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Coastal Habitat mapping using UAVs; a tool for enhanced Protected Area Management in the Buccoo Reef Marine Park, Tobago

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ABSTRACT

The effective management of Marine Protected Areas requires the use of various tools to monitor and evaluate constantly changing coral reef, mangrove forest and seagrass environments. Tools such as field survey methods are time consuming while others such as satellite imagery can be costly to acquire and are subject to environmental conditions. The use of unoccupied aerial vehicles (UAV) or drones provides an alternative and effective tool for habitat mapping in coastal environments.

The aim of this study was to produce updated and accurate habitat maps for several critical areas in the Buccoo Reef Marine Park, Tobago using UAV imagery derived from a consumer grade DJI Mavic Mini. Using flight programming software DroneLink, aerial imagery of seven sites within the study area was acquired and orthomosaics were created using Agisoft software. Using visual interpretation protocols, key benthic habitats were identified, classified and compared with habitat classification derived from field survey methods.

The results of an error matrix indicated an 89.7% overall accuracy rate for benthic maps produced from UAV imagery when compared with underwater field surveys. The results of this research should encourage the use of UAVs as a cost effective and efficient tool for habitat monitoring and conservation in Marine Protected Areas in Trinidad and Tobago and the wider Caribbean Region. Additionally, habitat maps for these critical areas will be integrated into a wider project aimed at the development of a Marine Spatial Plan for the Buccoo Reef Marine Park.

Keywords: Unoccupied Aerial Vehicles (UAVs); Marine Protected Areas; Tobago; habitat mapping; Marine Spatial Planning (MSP).

1.0 INTRODUCTION

1.1 Importance of mangroves

Marine Protected Areas (MPAs) are effective tools to facilitate the preservation of habitats and provision of ecosystem services [1,2]. Notable benefits of MPAs include maintaining biodiversity and protection of endangered or threatened species, providing a spawning area or nursery for fish and other marine species, improving fish stocks both within and outside the protected area, maintaining livelihoods, providing an area for scientific research, education and awareness and enhancing ecosystem resilience to the effects of climate change [3-5].

With respect to tourism, MPA's can add tremendous value to this sector by attracting visitors. The Caribbean region is especially suitable to nature-based tourism due to its species-rich ecosystems and vibrant coral reefs which act as avenues for SCUBA diving, snorkelling and water sport activities [6, 7]. Coral Reefs provide housing for high levels of biological diversity and have strong intrinsic cultural value to humans [8]. Despite their importance, these ecosystems are rapidly degrading due to coastal development, land clearance, intensive agriculture which leads to sedimentation and pollution and overfishing [9].

Resource managers utilize various tools to facilitate short, medium and longer-term management of marine spaces and performance is measured by key indicators in the MPA and adjacent areas [3, 5]. Ecological assessment programs include the Atlantic and Gulf Rapid Reef Assessment (AGRRA) protocol, Caribbean Coastal Monitoring Programme (CARICOMP) and Reef Check [10] which allow for coral, fish and benthic monitoring. While these methods utilize in-situ assessments [11, 12], other active monitoring methods include the use of geographic information systems (GIS) and remote sensing (RS) mapping techniques [13, 14].

Coral reefs have been mapped using remote sensing technologies which includes the use of satellites, airborne sensors, unoccupied aerial systems, boat-based systems and autonomous underwater vehicles [15]. Despite widespread and worldwide use, commercial satellite imagery (Landsat-8, Sentinel-2, IKONOS, Worldview and Planet Dove) is not without its limitations. Typically, satellite imagery lacks the spatial resolution which can provide the required level of detail (at the species or colony level) for effective coral reef management [16, 17] and is often constrained by weather conditions such as cloud cover [18]. The use of Unoccupied Aerial Vehicles (UAV) or drones can therefore be utilized as a tool to capture detailed and homogenous imagery for coral reef mapping [16].

The use of drones for coastal and marine applications is becoming increasingly popular worldwide and has been used regionally in the case of Belize [19], St. Kitts and Nevis [20] and the Bahamas [21]. UAV use for marine applications can include two-dimensional habitat mapping [16, 22, 23], three-dimensional habitat complexity models [24], underwater 3-D modelling [25], marine litter mapping [26], coastline zone mapping [27, 28, 29] and identification of marine megafauna and protected species [21, 30]. The case of the Buccoo Reef Marine Park in Trinidad and Tobago, where state agencies have sought to enhance its management mechanisms in recent months, provides for the illustration of UAVs as a cost-effective method to monitor and map benthic habitats.

The overall goal of this study was to determine the location and extent of key benthic habitats in the Buccoo Reef Marine Park, the only Marine Protected Area in the country, using aerial photography derived from an Unoccupied Aerial Vehicle (UAV) or drone. The primary objectives include: 1) to provide baseline data on habitat classification for selected areas in the Buccoo Reef Marine Park, 2) to determine the accuracy of UAV mapping as compared with field survey methods and 3) to illustrate the effectiveness of UAV use as a conservation and management tool for the MPA. Ultimately, this research will contribute to a wider study that aims to develop a Marine Spatial Plan for the Buccoo Reef Marine Park in Tobago.

2.0 Materials and methods

2.1 Study site

Trinidad and Tobago is an archipelago (comprising the two large islands and twenty-one smaller islets) located in the Caribbean Sea some 11 kilometres from the South American coast between 10° 02′ -10° 50′N latitude and 60° 55′- 61° 56′W longitude (Figure 1). The country covers a terrestrial area of 5,128 km2 with its Exclusive

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Economic Zone (EEZ) extending to 200 NM [31]. Trinidad's coastline covers an area of 420 km while Tobago, the smaller of the two islands, has 120 km of coastline. The landscape varies between the two islands with Trinidad's landscape characterized by three mountain ranges separated by plains with a midland plain dominating three quarters of the island.

In 2017, the population of Trinidad and Tobago was estimated at 1.4 million, with Tobago's population accounting for 4% of the national total [32]. In Tobago, the population density is highest in the southwest with the government (Tobago House of Assembly) acting as the prime employer and source of income for many residents [33]. The economy is driven by the oil and gas sector in Trinidad while Tobago depends primarily on tourism [34]. Fringing reefs can be found on Trinidad's northeast coast, around offshore islets and more extensively in Tobago. Marine ecosystems are largely influenced by the Orinoco River which is adjacent to the Trinidad's Gulf of Paria.

The country's only Marine Protected Area is located off the southwest coast of Tobago (Figure 1). This Protected Area is 7 km² and is a major economic asset, attracting tens of thousands of visitors per year [35]. The area is home to approximately 70 species of tropical fish (as well as the invasive lionfish) and over 40 coral species. In addition to its ecological importance, its economic value cannot be understated as indicated in a 2008 report (the sole economic valuation report) which valued the total economic impact of reef-related tourism and recreation in Tobago at between US$101 and US$130 million [9].

Coined the Buccoo Reef Ecosystem Complex by Richard Laydoo in 1985, this Marine Park comprises of contiguous mangrove forest, seagrass beds and coral reef ecosystems. The Bon Accord Lagoon, which acts as a nursery and spawning area, was designated as a Ramsar Site (#1496) under the United Nations Ramsar Convention in 2005. It is the largest mangrove forest in Tobago, (predominantly *R. mangle*) and covers an area of 90.8 hectares inclusive of open water lagoons [36]. Seagrass beds are found in the Complex, with larger communities located in nearshore areas close to Buccoo Bay, Pigeon Point Windhole Beach, the Bon Accord Lagoon and the Nylon Pool. *Thalassia testudinum* is dominant in these areas with smaller communities of *Halophila decipiens* and *Halodule wrightii* observed.

Coral habitats are typically found on the seaward size of the Marine Park [37] with the larger reef located at Outer Reef, Western Reef and Coral Gardens. Hard corals are predominant on the Outer Reef while soft corals (gorgonians) a mix of hard corals are found on the Western Reef. A total of 11 hard coral species were noted at the Outer Reef and 14 species at the Western Reef with *Orbicella faveolata* observed as the most abundant species. Other common species in the Marine Park include *Colpophyllia natans, Siderastrea siderea* and *Pseudodiploria strigose* [37]. Permanent monitoring stations are established at these sites and monitoring takes place by the Institute of Marine Affairs (IMA) on an annual basis.

The Buccoo Reef, like other coastal and marine ecosystems throughout Tobago is subject to numerous pressures. A 2009 study indicated a decline in coral cover, especially at shallower depths, a proliferation of macro algae and zoanthids and a decrease in populations of environmentally important species such as the sea urchin [38]. High incidences of coral diseases (such as the white band disease in Elkhorn coral) were also reported as well as coral bleaching events in 2005 and 2010 [39]. There has also been a large-scale expansion of sea grass communities to the Nylon Pool due to nutrient enrichment [40]. A more recent report by the IMA in 2016 indicated that Buccoo Outer Reef has shown a slight decrease in hard coral cover as well as crustose coralline algae (CCA) whereas microalgae has been steadily increasing.

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Seven study sites (not previously documented) within the Buccoo Reef Marine Park were selected for this study due to the variation in their benthic composition and relatively shallow to moderate depth (ranging from 2 to 15 feet) which are well suited for the aerial imagery acquisition and accurate habitat classification. The sites ranged in extent 3, 8625 m2 to 51, 330 m² and comprised coral reef and seagrass habitats. Additionally, existing data was readily available as these seven sites were utilized in a larger-scale project where field surveys (coral, fish and benthic surveys) were conducted to determine benthic composition.

Figure 1. Location of the study area (inset map) in Tobago.

2.2 Application and authorisation requirements for UAV

The Buccoo Reef Marine Park, due to its proximity to the ANR Robinson International Airport, is located in a no-fly zone (41). Researchers therefore had to apply for a special exemption to operate within this zone from the Civil Aviation Authority of Trinidad and Tobago (CAA). Supporting documents attached to this application included a) authorization letter from the Tobago House of Assembly to operate within the area under their jurisdiction, b) submission of flight plans and c) a letter of indemnity. Conditions attached to the approval included a) notification to CAA prior to and following drone flights, b) specific dates and times for drone flights and c) altitude restrictions.

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2.3 UAV model specifications

UAV model suitability was determined after Joyce et al., 2018 and Doukari et al., 2019 and based on factors including i) cost, ii) camera specifications and iii) suitability for local environmental. In this study, the team utilized a DJI Mavic Mini Quadcopter drone to collect true colour aerial imagery of seven key sites in the Buccoo Reef Marine Park, southwest Tobago. The drone camera was equipped with a 1/2.3-inch CMOS sensor, 12 megapixels and had a photo resolution of 4000×3000 and a video resolution of 2.7K: 2720×1530 25/30p. The UAV system was a Vertical Take-off and Landing (VTOL) configuration with independent capability to take off and land.

2.4 Data collection

A total of four trial flights were conducted in the study area at varying times of day to determine the most suitable environmental conditions (wind speed, wind direction, cloud cover and angle of the sun as outlined by Joyce et al., 2018 [16] for aerial photo acquisition. The UAV specifications including battery life, maximum altitude, swath width and camera tilt were tested during the trial flight and a pre-developed flight map was refined. Placement for GCPs was also identified based on substrate type.

Manual flights proved unsuccessful for image mosaicking due to inconsistencies with image orientation and a flight planning software, DroneLink was therefore utilized to conduct flights for image acquisition. This software allowed for flight planning using a desktop computer and UAV programming using pre-defined parameters including altitude, speed, camera capture angle pitch and camera capture interval. The software determined the flight path, flight duration and the number of photographs required to map the areas of interest.

Using the flight planning software, UAV flights for data collection were conducted between 0700 and 1300 hours at a sun elevation angle of between 10 degrees and 45 degrees to reduce sun glint. Flights were conducted from November 2020 to August 2021 with multiple flights per day in some cases, each lasting an average time of twenty minutes. Aerial imagery was acquired at an altitude of 116 feet above sea level giving a ground sampling distance of ~2.159cm. All photographs were taken at nadir (-900) with an 84% side overlap and an 80% front overlap to allow for mosaicking during data analysis (adapted after studies conducted by Papakonstantinou et al.,2020 [42]; Husson et al, 2017 [43]; Jing et al., 2017 [44]. During the programmed flights, photographs were taken at 5 second intervals.

To map inaccessible areas, the UAV was launched from a vessel anchored approximately 20 feet from the coastline while for easily accessible areas, the UAV was launched on land in close proximity to the area of interest. The UAV was kept within a range of visible sight at all times by field assistants and the primary researcher. Wind speed fluctuated between 4.8 and 5.9 m/s with gusts not exceeding 7.2 m/s in the study area. Flights were conducted at varying tidal times for coastline mapping. UAV mapping of seaward sites during low tide allowed for comparatively less wave action (especially in shallow-water coral reef habitats) and ultimately optimum image clarity.

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For georeferencing purposes, a total of 35 Ground Control Points (GCPs) (brightly coloured floating marker buoys, (figure 2B), fastened to sandy areas of the seafloor using concrete blocks) were deployed on the surface of the water at the 6 sites under observation (after Tonkin and Midgley, 2016 [45]). A handheld GPS unit (spatial accuracy of 5m) was used to record the location of the GCPs. Buildings or permanent smaller structures were also used as GCPs along the coastline in accessible areas.

Underwater surveys were conducted via snorkelling for sites not exceeding 5 feet in depth and via SCUBA for sites between 5 to 18 feet in depth. A total of seven 10-meter long transects were surveyed at each site and benthic composition was recorded. The extent of benthic habitat types was recorded using a handheld GPS and in-situ underwater images were also captured using a GoPro Hero 8 camera. Images were reviewed by the researcher after uploading to a PC and were used as a visual interpretation of habitat types as shown in Figure 2D.

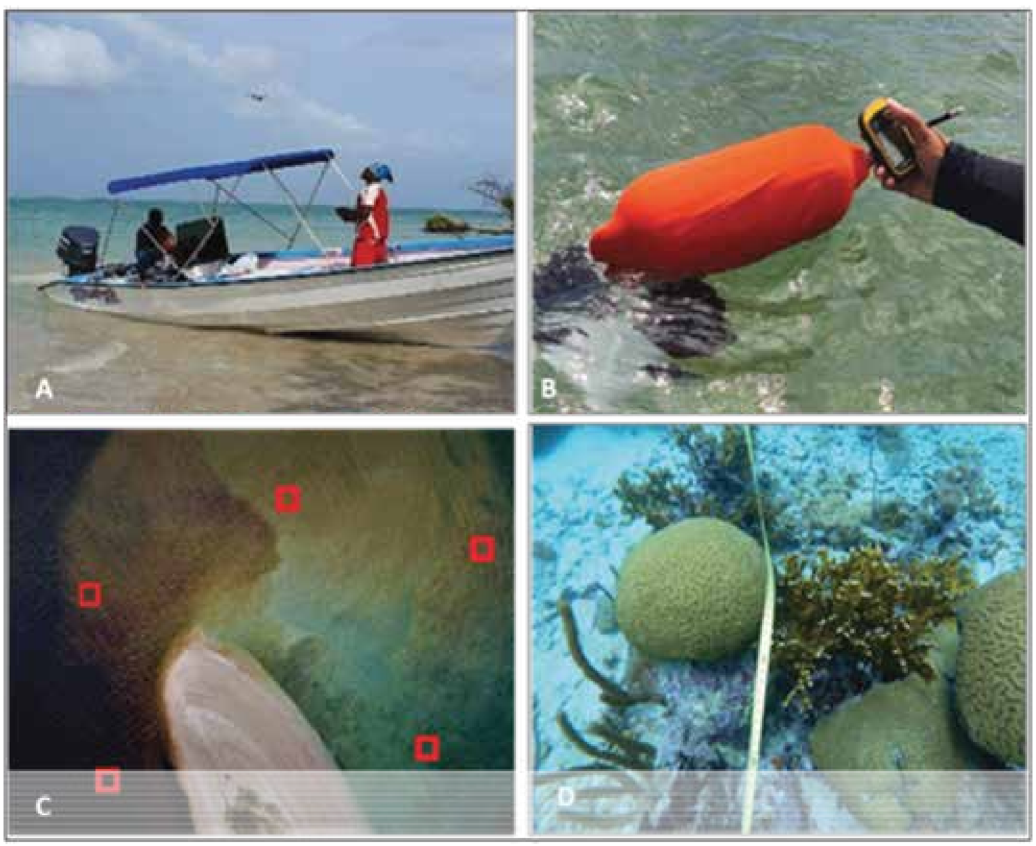

Figure 2. UAV launch from Vessel (A), deployment of Ground Control Points and georeferencing (B), GCPs at study site (marked by red squares) adapted from drone footage (C) and underwater transects for benthic surveys (D).

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2.5 Image processing

UAV imagery was processed using Agisoft Metashape Professional 64-bit software. Georeferenced photographs were uploaded, aligned and dense point clouds and digital elevation models were created followed by the creation of an orthomosaic. The orthomosaics were saved as TIFF files and imported into ArcGIS Pro. To further reduce error, the TIFF files were georeferenced to an aerial photo orthomosaic of Tobago accessed from the ARCGIS online platform. This was done by adding control points using the georeferencing toolbar (after Zhu et al., 2018 [46]. Polygons were delineated from the orthomosaic to represent substrate features. Polygons were classified using the ground truth data for substrate type and attributes were created for sizing the polygons using a constant metric (m^2). Habitat identification followed the protocol outlined by Finkbeiner, 2001 [23]. Extent of habitat types was created using ArcGIS Pro attribute table data and compared with data gathered from in-situ field surveys. An Error Matrix, designed after (Rwanga and Ndambuki, 2017 [47], was developed to determine the level of accuracy for habitat identification and classification.

3.0 RESULTS AND ANALYSIS

Aerial photographs acquired at an altitude of 116m allowed for clear distinction between main habitat types found in the study area. Habitat type was distinguishable at shallow depths (5 feet or less) intermediate depths (between 5 to 8 feet) and deeper depths (between 8 to 15 feet) using visual observation techniques (Figure 3) and results from in-water survey for cross referencing purposes.

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Figure 3. Drone images of some study sites illustrating dominant habitat types clearly identifiable at shallow, intermediate and deeper depths. Coral colony at shallow depth (delineated by red circle) (A), coral colony at deeper depth (B), Thalassia seagrass beds at shallow depth (C), Thalassia seagrass beds at intermediate depth (D) sand habitats at shallow and deeper depths (E).

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The results indicate a habitat classification of six main habitat types found within the study area: coral colony, coral reef, seagrass beds, sand, coral rubble, and sand and seagrass (Figure 4). For the marine habitats, seagrass beds were the most dominant habitat type found in the study area with a total extent of 113,375 m² (Table 1). Coral reefs comprised an area of 51,330 m² while coral colonies covered an area of 14,528 m² and coral rubble covered an area of 26,364 m². The mixed habitat area of sand and seagrass covered an area of 3, 8625 m². While macroalgae was observed during the in-water surveys, this was not distinguishable from UAV imagery. The results of an error matrix indicated an overall accuracy rate of 89.7% with an accuracy rate of 81% for coral reef habitats and 91% for seagrass habitats. The habitat mapping accuracy was determined by overlaying the reference data on the remotely sensed classification.

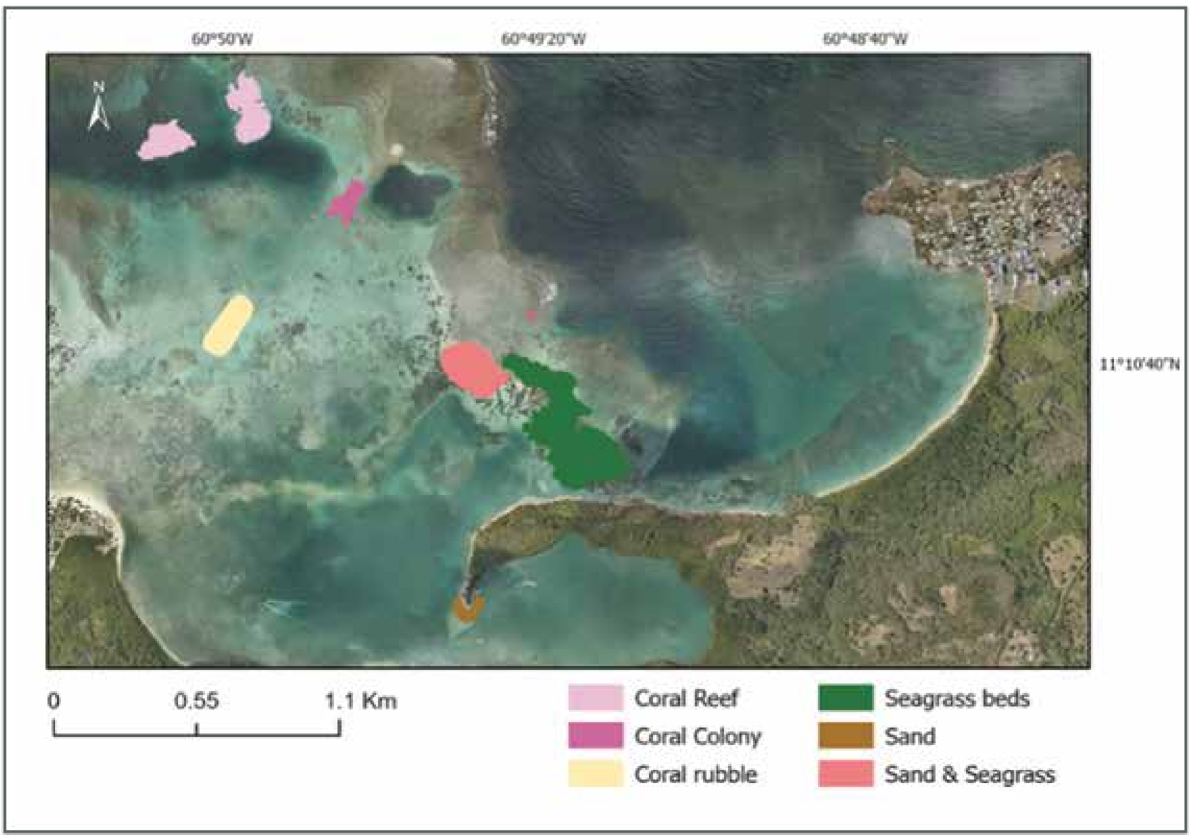

Figure 4. Main habitat types found in the study area

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Table 1. Class, description and extent of marine habitat types found in study site

Key	Class	Description	Extent (m2)	% total
	Coral Reef	Areas covered in coral habitat of considerable size comprised of numerous colonies and having morphological characteristics of coral reefs.	51,330	20.37
	Coral Colony	Areas covered by one or few individual coral colonies.	14,528	5.76
	Coral Rubble	Fragments of reef corals that have detached from coral reefs, reef crests and colonies.	26,364	10.46
	Seagrass beds	Densely covered areas comprising primarily of *Thalassia.*	113,375	45.0
	Sand	Areas comprised of unconsolidated material derived from degraded calcium carbonate.	7,684	3.05
	Sand & Seagrass	A mixed area comprised of unconsolidated material derived from degraded calcium carbonate and *Thalassia.*	3,8625	15.33

The results from in-water surveys (Table 2) using a combination of in-situ data (GPS points) overlain on the image data and researcher observation confirm the main habitat types identified in UAV image analysis.

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Table 2. Results from in-water surveys showing dominant habitat type at study sites

Study Site	Waypoints	Survey type	Dominant habitat type (researcher observation)
1	80-89	Transects	Coral reef
2	70-79	Transects	Coral reef
3	90-99	Transects	Coral colony
4	100-110	Transects	Coral rubble
5	59-68	Transects	Sand & seagrass
6	112-125	Transects	Seagrass beds
7	112-125	Transects	Sand

4.0 DISCUSSION

This study is one of the first to demonstrate the application of UAVs to map critical habitats in the Buccoo Reef Marine Park, Tobago. Coral reefs and other associated coastal habitats such as seagrass beds were typically mapped using GIS and RS technology, which are constrained by a few factors including weather and through field surveys which are time and resource intensive. The study also illustrated that consumer-grade UAVs, with minimum specifications as the model used in this study, provide a cost-effective and accurate tool for habitat mapping in the entire 7 km^2 expanse of the MPA.

Results indicate a high accuracy rate (89.7%) for habitat identification for depths up to 15 feet in near-calm oceanic conditions at a maximum altitude of 116 m. The accuracy results obtained from this study are consistent with previous research where accuracy results range from 74% [48] to 86% [49]. The results of this study may suggest that the use of UAV imagery at lower altitudes may be used to identify coral types based on morphological and environmental conditions, thus further indicating the relevance of this methodology for Protected Area Management. Ultimately, the habitat maps produced from this study will be incorporated with large-scale habitat mapping and used as an integral component of the creation of an MSP for the MPA.

4.1 Management Considerations

Small Island Developing States such as Trinidad and Tobago are often challenged with limited resources, particularly with respect to consistent and efficient monitoring systems for resource management. UAVs

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provide an alternative for physical on-site monitoring that is typically human resource and time intensive. Larger areas can be monitored in real-time for a single UAV flight with the capacity for several repeated flights, which can then be utilized for capturing time-series data. Habitat change, for instance coastal erosion and species die-off, can be monitored over time and seasonal patterns detected. Critical, threatened and ecologically important species such as turtles, sharks [50] and other megafauna can also be monitored and tracked using UAVs [51]. In the Caribbean, UAVs have been used to monitor manatee populations [52], and more recently to assess hurricane impacts [53] and as a tool for ecosystem restoration [54].

In the case of the Buccoo Reef Marine Park, consistent monitoring of human activities is a recurring challenge. UAVs also provide an option for monitoring human activities particularly with respect to poaching of target species. The methods utilized for this study, with alterations including flight altitude and UAV model, provides a practical approach for monitoring in this regard. Park rangers can be deployed when such activity is observed during aerial flights thus simplifying the enforcement process and ensuring a quick response time. Additionally, zones which restrict various types of human activities can also be monitored. For instance, Jet Ski use can be tracked in sensitive nursery areas or unregulated anchoring monitored in coral reef habitats. On a more practical level, the number of vessels and crafts utilizing the Protected Area can be monitored on a daily basis, thus allowing for data acquisition on visitor numbers on a daily and seasonal basis. Habitat and human use data is critical in ultimately developing a Spatial Plan for the Marine Park in Tobago.

It must be noted however, that significant advancements have been made with respect to technologies and methodologies for UAV use as conservation tools. Advancements in UAV applications include machine learning technologies to automate the process of habitat mapping to monitor and estimate sea cucumber densities in shallow habitats [55] and object-based image analysis (OBIA) to produce weed cover maps for rice farming [56, 57]. Additional novel technologies integrate aerial and underwater surveys along with the use of multivariate statistics to generate habitat maps for key assemblages in shallow waters [58]. Such technologies can significantly advance the work highlighted in this study and allow for habit mapping on larger spatial scales in Tobago's existing and proposed MPAs.

Despite the technological advancements, it is likely that UAV use will continue to be constrained by variables including weather conditions, water clarity and depth and flight altitude, ultimately affecting data quality [59]. Notwithstanding these advancements, particularly within the last 5 years, the methods employed in this study can be scaled up to facilitate widespread use at the country (Trinidad and Tobago) level as it is still considered to be a novel technology. At the national and regional levels, this research highlights a simple and cost-effective method for protected area monitoring and habitat classification.

4.2 Challenges and potential applications

While this study demonstrates the potential for mapping the entire MPA, some recommendations are made to alleviate challenges. These include the use of a more advanced model UAV (for e.g DJI Mavic Pro with an approximate cost of USD 1,800.00) to facilitate longer flight times and resistance to higher wind speeds. Additional costs to support the use of a UAV as a mapping tool, such as flight programming software and GIS, must also be considered. Average flight times of twenty minutes and flight interruptions due to periods of moderate to high wind speeds significantly restricted imagery acquisition for this study. GCPs were used to ensure a higher level of accuracy as wind caused displacement of the drone which affected geo-location capabilities.

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Data processing and management presented some challenges with respect to the learning curve associated with the accuracy of visual interpretation and manipulation of the software. As such, the methodology requires advance researcher knowledge in GIS software and it is also recommended that visual interpretation be verified by a second researcher to ensure accuracy. Budget restrictions resulted in the use of a UAV with fewer technical capabilities than advanced models. For larger scale projects, both in terms of the area to be covered and the frequency of UAV use, the budget required will be significantly greater than required for this small scale study.

5.0 CONCLUSION

Consumer grade UAVs can be applied for habitat identification and classification in nearshore Marine Protected Areas. UAV imagery can be used to identify habitats with a high level of accuracy, determine the extent of these habitats and in some cases, provide detailed information at the species level as demonstrated for some coral species. This paper demonstrates the potential for UAV use as a primary mechanism for monitoring, protection and conservation in the Buccoo Reef Marine Park. Data derived from this study illustrate the applicability for widespread classification of habitats throughout the Protected Area and other coral reef habitats around the island. This study produced the most up-to-date habitat maps of the study area and will be used as a key component in a wider project to develop a Marine Spatial Plan for the Buccoo Reef Marine Park in Tobago.

Conflicts of interest

The authors declare that they have no conflicts of interest.

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