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

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Evaluationoftheuseofdronestomonitoradiversecrocodylianassemblagein West Africa

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Abstract

Context.West African crocodylian populations are declining and in need of conservation action. Surveys and othermonitoringmethodsarecriticalcomponentsofcrocodileconservationprograms;however,surveysareoftenhinderedbylogistical,financialanddetectabilityconstraints.Increasinglyusedinwildlife monitoringprograms,dronescanenhancemonitoring andconservationefficacy.

Aims.Thisstudyaimedtodetermineastandarddronecrocodyliansurveyprotocolandevaluatethe dronesasatooltosurvey thediversecrocodylianassemblageofWestAfrica.

Methods.WesurveyedcrocodilepopulationsinBenin,Coˆted'Ivoire,andNigerin2017and2018,by usingtheDJIPhantom 4 Pro drone and via traditional diurnal and nocturnal spotlight surveys. We used a series of test flights to firstevaluatetheimpactofdronesoncrocodylianbehaviouranddeterminestandardflightparametersthatoptimisedetectability. We then, consecutively, implemented the three survey methods at 23 sites to compare the efficacy ofdrones againsttraditionalcrocodyliansurveymethods.

Keyresults.Crocodylus*suchus*canbecloselyapproached(⁓10maltitude)andconsumer-gradedronesdonotelicitflightresponsesinWestAfricanlargemammalsandbirdsataltitudesof⁓40–60m.Altitudeandotherflightparametersdidnotaffectdetectability,becausehigh-resolutionphotosallowedaccuratecounting.Observerexperience,field conditions (e.g. wind, sun reflection), and site characteristics (e.g. vegetation, homogeneity) all significantly affecteddetectability. 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 nocturnalspotlight counts. The latter not only detected more individuals, but also a greater size-class diversity. However, dronesurveys provide advantages over traditional methods, including precise size estimation, less disturbance, and the ability tocover greater and more remote areas. Drone survey photos allow for repeatable and quantifiable habitat assessments,detectionofencroachmentandotherillegalactivities,andleaveapermanentrecord.

Conclusions. Overall, drones offer a valuable and cost-effective alternative for surveying crocodylian populations withcompellingsecondarybenefits,althoughtheymaynotbesuitableinall casesandforallspecies.

Implications. ***We***proposeastandardisedandoptimisedprotocolfordrone-basedcrocodyliansurveysthatcouldbeused forsustainableconservationprogramsof crocodyliansin WestAfricaand globally.

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

Introduction

Dronesareanincreasinglyusefulandusedtoolinconservationscienceandnaturalresourcesmanagement,andtheyare alreadyrevolutionising research into wildlife and habitats (Evans*et al.2016*).Droneshaveseveraladvantagesovertraditionalmethodsof observation. They can collect very high-resolution images(McEvoy*et al.*2016), are cheaper and safer than helicopters andsmall bush planes (Ogden2013; Zahawi*et al.*2015), and theycan successfully perform autonomous flights over varying dis-tances (Floreano and Wood2015; Ventura*et al.*2016). Eventhough they are advanced technology, commercially available,consumerdronesarerelativelyeasytopilotandrequirelimitedtrainingforefficientuse(KohandWich2012).Importantly,forconservation,unmannedaerialvehicles (UAVs)haveasmallerecological footprint than does a gasoline-powered aircraft andtheirquietengineshavelessstressimpactonwildlife(Vas*etal.2015*).Finally,dronescancloselyapproachanyobjectandtheirremotelypilotedcapacityforlong-distanceflightallowsresearchers to access dangerous or remote areas and approachchallenging species safely (Gademer*et al.*2009). As a result,drones are now being used for habitat monitoring (Koh and Wich2012), 3D mapping (Lisein*et al.*2014), animal populationcensuses (Hodgson*et al.*2018), and even in anti-poaching(Mukwazvure andMagadza2014).

Ascharismaticspecieswithahighpotentialecological, economic,andsocioculturalimportance(Somaweera*etal.2020*), crocodylians are globally embraced as important targetspeciesforconservationandmanagementprograms.Theyhavealso been shown to be ideal indicators of critical habitat andecosystemrestorationinitiatives(Droulers2004;Mazzotti*etal.2009*). Unfortunately, crocodylians also represent one of themost threatened vertebrate Orders, with 25% of recognisedspecieslistedasCriticallyEndangered.Global crocodyliandeclines have been attributed to many of the same factors asmost species globally, including habitat loss (Myers*et al.*2000),conflicts with artisanal fisheries (Brashares*et al.*2004), bush-meat trafficking (Shirley*et al.*2009; Covey and McGraw2014),hydrocarbonpollution(Dallmeier*etal.2006*),andillicittradeinskins (Thorbjarnarson1999).

Crocodylians and their unique natural histories pose manychallenges for researchers and program managers seeking todetermine program efficacy via established monitoring proto-cols.Theyarecryptic,mostlynocturnal,mostlyaquatic,and,inplaces with more than one species, often exhibit partitioningsuch that the best survey method for one species is not always thebest for others (Shirley and Eaton2012). Crocodylian surveysaretypicallyimplementedasnocturnalspotlightsurveysfromaboatoronfoot(ShirleyandEaton2012).Althoughthesemethodsareproveneffective(FerreiraandPienaar2011;Shirley*etal.2012*),theyare,nonetheless,limitedbyhabitat structural heterogeneity and inaccessibility of many wetlandhabitats,theyaretime-consuming,andoftenrequiresignificanthuman resources. Further, the close approach required to iden-tify and demographically categorise detected individuals mayhaveunknownconsequencesforthe animals.

Dronesmayprovideanopportunitytoovercome someoftheseconstraints,withcostslowerorequaltothoseoftraditionalmethods.Droneshaverecentlybeenusedtoinvestigateaspectsofcrocodylianpopulationsinthe USA(Martin*etal.2012*;ElseyandTrosclair2016),Asia(Evans*etal.2016*;Thapa*etal.2018*),Australia(HarveyandHill2003;Bevan*etal.2018*),Argentina(ScarpaandPiña2019)andSouthAfrica(Ezat*etal.2018*).Mostofthesestudiesfocussedonmappingandcountingcrocodyliannests,whereastwo compareddronestotraditionaldaytimeon-groundsurveys(Ezat*etal.2018*;Thapa*etal.2018*).OnlyBevan*etal.* (2018)haveevaluatedoptimaldronesurveyparameters(suchasheightandspeed)foroneormorecrocodylianspecies.West Africapresents auniquesetting inwhich totest theefficacyofdronesastoolsforcrocodylianpopulationsurveys.Here,threeendemicspeciesareallecologicallyuniqueandhavedifferentconservationstatuses,andyetoftenoccursympatri-cally.Themostabundantofthesespecies,theWest Africancrocodile(*Crocodylussuchus*),isdistributedthroughoutWestAfricaandoccupieshabitatsrangingfromcoastalforestedlagoonsandlargewoodedriversallthewayintonorthernsavannaandSahelhabitats(Brito*etal.2011*;Cunningham*etal.2016*). *Crocodylussuchusis*a cavity-nestingspecies thatoftenbasksduringthedayandiscurrentlybeingevaluatedforinclusionontheIUCNRedList.TheWestAfricandwarfcrocodile(*Osteolaemussp*.nov.aff.*tetraspis*)isasmall,forest-dwellingspeciesthatcanalsobefoundinforestedhabitats,adjacentcoastallagoons,andinriparianhabitatsinnorthernsavannas(Waitkuwait1989;Eaton2010).*Osteolaemussp*.nov.aff.*tetraspisis*amound-nestingspeciesthatisrarelyseenduringtheday(Waitkuwait1989)andiscurrentlybeingevaluatedforinclusionontheIUCNRedList.Finally,theWestAfricanslender-snoutedcrocodile(*Mecistopscataphractus*)isamedium-sized,forestedwetland-dwellingspeciespredominantlyfoundintheforestedsouthernwetlandhabitatsandthewoodedwetlandhabitatsofthenorth(Waitkuwait1989;Shirley2010).Itisamound-nestingspeciesthatsometimesbasksonfallentreesandsubmergedrocksduringtheday(Shirley*etal.2018*).*Mecistopscataphractusis*listedas CriticallyEndangeredon theIUCN RedList(Shirley2014).

In the present study, we assessed the efficacy of drones ascrocodilesurveytoolsforthisdiversecrocodylianspeciesassemblageinWestAfrica.Wecompared dronesurveystotraditionaldaytimeandnight-timecountingmethods,and investigated how flight parameters affect detectability anddisturbance.We,thus,alsoproposeastandardisedand

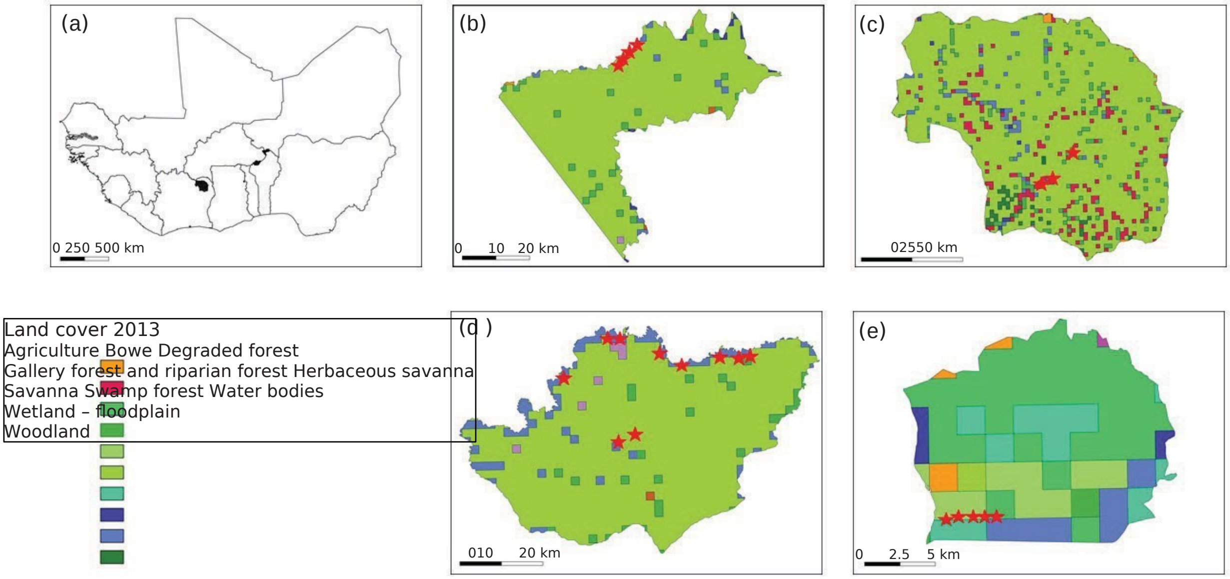


Fig.1.(*a*)DistributionofstudyareasinWestAfrica.(*b*)WNationalPark(WNP),Niger.(*c*)Comoe´NationalPark(CNP),Coˆted'Ivoire. (*d*)PendjariNationalPark(PNP),Benin.(*e*)AzagnyNationalPark(ANP),Coˆted'Ivoire.Studysitesarepondsandriversections(redstars);the map isbased onthe*LandscapesofWestAfricaatlas*(CILSS2016).

optimised protocol for drone-based crocodylian surveys, anddiscuss how drones can help establish evidence-based directivesfor sustainable conservation programs of crocodylians in WestAfrica,andglobally.

Materialsandmethods

Studyareas

We implemented this work in four different study sites in threedifferent countries in West Africa, as follows (Fig.1, Supple-mentarymaterialTableS1):

1. *Pendjari National Park (PNP), Benin*. We surveyed PNPfrom 18 March to 12 April 2017. PNP is located in north-western Benin (10830^{0}–11830^{0}N, 0850^{0}–2800^{0}E) and com-prises273123haofSudano-Guineansavanna,includinga diversity of wetland habitats ranging from the meanderingPendjari River to a series of natural and artificially main-tained dams. It has a marked dry season (generally fromNovember to April) and a single rainy season (generally fromJune to October; Rouxel2010). This park is known to containonly*C.suchus*,whichisabundant(Chirio2009). InPNP,wesurveyed crocodiles in a diversity of natural and artificialpools (TableS1).
2. *Comoe ´NationalPark(CNP),Coˆted'Ivoire*.WesurveyedCNP from 28 July to 1 August 2017. CNP is located in north-easternCoˆted'Ivoire(8ß5^{0}–9ß6^{0}N,3ß1^{0}–4ß4^{0}W)andcom-prises1 149 150haofSudano-Guineansavanna.ItisthelargestprotectedareainWestAfricaandwasgazettedasa UNESCO World Heritage Site in 1983 (UNESCO2003). Itcontainsadiversityofhabitats,includingtropicalgrasslandsand wooded savannas (Seydou*et al.*2017). This park isknowntocontainallthreeWestAfricancrocodylianspecies(Waitkuwait1989).WesurveyedasmallportionoftheIringouRiverandasmallpool'MareauxBuffles.'

For logistical reasons unrelated to the methodology, we wereunable to implement the diurnal surveys and all drone surveyreplicateson theComoe´andIringourivers.

3. *AzagnyNationalPark(ANP),Coˆted'Ivoire*.Wesurveyed ANP from 26 June to 30 June 2017. ANP is located on thecoast of Cote d'Ivoire (5814^{0}–5831^{0}N, 4876^{0}–5801^{0}W) andcomprises19400haofsubequatorialwetland(Djaha*etal*. 2008). It was classified as a Ramsar site in 1996 (Ramsar2018). Its climate comprises a long rainy season (generallylate April to mid-July), followed by a prolonged dry season(generally from December to April; Avenard1971). ANPhabitats are composed of large swaths of*Raphia hookeriswampland, mangroves (Rhizophora racemosa*and*Avicen-niaafricana*),andamanmadecanallinkingtheEbrie ´Lagoonto the Bandama River (Ake´ Assi1984). This park is known tocontain all three West African crocodylian species (Shirleyand Yaokokore-Beibro2008). We surveyed 5 km of theAzagny canaldividedintofive 1km contiguoussections.
4. *W National Park (WNP), Niger*. We surveyed WNP from12 February to 17 April 2018. WNP is located in south-western Niger (12835^{0}–11854^{0}N, 2804^{0}–2850^{0}E) and com-prises 330 000 ha of Sahelian and Sudano-Guinean savannavegetation.Itisanaridpark,receivinganaverageof640mm of raingenerally from Mayto September/October(Ipavec*et al.*2007). Niger's Park W is part of the trinational WAPcomplex, which is the largest transboundary protected area inWestAfrica,comprisingover1033 900ha,andisclassifiedas a World Heritage site (Inoussa*et al.*2017). Its wetlandhabitats include the Niger River, the Tapoa River, and aseries of natural and artificially maintained dams. This parkis known to contain only*C. suchus*, which is abundant(ShirleyandEaton2008;Chirio2009).Wesurveyed 2.5kmoftheTapoaRiverdividedintofive500mcontiguoussections.

Testingflightplansanddatacollectiontominimisedisturbanceandmaximisedetectability

We collected all described drone data using a Phantom 4 Pro(DJI,China)operatedfromaSamsungGalaxyTab6(Samsung,South Korea) using a DJI GO 4 tablet-based app. The Phantom 4Prohasamaximumflighttimeof ~30min, ¼ amaximumspeed ¼ ~70kmh^{-1},andapilot-controlledrangeof5km.Itcomesequippedwitha20MPcamerawithahighdefinition4K/60fps video capacity. We programmed all flight plans using Pix4Dcapture software (Pix4D, Switzerland). We ultimately assem-bledandortho-rectifiedallimagesusingAgisoftPhotoscanProver. 1.2.5.2594, which isnow Agisoft Metashape (Agisoft,Russia), and imported them into QGIS ver. 2.8.6 (QGis Devel-opmentTeam,USA)foranalysis.

Prior to implementing any drone-based crocodile surveys, wewanted first to test the drone for disturbance effects on thecrocodiles that might affect drone-based survey results (e.g.fleeing, submersion, or other evasive manoeuvres). We alsowantedtominimiseextremedisturbancetootherspeciespoten-tially encountered during surveys, and thus defined the mini-mumflightheightwithoutdisturbanceforeachspeciesgroupasthelastflightaltitudebeforethealtitudeduringwhichtheyfled.To test for disturbance, we flew the drone for 28 min over BaliPond (PNP), starting at 80 m and descending 5 m every 2 min(thetimeittooktoflyaslow,steadylaparoundthepond) toanaltitudeof5m.Weadditionallyapproachedspecificcrocodileswhile they were basking, starting from 10 m, and descendingslowlyto1m,todeterminethealtitudeatwhichtheywouldflee.Five observers equipped with binoculars observed an equalportion of the pond and its shores, monitoring the behaviour ofthe crocodiles, both on land and in the water, and other speciespresent(suchaselephants,warthogsandbirds).

Also, before implementing any drone-based crocodile sur-veys, we wanted to test flight, ambient light, and photographicparameters to optimise detectability in the resulting images.Higher-altitude flights increase surface-area coverage relative tobattery 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 maltitude); however, the number of photos to be processed alsodecreases. To establish flight and photographic parameters thatoptimise detectability, we flew four test flight sessions over BaliPond (PNP) consecutively on the same day, with 20 min inter-vals between each session. Each session included four flights,eachatadifferentaltitude(20,25,30and40m),corresponding todifferentphotoresolutions(0.62,0.72,0.95and1.22cm^{2}perpixel),resultinginfourmapspersessioncoveringthe1hapondarea.WeimportedthemapsintoaGIS,wherefiveexperienced,independentobserverscountedthenumberofindividualcroco-dylians they detected in each of the 16 maps by placing ageoreferenceddotoneachdetectedcrocodile.Welimitedobserversto10minpermapandtheywereblindtothecorresponding flight parameters. We additionally asked all theobserverstorankeachmap(from1to4;1low,2average, 3 good,4verygood)onthebasisoftheirperceptionoftheimagequalityandapparenteaseofsearchingforcrocodiles.Toverify observer reliability, a sixth observer performed an*aposteriorirecount*onallmapswithouttimelimittoestimate the number of individuals that went undetected and to estimatethe frequency of false detections. All analyses considered timeof day of flight, flight altitude, map rank, and observer identity asfactorsinfluencingcrocodilecounts.

Comparingdronestotraditionalcrocodilesurveymethods

We compared the effectiveness of drone surveys to two tradi-tional crocodile survey protocols, namely, diurnal counts andnight spotlight counts. We implemented each of the three surveytypes successively, following the protocols below, on the sameday, starting with a drone survey, at 23 sites (Fig.1, Supple-mentary material Table S1). We conducted diurnal and noctur-nal surveys in the same area at each site as the area covered bythe corresponding drone flight. At each site, we collected thefollowing additional data: cloud cover, ¼ aquatic ¼ vegetation ¼ den-sity,vegetationcover ¼ byvisualestimation,andwindspeed. Wescored each of the first three covariates on a quantitative scalefrom0to4(00%,11–25%,226–50%,351–75%and 4 ¼76–100%), and visually assessed wind speed, scoring it on aqualitativescalefrom0to 4.

(1) Dronesurveys

Following the results of our optimal flight evaluations (seeResults), we flew drone surveys at an altitude of 40 m and at aspeed of 5 m s^{-1}with 908camera orientation, autonomouslyfollowingapre-programmedflightplanfromtake-offtoland-ing. For each site, we repeated the same flight plan three times inthe same day (if the logistics allowed), namely, once between0900hoursand1100hours,oncebetween1300hoursand1500hours,andoncebetween1700hoursand1900hours.Weprogrammed the drone to take photos at regular intervals thatensured a minimum 60% overlap between two consecutiveimagestooptimisephotocollationandavoidshadowsonmaps(Koh and Wich2012). We made maps from each survey asdescribedaboveandvisuallysearchedmapstoidentifytospecies (using head shape visible in photographs) and quantifythenumberofcrocodilesdetected(Fig.2).

(2) Diurnalsurveys

We counted crocodiles immediately following the dronecount, searching for crocodiles with the aid of binoculars. Wetraversedthestudyploteitheronfootorbyusing a3.5mzodiacwith a 15 hp outboard motor travelling at a constant speed of6–8 km h^{-1}. Because of logistical issues, we could not alwaysreplicate the diurnal survey protocols three times (once perdrone count). For each detected crocodile, we identified it tospecies and took a GPS point of its location. Where crocodilescould not be approached for classification, we noted the sightingas eyesonly(EO).

(3) Nocturnalspotlightsurveys

Wecountedcrocodilesonetimeeachnightfollowingstandardeyeshinespotlightprotocol(e.g.Shirley*etal.2009*),startingandfinishing each survey between 2000 hours and 0200 hours. Weused a Streamlight Waypoint 550 lm spotlight and a 1-W LEDheadlamptodetectcrocodiles.Wetraversedthestudyploteitheronfootorbyusinga3.5mzodiacwitha15hpoutboardmotortravellingataconstantspeedof6–8kmh^{-1}Foreachdetected

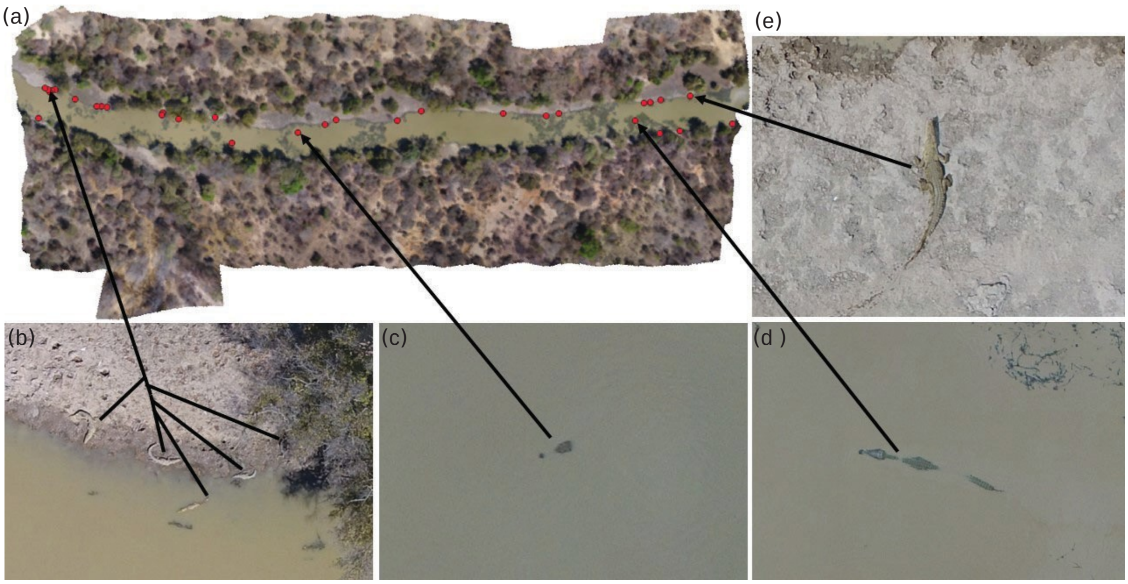


Fig.2.Crocodilecountsandmappingfromdronephotos. (*a*)Themainmapistheaggregationof120orthorectifiedphotos.Theredpointsarefordetectedcrocodiles,whichweredetected(*b*,*e*)ontheshoreand(*c*,*d*)inthewater.Flightparameters:altitude40m,speed5 ms^{-1},overlap 60%.TapoaRiver, W NationalPark, Niger.

crocodile,weidentifiedittospeciesandtookaGPSpointofitslocation.Wherecrocodilescouldnotbeapproachedforclassifi-cation,wenotedthesightingaseyesonly(EO).

Statisticalanalysis

We used Poisson regressions, a particular case of generalisedlinear model (McCullagh2018), to model crocodile count datawiththelogarithmasthelinkfunction.Whenrelevant, weusedthe quasi-Poisson distribution instead of the simple Poisson totakeintoaccountoverdispersioninthedata.Weusedlikelihoodratiotests(LRT)tostudytheeffectofcovariatesandinteractionsamongcovariates.WeperformedallanalysesinRversion3.5.2(R CoreTeam2018).

To assess flight parameters and the analysis of the observereffect,wemodelledcrocodilecountdataagainsttimeofdayofflight,flightaltitude,maprankandobserveridentity.Weseparately modelled the number of false or missed detectionsagainstthesamecovariates.

Tocomparethethreesurveymethods,wemodelledcrocodilecount data against site identity (10, 8, and 5 sites for Benin, Coted’Ivoire and Niger respectively) and count method (3 droneinvestigationsduringtheday,1diurnalsurvey,and1 nocturnalsurvey). For drone surveys only, we modelled crocodile countsagainsttimeofday,windstrength,cloudcoverand,additionally,asiteeffect.We,ultimately,didnotincludethe vegetationindexin the model as a covariate because there is no variation of thisvariablewithinasite.Weanalyseddataindependentlyforeachcountry andforallcountriescombined.

Results

Testingflightplansanddatacollectiontominimisedisturbanceandmaximisedetectability

At Bali Pond (PNP), we found that*Crocodylus suchus*was theleast disturbedbythe droneofallspecies present,withthe flee altitude ranging from 1 to 10 m (Fig.3). In contrast, all mammalswerethemostsensitivetothedrones,withfleealtitudesrangingfrom 60 m for*Loxodonta africana*to 20 m for*HippopotamusamphibiusandPapioanubis*,whereasbird fleealtitudesrangedfrom 10 to 15 m (Fig.3). Flight responses of other speciespresentaroundthepondindicatednobehaviouralchangeinthecrocodiles. On the basis of these results, we determined thatcrocodylianspeciesinWestAfricawereunlikelytobeperturbedbydronesurveystothepointoffleeingexceptbelow11 mand,therefore, crocodile drone surveys should be flown at altitudesabove thisminimum.

Inouranalysisoftestflightparametersthatoptimisedetect-ability,everycovariate,exceptaltitude,hadasignificantimpactoncounts(Fig.4*a*,Table1).Wefoundthatthefiveindependentobserverscounted,onaverage,18.21crocodilespermap, ranging from 4 to 39, where the best observer counted, onaverage, 28.38 and the worst observer 9.44. The independent,unconstrained observer counted an average of 34.94 crocodilesper map (24–47), and found, on average, 1.23 more crocodilesthandidthebestobserverand3.7morethanthewor stobserver(Table1). The variation between observers was significant, bothincluding and excluding (result not shown) the independent,unconstrainedobserverimplementingtheexhaustivecount(Table1).

In terms of false detections or undetected individuals, alti-tude, map quality, and time of day had no significant relation-ship, but observer identity and time of day had a significantimpact (Table1). On average, the five observers missed 16.79individualspermap,rangingfromsevenforthebestobserverto 23.19 for the worst, and the inter-observer differences werehighlysignificant($F_{4,74}$23.98,*P1.8x10*$^{-12}$ ¼ ;Fig.4*b*,Table1). Observers made an average of 0.63 false detectionsper map, ranging from 0.44 to 1.06, although inter-observerdifferenceswerenotsignificant($F_{4,74}$¼1.0,*P*¼0.41;Fig.4*c*,

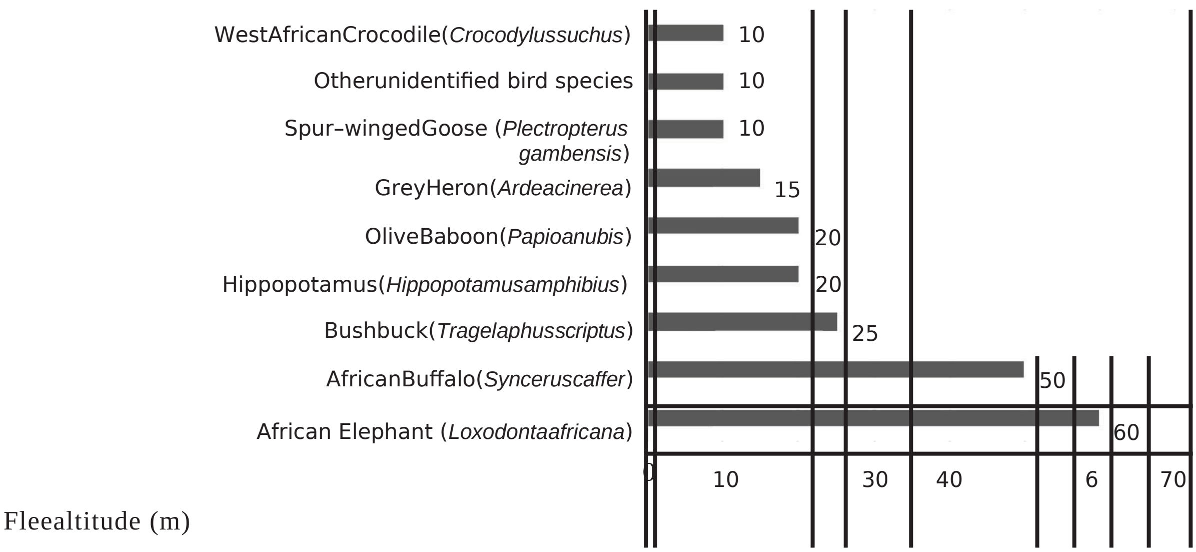


Fig.3.Droneflightaltitude(m)atwhichspeciesobservedatBaliPond,PendjariNationalPark,Benin,fledthedrone.

Table1). Generally, the best observers were either those with themost experience in the field and/or with technology. There was asignificant difference in the number of crocodiles observedacrossthefoursessions(i.e.timeofday;$F_{3,71}$¼4.86, *P*¼*0.004)*,withmorecrocodilesbeingdetectedduringthefirstsession. As altitude decreased (e.g. map resolution increased),theobserversdidnotdetectmorecrocodiles($F_{1,70}$¼3.06,*P*¼*0.085;*Fig.4*a*,Table1),nordidtheydetectmorecrocodilesonmapstheyjudgedtobeofhigherquality($F_{1,69}$¼4.19,*P*¼*0.044; Table*1). On the basis of these results, we flew allsubsequent drone surveys at 40 m altitude (see above), anddelayed flights when elephants and buffalos were present toavoid disturbance.

Comparingdronestotraditionalcrocodilesurveymethods

We detected very few crocodylians in Cote d’Ivoire, namely, 0atallsitesbyallmethods,exceptatMareauxBuffleswhere wedetected 0 by drone, 0 by day count, and 3 by night count. Weultimately excluded Cote d’Ivoire from further analysis. InBenin, we detected 49 crocodiles by drone, 30 by day survey,and71bynightsurvey,wheremostofthesedetectionswereexclusively in the Bali pond in PNP (Site 1; Supplementarymaterial Fig. S1). In Niger, we detected 156 crocodiles by drone,32bydaysurvey,and311bynightsurvey(Fig.S1). Weulti-matelyanalyseddatafromBeninandNigerseparatelytoreducethechanceforbiasowingtothedifferenceinscaleofnumberofcrocodiles detected. We found that night surveys detected sig-nificantly more crocodiles than either of the other two surveymethodsinbothcountries,andthatdronesdetectedsignificantlymorecrocodilesthandidstandarddaysurveys (Fig.5*a*,Table2:Niger$F_{2,18}$¼38.70,*P*¼3.56×10^{-6}; Benin:$F_{2,28}$¼59.39,*P*¼5.7×10^{-5};Fig.5*b*).

Environmentalfactorsonthedronedetectionefficiency

We observed no effect of the site on the number of crocodilesdetected in Niger ($F_{4,10}$¼0.648,*P*¼0.65; Table3), whereasinBeninthesiteeffectwassignificant($F_{4,10}$¼890.21, *P*2.610^{-7}; Table3). Time of day was not significant inNiger ($F_{2,8}$0.46,*P0.655; Table*3), but it was significant inBenin ($F_{2,8}$97.74,*P9.8*10^{-5}; Table3). Wind intensityhad no significant effect in Niger ($F_{3,5}$1.022,*P0.457;*Table3)orBenin$F_{3,5}$4.91,*P0.060;*Table3).Ultimately,we did not model cloud cover because there was not enoughvariationacrossdays,sitesortimes.

¼ ¼ ¼ ¼ × ¼ ¼

Discussion

We sought to assess the efficacy of drones as crocodile surveytools for a diverse crocodylian species assemblage in WestAfrica. In so doing, we tested several flight parameters thatallowed us to also establish a standardised and optimised pro-tocol for drone-based crocodylian surveys. We found that droneswereremoreeffectivecrocodilesurveytoolsthanweretraditionalday surveys for crocodylians in West Africa. However, as withtraditional day surveys, drone surveys were less effective thanweretraditionalnightsurveysbothbecausecrocodilesaregenerallymoreavailableanddetectable atnightandalsobecause typical consumer drones do not currently have noctur-nal filming capacity. Further, we found that drone flight para-meters that optimise flight efficiency and area coverage aremoreimportantconsiderationsforflightplanningthanarecharacteristics we pre-suppose will affect subsequent detect-abilityor disturbance.Here, wediscusseachofthesein turn.

Developingstandardflightprotocolsforuseofdronesincrocodyliansurveys

We assessed the effect of altitude, map rank, time of the day,observerbiasanddisturbanceoncrocodilecountsusingdronestoproposeastandardprotocolforsuchfuturestudies.Wefoundthatimageresolutionwhenusingthestandardcamera(4Kresolution)onthe DJIPhantom4Prowashighenough,sothatwefound noeffect on crocodile counts up to 40 m altitude. Forty metresaltitude is an optimal flight height to achieve time- and power-efficientcoverageofsites;however,futurestudiesshouldrepli-catethetestingprotocolofcrocodiledetectabilityat higher

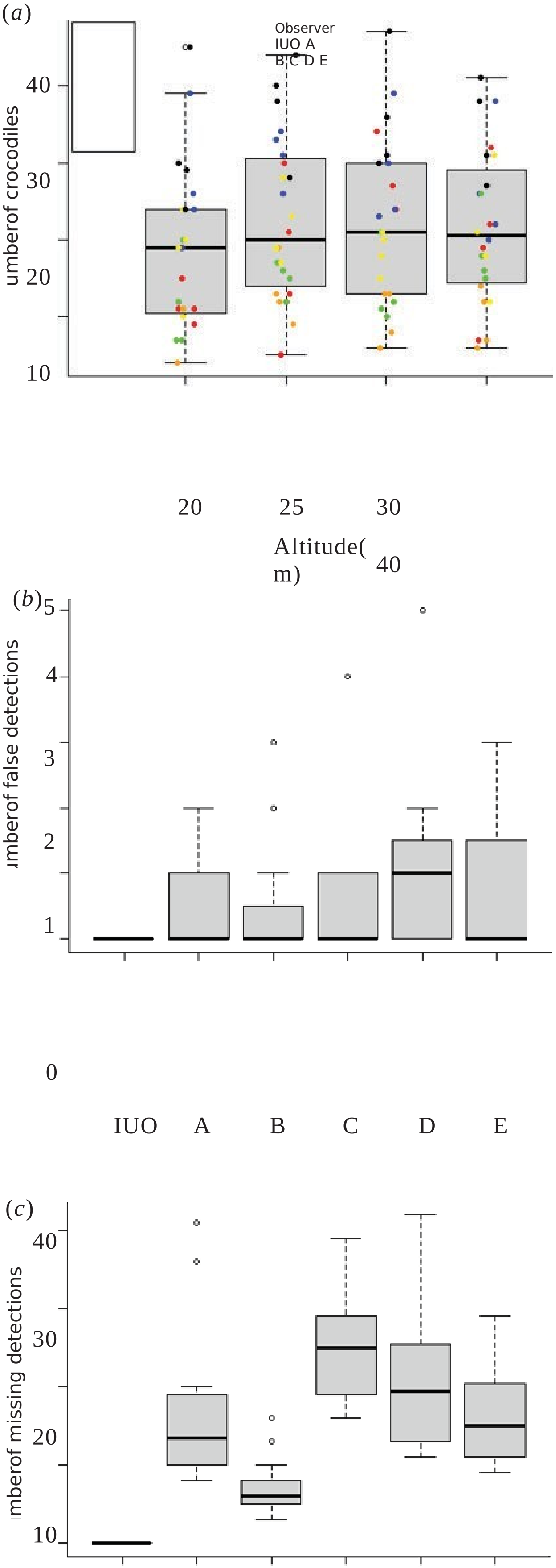
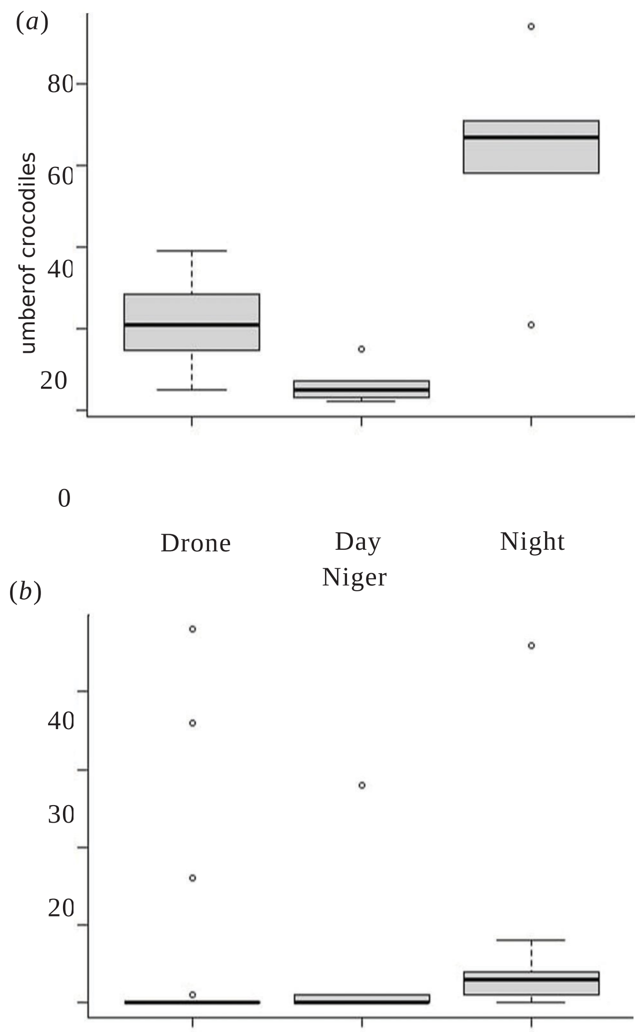


Table 1.Results of generalised linear model assessing the influence offlight, photo, and observer characteristics on the number of crocodilescountedby drones

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



0

IUO A B C D E

Observ er

umberof crocodiles

1 0

0

Drone Day Night

Benin

Fig.4.Observereffectsoncrocodiledetection. (*a*)Distributionofcrocodilecountsforeachobserverandflightaltitude.Eachobserver(A–E,eachwithadifferentcolour)had10mintocountthecrocodilesonthereconstitutedmaps(Bali pond, Pendjari National Park, Benin), and the independent, unconstrainedobserver(IUO)hadnotimelimit. (*b*)Numberofmisseddetectionsper observer and (*c*) number of false detections per observer. The boxplotsrepresent the aggregated counts for each height (median, 25% and 75%quartiles,whiskersrepresenting5%and95%quartiles).

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

Table2.Resultsofgeneralisedlinearmodelcomparing crocodyliansurveymethods

Site isthesiteidentity (asafixedeffect).Protocol referstosurveymethod(dronevsdiurnalcountvsnocturnal spotlightcount).Windandcloudcoverare both categoricalcovariates

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
Cloudcover	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
Cloudcover	2	13	3.7614	0.05142

Table3.Resultsofgeneralisedlinearmodelassessingth eimpactofenvironmental variables on drone surveys

Siteisthesiteidentity(asafixedeffect).TimeofdayandWi ndarebothcategorical 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

altitudestofurtheroptimisecoverage,time,andbatteryeffi -ciency,especiallyashigher-resolutioncamerasbecomeavailable.Theabilitytozoomi ntoimagesbecauseofthehigh4Kresolutionrenderedfalse detectionsrare,regardlessoftheobserver.Asaresult,obse rverbiasfarexceededtechnicalflightbiasasthemostinflue ntialfactoraffectingdrone-basedcroco-dile surveys, as it has been shown for standard spotlight counts(Nicholsetal.2000;Shirleyetal.2012).Countingcroc odilesonmapimagesisatedious,time-consumingtaskthatrequiresintenseconcentration;limite dto10minpermap,ittook3hforobserverstocountcrocodil esonthe161-hatestmaps,andittooktheindependent,unconstrainedobserver5 htodoanexhaustivesearch.Investmentin/ engagementwiththestudyandindividualexperiencearecriticalto achievinggoodresults.Ofsecondaryimportance, somemeteorologicalconditionscanhinderreconstructionorqual ityofmapimages(Fig.6*a*).Althoughtherewasnosignificanteffec toftimeofdayonthenumberofcrocodilesdetectedbythedroneint hepresentstudy,therewasanoticeabledecreaseinthequalityofae rialimagesintheevening.Tocounterbalancethelackoflight,thec ameraautomaticallyincreasesthesensorsensitivity(ISO),thusde gradingthequalityoftheimage.Thismaynot,ultimately,affectth edetectabilityofcrocodilesbyskilledobservers,althoughsiteswi thmoredebriswillcertainlybemore

complicated. In the middle of the day, as the sun orientationapproaches 908from the water surface, reflections back to thecamera effectively whiteout patches of habitat (Fig.6*c*). Theseobservations are similar to those in other drone studies foraquatic-wildlifemonitoring(Kiszka*etal*.2016;Linchant *etal*.2018).Meteorologicalconditionssuchaswindarealr eadyknowntobeunfavourableforobservingcrocodiles(S hirley*et al*.2012). Sun reflection and wind-generated waves alsodegradethequalityoftheaerialphotosanddisruptthea ssemblyof tiled photos (Fig.6*b*). Further, windy conditions make smalldrone flights challenging. For these reasons, we recommendflights in themorning (from0900 hoursto 1100hours).

Despite their small size, drones have been shown to bedisturbing to wildlife (McEvoy*et al*.2016), especially whenanimals are approached too closely (Bennitt*et al*.2019) or atsensitivenestingandbreedingsites(Dulava*etal*.2015;P omeroy*etal*.2015;Weissensteiner*etal*.2015).Weassesse dthealtitudeatwhichspeciescommonlyfoundinourstudy sitesfleddueto thepresenceofthedrone.Interestingly,*Cro codylussuchusfled*thedroneattheclosestapproachaltitud eofanyspeciesatourstudysite, and even showed signs of being more tolerant than othercrocodylianspecies(e.g.*Crocodylusporosus*;Beva n*etal*.2018).Indeed,withthesamedronemodelandsimilar methods,Bevan*etal*. (2018)observedthat*C.porosusresponded*todronesat30m withlateralheadmovementsandsubmergedorretreatedto deeper water at 10 m altitude. Although, due to our single testflight at different altitudes, we do not exclude the possibility ofhabituationofthecrocodilestothedroneathigher altitudes,andcautionshouldbeusedforfutureprojectsataltitudeslowerthan40 m. In comparison, mammals fled at much higher altitudes;however,theresultsfortheseotherspeciesmaynotberepresentative,giventhesingleflightandthelownumbersofindividualspresent, ranging from 1 to 10 or so, depending on the species,comparedwith100orsoforthecrocodiles.

WereporttherethefirstindicationsforAfricanbuffalo(*Synceruscaffer*),whichfledat50m.Ourresultsarecongruentwith those of Bennitt*et al.*(2019), who also found that elephants(*Loxodonta africana*) were perturbed at 60 m. Several studieshave shown that elephants avoid bees (Vollrath and Douglas-Hamilton2002; Ngama*et al.*2016; King*et al.*2017) and thenoiseemittedbythedronerotorscouldbeconfusedforaswarmof bees. Other species were much more tolerant of the drone,including hippos which fled at 20 m approach altitude, as wasfoundinotherstudies(Linchant*etal.2018*;Inman*etal.2019*).Finally,birdsofanyspeciesfledthedroneatanaltitudeofonly10–15m,beingcongruentwithwhathasbeenobservedatothersitesforotherbirdspecies(Vas*etal.2015*;McEvoy*etal.2016*;Brisson-Curadeau*et al.*2017; Rush*et al.*2018). The increasedaltitudes precipitating a flight response in large mammals willnot likely result in decreased detection of these species, giventheirenormoussize.And,eventhoughdrones havethepossibil-ity of disturbing these species, they are likely to be less disruptivethanhumansincloseapproachonfootorinanautomobile,andobservationfromadroneislessdangerousfortheobservers(Mulero-Pa´zma´ny*etal.2017*).Importantly,fleeingisnottheonlybehaviouralevidenceofdisturbancebydronesonwildlife,but rather the last-resort behaviour. For crocodylians, we did notobserve other behaviours potentially indicative of disturbance(suchasrepositioning,legandheadmovementsand

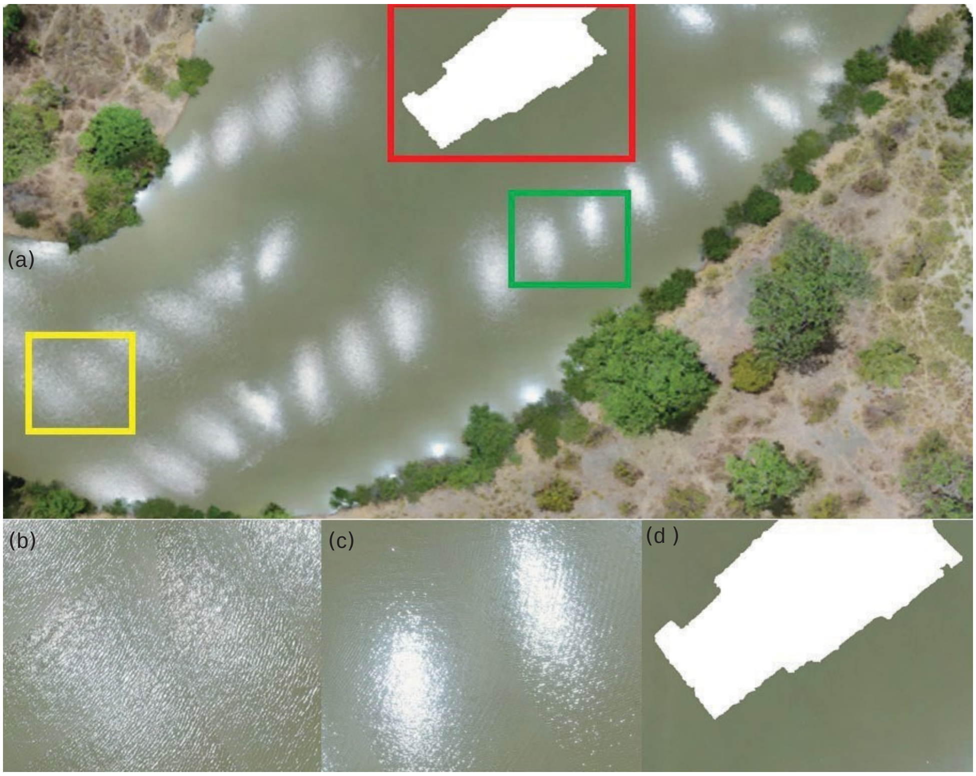


Fig. 6.Image-quality disturbance owing to wind and sunlight. (*a*) This reconstructed image of the Canard pond(PNP, Benin) shows how (*b*) the small waves generated by wind (yellow square in*a*) and (*c*) sunlight reflection (greensquarein*a*)canaffectthequalityoftheimage,andthuspotentiallythecrocodilecount.(*d*)Partofthisimageisalsotruncated(redsquare in*a*)becauseits homogeneity preventsphoto assemblyformap reconstruction.

submersion), but did not look for behaviours such as wingextension(Weimerskirch*etal.2018*),vocalisations(Wilson*et al.*2020) and head movements (Bennitt*et al.*2019) in theother species present at our study sites because of our focus oncrocodiles. Nonetheless, we find it interesting to present theseresults, given the very few data available for wildlife–droneinteractionsin WestAfrica.

Efficacy of and uses for drones to survey crocodiles in WestAfricaandelsewhere

Weaimedtocomparedronecountswithtraditionaldiurnal andnocturnal crocodile surveys. We found that nocturnal spotlightcounts detected significantly more crocodiles (87%) than dideither of the two other methods, although we detected 231%more crocodiles by drone than during traditional diurnal sur-veys, being congruent with previous studies counting crocodileswithdronesinAfrica(Ezat*etal.2018*).Thedrone wasincapableof detecting individuals smaller than 100 cm in total length inmost conditions; however, this is also a standard problem ofdiurnal crocodylian surveys (Shirley and Eaton2012). Unfor-tunately, the drone we used was not mounted with technologyenabling nocturnal drone surveys for more direct comparisonwith nocturnal spotlight surveys. As consumer drones withcameratechnologiespermittingnightfilmingbecomeavailable,we recommend testing nocturnal drone surveys as a potentiallypromising avenueforfutureresearch.

Despite detecting fewer individuals during the daytime thando traditional nocturnal surveys, drone surveys are likely tobringseveraladvantagesincrocodyliansurveyscompared withstandardspotlightortraditionaldiurnalsurveys.Forone ,because of the high-resolution map images (1.22 cm^2per pixelat 40 m), drones allow for unbiased measurement of the detectedindividual's size on the basis of either*in situ*scaling or use ofstandard head length to total length ratios (e.g. Fukuda*et al*.*2013*).Althoughthisiscertainlypossiblethroughcloseap proach of individuals during nocturnal surveys, even expertobservers are shown to be error prone (Choquenot and Webb1987),andthecloseapproachnecessarycanbestressful fortheanimals.Thesephotoscouldalsobeusedtoidentifyindi vidualspresent at study sites, resighting either artificial tags or naturalcrocodylian markings (Swanepoel1996; Bouwman and Cronje2016; Boucher*etal*.*2017*;Coetzee*et al*.*2018*).

Dronesprovidenotonlyarigorousandnon-invasivewaytocharacterise observed individuals, but also leave a permanentrecordofobservations,anadvantagethatcannotb eunderstated(Kelaher*etal*.*2020*).Maprecordscanbeusedfo rlaterverifica-tion of number, size, species and position, including habitatoccupied,ofalldetectedcrocodiles.Thereduceddistu rbancetoanimals compared with foot and boat surveys will also likelyresult in less double counting of individuals as they flee andsubmergeonlytoresurfaceelsewhere.Thishaslongbeenr ecognisedasanadvantageinaerialsurveysforcrocodiles,but withtheaddedadvantageofobjectivecountsfromphotosreduc-ing aerial survey observer bias and limitations (Nichols*et al.2000*). Drones share other advantages and disadvantages withmannedaerialsurveys.Bothcanbeusedtocovermoreterritoryfasterandforlesscostthanforboatsurveys,butbothfailtodetectdiversecrocodyliandemographics(Bayliss *etal.1986*).However,drones are cheaper than manned craft, with simpler logistics,smallerecologicalfootprints,andintroduceless disturbance.

Becauseoftheelevatedpointofview,dronescanovercomeseveralhabitat-relatedvisibilityissuesofcrocodilesurveys.Thepresenceofplantsandthecomplexityofthehabitatstronglyaffecton-groundvisibilityandareaprincipalsourceofbiasinestimat-ingcrocodylianpopulations(Shirley*etal.2012*).Inourstudy,wedetectedmorecrocodyliansusingdronesthanwithtraditionaldaysurveysdespitetheshrubbyvegetationcoveronthebanksandthepresenceofaquaticplantsontheTapoa River.Droneseffectivelyallowobserverstoseetypicallyunobservablespace,inthiscase,beyondthefirstlayerofvegetation,andmoregenerally,includingotherwise inaccessible or distant habitats (Vas*et al*.2015).However,whenhabitatsaretoohomogeneous,suchasthecentreofthewaterwithouttheshorelineorotherfeatures(e.g.aquaticvegetation, rocks, tree trunks) in the field of view, map recon-structionbecomesnearlyimpossiblebecauseofthelownumberofreferencepointsbetweenphotos(Fig.6*d*).Thecontinuousimprovementofimagecompilationandortho-rectificationsoft-wareshouldmitigateoreveneliminatethisinthecomingyears.Additionally,thepresenceofvegetationabovestudysitesmakes aerialphotoswithacameraorientedat908irrelevant.

Thelatterisamajorproblemforforestedwaterwayswhere crocodyliansatthewater’sedgewillalwaysbeundertreecoverand, therefore, undetectable from above. In West Africa, thismeans that drone surveys may never be a relevant method forcounting*Mecistops cataphractus*and*Osteolaemus*spp., whichboth prefer forested habitats and nest under closed canopy forestcover(Waitkuwait1989;Shirley*etal.2018*).Indeed, ourdronesurveysdidnotdetecteitherofthesespeciesatsiteswherethey areknowntobepresent.However,inCoted’Ivoire,thisisalsolikely to do as much with their rarity as with detectability issues,because our nocturnal surveys also failed to detect them (Shirley*etal.2009*,2018).Dronesareincreasinglyusedtosurveyforestvertebrates, although more generally primates, birds, and otherspeciesthatliveand/ornestinthecanopy(Weissensteiner*etal.2015*;Wich*etal.2015*;Bonnin*etal.2018*).

Finally,dronesareincreasinglyinexpensive(lessthan 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 multipleobservers with strong field experience, unlike standard noctur-nalanddiurnalsurveysdo(ShirleyandEaton2012).However,the limited battery life of the drone can limit the extent of thestudyarea,accesstoelectricitytorechargebatteriescanlimitthechoice of study sites, and increasingly strict national laws andprotected areas regulations concerning drone usage may preventsome usersfromemployingdrones.

Beyonddrones:someadditionalconsiderationsandobservationsfromthepresentstudy

ThesesurveysrepresentsomeofthefirstpublishedinformationoncrocodylianpopulationsinCoted’Ivoire,BeninandNiger.

We surveyed sites that contained up to three different croco-dylian species, including the Critically Endangered*Mecistopscataphractus*; however, we detected only*Crocodylus suchus*.This species is the most widespread and found in the greatestdiversity of habitats (Kofron1992; Teller´ıa*et al.*2008; Brito*etal.2011*;Luiselli*etal.2012*).Incontrast,*Osteolaemusspp.* and*Mecistops cataphractus*, although ranging from coastalswamp forest to gallery forest wetland habitats in Guineansavanna, are dependent on forested habitats (Waitkuwait1989;Shirley*et al.*2018). The lack of observations during nocturnalspotlight surveys at two sites where they were known to bepresentisofconcern.Atthesesites,weobservedunsustainableand illegal fishing and palm cultivation (ANP) and counted morethan 60goldpanningraftsontheComoeRiver(CNP).

Our study also underscored certain conservation issues for*Crocodylus suchus*. Night surveys on the Pendjari River and inthe surrounding ponds showed an extremely low crocodyliandensity, with often no individuals being observed, whereas thisspecies was seemingly abundant only a decade ago (Pooley1982; Chirio2009). In contrast, we observed many signs ofpoaching and fishing, including such as fishing nets, traps andsmokingplatforms,alongtheriverthatformstheborderbetween the Pendjari National Park (Benin) and Arly NationalPark (Burkina Faso). While poaching and fishing camps weremostly on the Burkina side, poachers extracted wildlife fromwithin the boundaries of both parks. Fishing and poachingactivities had already precipitated the near extinction of croco-diles in the Niger River bordering the WAP complex before2010 (Shirley and Eaton2008). By comparison, the Bali pondsituated closer to the centre of the PNP and with more touristpresence,hadmanycrocodiles.Similarly,crocodilesareextremely abundant in the Tapoa River (Park W, Niger), nearthe main ranger station and tourist axes (Shirley and Eaton2008).AfricanParkstookovermanagementofPendjariin2018andW(Benin)in2020,whichwill hopefullyresultinincreasingprotection for the crocodiles and all wildlife in this criticalconservationarea.Dronesmayevenprovideavaluabletoolforremotedetectionoftheseillegal activities.

Conclusions

Protecting crocodylians and their habitats is an urgent conser-vation need, especially in West Africa where they are not typi-cally present on the conservation agenda. Drones provide aninexpensive and effective tool for assessing and monitoringcrocodylian populations in some ecological contexts. They offeradvantages of reduced impacts on wildlife, limiting risks forobservers, easy logistics, potentially larger survey-area cover-age,anddatasecurity.Furtherworkismeritedacrosstheregiontounlocktheirfullpotential,bothforcrocodyliansand wildlifeand protectedareas.

Conflictsofinterest

The authorsdeclareno conflictsofinterest.

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Wildlife Research

Supplementary Material

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

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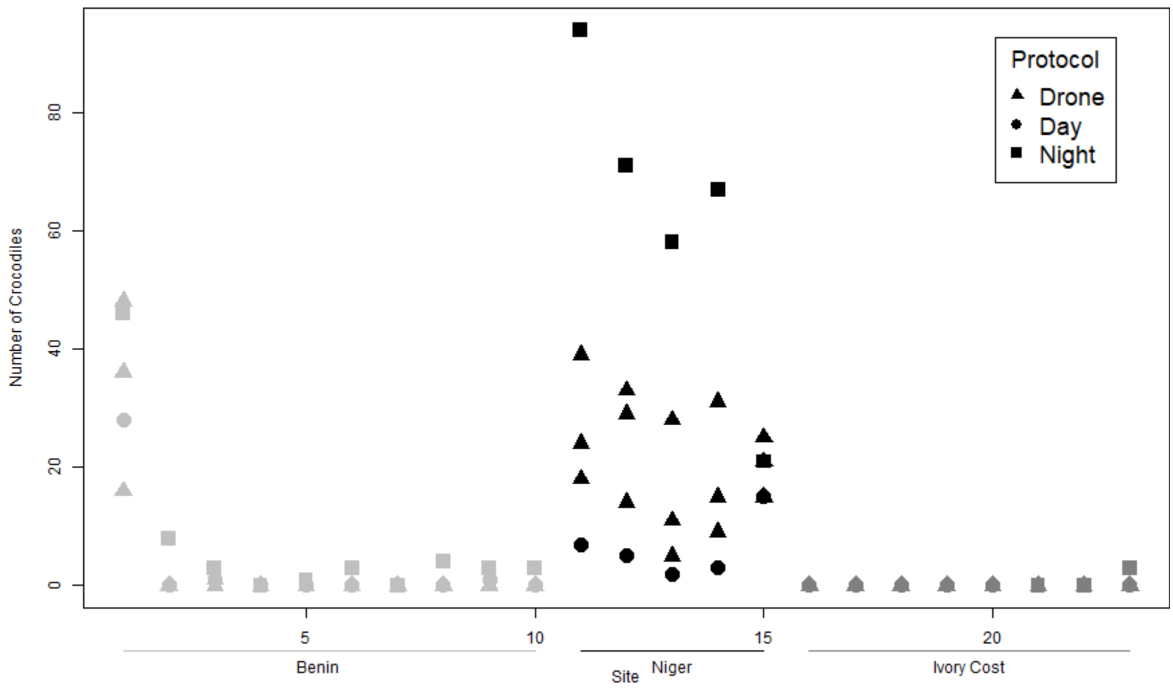

Figure S1. Number of crocodiles detected at each site by the three different surveymethods. We counted crocodiles at 23 sites (Table S1) across Benin (light grey), Niger(black), and Cote d'Ivoire (dark grey) using three protocols: drone (triangles) and groundvisualcounting by day (rounds) or by night (squares).

TableS1.Characteristicsofandcrocodiledetectionsateachstudysite

Country	NationalParc	SiteName	Site Number	Coveredareabydrone	No.ofCrocodilesDetected				
					Drone(session)			Day Survey	Night Survey
					1	2	3		
Benin	Pendjari	MareBali	1	13,175m^2	36	16	48	28	46
Benin	Pendjari	MareBaobab	2	4,603m^2	0	-	-	0	8
Benin	Pendjari	MareTiabiga	3	21,620m^2	1	0	0	1	3
Benin	Pendjari	MareKoudjedougou1	4	24,142m^2	0	0	0	0	0
Benin	Pendjari	MareKoudjedougou2	5	21,950m^2	0	-	-	0	1
Benin	Pendjari	MareDiwouni	6	38,608m^2	0	0	0	0	3
Benin	Pendjari	MareFogou	7	26,354m^2	0	-	-	0	0
Benin	Pendjari	MareSacree	8	10,583m^2	0	-	-	0	4
Benin	Pendjari	MareCanard	9	21,750m^2	0	0	0	1	3
Benin	Pendjari	MareYangouali	10		0	-	-	0	3
Niger	W	Tapoa1	11	500m	18	24	39	7	94
Niger	W	Tapoa2	12	500m	33	29	14	5	71
Niger	W	Tapoa3	13	500m	28	5	11	2	58
Niger	W	Tapoa4	14	500m	31	15	9	3	67
Niger	W	Tapoa5	15	500m	15	21	25	15	21
Coted'Ivoire	Azagny	Canal1	16	1,000m	0	-	-	0	0
Coted'Ivoire	Azagny	Canal4	17	1,000m	0	-	-	0	0
Coted'Ivoire	Azagny	Canal5	18	1,000m	0	-	-	0	0
Coted'Ivoire	Azagny	Canal6	19	1,000m	0	-	-	0	0
Coted'Ivoire	Azagny	Canal7	20	1,000m	0	-	-	0	0
Coted'Ivoire	Comoé	Pontdroit	21	250m	0	-	-	-	0
Coted'Ivoire	Comoé	Pontgauche	22	250m	0	-	-	-	0
Coted'Ivoire	Comoé	Mareaubuffle	23	5800m^2	0	-	-	0	3