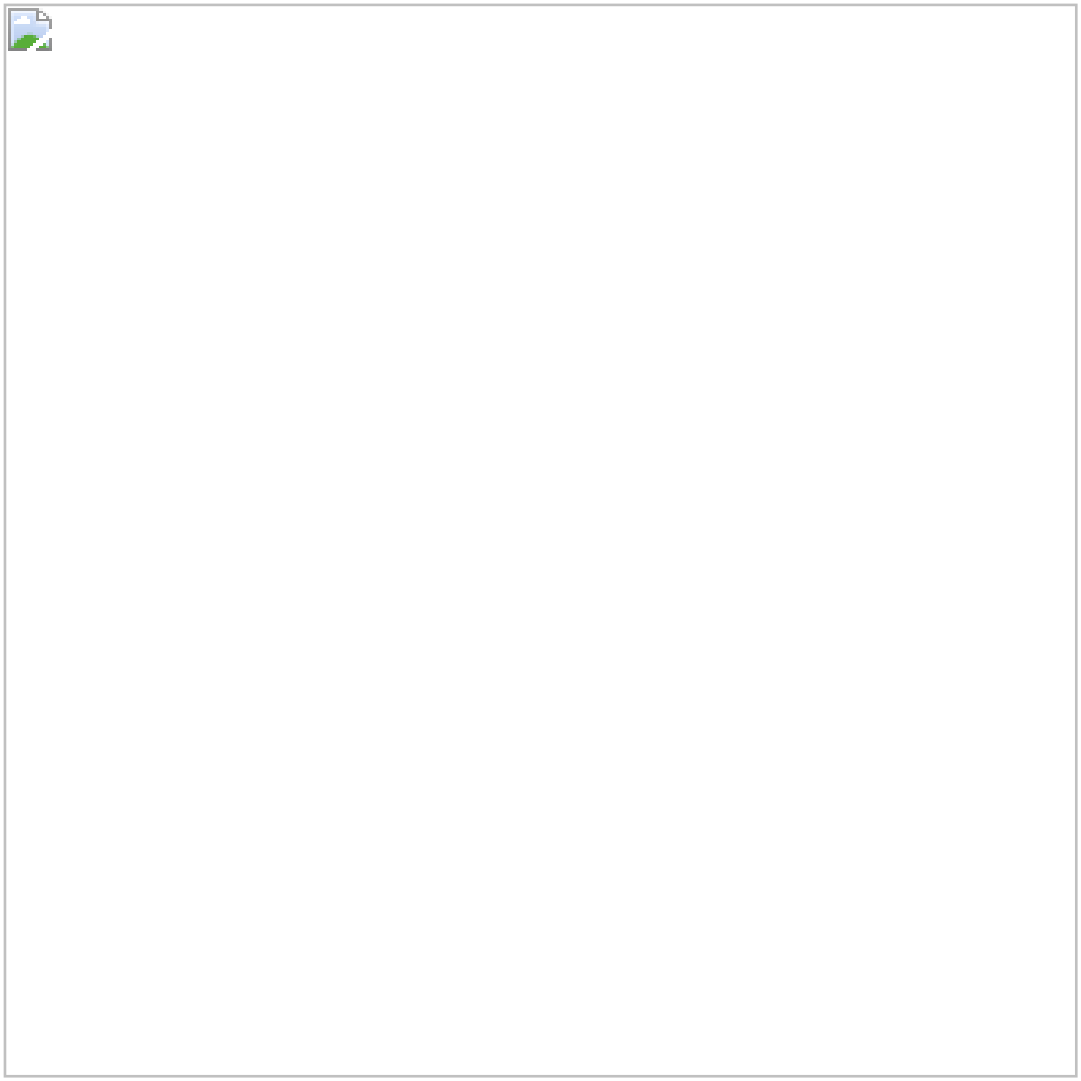

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Discovery of a suburban wetland refuge for a depleted American crocodile (Crocodylus acutus) population in northwestern Mexico, using a commercial Unmanned Aerial Vehicle

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Abstract

Background and Research Aims: The Urías Coastal Lagoon (UCL) is a heavily modified and polluted lagoon near Mazatlán, in northwestern Mexico. Once abundant in the UCL, the American crocodile (*Crocodylus acutus*) is now rarely seen in the area. A healthy population of apex predators is essential to maintain the trophic balance of ecosystems. Our research aim was to lay the groundwork for studies of American crocodile population ecology in the UCL.

Methods: Traditional boat surveys (day and night) of crocodiles were undertaken in the UCL in May-July 2022. Two exploratory aerial (~ 30 m altitude) surveys of a small wetland located close to a habitational complex in the vicinity of the UCL were performed in June and December 2022, using a commercial Unmanned Aerial Vehicle (UAV). We used images obtained with the UAV to estimate the size of the crocodiles detected in the wetland.

Results: This study confirms the presence of American crocodiles in the UCL and presents the first information on individuals of this species for this area. Aerial surveys revealed the presence of 17 individuals in the wetland; the mean size of nine of those individuals was 183.3 ± 60 cm (range: 130-310 cm). Two yearlings (~37 cm length), possibly born in June 2022, were captured in the same wetland in September 2022. We also surveyed 50.7 km of UCL coastline by boat, but no crocodiles were sighted.

Conclusion: The crocodiles seem to avoid the human-impacted UCL and likely use the less impacted surrounding wetlands as a refuge area, which they also use to reproduce. The presence of both yearlings and adults is a good sign for the survival of this vulnerable population.

Implications for Conservation: We believe that the surveyed wetland should be closely monitored for conservation purposes because it might be one of the last crocodile breeding refuges in the heavily modified and polluted coastal environment of the UCL. We summarize our results with a series of recommendations for local and federal authorities. These recommendations would likely help the conservation of the American crocodile population in the UCL.

Keywords

drones, conservation, ecological refuges, endangered species, anthropogenic disturbance

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Introduction

The American crocodile (*Crocodylus acutus*, Cuvier, 1807) is one of the largest crocodile species in the world, with males reaching up to 7 m in length (Thorbjarnarson, 2010). This large reptile primarily inhabits coastal brackish waters, such as the saltwater portion of rivers, mangroves, and coastal lagoons. This species is the most widely distributed of the New World crocodiles, ranging from the southern tip of Florida through the Atlantic and Pacific coasts of Mexico, Central America, and Northern South America (Peru, Ecuador, Colombia, and Venezuela), as well as some Caribbean Islands (Thorbjarnarson, 2010). The American crocodile is currently listed as Vulnerable in the International Union for Conservation of Nature (IUCN) Red List of Threatened Species. The main threats to the survival of this species are residential and commercial development, agriculture/aquaculture, transportation services (road construction), illegal hunting, invasive species, climate change, and hybridization with Cuban (*C. rhombifer*) and Morelet´s (*C. moreletii*) crocodiles (Cedeño-Vázquez et al., 2008; Weaver et al., 2008; Rainwater et al. 2021). Moreover, Mexican populations are listed in Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES, 2023) and as Subject to special protection (Pr) in the Norma Oficial Mexicana NOM-059-SEMARNAT-2010.

Crocodile sightings in public places (beaches, canals, etc.) increased inexplicably in Mazatlán, Sinaloa (Mexico), in 2022 (see examples in local news at https://www.elsoldemazatlan.com.mx/local/alerta-en-mazatlan-cocodrilos-salen-fuera-de-su-habitat-8779983.html, https://www.eluniversal.com.mx/estados/capturan-cria-de-cocodrilo-en-fraccionamiento-de-mazatlan-sinaloa, and https://www.youtube.com/watch?v=d-Wb4TFqSIA, all last visited on November 10, 2022). Information on American crocodiles in the state of Sinaloa, the northernmost area of distribution of this species in Mexico, is very scarce and there is no published literature on crocodile populations around Mazatlán (López-Luna et al. 2013). It is therefore difficult to answer questions about the proper handling and relocation of crocodiles captured or sighted in public areas of the municipality of Mazatlán. Thus, the main goal of our study was to conduct the first crocodile population surveys in the Urías Coastal Lagoon (UCL) and surrounding wetlands, in the vicinity of Mazatlán, using traditional survey techniques as well as an unmanned aerial vehicle (UAV) to obtain baseline information on location, number, and size of crocodiles present in this area. We make recommendations for the conservation management of this species in the area based on collected information.

Methods

Study Area

Mazatlán, in the state of Sinaloa (Figure 1), is one of Mexico's most important fishing ports and tourist destinations, with significant industrial activities that include shrimp farms; sardine, shrimp, tuna, and shark fishing fleets; a large seafood processing complex; several shipyards; transport/cargo vessel activities; and a thermoelectric plant that uses petroleum products. These industrial activities all take place within the 11.5 km long Urías Coastal Lagoon (UCL) (Figure 1). There is also significant discharge of untreated domestic and industrial waters into the UCL (Molino-Minero-Re et al. 2014). These anthropogenic disturbances cause a decrease in environmental quality, mainly through pollution and changes in land use (Ruiz-Luna and Berlanga-Robles 2003, Cardoso-Mohedano et al. 2015, García-Gasca et al. 2016, Cardoso-Mohedano et al. 2016). However, the UCL also presents the characteristics of an ideal habitat for the American crocodile: an abundant source of prey (fish), remote areas and canals, mangroves, and shrimp farms. The UCL is connected to the Gulf of California through a permanent inlet located SW of the lagoon; the average depth in the UCL is 1 – 3 m, except for the navigation channel (~ 13 m deep) (Montaño-Ley et al. 2008). Current dynamics in the UCL are dominated by mixed tides, with a mean tidal range of approximately 1 m (Montaño-Ley et al. 2008). The mean age of water in the upper UCL can be up to 70 days and contaminants can remain in the UCL for several days (Cardoso-Moheano et al. 2015). Mean salinities in the UCL are high, ranging from 25.8 to 38.4 PSU (Montaño-Ley et al. 2008); however, these values are within the survival range of *Crocodylus acutus* (Charruau et al. 2005).

Traditional Boat Surveys

We performed four boat surveys in May-July 2022, following two routes in the UCL (Fig. 1), according to the method described by Charruau et al. (2005). We traveled the survey routes once during the day and once at night aboard a 14-foot boat with a 25 HP outboard motor. During each survey we scanned the lagoon shore, using a hand lamp (700 lumens) during night surveys, in order to detect and count crocodiles. Daylight surveys were performed on June 1 from 13:16 to 15:36 for a distance of 13.56 km, and on June 28 from 10:02 to 12:39 for a distance of 11.46 km. Night surveys were performed on May 2 from 19:34 to 21:33 for a distance of 14.55 km, and on July 12 from 21:00 to 23:19 for a distance of 11.13 km. These surveys sum a total of 50.7 km of coastline sampled in 9 h 15 min.

Aerial Surveys Using an Unmanned Aerial Vehicle

We conducted two additional exploratory surveys using a DJI® mavic mini 2 UAV in a wetland with four water bodies, close (~130 m) to the Santa Fe housing complex (Figure 1-2). The mini 2 is a semi-professional commercial UAV, with a built-in GPS, and a camera that records 4K video and takes photos with a resolution of up to 20 megapixels. All metadata (GPS coordinates, altitude, camera settings) collected by the aircraft are embedded in the multimedia files, a very useful

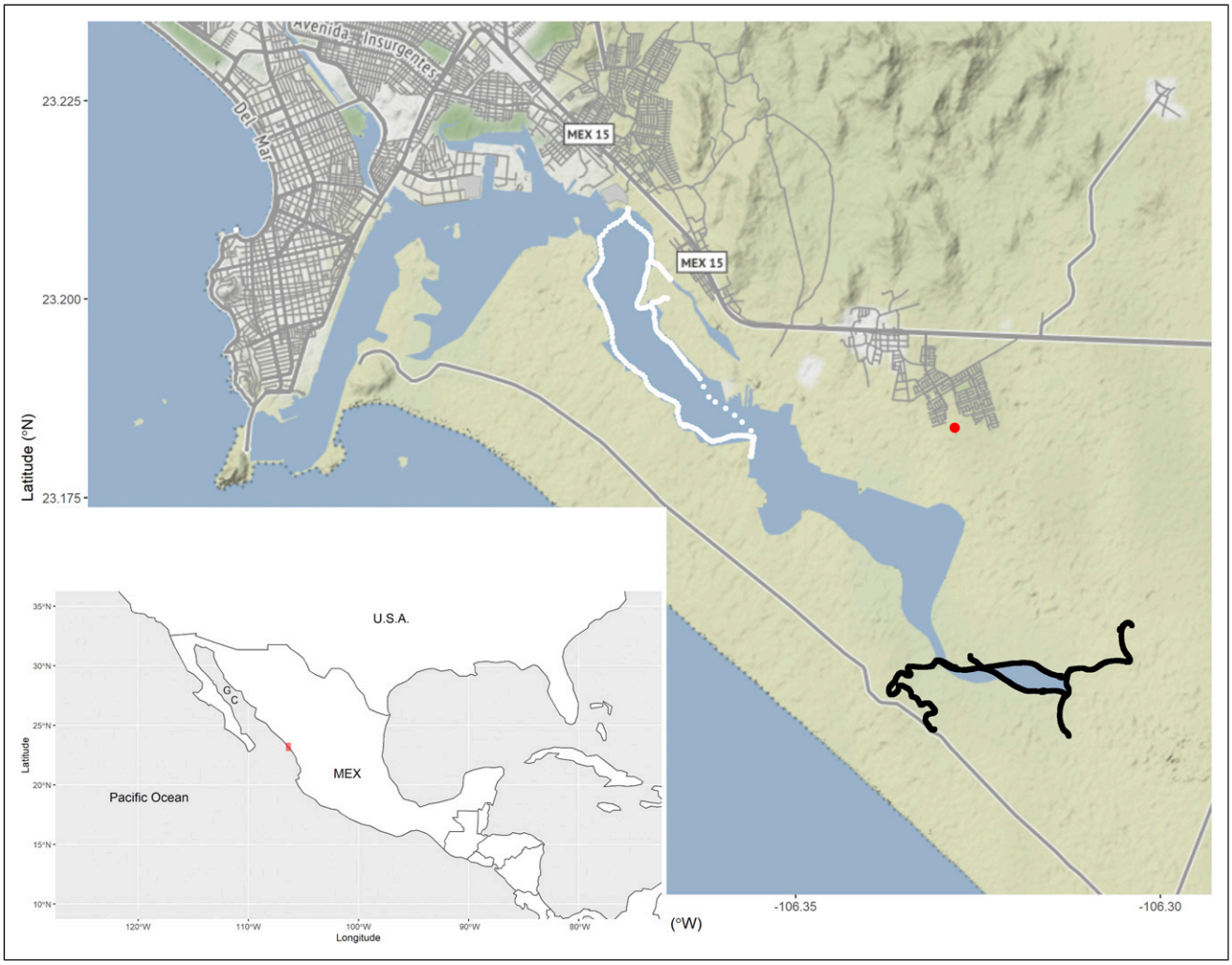

Figure 1. Study area. The rectangle in the lower insert shows the approximate location of the Urías Coastal Lagoon (UCL). The upper map shows a closeup of the UCL; the red dot depicts the location of the UAV surveys; and black and white lines show the spotlight survey routes undertaken at night and in the daytime, respectively, on May 12 and July 12, 2022.

feature for creating spatial models using photogrammetry by "gluing" a group of photos to an object of interest, such as a body of water. This UAV can fly at an altitude of up to 4,000 m above sea level at a wind speed of up to 38 km/h, and its portability (< 250 g and ~ 16 cm) allows the investigation of areas that are difficult to access, with a flight time per battery charge of about 25 minutes, depending on environmental conditions (Technical specifications available at: https://www.dji.com/mini-2).

Exploratory flights were conducted on June 22, 2022, and on December 22, 2022. The June survey flights were performed from 28.7 to 32 m altitude, and the December flights were performed from 10 to 30 m altitude. A flight mission was conducted in December 2022, using the dronelink ® app for Android (https://www.dronelink.com/); the mission covered one of the wetland water bodies, where the presence of crocodiles had been confirmed during the June survey. The flight mission was planned to an altitude of 30 m, due to the tall (~20 – 25 m) mangrove trees surrounding the water body. A total of 174 photos were taken by the UAV camera at an angle of 0° (nadir) to create an orthomosaic. The photos were individually examined for the presence of crocodiles.

Estimating the Size of Crocodiles

The first step in estimating the body size of crocodiles was to calculate the Ground Sample Distance (GSD) of the images (i.e., centimeters per pixel of each photo). GSD calculation was carried out using the Maps Made Easy (San Diego, California) online application (https://www.mapsmadeeasy.com/flight_planner, last accessed on January 11, 2022). Inputs for the calculation are flight altitude, image resolution, and UAV brand/model; the application automatically uses the UAV camera specification to provide an estimate of GSD (in cm/pixel). Once the GSD was calculated for each image, the pixels of each individual crocodile were counted from the tip

Figure 2. Upper panel: Google Earth ® view of the surveyed wetland. The approximate locations of crocodiles observed in June and December 2022 are shown by yellow and red pins, respectively. The capture location of juvenile crocodiles (September 2022) is shown by a blue pin. Mid and lower panels: aerial photos of four crocodiles observed in December 2022. Photos: Emigdio Marín-Enríquez.

Table 1. Estimated size of *Crocodylus acutus* individuals observed during June and December 2022 aerial surveys.

Survey	UAV flight altitude (m)	GSD (cm/pixels)	Approximate No. of pixels	Estimated size (m)
June	28	1.02	130	1.3
June	30	1.03	144	1.5
December	30	1.03	300	3.1
December	30	1.03	136	1.4
December	30	1.03	224	2.3
December	30	1.03	199	2.0
December	10.9	0.4	358	1.4
December	10.9	0.4	530	2.1
December	6.8	0.3	476	1.4

of the snout to the tip of the tail (whenever possible) using the compass tool in GIMP software Ver. 2.10.12. The number of pixels was multiplied by the GSD and the result was divided by 100 to obtain an estimate of the length in meters.

Capture of Juvenile American crocodiles

On September 1 and September 7, 2022, two juvenile crocodiles were captured near the surveyed wetland. Only one individual was measured, but both crocodiles were very similar in size. The approximate coordinates of the capture site were recorded with a Redmi ® note 10 pro smartphone using the application "my GPS coordinates" (https://play.google.com/store/apps/details?id=com.freemium.android.apps.gps.coordinates&hl=es&gl=US, last visited: September 22, 2022). The individuals were handed over to the Aquarium of Mazatlán.

Results

No crocodiles were detected during either day or night boat surveys. However, a crocodile tail mark was observed on the shore of the UCL on one occasion.

Three American crocodiles were sighted during the June survey using the UAV, in the water body closest to the Santa Fe habitational compound. The first crocodile was spotted in the northern part of the water body, and the other two individuals were observed in the southern part (Figure 2). The size of only two of the three individuals observed in the June survey could be estimated (~1.3 and 1.5 m) because the body of one of the individuals was submerged and the tail could not be observed. Fourteen crocodiles were observed during the December survey, and the size of only seven crocodiles was estimated because the other seven were either partially submerged or covered by bushes. The mean estimated size of the observed crocodiles was 183 ± 60 cm (n = 9), with a minimum of 130 cm and a maximum of 310 cm (Table 1). Figure 2 shows some crocodiles observed with the UAV and a short video of two individuals recorded during the December survey can be accessed at https://www.youtube.com/watch?v=w8ir_5-ex0Y.

The total length (TL) of the juvenile crocodile captured on September 7 was 37 cm.

Discussion

Evidence of Reproduction

The presence of both yearlings and adults suggests that breeding and nesting are occurring at or close to the studied wetland, which is a good sign for the survival of this population. American crocodiles <30 cm TL are considered hatchlings; individuals from 30.1 to 60 cm are considered yearlings; from 60.1 to 120 cm juveniles; from 120.1 to 180 subadults; and >180 cm adults (Platt & Thorbjarnarson, 2000). Accordingly, measured individuals included two yearlings (collected), five subadults, and four adults, with one noticeably large (>3 m) adult. The American crocodile usually nests during the annual dry season and eggs hatch at the beginning of the annual rainy season (Thorbjarnarson, 2010), which would correspond to the months of November to June, and late June, respectively, in the UCL (Jara-Marini et al., 2008). According to this information and existing models for estimating the age of American crocodiles based on individual growth rates (García-Grajales et al., 2012), the collected yearling crocodiles were probably born in early June 2022. However, the models depend on TL at birth and individual growth rates, which depend on local environmental characteristics of the habitat (Charruau et al., 2010; Charruau, 2011; Seijas, 2017). In addition, the wetland studied has a better nesting habitat than the main Urias lagoon which present higher wind and waves action, as well as anthropogenic activities. The wetland habitat is quieter, with minimal wind, no waves and much less human disturbance. Moreover, it has been observed that American crocodile hatchlings emerging from nests located in areas protected from wind and waves can remain near the nest site for about seven months (Kushland and Mazzotti, 1989). Thus, based on these observations and information, it is likely that collected yearlings emerged from nests located at the studied wetland rather than from distant areas; although the data seem adequate for the study site, more information is needed on the

ecology (e.g., reproduction, growth rates) of crocodiles in the UCL and associated wetlands.

Crocodile Refuge Areas

Some factors can cause the withdrawal of crocodile populations to smaller areas that can be used as refuges. For example, in the Yucatan Peninsula, Mexico, habitat loss and degradation resulting from tourist development decreased potential nesting areas and fragmented the populations of the American crocodile (Machkour M'Rabet et al. 2009). In this context, coastal islands are now refuges for the last genetically pure populations of *C. acutus* in the Mexican Caribbean, sheltering individuals from the hybridization process with *Crocodylus moreletii* that is occurring on the continent (Machkour M'Rabet et al. 2009). The Nile crocodile (*C. niloticus*) responds rapidly to environmental degradation, and areas with shallow pools and dense vegetation cover are refuge areas for this species in the Olifants River Gorge, South Africa (Ferreira and Pienaar 2011). We suggest that crocodiles are likely to avoid the UCL, where anthropogenic activities are taking place, and use the surrounding less disturbed wetlands as refuge. This is further supported by the apparent absence of crocodiles in the UCL that was recorded during our boat surveys and suggests that crocodiles make little or no use of this lagoon. The UCL exhibits most of the factors that can cause the displacement of crocodile populations to refuge areas: severe degradation of habitat quality, loss of nesting habitat due to human settlement, and intense human activities. Additionally, the wetland where we observed the crocodiles has some characteristics that are consistent with other crocodile refuge areas (lower presence of humans, dense vegetation cover, and apparent shallow depth), so we believe it is likely that this wetland is being used as a refuge area by this likely small population of American crocodiles inhabiting the UCL. However, a possible wariness of crocodiles towards humans in the UCL could be affecting detection of individuals in this area (Webb and Messel, 1979; Ron et al., 1998) and more surveys are needed to conclude on the density of crocodiles in the UCL.

Final Recommendations

We encourage Mexican federal and state authorities to take actions to protect crocodiles in the study wetland. We propose 1) declaring the area a protected area, 2) raising awareness among the human population of nearby settlements (perhaps through environmental education campaigns about crocodiles), 3) relocating individuals that were delivered to the Aquarium of Mazatlán within the same wetland, and 4) developing actions for the restoration of the UCL. We also recommend undertaking more studies on this crocodile population, especially focusing on its reproductive ecology and the determination of its size and structure. We believe that these actions could help improve the chances of prosperity of the American crocodile in the UCL.

Implications for Conservation

To the best of our knowledge, this study presents the first scientific evidence of what seems to be the last refuge area for the American crocodile in a heavily polluted coastal lagoon that individuals are likely using as a breeding ground. We hope that our contribution is the first step towards the development of a management plan for the reestablishment of the American crocodile population in the UCL. A healthy crocodile population will most likely result in an enhancement of the environmental conditions in the UCL, a coastal body of water that has suffered severe environmental degradation due to anthropogenic activities.

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Author Contributions

EME Came up with the idea, acquired the funds, wrote the first version of the manuscript, and analyzed the images. PC Provided a very detailed review of the manuscript and greatly contributed to the discussion on crocodile life stages and ecology. LAFS Performed some of the drone flights and reviewed the manuscript.

Declaration of Conflict of Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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