell size of the orthomosaic and the DSM can be changed for a higher or lower resolution output. The DSM and orthomosaic are automatically georeferenced based on the GPS measurements, and can directly be viewed and analysed in a GIS software.

## Calculating Volume using Pix4D

The Pix4D software provides tools to make volume measurements after the *Initial Processing* and the *Point Cloud Mesh* steps were correctly processed. To calculate volume of mangrove trees in Pix4D, we first create a "New Volume" (rayCloud => New Volume). In the rayCloud editor, we use the mouse to select the area for which we want to calculate the volume (figure 15).



*Figure 21. New Volume shape around a tree feature in the Pix4D rayCloud editor to initiate volume calculations.*

Photo 1.   New Volume shape around a tree feature in the Pix4D rayCloud editor to initiate volume calculations.

We then "Update Measures" in the properties window of the new volume and Pix4D will automatically calculate the volume of the 3-dimensional filled space above the selected area (figure 16).
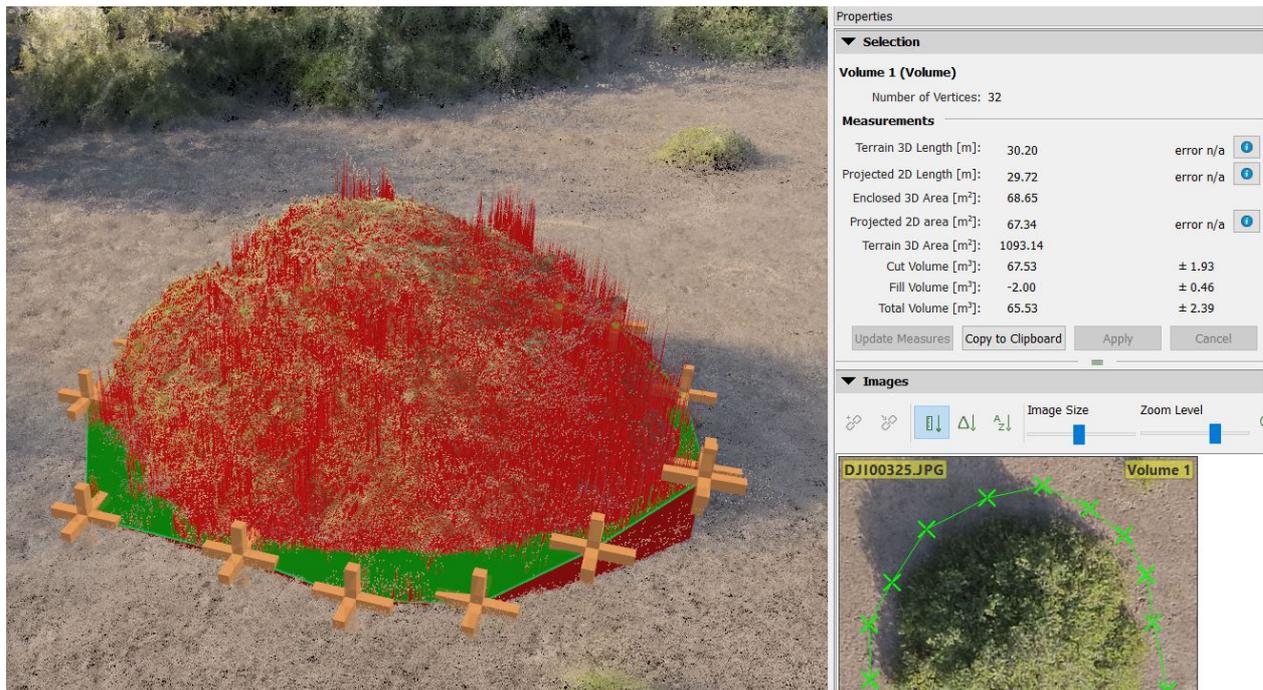
*Figure 22. Volume output calculations from Pix4D of the selected tree feature. Volume values are given in the Properties table on the right hand side. This particular mangrove tree has a total volume of 65.53m3 as computed by Pix4D.*

Photo 2.   Volume output calculations from Pix4D of the selected tree feature. Volume values are given in the Properties table on the right hand side. This particular mangrove tree has a total volume of 65.53m³ as computed by Pix4D.

The advantage of calculating volume in Pix4D is that it is simple and works well for unique trees surrounded by bare ground. However, there needs to be bare terrain around a tree or group of trees for Pix4D to evaluate the terrain elevation that it uses as a base to calculate volume. In the case of large tree canopies, Pix4D is not able to correctly evaluate volume because it has no information on the elevation of the base terrain under the feature for which it calculates volume. In the next section, we explain how volume calculations can be obtained using GIS software and the orthomosaic and Digital Surface Model (DSM) outputs from Pix4D to circumvent the limitations mentioned above.

## Calculating Volume using GIS Software

We chose to use ArcGIS[7] to process our orthomosaic and DSM raster datasets to calculate mangrove tree volume. To calculate mangrove tree volume we use the following formula: *tree average height* x *tree base area*. The three main steps are as follow: distinguishing tree from non-tree features in our study area, estimating the average tree height and base area values, and finally determining the tree volume.

---

[7] We are also evaluating the options of using open source GIS software, particularly QGIS, to process the same data and obtain mangrove tree volume estimates.

AGEDI | an initiative of
مبادرة أبوظبي العالمية للبيانات البيئية
Abu Dhabi Global Environmental Data Initiative
UNEP
هـيئـة الـبيئـة - أبـوظـبـي
Environment Agency - ABU DHABI

*Locating Tree Features*

To distinguish trees from non-trees we use the 4-bands (red, green, blue, and grayscale) orthomosaic image (figure 13) and the 1-band Digital Surface Model raster datasets of our study area (figure 14).

The *ISO Cluster Unsupervised Classification* ArcGIS tool (spatial analyst => multivariate) uses the value for each pixel in each of these bands to create clusters of pixels with similar height or color values. Because the mangrove trees are greener and have a higher elevation than the surrounding terrain, this tool can separate tree from non-tree features. In our case, to enhance the results obtained from the classification, we first edited the orthomosaic image in a simple photo editor to increase the saturation and brightness. This way, mangrove trees stand out in the orthomosaic of our study area (figure 17).



*Figure 23. Modified orthomosaic image of the study area to enhance mangrove trees in the image by increasing brightness and saturation values.*

Figure 10.   **Modified orthomosaic image of the study area to enhance mangrove trees in the image by increasing brightness and saturation values.**
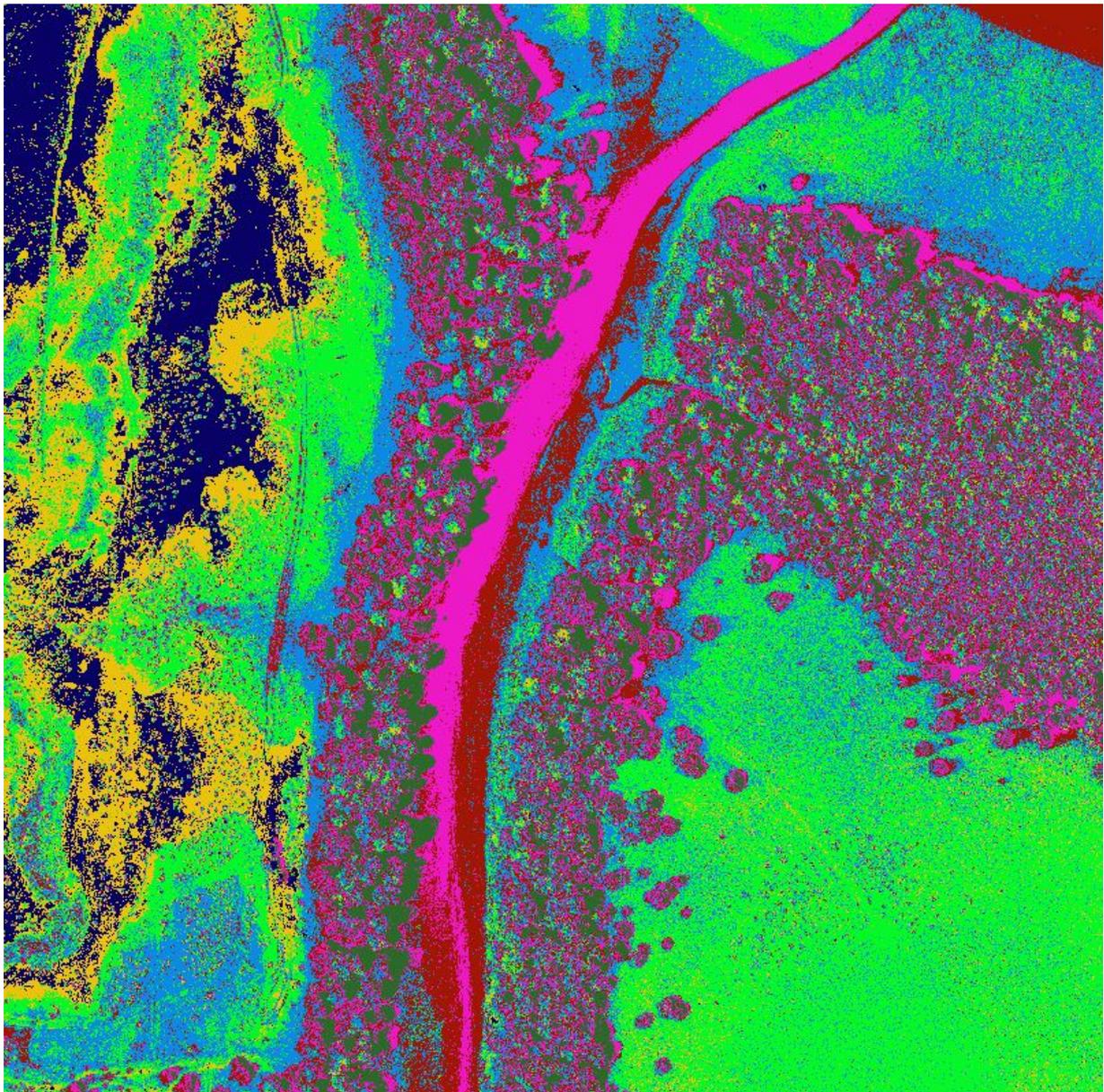
*Figure 24. Raster dataset output from the ISO Cluster Unsupervised Classification tool. Each pixel cluster in the image has a value between 1 and 8 depending upon the class it belongs to.*

Photo 3.  Raster dataset output from the *ISO Cluster Unsupervised Classification* tool. Each pixel cluster in the image has a value between 1 and 8 depending upon the class it belongs to.

Figure 15 shows the raster dataset that is created after using the *ISO Cluster Unsupervised Classification* tool. As we see on the image, other features such as shadows and water are also classified as unique features. Therefore, a reclassification (3D analyst => raster reclass) of the classification output is necessary to locate trees only. In our reclassification calculations, we make all non-tree clusters of pixels equal to NoData, and all tree clusters of pixels equal to 1. The new raster datasets is saved as a polygon using the *Raster to Polygon* tool (conversion tools => from raster) to create a shapefile with mangrove tree features only (figure 19).

*Figure 25. Polygon shapefile of mangrove tree features derived from the ISO classification output after a reclassification of the raster dataset. To clean the data, the area of each feature is calculated and small polygons that are non-tree features such as shrubs are selected and deleted in the editor menu.*

Photo 4.  Polygon shapefile of mangrove tree features derived from the ISO classification output after a reclassification of the raster dataset. To clean the data, the area of each feature is calculated and small polygons that are non-tree features such as shrubs are selected and deleted in the editor menu.

After this process, it is possible to manually edit the polygon to delete any non-tree features from the mangrove tree polygon shapefile, or to slightly buffer and merge the mangrove tree polygon shapefile to join each small clusters of "tree features" in the image.

## Determining Tree Height

We use the Digital Surface Model (DSM) output from Pix4D that shows change in elevation, including tree features, and a Digital Terrain Model (DTM) that shows change in terrain elevation, excluding tree features, to estimate mangrove trees mean heights in our study area (figure 20).
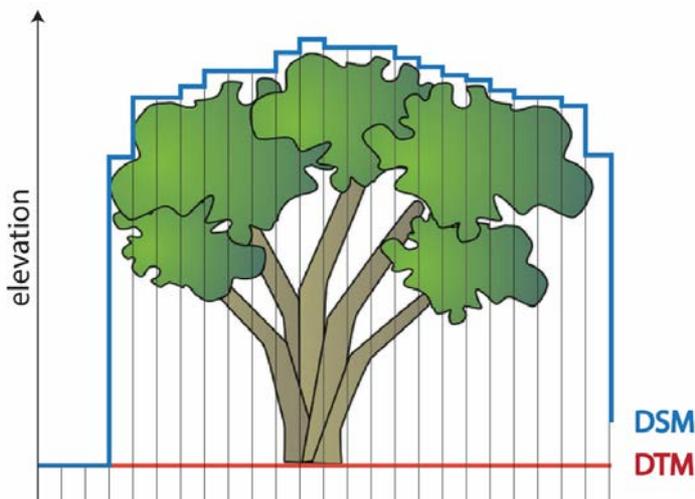


*Figure 11.Figure 26. **Explanation figure to differentiate the Digital Surface Model (DSM) that shows change in elevation/pixel including features such as trees from the Digital Terrain Model (DTM) that shows change in elevation/pixel at the ground level, excluding above ground features.***

Figure 12. Explanation figure to differentiate the Digital Surface Model (DSM) that shows change in elevation/pixel including features such as trees from the Digital Terrain Model (DTM) that shows change in elevation/pixel at the ground level, excluding above ground features.

By subtracting the DTM from the DSM it is possible to create a raster dataset with tree height values that will be used to calculate mangrove tree volume. Although it is possible to also create a DTM output in Pix4D, it is still a beta tool, and thus far, outputs using that tool have been of very low quality. Therefore, we chose to use the DSM raster dataset supplemented with GPS elevation data, to create our own DTM of the study area.

To create a DTM, we first mask the tree features from our DSM raster dataset using the *Extract by Mask* tool (spatial analyst => extraction) (figure 21).
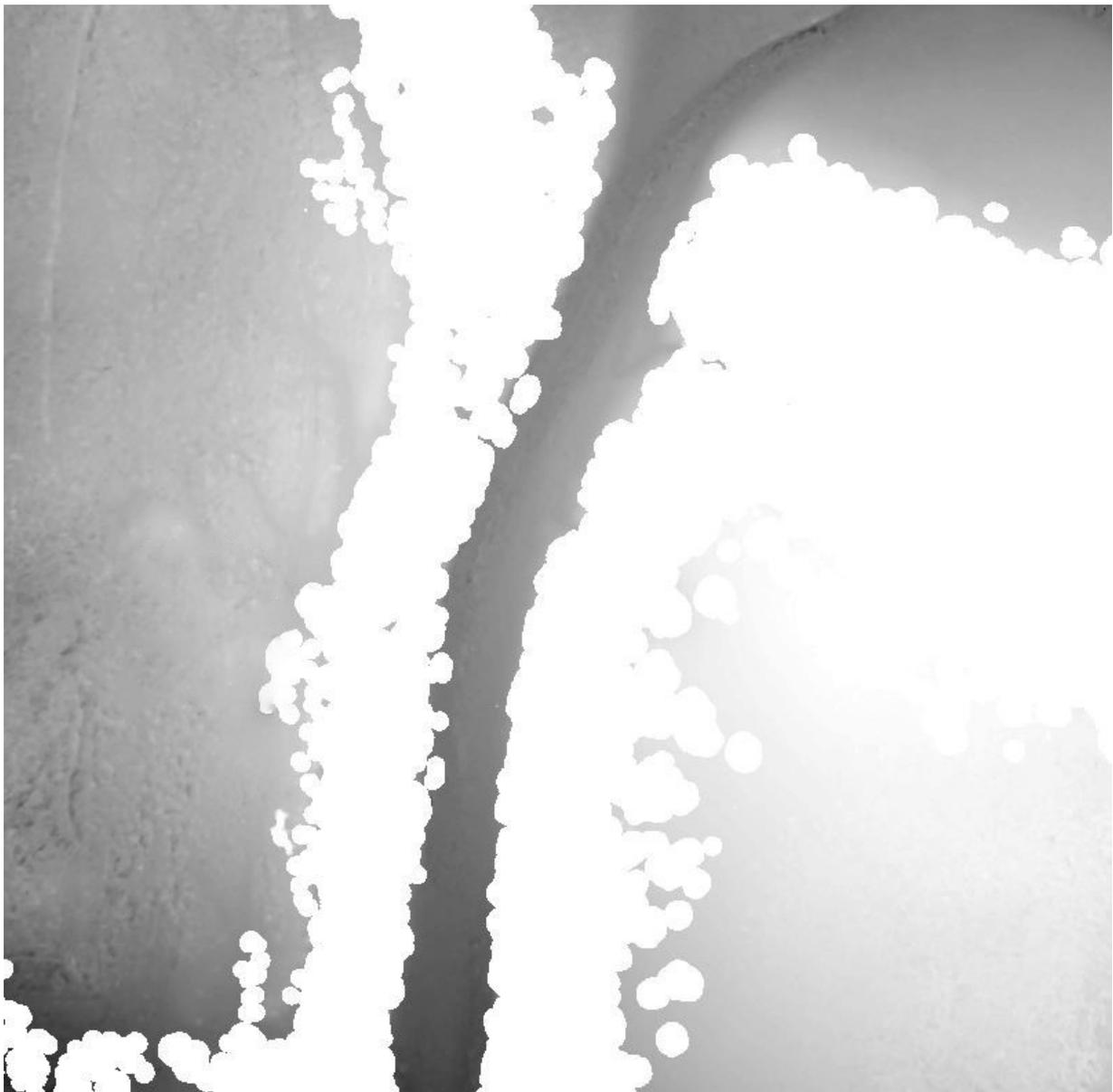


*Figure 27. DSM Raster dataset with NoData (white) values for where trees were originally located. The Extract by Mask tool was used to create this output.*

Photo 5.   DSM Raster dataset with NoData (white) values for where trees were originally located. The *Extract by Mask* tool was used to create this output.

Through this process, we create a template for our DTM with empty areas where the trees were originally located. To fill the empty areas with an estimate value of the terrain height in those locations, we first create a new point shapefile with point features all along the shape of the empty area where trees were located. To do so, we use the *Feature Vertices to Points* tool (data management => features) (figure 22).



*Figure 28. Points created around the mangrove tree features from the tree polygon shapefile. Using the Zonal Statistics tool, we assign elevation values from the DSM to each point.*

Figure 22: Points created around the mangrove tree features from the tree polygon shapefile. Using the *Zonal Statistics* tool, we assign elevation values from the DSM to each point.

Second, we allocate elevation data from the original DSM to each newly created point using the *Zonal Statistics* tool (spatial analyst => zonal). We now have created a point shapefile where each point has the terrain elevation value at that location. It is possible that some points fall outside of the DSM raster dataset and are assigned an elevation value of 0, or are located just next to a tree and pick up the elevation of the tree rather than the ground elevation. These outliers should be deleted for more accurate results.

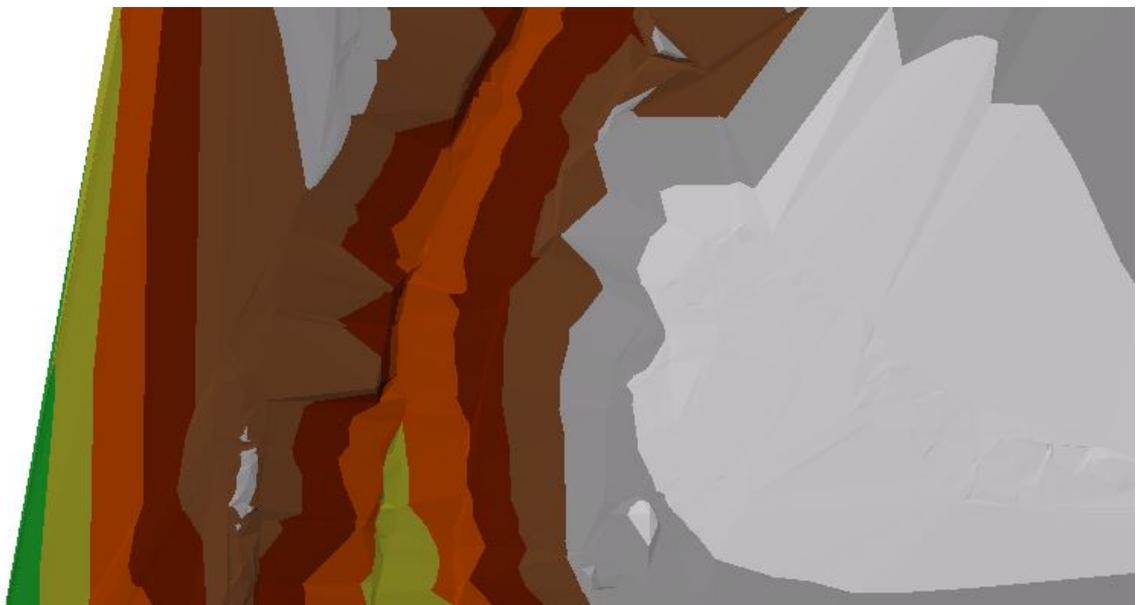Using the *Create Tin* and *Tin to Raster* tools (3D analyst => data management) on the point shapefile, the points' elevation values are extrapolated across space (figure 23) and a new raster dataset with an estimate value of the terrain elevation under the trees is created.



*Figure 29. TIN output created using the Create Tin tool in ArcGIS that extrapolates the elevation values from the points created in figure 18 across space.*

Figure 23: TIN output created using the *Create Tin* tool in ArcGIS that extrapolates the elevation values from the points created in figure 18 across space.

When the tin is created, GPS points collected in the field with elevation data of the ground elevation below the trees can be added for better results. If the error from the GPS measurements is too high because of a poor GDOP or a bad visibility, adding GPS points could also increase the error in our measurements. By using the *Mosaic to New Raster* tool (data management => raster) to merge the DSM with NoData values where trees were located with the raster dataset created from the tin that shows change in terrain elevation below the tree canopy, we create a full Digital Terrain Model (DTM) of the study area (figure 24).
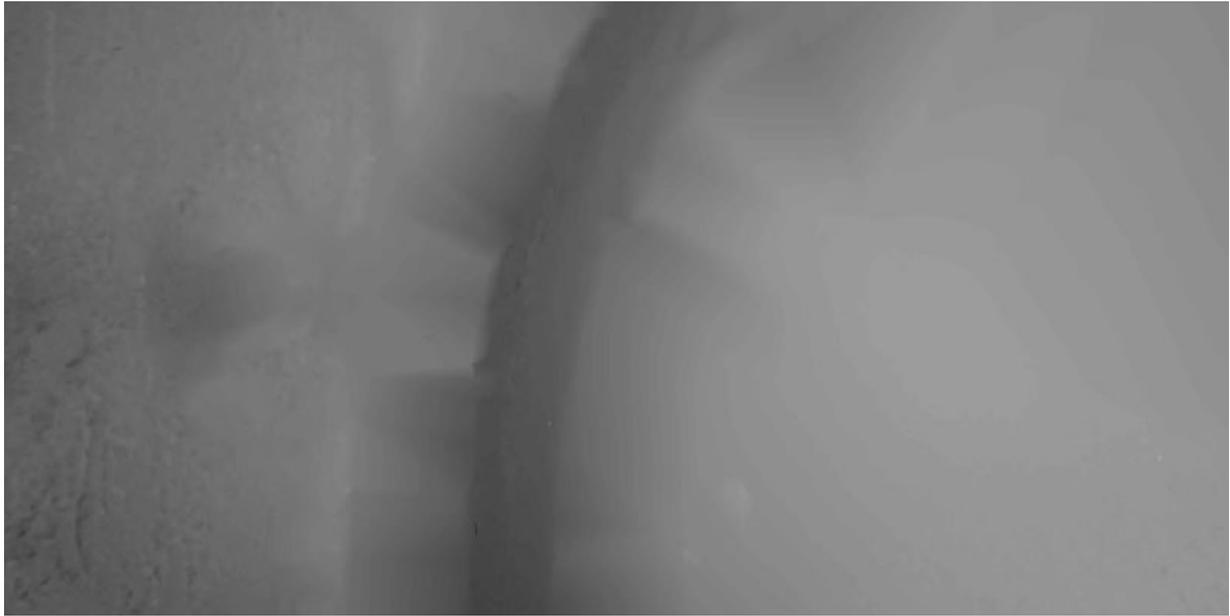
*Figure 30. Full Digital Terrain Model (DTM) created using the Mosaic to New Raster tool, combining the DSM with NoData values for where trees were located with the tin raster.*

Figure 24: Full Digital Terrain Model (DTM) created using the *Mosaic to New Raster* tool, combining the DSM with NoData values for where trees were located with the tin raster.

To calculate tree height, we now simply compute DSM - DTM using the Raster Calculator tool (spatial analyst => map algebra). Figure 25 shows the final raster output with each cell having either a value of zero meaning that there is no tree, or a pixel-specific tree height value.

*Figure 31. Raster dataset with pixels having either tree height values or 0 (grey) if they do not overlap with tree features; output from the DSM - DTM calculations using Raster Calculator.*

**Figure 25: Raster dataset with pixels having either tree height values or 0 (grey) if they do not overlap with tree features; output from the DSM - DTM calculations using *Raster Calculator*.**

## Calculating Tree Volume

After creating a raster dataset with tree height values, we calculate the mangrove trees' base area values. The mangrove trees base area values can be simply computed using the "Calculate Geometry" tool in the attribute table of the mangrove tree polygon shapefile (figure 19). Using the *Zonal Statistics* tool with the statistics options as MEAN (spatial analyst => zonal), we then estimate the average value of each pixels from the tree height raster dataset (figure 25) that overlap with a tree feature from the mangrove tree polygon shapefile (figure 19). In the attribute table of the mangrove tree polygon shapefile, we now have two columns: one with the total area value for individual or cluster of tree feature, and another with their average height. To finalize our volume calculations, using the "Field Calculator" tool on a new field in the attribute table, we multiply values from the tree average height column with values from the tree base area value column to obtain volume estimates for each mangrove tree or cluster of mangrove trees features (figure 26).

## FINAL_Tree_volume

| | FID | Shape * | base_area | height | volume |
|---|---|---|---|---|---|
| | 0 | Polygon | 3.02 | 2.180084 | 6.583853 |
| | 1 | Polygon | 21.65 | 1.12599 | 24.377681 |
| | 2 | Polygon | 12.835 | 0.67018 | 8.601759 |
| | 3 | Polygon | 11.5 | 1.139781 | 13.107482 |
| | 4 | Polygon | 12.5675 | 0.605215 | 7.606038 |
| | 5 | Polygon | 14.5675 | 0.501886 | 7.311231 |
| | 6 | Polygon | 29.19 | 0.56527 | 16.500217 |
| | 7 | Polygon | 26.9625 | 0.904759 | 24.394566 |
| | 8 | Polygon | 26.5625 | 1.189497 | 31.596021 |
| | 9 | Polygon | 30.7725 | 1.063127 | 32.715069 |
| | 10 | Polygon | 21.9025 | 0.605038 | 13.251841 |
| | 11 | Polygon | 10.335 | 0.462579 | 4.780759 |
| | 12 | Polygon | 22.96 | 0.879847 | 20.201291 |

*Table 1. Attribute table of the tree polygon shapefile showing the average height, the base area, and the volume of each tree or cluster of trees features in the study area.*

Figure 13.  **Figure 26: Attribute table of the tree polygon shapefile showing the average height, the base area, and the volume of each tree or cluster of trees features in the study area.**

## 12.     Limitations of Methodology towards calculating carbon by volume

The complex nature of mangrove trees' shape and height hinder our ability to calculate exact mangrove tree volume. In this particular methodology, by computing DSM - DTM to calculate mangrove tree height and multiplying these values by the mangrove tree base area, we include in our volume measurements the volume between the bottom of the mangrove tree and the terrain. Relationships between volume and biomass, such as that outlined by the FAO, estimate above-ground woody biomass (stem, bark, branches; excluding foliage). We used drone-estimated volume and the wood density value of the mangrove tree species *Avicennia marina* (Simpson, 1996) to estimate above-ground woody biomass. The drone-based volume estimates calculate volume based on base area x height, which effectively yields the volume of the entire rectangular space occupied by and below the maximum width of the canopy, including the space *below* the canopy. Because this volumetric space greatly exceeds the volume of actual trees/stems (i.e., woody material), when applying the existing formula (i.e., FAO), biomass and subsequent C stock estimates are greatly exaggerated (e.g., total above-ground woody carbon of >36,000 mg/ha (i.e., example calculations). In addition, our drone-based volume estimates include volume estimates ranging from single trees to clusters of ≤100s of trees. These variable-sized units are likely too large to represent ecologically meaningful units. To our knowledge, no existing formulas can accurately translate these drone-measured volume estimates, including foliage and the space beneath the canopy, in to above-ground biomass estimates. For this existing equation to work, it would require accurately estimating the volume individual trees/stems, which is not possible with drone imagery given its 2-D nature and the density of mangroves in the UAE.

## 13.    Next Steps

The complex nature of mangrove trees' shape hinder our ability to calculate exact mangrove tree volume. In this particular methodology, by computing DSM ‑ DTM to calculate mangrove tree height and multiplying these values by the mangrove tree base area, we include in our volume measurements of the volume between the bottom of the mangrove tree and the terrain. What's more, our volume estimates include a liberal estimate of foliage, whereas the existing FAO equation estimates above-ground woody biomass (i.e., totality of woody material *excluding* foliage).

To date, there is no equation that links our volume measurements with biomass estimates; however, there are equations that permit to calculate mangrove tree biomass using height and/or diameter at breast height (DBH) measurements. In particular, existing/additional DBH measurements hold great promise to establish a relationship between drone-measured volume and above-ground biomass. Once this relationship is determined/if strong enough, it could then be used to estimate biomass for other mangrove ecosystems with similar ecological characteristics.

As such, the way forward includes the following steps:

- Further segment/partition drone imagery, so that "mega-clusters" comprised of 100s of trees do not dominate. Additional segmentation helps reduce the image to ecological meaningful units, ideally comprised of as few trees as possible.

- Create a gridded map of further segmented drone imagery, stratified by drone-measured height. Given the known relationship between height and DBH, and the availability of a spatially explicit grid of tree height, height-based strata would help ensure that we represent the variability of mangroves throughout the study area through our sampling effort.

- Using stratified (i.e., drone height-based) sampling (systematic or random), confidently locate individual trees/small tree clusters which have previously had their DBH measured; augment existing measurements with new measurements as needed. If dealing with a tree cluster, best case scenario, it is comprised of similarly sized trees, worst case scenario an average DBH value would need to be determined for the cluster. Regardless, the goal here is confidently locate individual trees/tree clusters on the ground *and* in the imagery across the full range of height-defined strata. This captures variability and ensures we know precisely for which trees/tree clusters we can link DBH and drone-estimated volume. To ensure the link between drone-measured volume and DBH, trees/tree clusters should have their geographic position measured as accurately as possible. With as many confidently located trees/tree clusters with corresponding DBH measurements located in our study area, we can use existing, published allometric equations for *Aicennia marina*are based on DBH.

- Explore the relationship between the AGB of for the selected trees/tree clusters and drone-measured volume.

- If there is a strong relationship, develop a new mathematical equation that describes this relationship and could be used later to directly estimate mangrove tree biomass using drone derived volume measurements in other ecologically similar areas; though ground validation would be required. .

- An additional option is exploring the relationship between field and/or drone-measured height and biomass, based on existing published allometric equations for *Avicennia marina*. This option, as with DBH, requires precisely and confidently locating individual trees/tree

clusters for which field or drone-measured height is known, and exploring the relationship between height-estimated AGB and drone-estimated volume. If strong, this relationship could also be used to directly estimate mangrove tree biomass with drone derived volume measurements in other ecologically similar areas; though ground validation would be required.

There is no guarantee that there is a relationship between mangrove tree volume. The more samples of mangroves of different height, DBH, and volume measurements taken to visualize this potential relationship, the easier it will be to assess if this relationship exists, how strong it is, and how it translates into a mathematical equation.

## 14.    References

Kauffman, J.B.; Donato, D.C. *Protocols for the Measurement, Monitoring and Reporting of Structure, Biomass and Carbon Stocks in Mangrove Forests. Working Paper 86*; CIFOR: Bogor,Indonesia, 2012.

Simpson, W.T. *Method to Estimate Dry-Kiln Schedules and Species Groupings: Tropical and Temperate Hardwoods*; US Department of Agriculture, Forest Service, Forest Products Laboratory: Washington, DC, USA, 1996.

Nellemann, Christian et al. (2009): Blue Carbon. The Role of Healthy Oceans in Binding Carbon. A Rapid Response Assessment. Arendal, Norway: UNEP/GRID-Arendal

[1]Laffoley, Dan and Grimsditch, Gabriel (2009): The Management of Natural Coastal Carbon Sinks. Gland, Switzerland: IUCN

Murray et al. (2010): Payments for Blue Carbon. Potential for Protecting Threatened Coastal Habitats. Durham, USA: Nicholas Institute for Environmental Policy Solutions

Crooks, Stephen et al. (2011): Mitigating Climate Change through Restoration and Management of Coastal Wetlands and Near-shore Marine Ecosystems: Challenges and Opportunities. Washington D.C., USA: World Bank

AGEDI 2013, Blue Carbon in Abu Dhabi – Protecting our Coastal Heritage: The Abu Dhabi Blue Carbon Demonstration Project, Executive Summary.