Melissa.schiele@ioz.ac.uk

Report prepared by Melissa Schiele and Dr Tom Letessier
Zoological Society of London

Amphibious Drone Field Report, Belize

In partnership with the Turneffe Atoll Sustainability Association, the Marine Management Organisation and the Bertarelli Foundation

Acknowledgments

We thank the Bertarelli Foundation and the Marine Management Organisation (MMO) funding supporting salary and field-work. We thank the Turneffe Atoll Sustainability Association's Director, Valdemar and Eliceo, the Education and Outreach programme coordinator, for their continued support and vision throughout the expedition. We would like to thank Jayron and Maurice, two dedicated Belizean Conservation Officers, who made sure our trials were a success in the field, whilst eagerly embracing us, new technology and the project. Without the engineering capabilities and comradery from Mauricio and Julian at Aeromao, our UAV would not be the success it is, today.

How to cite this report

Schiele MA, Letessier TB. 2019. *Amphibious Drone Field Report, Belize.* Scientific and field report to the Bertarelli Foundation, Marine Management Organisation and Turneffe Atoll Sustainability Association.

Executive Summary

A trial aiming to explore the use of a novel fixed-wing UAV as an enforcement and monitoring tool in the Turneffe Marine Atoll (Belize), was conducted in partnership between the Turneffe Atoll Sustainability Association (TASA) and the Zoological Society of London (ZSL). The Turneffe marine protected area (MPA) in Belize, was delineated in 2012, but is difficult to manage, in part due to illegal fishing, its remoteness, and high running costs.

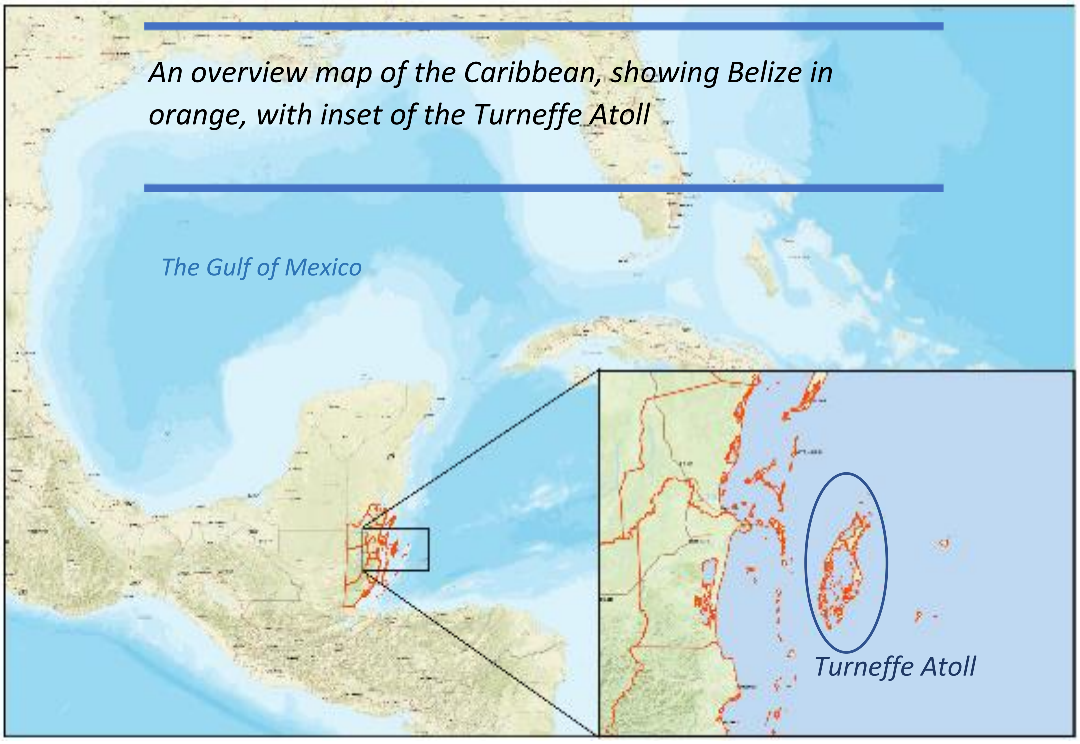
The trial was conducted from February 18th-March 15th and was field-led by UAV technician and ZSL researcher, Melissa Schiele, under project PI Dr Tom Letessier. Twenty-four flights were completed, average length of 10.9km and with total transect lengths of 263km. The UAVs maintained full waterproofing which enabled multiple flights per day. The live front camera link uses a large parabolic antenna which provides a clear image, which can be recorded on either the camera or its viewing screen, although the antenna needed to be manually directed at the drone at all times. We were able to detect megafauna (turtles, manatee, eagle rays), vessels, lobster fishing gear and multiple habitats. Transects were flown at heights of 75m, 85m, 95m and 110m to test the detection capabilities of the camera at different altitudes, both for ecology and surveillance. Deployment from a small vessel was successful and the UAV reached a furthest point Beyond Visual Line of Sight (BVLOS)[1] of 11.3km. Two Conservation Officers responsible for enforcement patrols were trained in deployment, flying, and transect planning. Reports from the Conservation Officers highlighted benefits for using it as part of the reserve enforcement strategy, such as reducing the number of skiff patrols needed, which would save fuel. The weather was suitable for flying most days (n=13). Winds were deemed too strong (>15 knots) on 7 days. Sea state ranged between Beaufort 2 and 3, occasionally 4, for the duration of the trip.

Future development of the UAV now prioritises on improving the following 1) telemetry link between the UAV and the computer, in order to maintain its pre-programmed trajectory and avoid the UAV entering 'fail-safe' and return-to-home and 2) developing a system where the antenna for the live video link does not need to be manually directed at the UAV, most likely by installing a omnidirectional antenna into the system, and 3) establishing features enabling use of a Dynamic Home Point, for deployments from moving vessels.

Key Achievements

1. First deployment of our water-landing fixed-wing UAV in the Caribbean.
2. First time a live-link fixed-wing is used in the marine reserve.
3. First two Belizean Conservation Officers trained to use our UAV system.
4. Reconnaissance images were gathered successfully.
5. First ever deployment of the UAV from a small, moving skiff.
6. Detection of eagle rays, manatee, birds, cushion star, bone fish and turtles.
7. Twenty-four transects flown, with a total flight length of 263km.

[1] BVLOS; Beyond visual line of sight. Our UAV is BVLOS after around 1.8km.



Expedition roster

Melissa Schiele	Zoological Society of London	Drone technician, pilot and postgraduate research assistant
Dr Tom Letessier	Zoological Society of London	Principle Investigator and post-doctoral researcher
Sarah Keynes	Marine Management Organisation	Marine Technology Senior Innovation Lead
Julian Villada	Aeromao Ltd, Canada	Engineer
Patricia Rybarczyk	Three Wise Monkeys Productions	Film crew
Sacha Bennett	Three Wise Monkeys Productions	Film crew
Theirry Volant	Three Wise Monkeys Productions	Film crew
Russell Pierpoint	Evolved Media	Director and digital asset management expert
Sophia Ellis	Essex University/Zoological Society of London	MSc Student

Stakeholder roster

Valdemar Andrade	TASA	Executive Director
Eliceo Cobb	TASA	Education and outreach programme coordinator
Gil Williams	TASA	Finance manager
Jayron Young	TASA	Chief Conservation officer
Maurice Westby	TASA	2nd in command, Conservation officer
Dr. Leandra Cho Ricketts	University of Belize	Administrative Director & Science Director, Marine

Contents

1. Introduction

The Turneffe Atoll is situated off the coast of Belize within the 274km of coastline and is a uniquely biodiverse atoll with around 25% of its reefs covered with mangroves. Different mangroves types are represented here (red, black, white and buttonwood) as well as large sea grass beds, coral reefs, sandy lagoons and deep water >200m (Healthy Reefs, 2018). The atoll measures around 52km long by 16km at its widest point. It is part of the Mesoamerican Barrier Reef System, which in part, stretches the length of the Belizean coast, and is the largest barrier reef in the Northern Hemisphere. The atoll has around 150 islands (Fairweather and Myvett, 2014) and the area is distinctly multi-strategy in management (App3Fig. 1.), which is a system often used to manage fisheries as it aims to placate all stakeholders. Fully protected species of interest include manatees, cetaceans, salt water crocodiles, turtles and corals (extraction is prohibited). Species which require permits to extract and/or have restricted fishing seasons include lobster, conch and shark. There is currently a full ban on extraction and exportation of sea cucumbers, also.

Belize's population is around 380,000 people, and 2000 of these are registered fisherfolk[2] (Fujita et al., 2019). In the Turneffe Atoll, the main fisheries are for Caribbean Spiny Lobster (*Panulirus argus*) and Queen Conch (*Strombus gigas*). The lobster season is closed from 14th February to 13th June and conch season is closed from 1 July to 30 September (Huitric, 2005), allowing for breeding and recovery of these species based on research done by various research groups (Wildtracks, 2012). The fishers in Turneffe are mainly from Belize City and use unbaited lobster traps made from palmetto (a small palm) wood slats. It takes two people to install these traps, which lobsters are attracted to, for shelter. However, fisher folk from the North tend to come in sail boats and target finfish using hand lines (correspondence with Jayron).

A permit to fish in specific zones within the marine reserve are available for a B$25 fee. Shark permits are available but are expensive in comparison to lobster and conch and few are sold (B$100). Fishing in the Turneffe Atoll has happened historically, and fishers have between themselves, delineated their 'turfs' within the zones over the years. As new legal fishers come to the area, increased pressure is put on the stability of the target species, and as a result, some fishers try to outcompete each other and maximise their profit by participating in illegal activities. Illegal fishing activity includes, but is not exclusive to, taking target species outside of their fishing seasons, illegal fishing methods and landing undersized species.

Belize to date has protected 4.5% of its waters soon to increase to 11.6% in the form of more preservation zones which are fully 'no-take' (BBN Staff, 2019). These will be put in place within the existing marine reserves but also in the EEZ, to protect important reef based biological functions which underpin the fisheries industry in Belize (BBN Staff, 2019). Belize has aspiration to protect its waters, by reassessing its fisheries management strategies and increasing the size of its preservation zones. However, even with seemingly robust plans and marine reserves in place, enforcement of the rules and laws which underpin the strategy decisions, are essential to ensure the success of the marines protected areas.

The development of methodologies using UAVs is being explored by many research groups, but none use a fixed-wing which water lands (Hodgson, Peel and Kelly, 2017; Schofield et al., 2017; Colefax et al., 2019). The ZSL, in collaboration with a Canadian drone producer, has developed an amphibious UAV. The UAV has the ability to conduct wildlife surveys whilst

[2] Fisher-folk is a term which encompasses all people who fish

providing live vessel surveillance (Schiele, 2018). The UAV is hand-launched and can water-land, making it especially useful in island locations, where deployment from large catapults, and landing in nets or on large swathes of land, is not possible. The trials reported here determine the success of the UAV as a tool for enforcement and ecological monitoring in the Turneffe Atoll.

2. The Amphibious Fixed-Wing UAV

2.1 Background

The Turneffe Atoll Sustainability Association (TASA) visited the UK in September 2018 and attended the Bertarelli Symposium of Marine Science at the Royal Geographical Society. They met Dr Tom Letessier and Melissa Schiele from the Zoological Society of London (ZSL) UAV team as well as representatives from the Marine Management Organisation. TASA invited the UAV team to come and trial the newest iteration of the Amphibious UAV at the Turneffe Atoll Marine Reserve (TAMR); an area which contains delineated zones and is managed using a primarily, multi-use strategy (Coastal Zone Management Authority & Institute, 2013).

The original prototype of the UAV was trialled in the British Indian Ocean Territories (BIOT) from May-July 2018 by Melissa Schiele and Dr Tom Letessier. The BIOT marine protected area is 640,000km^2 and consists of around 60 small islands. The initial criteria for the UAV was two pronged. Firstly, the Marine Management Organisation's interest in using the UAV as an IUU surveillance tool in BIOT was to help conserve fuel used by the BIOT Patrol Vessel (BPV) and to gather essential intelligence and legal evidence (such as photographs of fishers, and the ID of the vessel with a geotag[3]). The secondary criteria pertained to the ZSL's interest in using the UAV as a tool for ecological surveying and was specifically assigned to detect megafauna (large marine animals) in areas where traditionally, catch-data would be used to determine animal populations (Schiele, 2018).

A technical report was produced after the trials was completed, which clearly outlined improvements needed. The main issues with the UAV were related to waterproofing, camera quality and live camera link signal. The new iteration of the UAV has been fully waterproofed, and both the live camera and nadir camera have been upgraded. The live link signal to the viewing screen has been vastly improved allowing for excellent quality of video, which is recordable both on the camera itself and by the viewing screen.

The UAVs are engineered by a Canadian company, Aeromao, using specifications and technical lead from the ZSL run field trials from BIOT, and now, Belize.

[3] Geographical coordinates associated with an image, taken by a camera.

2.2 Operation

The following are the UAV specifications from the Aeromao website:

- Construction: EPO foam (durable, easy to repair, carbon fiber reinforced).
- Wingspan: 2 m.
- Weight:3600 grams.
- Endurance:2 Hours.
- Launch: Very easy to hand-launch.
- Take off: Fully automatic.
- Landing: Automatic belly landing on water or land. Parachute landing on land available.
- Range: +30kms. Tested in real BVLOS flight operations (Beyond Visual Line of Sight).
- Max. Altitude: About 4500 masl.
- Cruise speed: 62Km/h.
- Camera: 20Mp stills or up to 4K video, nadir orientation.
- Flight modes: Manual, Stabilize, Return to Home, Fly be Wire (automatic holding altitude and airspeed), Auto.
- Wind Tolerance: up to 45 km/h. for flight and autonomous belly landing. 25km/h for parachute landing.
- Maximum speed: +85 Km/h – Great stability and minimal roll & pitch oscillations in gusty conditions = no gimbal required for cameras & sensors.
- Failsafe: Automatically returns to home & loiter upon loss of RC link. Other fail-safe routines available.
- Telemetry: Battery status, alt, ground speed, compass, altitude, distance travelled, time on air (speech enabled), and more than +200 parameters more.
- Moving map display/telemetry: UAV position and heading, commands on map, fly to point on map, altitude changes, remote spot camera trigger, mission route, and more.
- Weather: All-weather performance. -20°C to +40°C

The UAV's flight transects are planned using Mission Planner software, and are also controlled using an RC controller, on a 2.5Ghz frequency. The live camera link has been improved, and a large parabolic aerial allows for a clearer signal and good quality footage. When the UAV lands on water, it is retrieved by two people on a small vessel. Twenty-four flights were successfully completed (Fig. 1).

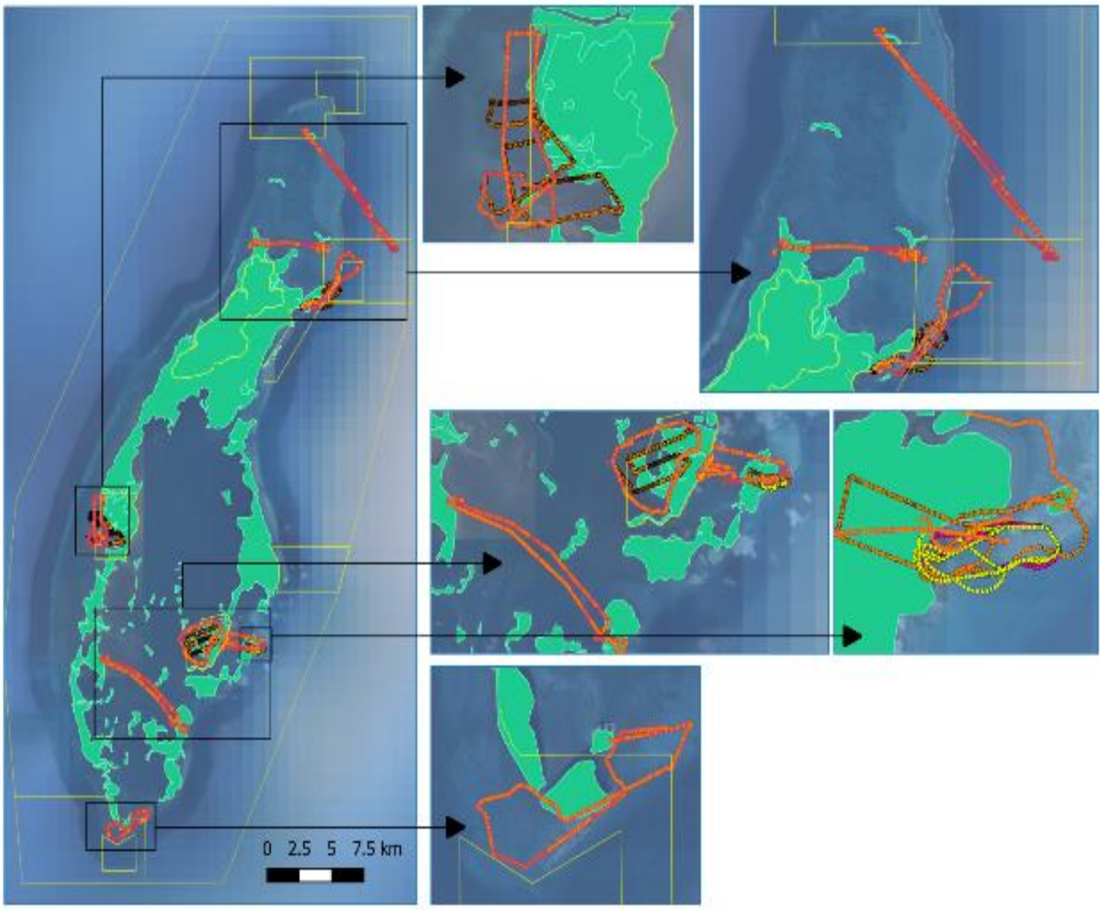


Fig. 1. Twenty-four transects were flown in the marine reserve. Only two of the protected zones were unreachable, due to an airstrip prohibiting flight and lack of a suitable deployment spot.

Operation of the drone and flight planning required consideration and understanding of wind patterns, strength and flight theory, in order to plan trajectories safely. Take-off and landing occurred against the prevailing wind, to a) generate lift on take-off and b) slow the UAV down on landing. This is considered good practise in UAV flying. In Turneffe, the prevailing wind was easterly (north or south) and the transect designs reflect these environmental variables.

3. TASA

The Turneffe Atoll Sustainability Association is a dedicated association for the management and monitoring of the Turneffe Atoll, under the Belizean government, and is co-managed in collaboration with the University of Belize, the Coastguard and the Fisheries Department. TASA has three field stations within the atoll; Mauger Caye in the North, Calabash Caye on the Eastern central point and Caye Bokel in the South and a headquarters based in Belize City.

There will be 3-5 Conservation Officers based at each field station at any one time, and they conduct pre-planned patrols around the atoll and produce reports outlining observations and interventions. They have the power to confiscate vessels and arrest individuals who have broken the atoll laws pertaining to fishing. Laws pertaining to the killing of (for example) crocodiles and land-use change fall under the jurisdiction of the environment department and wildlife, so they can only report observations of infractions to these relevant teams.

3.1 Previous UAV use in the atoll

The fisheries department in conjunction with the Wildlife Conservation Society (WCS) has previously used a fixed-wing UAV. This UAV was smaller than the Aeromao talon (by around 25%) and had its propeller on the front [4].

Recently, a 'moving tower' strategy has been employed, using a DJ Mavic 2 quadcopter, as part of the regular skiff patrols: the UAV is flown to a selected altitude and rotates on the spot, like a lighthouse beacon, surveying an area. It is also used to inspect areas where suspect activity and stealth are required, such as subtle scoping, or to locate (for example) the source of a fire. There are currently no regular planned enforcement surveys or surveillance being done with the quadcopter, only these occasional opportunistic flights (AppFig. 2).

3.2 Criteria

TASA have specific areas of governance that may be improved, using UAV technology. The criteria below were derived following discussions between the ZSL and the TASA director.

1.	To monitor land-use change of resorts and other developments within the TAMR
2.	To assess the most commonly used boat routes in order to ascertain best areas for mariculture (seaweed farming)
3.	To habitat map the atoll (seagrass and mangrove preference) for carbon stock measuring
4.	To survey for illegal fishers' boats
5.	To see if it's possible to detect lobster catching gear from UAVs
6.	To detect hiding spots of illegal fishers in the mangroves
7.	To train TASA staff to fly the UAV and assess its suitability as a tool for enforcement

3.3 Results

3.3.1 Land use change

TASA have concerns that some of those who have permits to build within the atoll are disobeying the restrictions within their permit and wanted to ascertain if the UAV could fly, undetected and gather reconnaissance at selected sites. We opted to conduct a reconnaissance

[4] A brief video of this project is available here https://news.nationalgeographic.com/2016/12/UAVs-fig.ht-pirate-fishing-belize-conservation/.

flight over a local resort being built, due to reports of mangroves clearings for an unlicensed airstrip.

The UAV was able to detect that an airstrip had been built recently. Considering that the flight plan was a general survey of the site, it was noted that the UAV images were able to detect a lot of the airstrip, enough to estimate its length, as it ran the length of a pre-known, manmade channel. The UAV was also able to identify potentially unlicensed mangrove clearance, (App3Fig. 3 and App3Fig. 4). Ordinarily, the Conservation Officers may use a quadcopter to gather information on land-use change in places which are difficult to land a skiff on.

3.3.2. Boat routes

The commonly used navigation routes used by the fisherfolk are known to the TASA Conservation Officers and fisheries departments and are typically used as the basis of for their skiff patrols. These routes connect to the 25 or so fishing camps which are scattered around the atoll. Boats will leave 'scars' through the seagrass if the boat is so shallow that the propellers churn up the seagrass. These 'scars' were detected by the UAV and highlighted previously unknown areas of elevated activity at on the eastern edge of Zone V, which is a fully no-take preservation zone. The shape of the 'scars' at the mouth of the channel (App3Fig. 5) indicate a vessel has had difficulties navigating the shallow waters, suggesting an inexperienced captain, new to the area.

3.3.3. Habitat mapping capabilities

The UAV has a Sony RX0 nadir camera with 20mp and was able to capture high definition images of habitats. The UAV's nadir camera has a 10-degree angle of inclination, which was a feature recommended by the remote sensing team at the Royal Botanical Gardens, Kew, to help with habitat mapping of terrestrial areas. The images were geo-referenced retrospectively, using the image time-stamp and the UAV telemetry log. We were able to capture a variety of habitats, and to identify environmental issues, such as accumulation of plastic debris, and of sargassum seaweed which can cause deoxygenation of the water and block out sunlight (App3Fig. 6).

3.3.4. Vessel detection

A key requirement for the UAV is to be able to see and detect vessels, using both the live front camera and the nadir survey camera. We explored flying at different altitudes, in order to determine any effect on the photographs of the vessels. However, a primary concern regarding clarity of photos, was the white glare of the fiberglass in the sun, which made it difficult to identify any details such as ID number. Figure 7 A, B, and C (Appendix 3) were all taken using the nadir camera. The UAV is as manoeuvrable as it was in BIOT and can change flight plan to loiter over an area of choice, informed by the live camera link. It is this dynamic feature that increases the operational applications of the UAV, making it suitable for inspection of a situation and not just reconnaissance of an area on a planned route. The improved live-link front camera enabled the ground team to have a clear view of the UAV's route (Fig. 2).

Fig. 2. Video still taken from the live front video camera showing a small skiff and a launch (small speed boat used for patrols by the coast guard). The UAV live cam can see 2-3km in front of it. This image is from 60m altitude.

3.3.5. Lobster pot/shade detection

Lobster shades are large zinc sheets cut into rectangles which are placed in the lagoons during the lobster season. The lobster traps are set beneath them, and the lobsters are attracted by the shade from the sun. We were able to detect the shades (App3Fig. 8, A-D). When a shade is removed at the end of the lobster season, it leaves a rectangle of bare sand where grass has died over the course of the season. We were able to detect these as well.

3.3.6. To detect hiding spots

Some fishers in the area are suspected of making hiding spots within in the mangroves themselves, where they are cleaning fish and potentially storing them, in ice boxes, outside of the designated fishery season, especially for conch and lobster, as has been previously observed by the Conservation Officers. Such an area was potentially located on the edge of a fully no-take zone, where an unnatural looking patch of mangrove, and clusters of garbage, suggest interference and clearing (App3Fig. 9). The unnatural nature of the area was concluded by both TASA staff and a visiting Fisheries department worker. These are the types of locations which the patrol team will dedicate time to survey for with a UAV, and when found, can feed into patrol plans for the area, using skiffs.

3.3.7. Team performance

Two participants from TASA were involved in the specific drone deployments and participated on all flights, becoming trained and integral members of the flight team (App3Fig. 10 (A)), (Jayron and Maurice). Using their experiences working at sea and therefore being able to understand weather patterns and wind, they were able to quickly grasp aviation concepts and plan flight routes safely, in the Mission Planner software. Both Maurice and Jayron were also able to deploy (App3Fig. 10 (B)) and recover the UAV safely. They were able to offer constructive insight into the problems faced by TASA and were able to show us where they thought our UAV could be useful in detecting something of interest. The good relationship that the TASA team maintain with the local fishing camps was evident, as we were able to deploy from four different ones and borrow kit from another and using one hut as a make-shift hanger (App3Fig. 10 (C)).

3.4 Feedback

The enforcement team at TASA, who were involved in the UAV flights, have given positive feedback in terms of the usage and the potential applications of the UAV. The TASA officers saw immediate value with the live camera function also. They viewed this tool as a way to extend their vision of the atoll and were particularly interested to understand how the telemetry system could be improved, allowing for other stations to watch the live link camera even if a different field station base were operating it. Feedback from Valdemar and Eliceo continues to be positive and is underpinning the start of a mutually beneficial partnership between TASA and the ZSL. We are confident that the UAV can become a valuable tool for the enforcement team, and we are working to raise the necessary funds to realise this vision.

3.5 Drone patrol cost vs boats

The average cost of fuel per gallon varies in Belize. Each patrol is a 49km average round trip and the cost of fuel is B$11 per gallon and each trip is 10 gallons of fuel, meaning each trip is costing them c. B$110. Multiplied across three bases, this gives a conservative daily fuel cost of B$330. If TASA are patrolling 5 days a week, that's B$1650 per week, or B$6,600 per month. In times of season closure or opening, holidays and other leads, these patrols may increase in length and frequency, increasing expenditure to around B$10,000 per month (from correspondence with TASA conservation officers).

The UAV is electricity powered, supplied by two 4500 mAh batteries for the engine, and one for the live camera (5200 mAh), and one for the RC controller (2000 mAh). It takes 2 hours to fully charge the batteries and overnight for the RC controller. As the base runs on solar energy, the cost to charge the batteries for the UAV are negligible. It was estimated by Jayron, that around a third of the patrols currently done could immediately be switched to a drone transect and flown from each of the three bases. That alone, would save TASA B$2200, per month, or a yearly saving of B$26,400, **or $13,200 US**, almost enough to buy a new fixed-wing amphibious drone, or several Mavic Pro Duos.

3.6 Future suggestions

TASA are looking to improve their effectiveness as an organisation, in terms of marine protected area management. This challenge is not unique to the Turneffe Atoll and one where innovation is needed. The challenges that were highlighted to us included locating illegal vessels, monitoring land-use changes and ensuring that reefs are not being over used.

Ultimately, we envision the UAVs to be integrated into the everyday enforcement strategy and flown by the TASA Conservation Officers. Currently, TASA have been documenting their relatively recently introduced patrols, which have the explicit purpose of policing the atoll. Not only are they logging their patrols, but also wildlife sightings and where they are carrying out fisheries interventions, such as giving warnings, fines, searches or other activities.

Using the data, it is possible to produce a heatmap to highlight where most of the enforcement activities were occurring in 2018. The areas around Calabash Caye, Caye Bokel and Cockroach Caye are likely hotspots for enforcement intervention. We were able to fly multiple transects at these sights easily (Appendix 2) suggesting that the use of the UAVs can be implemented and integrated simply and have a higher chance to detect fishers in those areas.

A technical report for the second iteration of the UAV was produced after the Belize trial (Appendix 1) and will be used by the development team as a reference point for future UAV improvements.

4. MMO

The MMO is a UK government department responsible for the management and enforcement of laws in UK waters. Our MMO partner, Sarah Keynes is the Marine Technology Senior Innovation Lead as part of the Blue Belt project, which seeks to sustainably manage and protect as much of our overseas territories as possible (CEFAS, 2017).

4.1 Criteria and results

The MMO are primarily interested in the UAV as a tool for IUU vessels detection. As they are interested in using this UAV in other Overseas Territories, their criteria, in part, reflects those of TASA. They are specifically interested in the range of the UAV and if it is possible to deploy it from a boat and if it can circle in on vessels it detects, at the control of the pilot. The main proportion of their criteria has been addressed in the MMO 'Essential Requirements' document, which has not been included in this report, as it is a government working document.

We were able to do several successful launches of the UAV from a small vessel, which has never been done before. Although the UAV was launchable from the skiff, it is still not possible to power-on and calibrate the UAV on the vessel, as the movement is too much for the gyros and GPS components. A solution for this is being currently devised, which will enable the UAV control station to become mobile. This feature would enable increased manoeuvrability for patrol design and would also mean that technically difficult flights would be possible as the take-off point can be moved into the wind.

The UAV reached a maximum distance of 11.3km (round trip of 25km) which is approximately a quarter of the entire length of the atoll. This distance is adequate for the needs of the TASA team, but will need to fly further, for MMO needs. The UAV has a system which is capable of 30km+ telemetry and live link radio. Limitations to the system arose when the signal was disrupted by high mangrove trees and potentially, humidity. We plan to address this by elevating the telemetry receiver and the live link aerial to ensure that a better signal strength between the UAV and the control station.

5. ZSL

5.1 Criteria

The objectives were chosen to reflect the ongoing work which began in BIOT. The ZSL team are interested to test the new onboard camera systems, and the MSc student's work will contribute to understanding of the types of ecological data that can be derived from the image sets.

The main objectives of the expedition were:

1.	To conclude whether the new UAV iteration was fit for use out at sea.
2.	To ascertain whether MPA officers could be trained to use the UAV, within a short space of time.
3.	To explore if an ecological systematic transect design detected different numbers of megafauna, in comparison to the IUU patrol style transect, which are used to target illegal fishers, only.
4.	MSc student's project: To test whether varying altitudes of height influence habitat classification from UAV images.

5.2 Flights and methods

Melissa trained the 3 to set up and assist in flying the UAV, conducting 24 successful flights around the atoll over three weeks (Appendix 2). The first week, UAV engineer Julian Villada was also present and helped teach Melissa about the modifications that been installed, including a homing beacon system, which was tested on foot and to the live link camera system and the fuselage.

All the technical issues from the last version of the drone which was tested in BIOT (Schiele 2018) had been fixed, which meant that the new drones were fully waterproofed and functional.

Each evening, a plan for the next day, based on the overall criteria of the expedition was created by Melissa and the two conservation officers. It was ascertained where the most at-risk zones were at the time, and where flights should be conducted. The TASA team would plan the transect for the surveying flight in Mission Planner, also known as the IUU transect and Melissa would create a corresponding ecological systematic transect for the same area. Melissa also planned transect routes for Sophia's MSc project which required 3 flights at the altitudes of 75m, 85m and 110m over the reefs, at three sites. All marine zones within the TAMR were flown in, except for zone IV, which is too close to a landing strip and airfield, disqualifying us from flying there as per our permit.

5.3 Observations

The ZSL's primary ecological interest were in being able to detect if observation opportunities are lost if only IUU transects are flown and if ecological systematic transects can detect more megafauna. The images are yet to be analysed, but preliminary observations show that the UAVs new camera can photograph a good selection of megafauna.

On flights 20 and 21 at Long Bough (Appendix 2) an IUU transect and an ecological style transect were flown and within the ecological transect, a manatee was detected, which was absent in the IUU survey (Fig. 3).

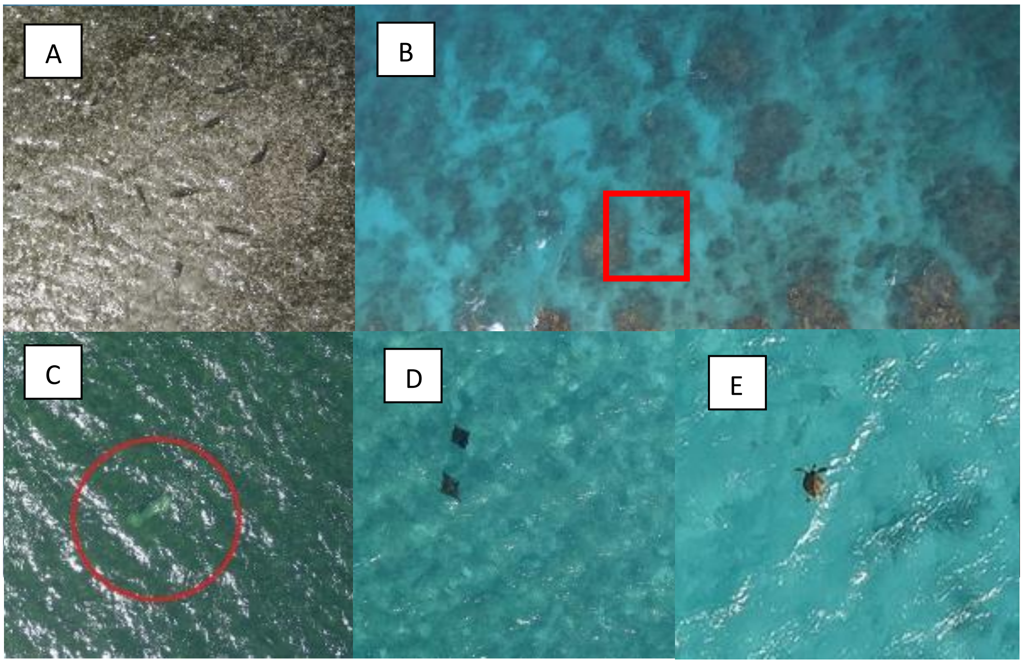


Figure 3. Megafauna observations from the image sets, thus far, with altitudes. A; bony fish at 20m. B; two long barracuda-like fish, consistent with those seen during ground-truthing, at 85m. C; manatee at 85m. D; eagle rays at 85m. E; green turtle at 85m.

6. UAV based infra-red camera use at night

A self-funded partner of ZSL, Russel Pierpoint, who is the Director of Evolved Media[5], joined the expedition for a week, bringing with him two quadcopter drones, where one was the new DJI Mavic Pro Duo FLIR, which has the capability to fly and record in RGB and infra-red (Fig. 4).

All stakeholders had interest in seeing the capability of this new UAV, as currently, no other UAV on the market has FLIR cameras and is within an affordable price bracket. This UAV costs around £3000 (US $3,900). Ten flights were conducted over the duration of one week, either at dusk or at night, at the Calabash Caye Field station or Caye Bokel (private property). Russell controlled the UAV using a hand-held controller and was able to fly up to 4km away. The endurance of this UAV is around 23 minutes. The UAV also has very bright spotlights which can be used to illuminate suspect vessels, and this allows the drone to gather information about the vessel, such as type, ID and number of people on board (if batteries allow, a closer inspection of the suspect vessel will allow for high enough resolution images to warrant facial ID). The UAV has a unique feature where a voice message can be recorded by the pilot, and then played out from a speaker on the drone itself. This could act as a huge deterrent and to give instructions to illegal vessel captains (i.e. “move away from this area, you are committing an infraction and will be cautioned”).

It was concluded by Russel, Melissa and Jayron, that a duel-system, where the Amphibious UAV is flown at day and the Mavic Pro Duo at night, would make for a robust 24-hour surveillance system which would be easy and workable for the TASA enforcement team. The power of UAVs as deterrents for illegal fishing activity is posited but would require more qualitative research to conclude.

[5] Evolved Media are a digital asset management firm, developing and creating workflows for vast amounts of imagery http://www.evolvedmediasolutions.co.uk/

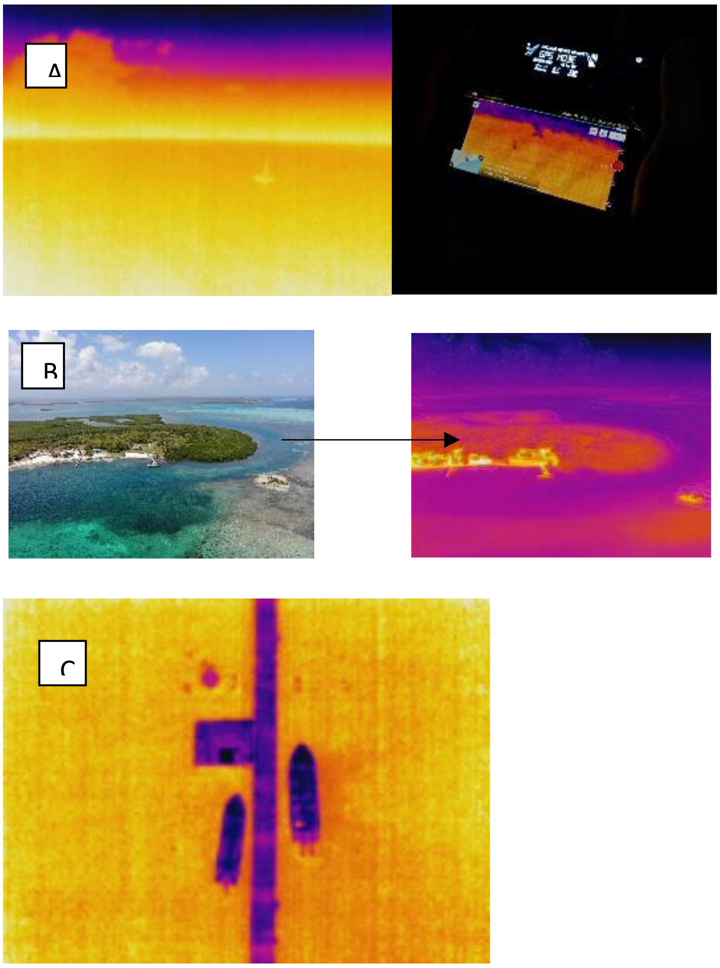


Figure. 4. A) A vessel is detected on the infra-red FLIR camera on the DJI Mavic quadcopter (21:00hrs). B) An example of the Mavic capability during the day (RGB camera) and the same image in IR. C) Vessels at a jetty (20:00hrs). The fiberglass hulls retain heat for many hours after sunset.

7. Digital Asset Management

As drones become more affordable, and camera technology better, (Colefax, Butcher and Kelaher, 2017), we face the challenge of ever-increasing sizes of image sets from expeditions. From BIOT, the total size of all the flight images was around 60GB. Our image set from Belize is over 440GB. Having multiple external hard drives for the storage and moving of data from the field to the office, is unstable and risky, and many ecologists and science teams rely on this method (personal correspondence). There is scope to move into using hard drives which work by copying images directly into a cloud, when back at basecamp, as the hard drive creates its own hotspot connection (as commonly used by the film and photography industry). This allows for large amounts of images to be accessible to anyone in the world, within hours of the initial image collection process, either via a cloud or dedicated database system, though to use this feature a basic internet connection is required.

Russell's team specialise in building databases and creating online storage facilities for huge amounts of images (millions). The databases are known as digital asset management (DAM) systems, and Russell's team specialise in the ELVIS DAM system, which was originally developed by Woodwing[6]. The vision shared by Russell and the ZSL team, is to create a dynamic and AI driven database, which allows fast and smart interrogation of the images, through easy navigation and customisable components. For example, locating all the images which have 'land' in them could be done by selecting and filtering, using the metadata tag of 'land', or you can ask the system to search for all the images which contain 'manatees'. These are very basic examples of the things this system can do. It can also be linked with google and other AI platforms, which will help our database identify things in the images, such as 'birds', as we take advantage of the online training databases available. It will also be easy to share access to this system; we would be fully able to select which parts of the database would be accessible to whom and for what duration of time. This interdisciplinary solution to our ever-increasing amounts of images will make the entire process manageable and will free up valuable time for the scientists. We may see this DAM system become a benchmark for other UAV users, also.

[6] https://www.woodwing.com/en/digital-asset-management-system

8. References

BBN Staff (2019) *Cabinet approves expansion of Fisheries Replenishment (No-Take) Zones*, *Breaking Belize News*. Available at: https://www.breakingbelizenews.com/2019/04/03/cabinet-approves-expansion-of-fisheries-replenishment-no-take-zones/ (Accessed: 9 April 2019).

CEFAS, M. (2017) 'Introducing the Blue Belt Programme'.

Coastal Zone Management Authority & Institute (2013) 'Turneffe Atoll Coastal Zone Management Guidelines'.

Colefax, A. P. *et al.* (2019) 'Reliability of marine faunal detections in drone-based monitoring', *Ocean & Coastal Management*. Elsevier, 174(October 2018), pp. 108–115. doi: 10.1016/j.ocecoaman.2019.03.008.

Colefax, A. P., Butcher, P. A. and Kelaher, B. P. (2017) 'The potential for unmanned aerial vehicles (UAVs) to conduct marine fauna surveys in place of manned aircraft', *ICES Journal of Marine Science*, 75(February), pp. 1–8. doi: 10.1093/icesjms/fsx100.

Fairweather and Myvett, G. (2014) 'Lobster Trapping Tenureship Survey', (February), p. 20 + Appendix.

Fujita, R. *et al.* (2019) 'Viability and Sustainability of Small-Scale Fisheries in Latin America and The Caribbean', 19, pp. 177–195. doi: 10.1007/978-3-319-76078-0.

Healthy Reefs (2018) 'Mesoamerican Reef Report Card', p. 17. Available at: www.healthyreefs.org.

Hodgson, A., Peel, D. and Kelly, N. (2017) 'Unmanned aerial vehicles for surveying marine fauna: Assessing detection probability', *Ecological Applications*, 27(4), pp. 1253–1267. doi: 10.1002/eap.1519.

Huitric, M. (2005) 'Lobster and Conch fisheries of Belize: A history of sequential exploitation', *Ecology and Society*, 10(1). doi: 10.5751/ES-01319-100121.

Schiele, M. (2018) 'Development and assessment of an amphibious fixed-wing UAV for marine megafauna surveys and enforcement', (December), pp. 1–46.

Schofield, G. *et al.* (2017) 'Detecting elusive aspects of wildlife ecology using drones: New insights on the mating dynamics and operational sex ratios of sea turtles', *Functional Ecology*, 31(12), pp. 2310–2319. doi: 10.1111/1365-2435.12930.

Wildtracks (2012) 'Turneffe Atoll Marine Reserve Management Plan', *Belize Fisheries Department*, p. 293.

Appendix 1. Technical Report

Issue	Improvement needed	Solution suggested
There is no dynamic home positioning	Dynamic home position is still not actionable. This function is apparently possible on some quadcopters, but it is not yet available on our UAV. Enabling this would mean that those at the launch point could move, safe in the knowledge that the drone, if in RTL mode, will find them where they are, and not at the original launch point.	There is dynamic home positioning available on new recreational grade quadcopters (DJI). We appreciated the task here a lot more complex with a fixed-wing but this needs to be researched and addressed.
It's not possible to set up the drone on a small boat due to the compass, gyros etc needed stabilisation	We need a method where the drone can be set up on a boat, or at least an understanding of the size of boat needed to do this i.e. 40ft minimum size.	I have the idea of carrying/towing a floating pontoon in the boat. When the desired location is found, to pontoon is deployed and weighted to keep it stable. This pontoon is used to set up the drone. OR a gimbaled table. There may be solutions to this in yacht furniture design. http://www.nauticexpo.com/prod/balance-srl/product-55803-453501.html I am also devising a hanging solution using counter weights… to be tested.
The lid of the drone is secured using screws	The drone lid needs to be clicked shut and not with little screws, as we have found this system tedious and slow.	Perhaps a similar system used to close waterproofed cameras, would be better. The fewer small parts, the better for su in the field.
The camera (nadir) has small screws and an elastic band to secure it	Sophia had many issues with this system where no photos would be taken for the flights. Playing with the elastic band wastes time and introduces to much opportunity for things to go wrong.	A more robust click in system is needed, which can incorporate an automatic trigger for the camera. Just push into place and automatically starts taking photos.
The nadir camera does not have geotagging capability	Ideally, a camera with an integrated image tagging system is preferred. The current protocol we are using require post processing in Mission	As technology improves and prices come down, we will look for a newer camera which is of the same compact size, 20mp quality and has geotagging. Also, there are some concerns over the geotagging capability of Mission Planner, in that is

	Planner and this is sub optimal and requires a decent amount of computational ability- my laptop seems to be crashing a bit during this process.	sometimes seems to tag fewer or more photos, than anticipated. To be discussed.
The front camera teeters a little precariously for use. On heavy landing it's bracket will break (although this is fixable)	Front camera bracket needs to be stronger/tougher as it is far too fiddly and breaks too easily. The screws are impossible to screw into the 3d printed brackets. The 3d printed brackets were sent not fully finished which caused issues. We need to be able to fig.ure out the correct position (so we see the horizon). Up and down as well as side to side would be perfect. Also, zoom, but we understand the limitations here.	We need to totally rethink the front bracket. Go-pro seems to have simple and adjustable, click in place solutions for their cameras and adaptors. We need something like this.
Currently, it is really difficult or arduous to fig.ure out the true total distance of the flight, not just the proposed one.	When you are planning a flight in mission planner, it gives you the total distance of the planned transect. However, during flight, the actual route flown is often different. How can we disentangle the actual length of the flight, from the tlog?	Is there a way to disentangle this from the tlog? We need to fig.ure this out using a simple solution.
The propeller requires a washer and a nut to attach the propeller	The nut got damaged because we were using pliers to tighten it. Too many small parts which can get lost (and were dropped).	We bought a spanner, but a wingnut type system would be preferable.
The wings are still difficult to affix sometimes	We are still having issues with sliding the wings on gently and easily.	The bars inside the wings need to be set in such a way that they don't move and get the carbon rods stuck.
Can we replace the carbon poles with solid rods? Will this be stronger?	The rods are hollow, and they do snap easily, sending shards of carbon fibre everywhere.	A carbon rod (solid) could offer more strength and stability and could break less on heavy landings. OR

		Just supply us with way more spares. This seems to be the obvious solution here. It is clear from both trips, that 1 set of spares is NOT enough!
The v-tail rivets pop out mid flight	We have noticed that the rivets for the v tails pop out all the time (including mid-flight). Still too many loose parts flying around which can get lost.	This whole rivet system is not sufficient or secure. A new way to attach the v-tails is required. Perhaps a 'slide and click into place' idea?
LiPo batteries	We were initially told at the battery life is around 2 hours and we were informed in Belize, that realistically, its 1.5hrs. We were only able to test to half an hour, before we get RTL issues.	Can we reconsider the LiPo for one which lasts longer? Can we also have fireproof pouches provided with each LiPo, meaning we can transport them safely. Also, each drone needs to come with 2 sets of 4500 batteries- in Belize we did not have this, which limited our flying greatly.
Continuing issues with telemetry	We experienced RTL over trees, but also over water with no obstacles, at around 11km from home. I am confused as I have colleagues who fly smaller fixed wings in the rainforest and don't have issues…	If the UAV has a 20km+ range, we still need to prove this. The telemetry system is still having issues- we need to find the cause and make the correct changes to address this. The drone needs to exceed 12 nautical miles, which is 22km. We still have no proof it can do this. If it means putting the telemetry box on a telescopic system, please devise one and ensure it is suitable for the field.
Live link video difficult to maintain	A person has a constantly turn the aerial to maintain the live-link. This is a waste of person who could be doing something else, in a small team.	Omnidirectional antenna needed.

Appendix 2. Flight Log

ID	country	date	loc	UAV	Start	End	Time	Wind speed	Observation	beaufort	Team	issues	Retrieval	Furthest point	Total dist	Modes	alt	Purpose
1	BELIZE	20/02/2019	HQ	AquaQueen	15:42:00	15:58:00	16 min	16.6kmph-13kph	We had slight gust. Morning was way too windy to fly.	3	Julian/Tom deploying. Sarah on laptop, Melissa control and Sophia on live cam.	No issues with retrieval. No radios this time.	None	702m	10.89	auto	112m	Test flight 1 for AquaQueen
2	BELIZE	20/02/2019	HQ	AquaQueen	17:05:00	17:28:00	23 min	18.52-31kph	We had slight gust. Morning was way too windy to fly.	3	Julian/Tom deploying. Sarah on laptop, Melissa control and Sophia on live cam.	Tom crashed the drone on deployment and we had to get julian to deploy- V tail 3d printed component taped up.	None	702m	18.44	auto	112m	Test flight 1 for AquaQueen
3	BELIZE	21/02/2019	HQ	Breezy	14:52	15:17	25 min	start 22.3kmph end 19.8kmph	We should have flown in the morn. We flew after lunch but by the time we were ready for another the gusts were too strong	3	Julian/Tom deploying. Sarah on laptop, Melissa control and Sophia on live cam.	No issues with retrieval. No radios this time.	No issues	1.12km	2.5	auto/ fwbw	110	Test flight 1 for Breezy
4	BELIZE	23/02/2019	Rendevous point	Breezy	12:05	12:32	27 min	18.9 kph	The weather for once was good!	2	Julian deployed from boat, Melissa on controller, Sophia on laptop	The deployment was done from a boat, we had to reboot the donre on the boat, which meant th camera turned off. We didn't turn it on again. Boat deployment went well. Drone loast signal at 5.7km due to mangroves. Lots of RTL and falisafe. Seems to be an issue with the connection between the controller and the telemetry box.	OK	6.29km	14.5	all	120	BVLos
5	BELIZE	23/02/2019	Mauger Caye	Aquaqueen	16:19	16:51	30 min	14.4kph	Wind direction was blowing east south east to north east at 16:45	2	Julian had controller, Maurice deployed and Melissa on computer	Drone landed a littler furhter than expected and Tom and Julian swam out to it. Boat came, drone was retrived OK	The drone was deployed by Maurice for the first time- bit shaky but righted itself. Drone did BVLOS attempt. Had failsafe issues, RTL, circle, but made the trip back ok. Seems to be an issue with the connection between the controller and the telemetry box.	11.30km	25	all	120	BVLOS
6	BELIZE	24/02/2019	The strange place	AquaQueen	11:15	11:42	27 min	8.6 kph-20.0 kph	wind direction was blowing east south east	3	Julian deployed from boat, Melissa on controller, Sophia on laptop	The drone had a few hiccoughs and attempted RTLs through failsafe, but these were overcome and the drone came back well	Retrival OK	8.26km	17	all	110	reconnaisance
7	BELIZE	24/02/2019	HQ	Breezy	15:27	15:32	5 min	11.4-12.3kph	wind direction was blowing east south east	2	Melissa, Sophia, Jay Ron and Maurice	The mission planner crashed during the pre flight checklist	Retrival OK	0.75km	5	auto	85	First solo set up by drone team
8	BELIZE	26/02/2019	Cockroach channel	AquaQueen	14:45	14:59	14 min	12.6kph-7.5kph	wind direction was blowing east south east	2 to 3	Melissa, Sophia, Jay Ron and Maurice. Jay Ron launching	We actually wanted to fly Breezy but when we turned on the drone the noise that the motor made was wrong and we decided to fly AquaQueen instead. Flight with Aquaqueen went perfectly with NO failsafes. NO DATA at this 110m flight. Need to redo	Retrival OK	5.18km	13.52	auto	110	Tranects through 2 high protection zones with restrictions on fishing and gear use

9	BELIZE	26/02/2019	Cockroach channel	AquaQueen	15:48	16:04	16 min	11.6-3.5kph	wind direction was blowing east south east	2 to 3	Melissa, Sophia, Jay Ron and Maurice	Flight was good and a few failsafes around at the furhtest point of the flight. 85m alttitude. Camera was not set, so no images exist	Retrival OK	5.18km	13.52	auto	85	Tranects through 2 high protection zones with restrictions on fishing and gear use
10	BELIZE	27/02/2019	HQ	AquaQueen	14:13	14:21	8min	12.1kph-15.6kph	Slight crosswind but no issues	2	Melissa, Sophia, Jay Ron and Maurice and Dante watched	all ok	Retrieval by boat by Maurice and JR	1.12km	10.63	auto	75	Flight at 75m
11	BELIZE	01/03/2019	Cockroach channel	AquaQueen	15:18	15:36	18 min	10.8kph-7kph	wind direction was blowing east south east	2	Melissa, Sophia, Jay Ron and Maurice	all ok	Retrieval by boat by Maurice and JR	5.18km	13.52	auto	110	110m
12	BELIZE	01/03/2019	Cockroach channel	AquaQueen	16:05	16:21	16 min	12.1kph-0.1kph	wind direction was blowing east south east	2	Melissa, Sophia, Jay Ron and Maurice	all ok	Retrieval by boat by Maurice and JR	5.18km	13.52	auto	75	75m
14	BELIZE	02/03/2019	Douglass	AquaQueen	13:53	14:06	13min	17kph-10.5kph	wind direction was blowing east south east	1 to 2	Melissa, Sophia, Jay Ron and Maurice	Survey cam did not ake photo due to it being turned off during set up	Retrieval by boat by Maurice and JR	3.85km	12.5	auto	85	IUU transect
15	BELIZE	03/03/2019	Douglass	AquaQueen	13:55	14:15	20 min	11.4kph-16.1	wind direction was blowing east south east	1 to 2	Melissa, Sophia, Jay Ron and Maurice	all ok	Retrieval by boat by Maurice and JR	3.85km	14.2	auto	85	Ecological transect
16	BELIZE	03/03/2019	Douglass	AquaQueen	14:40	14:55	15 min	13.3-12.1	wind direction was blowing east south east	1 to 2	Melissa, Sophia, Jay Ron and Maurice	all ok	Retrieval by boat by Maurice and JR	3.85km	12.5	auto	85	IUU transect
17	BELIZE	03/03/2019	Cockroach channel	AquaQueen	17:12	17:24	12 min	8.9-17.2	wind direction was blowing east south east	3	Melissa, Sophia, Jay Ron and Maurice	all ok	Retrieval by boat by Maurice and JR	2.58km	10.1	auto	85	Ecological transect
18	BELIZE	06/03/2019	HQ	AquaQueen	12:38	12:43	5 min	6.3-8.6	Very low wind	2	Melissa, Sophia, Maurice and a new guy	When drone was intially deployed it failed as the 4300 batteries didn't boost the drone enough and Maurice didn't push enough/wait for throttle. After realising this he adjusted and the drone flew fine. Sophia failed to get photos on survey cam.	Retrival by Maurice and new guy	1km	5.37	auto	65-110	Maurice and Sophia transect to view reef and go over mangrove to back lagoon
19	BELIZE	06/03/2019	HQ	AquaQueen	13:12	13:34	22 min	3.5-4.2	Very low wind	2	Melissa, Sophia, Maurice and a new guy	Drone came down after confusion between RTL, it, misson planner and resetting of the route. Damage to wings only. Melissa attached camera and syrvey cam took photos.	Retrival by Maurice and new guy	2.57km	10	many failsafes and RTLs	85-130	BVLOS and mangrove test
20	BELIZE	07/03/2019	HQ	Breezy	15:25	15:32	8 min	4.5-5.8	nothing notable	2	Melissa, Sophia, Jay Ron and Maurice	no isses, drone flew well after previous crash	Retrieval by boat by Maurice and JR	1km	5.37	auto	65	65m flight and testing Breezy is OK
21	BELIZE	08/03/2019	Long Bough	AquaQueen	12:00	12:12	12 min	2.8-4.5	medium wind around 12 knots	2 to 3	Melissa, Sophia, Jay Ron and Maurice	no issues	Retrieval by boat by Maurice and JR	2.91km	10.5	auto	85	IUU transect
22	BELIZE	08/03/2019	Long Bough	AquaQueen	12:43	12:58	15 min		medium wind around 12 knots	2 to 3	Melissa, Sophia, Jay Ron and Maurice	no issues	Retrieval by boat by Maurice and JR	2.72km	13.1	auto	85	Ecological transect
23	BELIZE	09/03/2019	TIR	Breezy	09:48	10:03	15 min	16.1-8.6	The wind at take off wasn't so bad but the gusts reached 61kph as the drone climbed	3	Melissa, Sophia, Jay Ron and Maurice	No issues, but when we tried to get Breezy ready for the second flight we got an error due to acels and it would not arm so we swtiched to aplha	Retrieval by boat by Maurice and JR	2.42	10.65	auto	110	110m transect
24	BELIZE	09/03/2019	TIR	Aquaqueen	11:21	?	Around 4min	13.3	The wind at take off wasn't so bad but the gusts reached 61kph as the drone climbed	3	Melissa, Sophia, Jay Ron and Maurice	As the drone was climbing, the v-tail rivet on the undeside, came loose and the v-tail was flapping. This is what cause the drone to be unable to climb. All other parameters were perfect. Manufactorer fault.	The drone got stuck in a coconut palm after it RTL'd at 10m altitude. Mauric climbed the tree and Jayron helped him recover it! They had to wade to the island as the boat couldn't get too close. Very impressive recovery effort.	1km	1.5	auto, failsafe, rtl	n/a	85m transect
															263.83			

Appendix 3. Figures

Fig. 1. The delineated zones are designated either as conservation zones, preservation zones (100% no-take), special management areas or general use zones.

Fig. 2. A Conservation Office retrieving a quadcopter after a short reconnaissance flight to check for land-use change.

Fig. 3. Potentially unlicensed airstrip within the TAMR.

Fig. 4. Previously unknown clearing of mangrove wood.

Fig. 5. Propellers from vessel engines leave 'scars' through the seagrass beds.

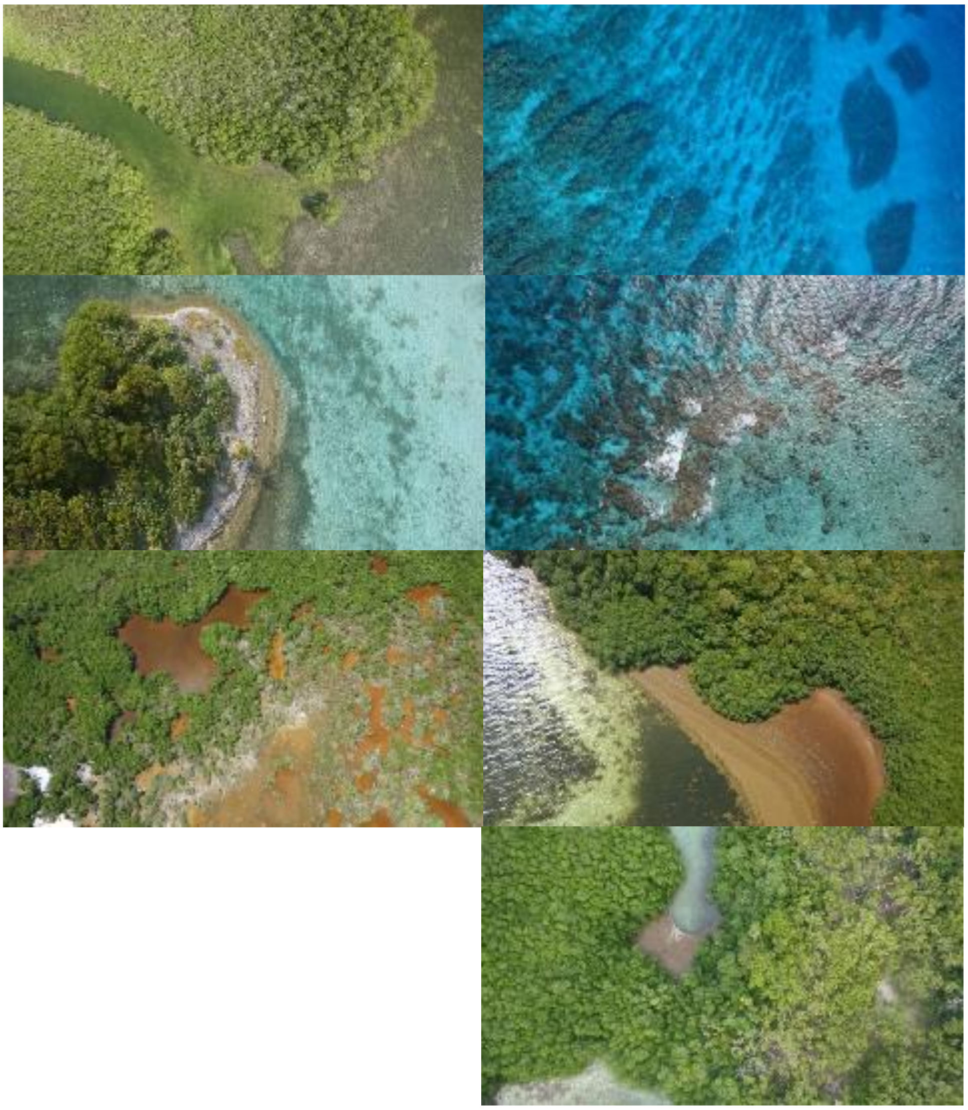


Fig. 6. Examples of different types of terrestrial and marine habitats within Turneffe.

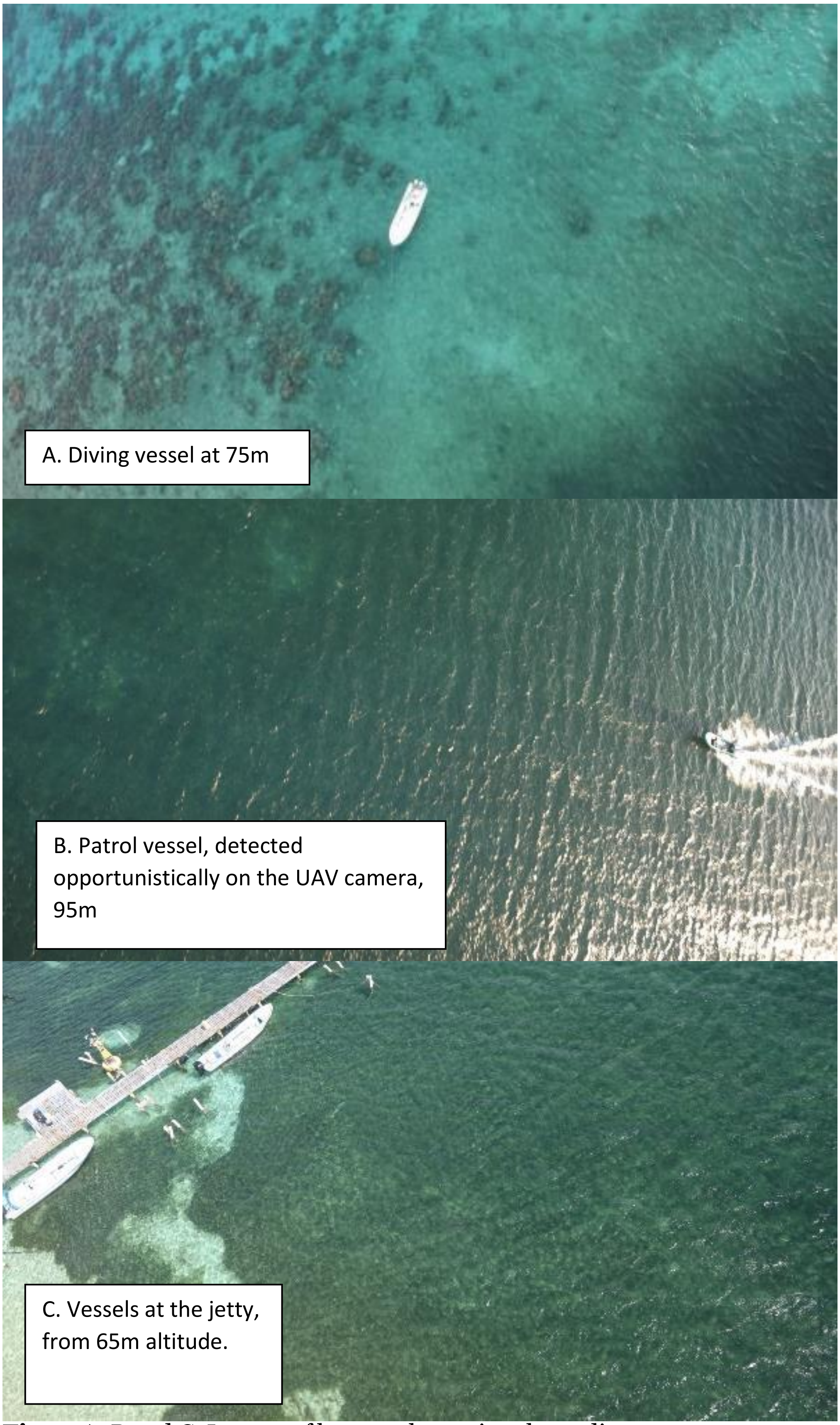


Fig. 7. A, B and C. Images of boats, taken using the nadir 20mp camera.

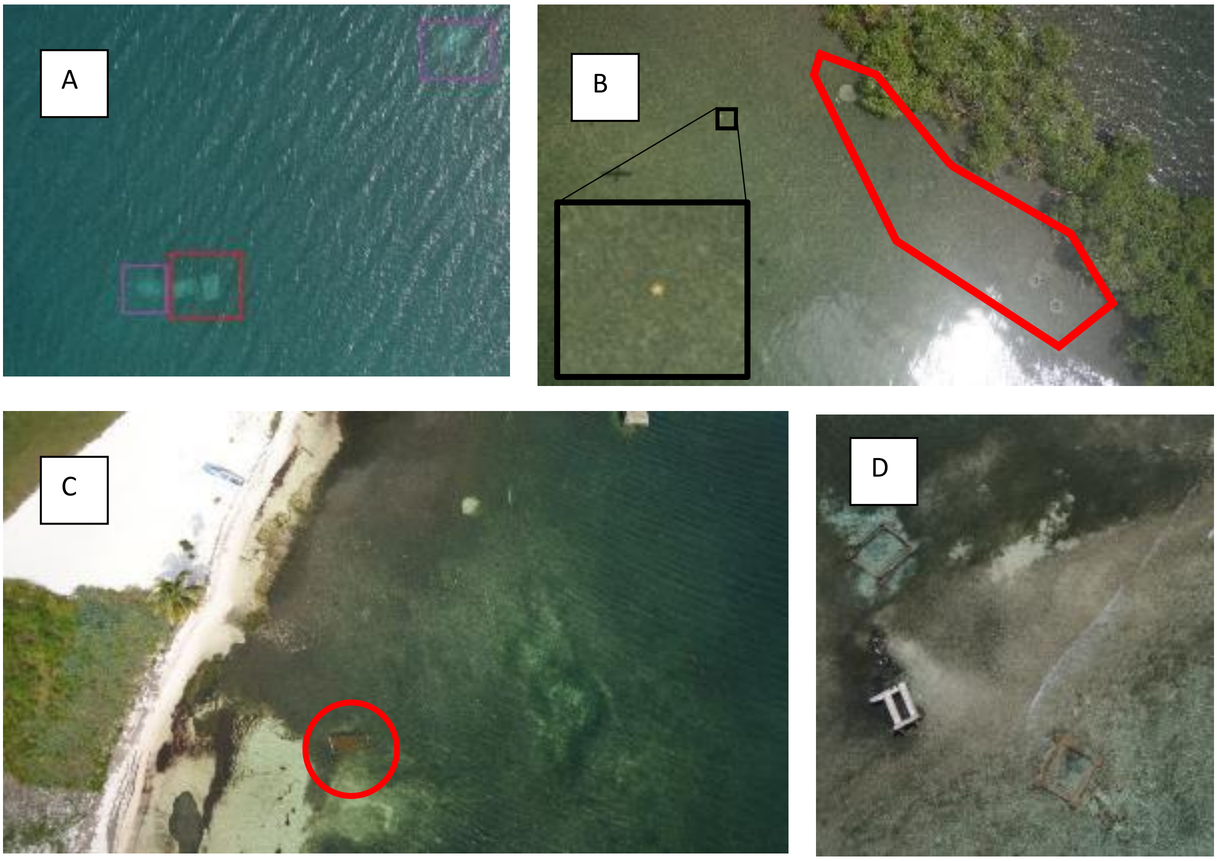


Fig. 8. A) lobster shades and areas where shades were, 110m altitude, B) 60m altitude, large starfish and tyres, in shallow water near a fishing camp, C) seaweed frames at 75m altitude and D) Fragments of unknown origin, 110m altitude

Fig. 9. A patch of dead/cleared mangrove is detected. Circled is waste and plastic. Location is on the eastern edge of Zone V, which is within a fully no-take preservation zone.

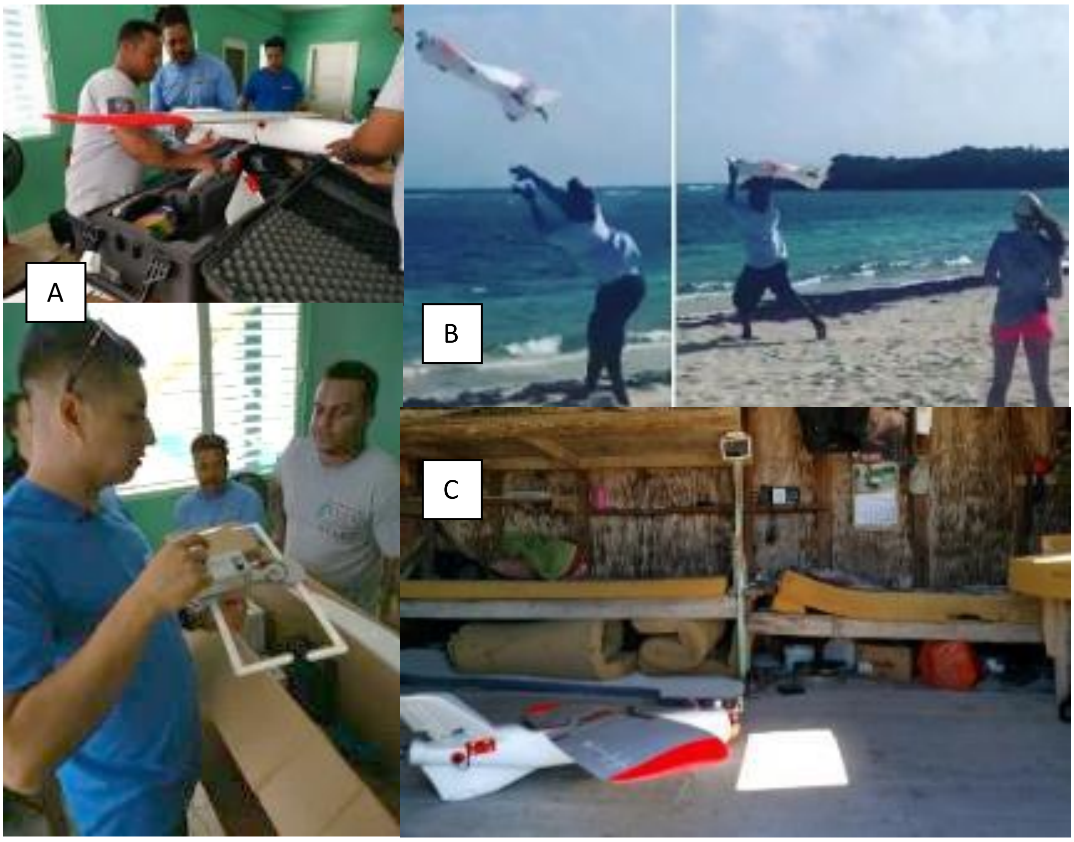


Fig. 10. A) Julian teaching the TASA team about the drone, B) Maurice deploying the drone for the first time, C) Using a fishermen's hut as a make-shift hanger.