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Evaluation of the use of drones to monitor a diverse crocodylian assemblage in West Africa

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Abstract

Context. West African crocodylian populations are declining and in need of conservation action. Surveys and other monitoring methods are critical components of crocodile conservation programs; however, surveys are often hindered by logistical, financial and detectability constraints. Increasingly used in wildlife monitoring programs, drones can enhance monitoring and conservation efficacy.

Aims. This study aimed to determine a standard drone crocodylian survey protocol and evaluate the drones as a tool to survey the diverse crocodylian assemblage of West Africa.

Methods. We surveyed crocodile populations in Benin, Côte d'Ivoire, and Niger in 2017 and 2018, by using the DJI Phantom 4 Pro drone and via traditional diurnal and nocturnal spotlight surveys. We used a series of test flights to first evaluate the impact of drones on crocodylian behaviour and determine standard flight parameters that optimise detectability. We then, consecutively, implemented the three survey methods at 23 sites to compare the efficacy of drones against traditional crocodylian survey methods.

Key results. *Crocodylus suchus* can be closely approached (>10 m altitude) and consumer-grade drones do not elicit flight responses in West African large mammals and birds at altitudes of >40–60 m. Altitude and other flight parameters did not affect detectability, because high-resolution photos allowed accurate counting. Observer experience, field conditions (e.g. wind, sun reflection), and site characteristics (e.g. vegetation, homogeneity) all significantly affected detectability. Drone-based crocodylian surveys should be implemented from 40 m altitude in the first third of the day. Comparing survey methods, drones performed better than did traditional diurnal surveys but worse than standard nocturnal spotlight counts. The latter not only detected more individuals, but also a greater size-class diversity. However, drone surveys provide advantages over traditional methods, including precise size estimation, less disturbance, and the ability to cover greater and more remote areas. Drone survey photos allow for repeatable and quantifiable habitat assessments, detection of encroachment and other illegal activities, and leave a permanent record.

Conclusions. Overall, drones offer a valuable and cost-effective alternative for surveying crocodylian populations with compelling secondary benefits, although they may not be suitable in all cases and for all species.

Implications. We propose a standardised and optimised protocol for drone-based crocodylian surveys that could be used for sustainable conservation programs of crocodylians in West Africa and globally.

Keywords: *Crocodylus*, *Mecistops*, suchus, elephant, UAV, Pendjari.

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Introduction

Drones are an increasingly useful and used tool in conservation science and natural resources management, and they are already revolutionising research into wildlife and habitats (Evans *et al.* 2016). Drones have several advantages over traditional methods of observation. They can collect very high-resolution images (McEvoy *et al.* 2016), are cheaper and safer than helicopters and small bush planes (Ogden 2013; Zahawi *et al.* 2015), and they can successfully perform autonomous flights over varying distances (Floreano and Wood 2015; Ventura *et al.* 2016). Even though they are advanced technology, commercially available, consumer drones are relatively easy to pilot and require limited training for efficient use (Koh and Wich 2012). Importantly, for conservation, unmanned aerial vehicles (UAVs) have a smaller ecological footprint than does a gasoline-powered aircraft and their quiet engines have less stress impact on wildlife (Vas *et al.* 2015). Finally, drones can closely approach any object and their remotely piloted capacity for long-distance flight allows researchers to access dangerous or remote areas and approach challenging species safely (Gademer *et al.* 2009). As a result, drones are now being used for habitat monitoring (Koh and Wich 2012), 3D mapping (Lisein *et al.* 2014), animal population censuses (Hodgson *et al.* 2018), and even in anti-poaching (Mukwazvure and Magadza 2014).

As charismatic species with a high potential ecological, economic, and sociocultural importance (Somaweera *et al.* 2020), crocodylians are globally embraced as important target species for conservation and management programs. They have also been shown to be ideal indicators of critical habitat and ecosystem restoration initiatives (Droulers 2004; Mazzotti *et al.* 2009). Unfortunately, crocodylians also represent one of the most threatened vertebrate Orders, with 25% of recognised species listed as Critically Endangered. Global crocodylian declines have been attributed to many of the same factors as most species globally, including habitat loss (Myers *et al.* 2000), conflicts with artisanal fisheries (Brashares *et al.* 2004), bushmeat trafficking (Shirley *et al.* 2009; Covey and McGraw 2014), hydrocarbon pollution (Dallmeier *et al.* 2006), and illicit trade in skins (Thorbjarnarson 1999).

Crocodylians and their unique natural histories pose many challenges for researchers and program managers seeking to determine program efficacy via established monitoring protocols. They are cryptic, mostly nocturnal, mostly aquatic, and, in places with more than one species, often exhibit partitioning such that the best survey method for one species is not always the best for others (Shirley and Eaton 2012). Crocodylian surveys are typically implemented as nocturnal spotlight surveys from a boat or on foot (Shirley and Eaton 2012). Although these methods are proven effective (Ferreira and Pienaar 2011; Shirley *et al.* 2012), they are, nonetheless, limited by habitat structural heterogeneity and inaccessibility of many wetland habitats, they are time-consuming, and often require significant human resources. Further, the close approach required to identify and demographically categorise detected individuals may have unknown consequences for the animals.

Drones may provide an opportunity to overcome some of these constraints, with costs lower or equal to those of traditional methods. Drones have recently been used to investigate aspects of crocodylian populations in the USA (Martin *et al.* 2012; Elsey and Trosclair 2016), Asia (Evans *et al.* 2016; Thapa *et al.* 2018), Australia (Harvey and Hill 2003; Bevan *et al.* 2018), Argentina (Scarpa and Piña 2019) and South Africa (Ezat *et al.* 2018). Most of these studies focussed on mapping and counting crocodylian nests, whereas two compared drones to traditional daytime on-ground surveys (Ezat *et al.* 2018; Thapa *et al.* 2018). Only Bevan *et al.* (2018) have evaluated optimal drone survey parameters (such as height and speed) for one or more crocodylian species.

West Africa presents a unique setting in which to test the efficacy of drones as tools for crocodylian population surveys. Here, three endemic species are all ecologically unique and have different conservation statuses, and yet often occur sympatrically. The most abundant of these species, the West African crocodile (*Crocodylus suchus*), is distributed throughout West Africa and occupies habitats ranging from coastal forested lagoons and large wooded rivers all the way into northern savanna and Sahel habitats (Brito *et al.* 2011; Cunningham *et al.* 2016). *Crocodylus suchus* is a cavity-nesting species that often basks during the day and is currently being evaluated for inclusion on the IUCN Red List. The West African dwarf crocodile (*Osteolaemus* sp. nov. aff. *tetraspis*) is a small, forest-dwelling species that can also be found in forested habitats, adjacent coastal lagoons, and in riparian habitats in northern savannas (Waitkuwait 1989; Eaton 2010). *Osteolaemus* sp. nov. aff. *tetraspis* is a mound-nesting species that is rarely seen during the day (Waitkuwait 1989) and is currently being evaluated for inclusion on the IUCN Red List. Finally, the West African slender-snouted crocodile (*Mecistops cataphractus*) is a medium-sized, forested wetland-dwelling species predominantly found in the forested southern wetland habitats and the wooded wetland habitats of the north (Waitkuwait 1989; Shirley 2010). It is a mound-nesting species that sometimes basks on fallen trees and submerged rocks during the day (Shirley *et al.* 2018). *Mecistops cataphractus* is listed as Critically Endangered on the IUCN Red List (Shirley 2014).

In the present study, we assessed the efficacy of drones as crocodile survey tools for this diverse crocodylian species assemblage in West Africa. We compared drone surveys to traditional daytime and night-time counting methods, and investigated how flight parameters affect detectability and disturbance. We, thus, also propose a standardised and

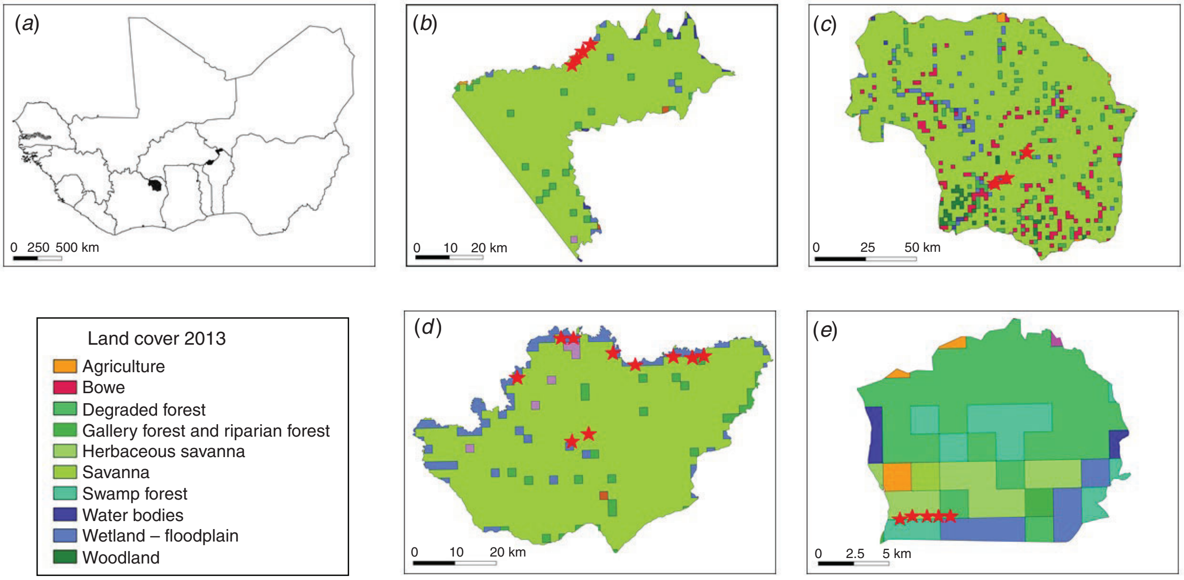

Fig. 1. (*a*) Distribution of study areas in West Africa. (*b*) W National Park (WNP), Niger. (*c*) Comoé National Park (CNP), Côte d'Ivoire. (*d*) Pendjari National Park (PNP), Benin. (*e*) Azagny National Park (ANP), Côte d'Ivoire. Study sites are ponds and river sections (red stars); the map is based on the *Landscapes of West Africa* atlas (CILSS 2016).

optimised protocol for drone-based crocodylian surveys, and discuss how drones can help establish evidence-based directives for sustainable conservation programs of crocodylians in West Africa, and globally.

Materials and methods

Study areas

We implemented this work in four different study sites in three different countries in West Africa, as follows (Fig. 1, Supplementary material Table S1):

1. *Pendjari National Park (PNP), Benin*. We surveyed PNP from 18 March to 12 April 2017. PNP is located in northwestern Benin (10°30′–11°30′N, 0°50′–2°00′E) and comprises 273 123 ha of Sudano-Guinean savanna, including a diversity of wetland habitats ranging from the meandering Pendjari River to a series of natural and artificially maintained dams. It has a marked dry season (generally from November to April) and a single rainy season (generally from June to October; Rouxel 2010). This park is known to contain only *C. suchus*, which is abundant (Chirio 2009). In PNP, we surveyed crocodiles in a diversity of natural and artificial pools (Table S1).
2. *Comoé National Park (CNP), Côte d'Ivoire*. We surveyed CNP from 28 July to 1 August 2017. CNP is located in northeastern Côte d'Ivoire (8°5′–9°6′N, 3°1′–4°4′W) and comprises 1 149 150 ha of Sudano-Guinean savanna. It is the largest protected area in West Africa and was gazetted as a UNESCO World Heritage Site in 1983 (UNESCO 2003). It contains a diversity of habitats, including tropical grasslands and wooded savannas (Seydou *et al.* 2017). This park is known to contain all three West African crocodylian species (Waitkuwait 1989). We surveyed a small portion of the Iringou River and a small pool 'Mare aux Buffles.' For logistical reasons unrelated to the methodology, we were unable to implement the diurnal surveys and all drone survey replicates on the Comoé and Iringou rivers.
3. *Azagny National Park (ANP), Côte d'Ivoire*. We surveyed ANP from 26 June to 30 June 2017. ANP is located on the coast of Cote d'Ivoire (5°14′–5°31′N, 4°76′–5°01′W) and comprises 19 400 ha of subequatorial wetland (Djaha *et al.* 2008). It was classified as a Ramsar site in 1996 (Ramsar 2018). Its climate comprises a long rainy season (generally late April to mid-July), followed by a prolonged dry season (generally from December to April; Avenard 1971). ANP habitats are composed of large swaths of *Raphia hookeri* swampland, mangroves (*Rhizophora racemosa* and *Avicennia africana*), and a manmade canal linking the Ebrié Lagoon to the Bandama River (Aké Assi 1984). This park is known to contain all three West African crocodylian species (Shirley and Yaokokore-Beibro 2008). We surveyed 5 km of the Azagny canal divided into five 1 km contiguous sections.
4. *W National Park (WNP), Niger*. We surveyed WNP from 12 February to 17 April 2018. WNP is located in southwestern Niger (12°35′–11°54′N, 2°04′–2°50′E) and comprises 330 000 ha of Sahelian and Sudano-Guinean savanna vegetation. It is an arid park, receiving an average of 640 mm of rain generally from May to September/October (Ipavec *et al.* 2007). Niger's Park W is part of the trinational WAP complex, which is the largest transboundary protected area in West Africa, comprising over 1 033 900 ha, and is classified as a World Heritage site (Inoussa *et al.* 2017). Its wetland habitats include the Niger River, the Tapoa River, and a series of natural and artificially maintained dams. This park is known to contain only *C. suchus*, which is abundant (Shirley and Eaton 2008; Chirio 2009). We surveyed 2.5 km of the Tapoa River divided into five 500 m contiguous sections.

Testing flight plans and data collection to minimise disturbance and maximise detectability

We collected all described drone data using a Phantom 4 Pro (DJI , China) operated from a Samsung Galaxy Tab 6 (Samsung, South Korea) using a DJI GO 4 tablet-based app. The Phantom 4 Pro has a maximum flight time of ~30 min, a maximum speed >70 km h^{-1}, and a pilot-controlled range of ±5 km. It comes equipped with a 20 MP camera with a high definition 4K/60fps video capacity. We programmed all flight plans using Pix4D capture software (Pix4D, Switzerland). We ultimately assembled and ortho-rectified all images using Agisoft Photoscan Pro ver. 1.2.5.2594, which is now Agisoft Metashape (Agisoft, Russia), and imported them into QGIS ver. 2.8.6 (QGis Development Team, USA) for analysis.

Prior to implementing any drone-based crocodile surveys, we wanted first to test the drone for disturbance effects on the crocodiles that might affect drone-based survey results (e.g. fleeing, submersion, or other evasive manoeuvres). We also wanted to minimise extreme disturbance to other species potentially encountered during surveys, and thus defined the minimum flight height without disturbance for each species group as the last flight altitude before the altitude during which they fled. To test for disturbance, we flew the drone for 28 min over Bali Pond (PNP), starting at 80 m and descending 5 m every 2 min (the time it took to fly a slow, steady lap around the pond) to an altitude of 5 m. We additionally approached specific crocodiles while they were basking, starting from 10 m, and descending slowly to 1 m, to determine the altitude at which they would flee. Five observers equipped with binoculars observed an equal portion of the pond and its shores, monitoring the behaviour of the crocodiles, both on land and in the water, and other species present (such as elephants, warthogs and birds).

Also, before implementing any drone-based crocodile surveys, we wanted to test flight, ambient light, and photographic parameters to optimise detectability in the resulting images. Higher-altitude flights increase surface-area coverage relative to battery power by decreasing necessary flight duration. But, when flight altitude increases, photo resolution decreases (e.g. from 0.62 cm^2 per pixel at 20 m to 1.22 cm^2 per pixel at 40 m altitude); however, the number of photos to be processed also decreases. To establish flight and photographic parameters that optimise detectability, we flew four test flight sessions over Bali Pond (PNP) consecutively on the same day, with 20 min intervals between each session. Each session included four flights, each at a different altitude (20, 25, 30 and 40 m), corresponding to different photo resolutions (0.62, 0.72, 0.95 and 1.22 cm^2 per pixel), resulting in four maps per session covering the 1 ha pond area. We imported the maps into a GIS, where five experienced, independent observers counted the number of individual crocodylians they detected in each of the 16 maps by placing a georeferenced dot on each detected crocodile. We limited observers to 10 min per map and they were blind to the corresponding flight parameters. We additionally asked all the observers to rank each map (from 1 to 4; 1 = low, 2 = average, 3 = good, 4 = very good) on the basis of their perception of the image quality and apparent ease of searching for crocodiles. To verify observer reliability, a sixth observer performed an *a posteriori* recount on all maps without time limit to estimate the number of individuals that went undetected and to estimate the frequency of false detections. All analyses considered time of day of flight, flight altitude, map rank, and observer identity as factors influencing crocodile counts.

Comparing drones to traditional crocodile survey methods

We compared the effectiveness of drone surveys to two traditional crocodile survey protocols, namely, diurnal counts and night spotlight counts. We implemented each of the three survey types successively, following the protocols below, on the same day, starting with a drone survey, at 23 sites (Fig. 1, Supplementary material Table S1). We conducted diurnal and nocturnal surveys in the same area at each site as the area covered by the corresponding drone flight. At each site, we collected the following additional data: cloud cover, aquatic vegetation density, vegetation cover by visual estimation, and wind speed. We scored each of the first three covariates on a quantitative scale from 0 to 4 (0 = 0%, 1 = 1–25%, 2 = 26–50%, 3 = 51–75% and 4 = 76–100%), and visually assessed wind speed, scoring it on a qualitative scale from 0 to 4.

(1) Drone surveys

Following the results of our optimal flight evaluations (see Results), we flew drone surveys at an altitude of 40 m and at a speed of 5 m s^{-1} with 90° camera orientation, autonomously following a pre-programmed flight plan from take-off to landing. For each site, we repeated the same flight plan three times in the same day (if the logistics allowed), namely, once between 0900 hours and 1100 hours, once between 1300 hours and 1500 hours, and once between 1700 hours and 1900 hours. We programmed the drone to take photos at regular intervals that ensured a minimum 60% overlap between two consecutive images to optimise photo collation and avoid shadows on maps (Koh and Wich 2012). We made maps from each survey as described above and visually searched maps to identify to species (using head shape visible in photographs) and quantify the number of crocodiles detected (Fig. 2).

(2) Diurnal surveys

We counted crocodiles immediately following the drone count, searching for crocodiles with the aid of binoculars. We traversed the study plot either on foot or by using a 3.5 m zodiac with a 15 hp outboard motor travelling at a constant speed of 6–8 km h^{-1}. Because of logistical issues, we could not always replicate the diurnal survey protocols three times (once per drone count). For each detected crocodile, we identified it to species and took a GPS point of its location. Where crocodiles could not be approached for classification, we noted the sighting as eyes only (EO).

(3) Nocturnal spotlight surveys

We counted crocodiles one time each night following standard eyeshine spotlight protocol (e.g. Shirley *et al.* 2009), starting and finishing each survey between 2000 hours and 0200 hours. We used a Streamlight Waypoint 550 lm spotlight and a 1-W LED headlamp to detect crocodiles. We traversed the study plot either on foot or by using a 3.5 m zodiac with a 15 hp outboard motor travelling at a constant speed of 6–8 km h^{-1} For each detected

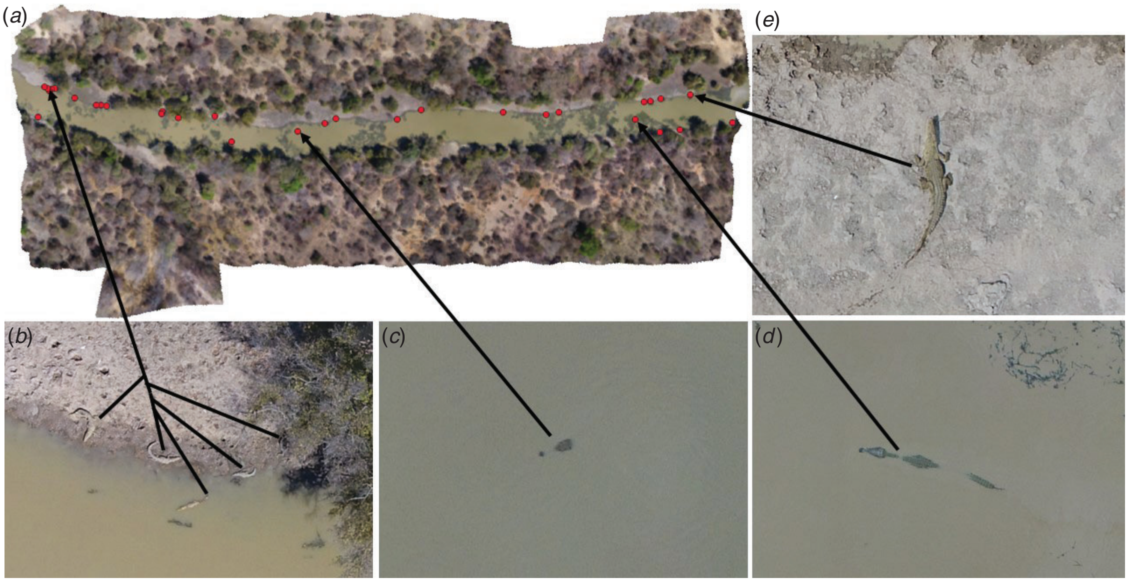

Fig. 2. Crocodile counts and mapping from drone photos. (*a*) The main map is the aggregation of 120 orthorectified photos. The red points are for detected crocodiles, which were detected (*b*, *e*) on the shore and (*c*, *d*) in the water. Flight parameters: altitude 40 m, speed 5 m s^{-1}, overlap 60%. Tapoa River, W National Park, Niger.

crocodile, we identified it to species and took a GPS point of its location. Where crocodiles could not be approached for classification, we noted the sighting as eyes only (EO).

Statistical analysis

We used Poisson regressions, a particular case of generalised linear model (McCullagh 2018), to model crocodile count data with the logarithm as the link function. When relevant, we used the quasi-Poisson distribution instead of the simple Poisson to take into account overdispersion in the data. We used likelihood ratio tests (LRT) to study the effect of covariates and interactions among covariates. We performed all analyses in R version 3.5.2 (R Core Team 2018).

To assess flight parameters and the analysis of the observer effect, we modelled crocodile count data against time of day of flight, flight altitude, map rank and observer identity. We separately modelled the number of false or missed detections against the same covariates.

To compare the three survey methods, we modelled crocodile count data against site identity (10, 8, and 5 sites for Benin, Cote d'Ivoire and Niger respectively) and count method (3 drone investigations during the day, 1 diurnal survey, and 1 nocturnal survey). For drone surveys only, we modelled crocodile counts against time of day, wind strength, cloud cover and, additionally, a site effect. We, ultimately, did not include the vegetation index in the model as a covariate because there is no variation of this variable within a site. We analysed data independently for each country and for all countries combined.

Results

Testing flight plans and data collection to minimise disturbance and maximise detectability

At Bali Pond (PNP), we found that *Crocodylus suchus* was the least disturbed by the drone of all species present, with the flee altitude ranging from 1 to 10 m (Fig. 3). In contrast, all mammals were the most sensitive to the drones, with flee altitudes ranging from 60 m for *Loxodonta africana* to 20 m for *Hippopotamus amphibius* and *Papio anubis*, whereas bird flee altitudes ranged from 10 to 15 m (Fig. 3). Flight responses of other species present around the pond indicated no behavioural change in the crocodiles. On the basis of these results, we determined that crocodylian species in West Africa were unlikely to be perturbed by drone surveys to the point of fleeing except below 11 m and, therefore, crocodile drone surveys should be flown at altitudes above this minimum.

In our analysis of test flight parameters that optimise detectability, every covariate, except altitude, had a significant impact on counts (Fig. 4*a*, Table 1). We found that the five independent observers counted, on average, 18.21 crocodiles per map, ranging from 4 to 39, where the best observer counted, on average, 28.38 and the worst observer 9.44. The independent, unconstrained observer counted an average of 34.94 crocodiles per map (24–47), and found, on average, 1.23 more crocodiles than did the best observer and 3.7 more than the worst observer (Table 1). The variation between observers was significant, both including and excluding (result not shown) the independent, unconstrained observer implementing the exhaustive count (Table 1).

In terms of false detections or undetected individuals, altitude, map quality, and time of day had no significant relationship, but observer identity and time of day had a significant impact (Table 1). On average, the five observers missed 16.79 individuals per map, ranging from seven for the best observer to 23.19 for the worst, and the inter-observer differences were highly significant ($F_{4,74}$ = 23.98, P = 1.8x10^{-12}; Fig. 4*b*, Table 1). Observers made an average of 0.63 false detections per map, ranging from 0.44 to 1.06, although inter-observer differences were not significant ($F_{4,74} = 1.0$, $P = 0.41$; Fig. 4*c*,

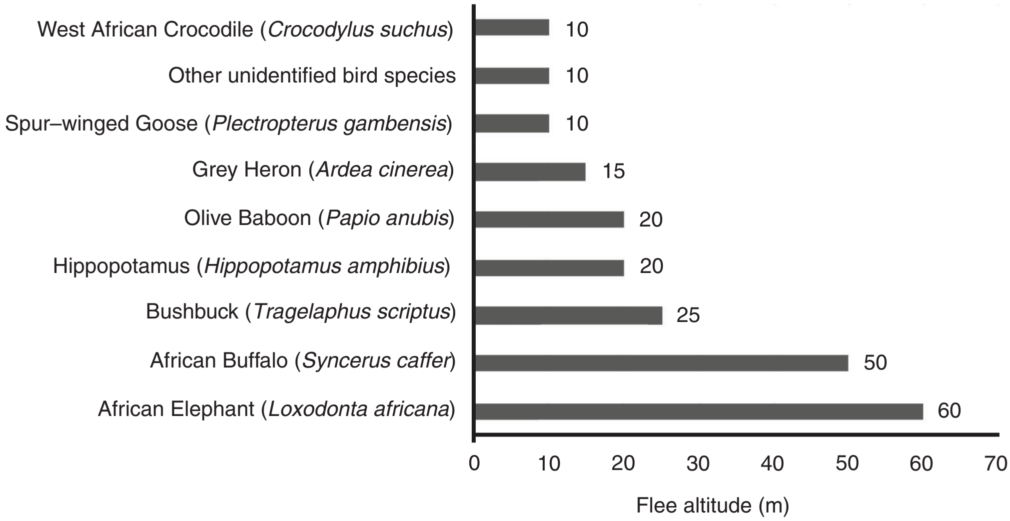

Fig. 3. Drone flight altitude (m) at which species observed at Bali Pond, Pendjari National Park, Benin, fled the drone.

Table 1). Generally, the best observers were either those with the most experience in the field and/or with technology. There was a significant difference in the number of crocodiles observed across the four sessions (i.e. time of day; $F_{3,71} = 4.86$, $P = 0.004$), with more crocodiles being detected during the first session. As altitude decreased (e.g. map resolution increased), the observers did not detect more crocodiles ($F_{1,70} = 3.06$, $P = 0.085$; Fig. 4*a*, Table 1), nor did they detect more crocodiles on maps they judged to be of higher quality ($F_{1,69} = 4.19$, $P = 0.044$; Table 1). On the basis of these results, we flew all subsequent drone surveys at 40 m altitude (see above), and delayed flights when elephants and buffalos were present to avoid disturbance.

Comparing drones to traditional crocodile survey methods

We detected very few crocodylians in Cote d'Ivoire, namely, 0 at all sites by all methods, except at Mare aux Buffles where we detected 0 by drone, 0 by day count, and 3 by night count. We ultimately excluded Cote d'Ivoire from further analysis. In Benin, we detected 49 crocodiles by drone, 30 by day survey, and 71 by night survey, where most of these detections were exclusively in the Bali pond in PNP (Site 1; Supplementary material Fig. S1). In Niger, we detected 156 crocodiles by drone, 32 by day survey, and 311 by night survey (Fig. S1). We ultimately analysed data from Benin and Niger separately to reduce the chance for bias owing to the difference in scale of number of crocodiles detected. We found that night surveys detected significantly more crocodiles than either of the other two survey methods in both countries, and that drones detected significantly more crocodiles than did standard day surveys (Fig. 5*a*, Table 2: Niger $F_{2,18} = 38.70$, $P = 3.56 \times 10^{-6}$; Benin: $F_{2,28} = 59.39$, $P = 5.7 \times 10^{-5}$; Fig. 5*b*).

Environmental factors on the drone detection efficiency

We observed no effect of the site on the number of crocodiles detected in Niger ($F_{4,10} = 0.648$, $P = 0.65$; Table 3), whereas in Benin the site effect was significant ($F_{4,10} = 890.21$, $P = 2.6 \times 10^{-7}$; Table 3). Time of day was not significant in Niger ($F_{2,8} = 0.46$, $P = 0.655$; Table 3), but it was significant in Benin ($F_{2,8} = 97.74$, $P = 9.8 \times 10^{-5}$; Table 3). Wind intensity had no significant effect in Niger ($F_{3,5} = 1.022$, $P = 0.457$; Table 3) or Benin $F_{3,5} = 4.91$, $P = 0.060$; Table 3). Ultimately, we did not model cloud cover because there was not enough variation across days, sites or times.

Discussion

We sought to assess the efficacy of drones as crocodile survey tools for a diverse crocodylian species assemblage in West Africa. In so doing, we tested several flight parameters that allowed us to also establish a standardised and optimised protocol for drone-based crocodylian surveys. We found that drones were more effective crocodile survey tools than were traditional day surveys for crocodylians in West Africa. However, as with traditional day surveys, drone surveys were less effective than were traditional night surveys both because crocodiles are generally more available and detectable at night and also because typical consumer drones do not currently have nocturnal filming capacity. Further, we found that drone flight parameters that optimise flight efficiency and area coverage are more important considerations for flight planning than are characteristics we pre-suppose will affect subsequent detectability or disturbance. Here, we discuss each of these in turn.

Developing standard flight protocols for use of drones in crocodylian surveys

We assessed the effect of altitude, map rank, time of the day, observer bias and disturbance on crocodile counts using drones to propose a standard protocol for such future studies. We found that image resolution when using the standard camera (4K resolution) on the DJI Phantom 4 Pro was high enough, so that we found no effect on crocodile counts up to 40 m altitude. Forty metres altitude is an optimal flight height to achieve time- and power-efficient coverage of sites; however, future studies should replicate the testing protocol of crocodile detectability at higher

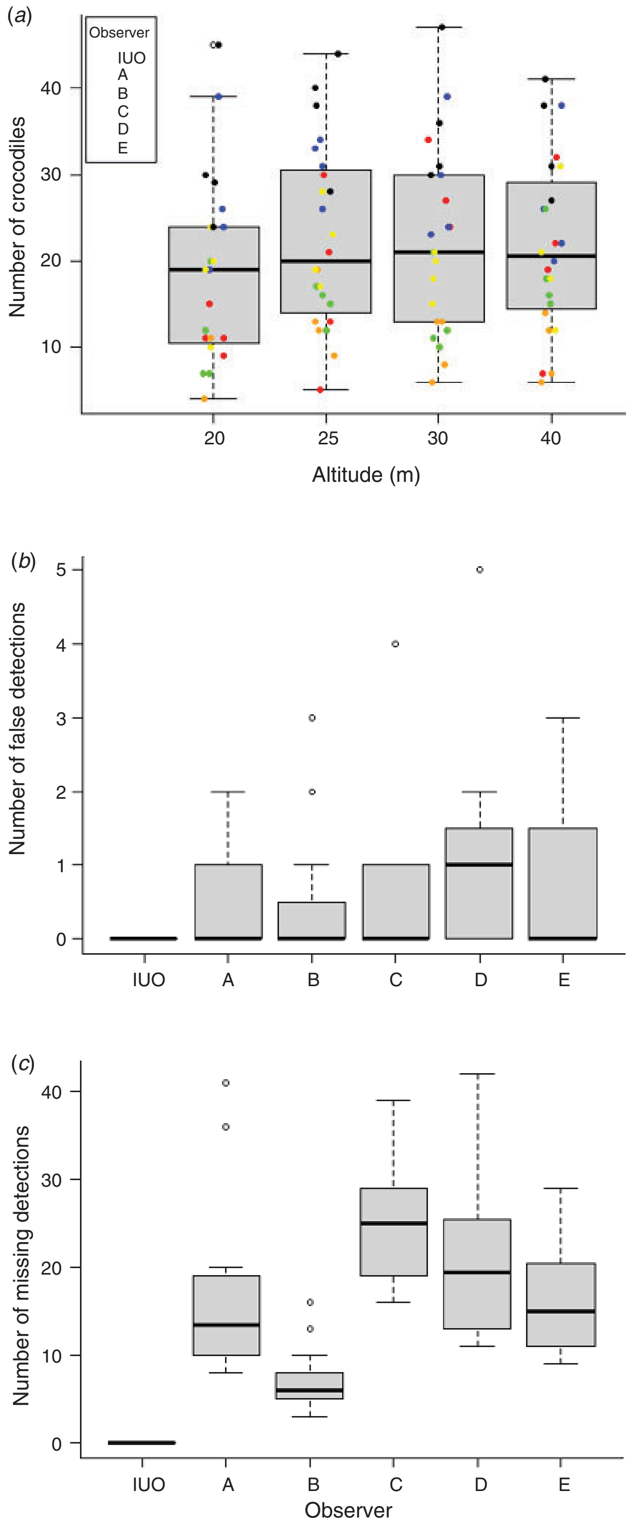

Fig. 4. Observer effects on crocodile detection. (*a*) Distribution of crocodile counts for each observer and flight altitude. Each observer (A–E, each with a different colour) had 10 min to count the crocodiles on the reconstituted maps (Bali pond, Pendjari National Park, Benin), and the independent, unconstrained observer (IUO) had no time limit. (*b*) Number of missed detections per observer and (*c*) number of false detections per observer. The boxplots represent the aggregated counts for each height (median, 25% and 75% quartiles, whiskers representing 5% and 95% quartiles).

Table 1. Results of generalised linear model assessing the influence of flight, photo, and observer characteristics on the number of crocodiles counted by drones

Variable	d.f. num.	d.f. denom.	*F*-value	*P*-value
Number of crocodiles counted				
Observer identity	4	74	22.44	6.73E–12
Time of flight	3	71	4.86	0.003978
Flight altitude	1	70	3.06	0.084852
Map rank	1	69	4.19	0.044535
Number of false detections				
Observer identity	4	74	1.0044	0.4113
Time of flight	3	71	1.4943	0.2238
Flight altitude	1	70	2.496	0.1187
Map rank	1	69	1.5352	0.2195
Number of missed detections				
Observer identity	4	74	23.9791	1.855E–12
Time of flight	3	71	12.8099	9.548E–07
Flight altitude	1	70	0.9668	0.3289
Map rank	1	69	0.6862	0.4103

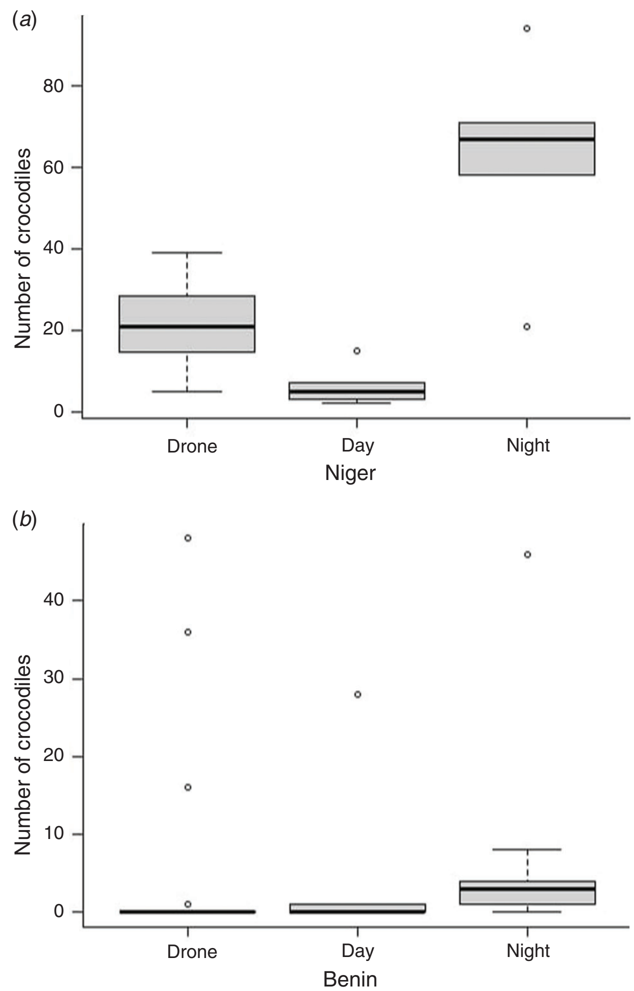

Fig. 5. Number of crocodiles detected for each survey protocol in (*a*) Niger and (*b*) Benin. The boxplots represent the median, 25% and 75% quartiles, whiskers representing 5% and 95% quartiles, and dots the outliers.

Table 2. Results of generalised linear model comparing crocodylian survey methods

Site is the site identity (as a fixed effect). Protocol refers to survey method (drone vs diurnal count vs nocturnal spotlight count). Wind and cloud cover are both categorical covariates

Variable	d.f. num.	d.f. denom.	*F*-value	*P*-value
Benin				
Site	9	30	92.7694	2.119E–15
Protocol	2	28	15.7479	5.690E–05
Wind	3	25	5.5811	0.005296
Cloud cover	3	22	14.2627	2.222E–05
Niger				
Site	4	20	2.3649	0.10693
Protocol	2	18	38.6973	3.365E–06
Wind	3	15	1.2516	0.33146
Cloud cover	2	13	3.7614	0.05142

Table 3. Results of generalised linear model assessing the impact of environmental variables on drone surveys

Site is the site identity (as a fixed effect). Time of day and Wind are both categorical covariates

Variable	d.f. num.	d.f. denom.	*F*-value	*P*-value
Benin				
Site	4	10	890.208	2.574E–07
Time of day	2	8	97.739	9.823E–05
Wind	3	5	4.911	0.05955
Niger				
Site	4	10	0.6480	0.6524
Time of day	2	8	0.4610	0.6550
Wind	3	5	1.0223	0.4569

altitudes to further optimise coverage, time, and battery efficiency, especially as higher-resolution cameras become available.

The ability to zoom into images because of the high 4K resolution rendered false detections rare, regardless of the observer. As a result, observer bias far exceeded technical flight bias as the most influential factor affecting drone-based crocodile surveys, as it has been shown for standard spotlight counts (Nichols *et al.* 2000; Shirley *et al.* 2012). Counting crocodiles on map images is a tedious, time-consuming task that requires intense concentration; limited to 10 min per map, it took 3 h for observers to count crocodiles on the 16 1-ha test maps, and it took the independent, unconstrained observer 5 h to do an exhaustive search. Investment in/engagement with the study and individual experience are critical to achieving good results.

Of secondary importance, some meteorological conditions can hinder reconstruction or quality of map images (Fig. 6*a*). Although there was no significant effect of time of day on the number of crocodiles detected by the drone in the present study, there was a noticeable decrease in the quality of aerial images in the evening. To counterbalance the lack of light, the camera automatically increases the sensor sensitivity (ISO), thus degrading the quality of the image. This may not, ultimately, affect the detectability of crocodiles by skilled observers, although sites with more debris will certainly be more complicated. In the middle of the day, as the sun orientation approaches 90° from the water surface, reflections back to the camera effectively whiteout patches of habitat (Fig. 6*c*). These observations are similar to those in other drone studies for aquatic-wildlife monitoring (Kiszka *et al.* 2016; Linchant *et al.* 2018). Meteorological conditions such as wind are already known to be unfavourable for observing crocodiles (Shirley *et al.* 2012). Sun reflection and wind-generated waves also degrade the quality of the aerial photos and disrupt the assembly of tiled photos (Fig. 6*b*). Further, windy conditions make small drone flights challenging. For these reasons, we recommend flights in the morning (from 0900 hours to 1100 hours).

Despite their small size, drones have been shown to be disturbing to wildlife (McEvoy *et al.* 2016), especially when animals are approached too closely (Bennitt *et al.* 2019) or at sensitive nesting and breeding sites (Dulava *et al.* 2015; Pomeroy *et al.* 2015; Weissensteiner *et al.* 2015). We assessed the altitude at which species commonly found in our study sites fled due to the presence of the drone. Interestingly, *Crocodylus suchus* fled the drone at the closest approach altitude of any species at our study site, and even showed signs of being more tolerant than other crocodylian species (e.g. *Crocodylus porosus*; Bevan *et al.* 2018). Indeed, with the same drone model and similar methods, Bevan *et al.* (2018) observed that *C. porosus* responded to drones at 30 m with lateral head movements and submerged or retreated to deeper water at 10 m altitude. Although, due to our single test flight at different altitudes, we do not exclude the possibility of habituation of the crocodiles to the drone at higher altitudes, and caution should be used for future projects at altitudes lower than 40 m. In comparison, mammals fled at much higher altitudes; however, the results for these other species may not be representative, given the single flight and the low numbers of individuals present, ranging from 1 to 10 or so, depending on the species, compared with 100 or so for the crocodiles.

We report here the first indications for African buffalo (*Syncerus caffer*), which fled at 50 m. Our results are congruent with those of Bennitt *et al.* (2019), who also found that elephants (*Loxodonta africana*) were perturbed at 60 m. Several studies have shown that elephants avoid bees (Vollrath and Douglas-Hamilton 2002; Ngama *et al.* 2016; King *et al.* 2017) and the noise emitted by the drone rotors could be confused for a swarm of bees. Other species were much more tolerant of the drone, including hippos which fled at 20 m approach altitude, as was found in other studies (Linchant *et al.* 2018; Inman *et al.* 2019). Finally, birds of any species fled the drone at an altitude of only 10–15 m, being congruent with what has been observed at other sites for other bird species (Vas *et al.* 2015; McEvoy *et al.* 2016; Brisson-Curadeau *et al.* 2017; Rush *et al.* 2018). The increased altitudes precipitating a flight response in large mammals will not likely result in decreased detection of these species, given their enormous size. And, even though drones have the possibility of disturbing these species, they are likely to be less disruptive than humans in close approach on foot or in an automobile, and observation from a drone is less dangerous for the observers (Mulero-Pázmány *et al.* 2017). Importantly, fleeing is not the only behavioural evidence of disturbance by drones on wildlife, but rather the last-resort behaviour. For crocodylians, we did not observe other behaviours potentially indicative of disturbance (such as repositioning, leg and head movements and

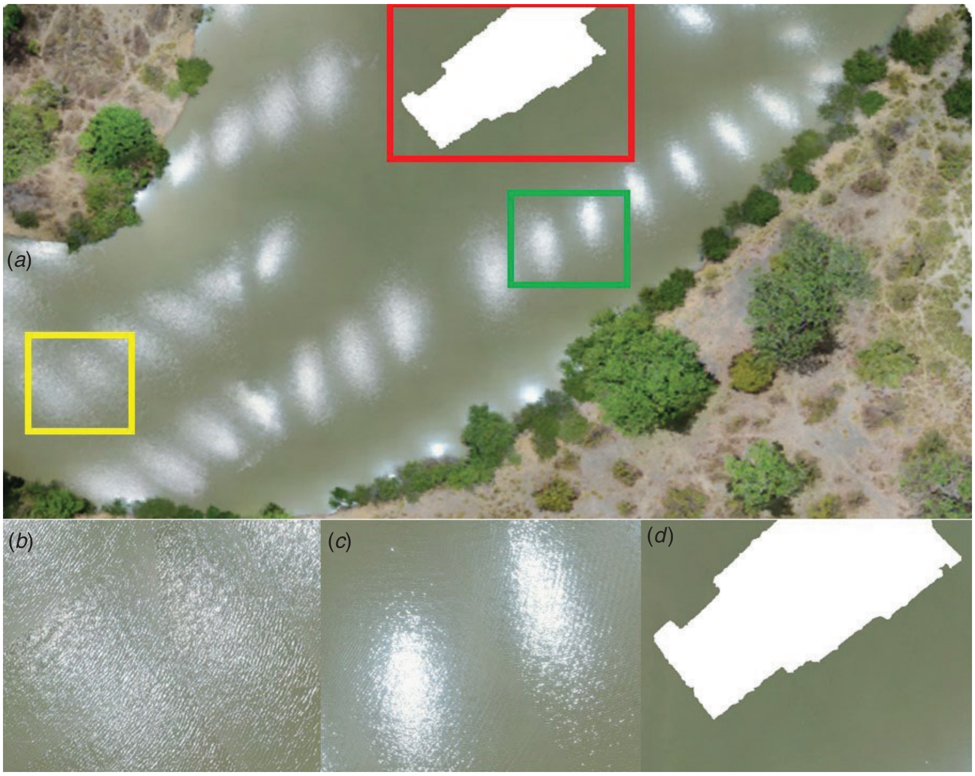

Fig. 6. Image-quality disturbance owing to wind and sunlight. (*a*) This reconstructed image of the Canard pond (PNP, Benin) shows how (*b*) the small waves generated by wind (yellow square in *a*) and (*c*) sunlight reflection (green square in *a*) can affect the quality of the image, and thus potentially the crocodile count. (*d*) Part of this image is also truncated (red square in *a*) because its homogeneity prevents photo assembly for map reconstruction.

submersion), but did not look for behaviours such as wing extension (Weimerskirch *et al.* 2018), vocalisations (Wilson *et al.* 2020) and head movements (Bennitt *et al.* 2019) in the other species present at our study sites because of our focus on crocodiles. Nonetheless, we find it interesting to present these results, given the very few data available for wildlife–drone interactions in West Africa.

Efficacy of and uses for drones to survey crocodiles in West Africa and elsewhere

We aimed to compare drone counts with traditional diurnal and nocturnal crocodile surveys. We found that nocturnal spotlight counts detected significantly more crocodiles (87%) than did either of the two other methods, although we detected 231% more crocodiles by drone than during traditional diurnal surveys, being congruent with previous studies counting crocodiles with drones in Africa (Ezat *et al.* 2018). The drone was incapable of detecting individuals smaller than 100 cm in total length in most conditions; however, this is also a standard problem of diurnal crocodylian surveys (Shirley and Eaton 2012). Unfortunately, the drone we used was not mounted with technology enabling nocturnal drone surveys for more direct comparison with nocturnal spotlight surveys. As consumer drones with camera technologies permitting night filming become available, we recommend testing nocturnal drone surveys as a potentially promising avenue for future research.

Despite detecting fewer individuals during the daytime than do traditional nocturnal surveys, drone surveys are likely to bring several advantages in crocodylian surveys compared with standard spotlight or traditional diurnal surveys. For one, because of the high-resolution map images (1.22 cm^2 per pixel at 40 m), drones allow for unbiased measurement of the detected individual's size on the basis of either *in situ* scaling or use of standard head length to total length ratios (e.g. Fukuda *et al.* 2013). Although this is certainly possible through close approach of individuals during nocturnal surveys, even expert observers are shown to be error prone (Choquenot and Webb 1987), and the close approach necessary can be stressful for the animals. These photos could also be used to identify individuals present at study sites, resighting either artificial tags or natural crocodylian markings (Swanepoel 1996; Bouwman and Cronje 2016; Boucher *et al.* 2017; Coetzee *et al.* 2018).

Drones provide not only a rigorous and non-invasive way to characterise observed individuals, but also leave a permanent record of observations, an advantage that cannot be understated (Kelaher *et al.* 2020). Map records can be used for later verification of number, size, species and position, including habitat occupied, of all detected crocodiles. The reduced disturbance to animals compared with foot and boat surveys will also likely result in less double counting of individuals as they flee and submerge only to resurface elsewhere. This has long been recognised as an advantage in aerial surveys for crocodiles, but with the added advantage of objective counts from photos reducing aerial survey observer bias and limitations (Nichols *et al.* 2000). Drones share other advantages and disadvantages with manned aerial surveys. Both can be used to cover more territory faster and for less cost than for boat surveys, but both fail to detect diverse crocodylian demographics (Bayliss *et al.* 1986). However, drones are cheaper than manned craft, with simpler logistics, smaller ecological footprints, and introduce less disturbance.

Because of the elevated point of view, drones can overcome several habitat-related visibility issues of crocodile surveys. The presence of plants and the complexity of the habitat strongly affect on-ground visibility and are a principal source of bias in estimating crocodylian populations (Shirley *et al.* 2012). In our study, we detected more crocodylians using drones than with traditional day surveys despite the shrubby vegetation cover on the banks and the presence of aquatic plants on the Tapoa River. Drones effectively allow observers to see typically unobservable space, in this case, beyond the first layer of vegetation, and more generally, including otherwise inaccessible or distant habitats (Vas *et al.* 2015). However, when habitats are too homogeneous, such as the centre of the water without the shoreline or other features (e.g. aquatic vegetation, rocks, tree trunks) in the field of view, map reconstruction becomes nearly impossible because of the low number of reference points between photos (Fig. 6*d*). The continuous improvement of image compilation and ortho-rectification software should mitigate or even eliminate this in the coming years. Additionally, the presence of vegetation above study sites makes aerial photos with a camera oriented at 90° irrelevant.

The latter is a major problem for forested waterways where crocodylians at the water's edge will always be under tree cover and, therefore, undetectable from above. In West Africa, this means that drone surveys may never be a relevant method for counting *Mecistops cataphractus* and *Osteolaemus* spp., which both prefer forested habitats and nest under closed canopy forest cover (Waitkuwait 1989; Shirley *et al.* 2018). Indeed, our drone surveys did not detect either of these species at sites where they are known to be present. However, in Cote d'Ivoire, this is also likely to do as much with their rarity as with detectability issues, because our nocturnal surveys also failed to detect them (Shirley *et al.* 2009, 2018). Drones are increasingly used to survey forest vertebrates, although more generally primates, birds, and other species that live and/or nest in the canopy (Weissensteiner *et al.* 2015;Wich *et al.* 2015; Bonnin *et al.* 2018).

Finally, drones are increasingly inexpensive (less than US$1500), easy to master, can often facilitate field logistics, and reduce costs compared with other crocodile survey methods. Drone surveys do not require a boat, fuel, driver, and multiple observers with strong field experience, unlike standard nocturnal and diurnal surveys do (Shirley and Eaton 2012). However, the limited battery life of the drone can limit the extent of the study area, access to electricity to recharge batteries can limit the choice of study sites, and increasingly strict national laws and protected areas regulations concerning drone usage may prevent some users from employing drones.

Beyond drones: some additional considerations and observations from the present study

These surveys represent some of the first published information on crocodylian populations in Cote d'Ivoire, Benin and Niger. We surveyed sites that contained up to three different crocodylian species, including the Critically Endangered *Mecistops cataphractus*; however, we detected only *Crocodylus suchus*. This species is the most widespread and found in the greatest diversity of habitats (Kofron 1992; Tellería *et al.* 2008; Brito *et al.* 2011; Luiselli *et al.* 2012). In contrast, *Osteolaemus* spp. and *Mecistops cataphractus*, although ranging from coastal swamp forest to gallery forest wetland habitats in Guinean savanna, are dependent on forested habitats (Waitkuwait 1989; Shirley *et al.* 2018). The lack of observations during nocturnal spotlight surveys at two sites where they were known to be present is of concern. At these sites, we observed unsustainable and illegal fishing and palm cultivation (ANP) and counted more than 60 gold panning rafts on the Comoe River (CNP).

Our study also underscored certain conservation issues for *Crocodylus suchus*. Night surveys on the Pendjari River and in the surrounding ponds showed an extremely low crocodylian density, with often no individuals being observed, whereas this species was seemingly abundant only a decade ago (Pooley 1982; Chirio 2009). In contrast, we observed many signs of poaching and fishing, including such as fishing nets, traps and smoking platforms, along the river that forms the border between the Pendjari National Park (Benin) and Arly National Park (Burkina Faso). While poaching and fishing camps were mostly on the Burkina side, poachers extracted wildlife from within the boundaries of both parks. Fishing and poaching activities had already precipitated the near extinction of crocodiles in the Niger River bordering the WAP complex before 2010 (Shirley and Eaton 2008). By comparison, the Bali pond situated closer to the centre of the PNP and with more tourist presence, had many crocodiles. Similarly, crocodiles are extremely abundant in the Tapoa River (Park W, Niger), near the main ranger station and tourist axes (Shirley and Eaton 2008). African Parks took over management of Pendjari in 2018 and W (Benin) in 2020, which will hopefully result in increasing protection for the crocodiles and all wildlife in this critical conservation area. Drones may even provide a valuable tool for remote detection of these illegal activities.

Conclusions

Protecting crocodylians and their habitats is an urgent conservation need, especially in West Africa where they are not typically present on the conservation agenda. Drones provide an inexpensive and effective tool for assessing and monitoring crocodylian populations in some ecological contexts. They offer advantages of reduced impacts on wildlife, limiting risks for observers, easy logistics, potentially larger survey-area coverage, and data security. Further work is merited across the region to unlock their full potential, both for crocodylians and wildlife and protected areas.

Conflicts of interest

The authors declare no conflicts of interest.

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