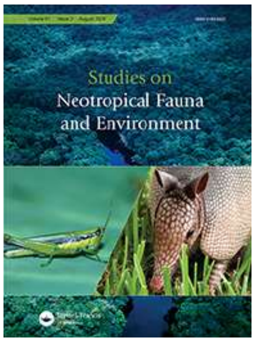

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Using unmanned aerial vehicles to estimate the abundance, density, body size structure, and seasonal site use of *Caiman yacare* in the northeastern Pantanal, Brazil

Carolline Zatta Fieker , Italo Afonso Alves Rondon , Matheus Gonçalves dos Reis , Ana Silvia Tissiani , Marinez Isaac Marques & Karl-L. Schuchmann

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Using unmanned aerial vehicles to estimate the abundance, density, body size structure, and seasonal site use of *Caiman yacare* in the northeastern Pantanal, Brazil

Carolline Zatta Fieker [a,b], Italo Afonso Alves Rondon [a,b], Matheus Gonçalves dos Reis [a,b], Ana Silvia Tissiani [a], Marinez Isaac Marques [a,b,c] and Karl-L. Schuchmann [a,c,d]

[a]National Institute for Science and Technology in Wetlands (INAU/CNPq), Computational Bioacoustics Research Unit (CO.BRA), Federal University of Mato Grosso (UFMT), Cuiabá, Brazil; [b]Instituto Nacional de Pesquisa do Pantanal (INPP/MCTI), Cuiabá, Brazil; [c]Programa de Pós-Graduação em Zoologia (PPGZOO/UFMT), Cuiabá, Brazil; [d]Department of Ornithology, Zoological Research Museum A. Koenig (ZFMK), Bonn, Germany

ABSTRACT
Wildlife research in natural habitats is essential for understanding natural history; however, substantial financial and sampling efforts are required. Cost-effective methodologies, such as drone applications, can overcome these limitations. Although this approach has already yielded substantial results, applications in studies on crocodilians remain scarce in South America. Given this, the objective of this study was to assess the use of drones in population surveys of *Caiman yacare* (Daudin, 1802) in bays of Parque SESC Baía das Pedras, northeastern Pantanal. Seasonal sampling was conducted by flying over 7 bays, taking photos, and counting individuals in real time. Water temperature and depth were measured to examine their associations with site use. A total of 1,118 detections were recorded, with the highest counts occurring during the dry season. Total length was estimated for 249 individuals from aerial images, and smaller size classes were the most common. Seasonality strongly influenced the number of caimans detected. Counts were highly heterogeneous among bays. Water temperature was not associated with counts, whereas water depth showed a weak positive association. In addition to providing valuable information on the caiman population in the study area, these results support the use of drones for crocodilian population surveys.

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Crocodilian; drones; pantanal; drought; flood pulse

Introduction

Habitat changes and losses are among the main causes of vertebrate decline worldwide, both in terrestrial (Haddad et al. 2015) and aquatic environments (Moyle and Leidy 1992; Quesnelle et al. 2013). In recent years, the surface area covered by water has substantially decreased in Brazil, and the Pantanal was the most affected biome from 1985 to 2023 (MapBiomas 2023). This biome has been suffering from prolonged droughts and increased fires, phenomena that are part of a cyclical hydrological regime but have intensified in recent decades due to climate change, in addition to human actions such as the channeling of rivers and the creation of river dams, which aggravate environmental impacts (Junk et al. 2006; Thielen et al. 2020).

Caiman yacare (Daudin, 1802), a medium-sized crocodilian reptile widely distributed in the Pantanal (Figure 1), is a species affected by changes in the environment and climate. Previous estimates indicated a population of approximately 30 million individuals (Coutinho 2000). However, in recent years, this species has faced challenges due to water and food shortages resulting from prolonged droughts (Campos and Mourão 2020; Schuchmann et al. 2021), emphasizing the importance of population monitoring.

Agile and efficient collection of data to assess how animal populations behave in the face of changes in their habitats, especially in aquatic environments, is essential for the management of natural areas and the strategic execution of conservation actions (Wich et al. 2021). Unmanned aerial vehicles (UAVs), or drones, have become valuable tools for wildlife studies (Hodgson et al. 2018), and their application has been effective for several taxonomic groups, including mammals (Aniceto et al. 2018), birds (Hong et al. 2019), and reptiles (Bevan et al. 2016; Evans et al. 2016; Ezat et al. 2018). Drones offer advantages such as obtaining high-resolution images (McEvoy et al. 2016), reducing the

CONTACT Karl-L. Schuchmann klschuchmann@googlemail.com

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Figure 1. *Caiman yacare* in Parque SESC Baía das Pedras, northeastern Pantanal, Poconé, Mato Grosso, Brazil (16°29″55″ S, 56° 24″47″ W).

impact of the presence of researchers on animals (Paquier et al. 2006; Vas et al. 2015) and the ability to access remote and difficult-to-reach areas (Fiori et al. 2020). These characteristics facilitate the sampling of large areas, reduce financial costs, and reduce risks for researchers associated with difficult access to flooded terrain, navigation hazards, and proximity to wildlife (Sawan et al. 2023).

Research using drones to monitor crocodilians has been conducted mainly with the genus *Crocodylus* in South Africa and Indonesia (Evans et al. 2016; Ezat et al. 2018). In Brazil, the use of this technology is still recent, but it has already been applied to the monitoring of *C. yacare* nests in the Pantanal of Mato Grosso do Sul (Campos et al. 2020). In this context, this study aimed to evaluate the use of drones to quantify seasonal variation in the abundance and density of *Caiman yacare* in the bays of Parque SESC Baía das Pedras (Poconé, Mato Grosso, Brazil) and to characterize population size structure based on size classes derived from total length measurements obtained from aerial images. Additionally, we evaluated whether water temperature and water depth were associated with seasonal variation in counts.

Methodology

Study area

This study was conducted in seven bays in Parque SESC Baía das Pedras (16°29″55″ S, 56°24″47″ W,

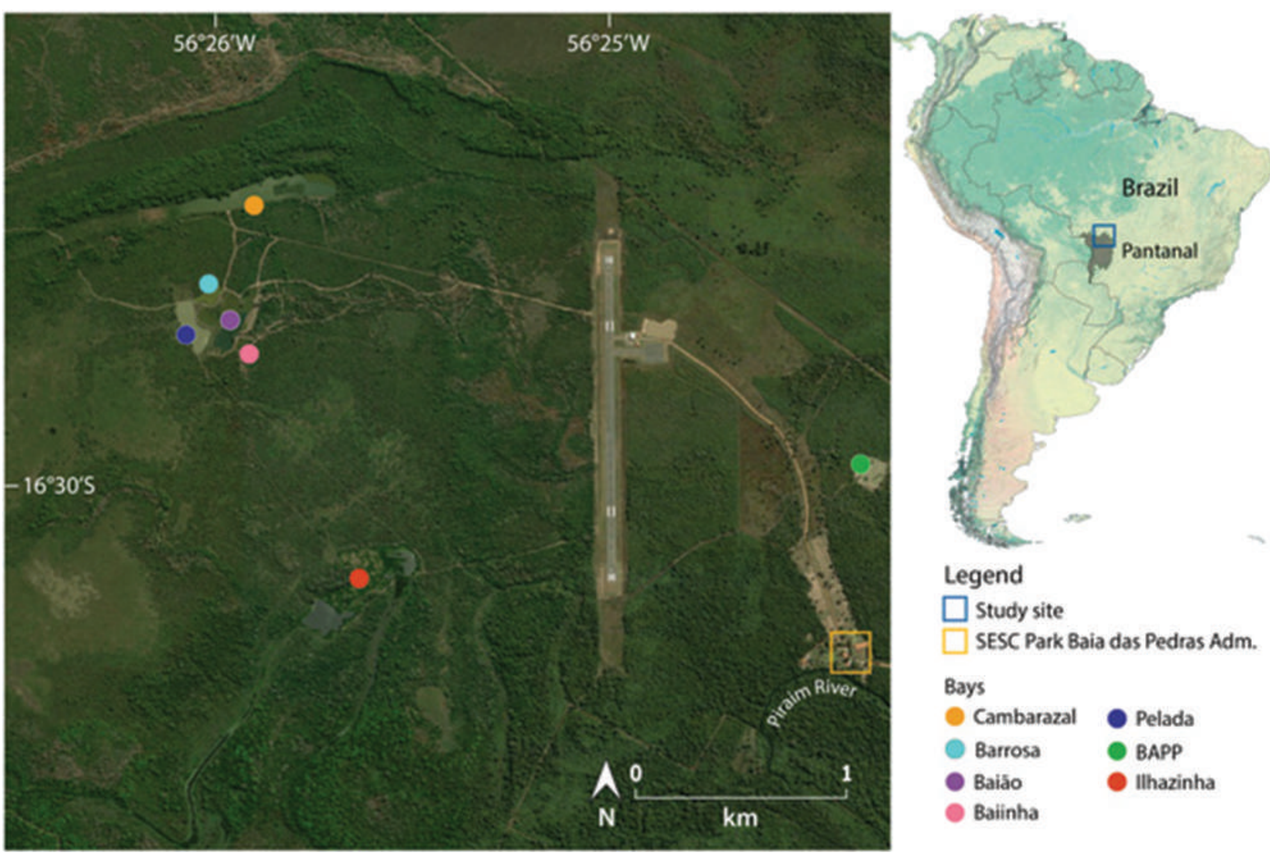

Figure 2. *Caiman yacare* monitoring bays in Parque SESC Baía das Pedras, northeastern Pantanal, Poconé, Mato Grosso, Brazil.

119–131 m in altitude), Poconé municipality, Mato Grosso State, Brazil (Figure 2). The reserve covers 4,200 ha and consists of a mosaic of phytophysiognomies such as savannah areas, cambarazais, and semi-deciduous forests (Nunes da Cunha and Junk 2004; Deus et al. 2020). Its main tributaries responsible for flooding are the Corixão and Cuiabá Rivers. The studied bays are locally known as Baiinha (0.32 ha), Baião (2.44 ha), BAPP (1.36 ha), Cambarazal (6.57 ha), Pelada (2.05 ha), Barrosa (0.47 ha), and Ilhazinha (3.98 ha) and together occupy approximately 17.19 ha (Figure 2), estimated as the planimetric surface area of the bays delineated in Google Earth Pro (imagery date: September 2021). All the bays have anthropogenic origins, having been formed by excavation and removal of substrate to create embankments for roads and the aerodrome infrastructure located in the study area, which facilitates the identification of bay boundaries for area calculation regardless of the water-covered surface at the time of sampling.

Data collection

The data were collected between September 2021 and May 2022, comprising one sampling in each hydrological season: dry (September 2021), rising (November 2021), wet (March 2022), and receding (May 2022). Sampling in Ilhazinha Bay could not be conducted during the wet season because the access roads were flooded. During each hydrological season, two surveys were conducted in each of the seven bays, one in the morning and the other in the afternoon.

Caiman yacare counts were performed via unmanned aerial vehicles (UAVs) along transects established across each bay, which were planned and designed from fixed landscape reference points according to the bay geometry and area. Four to six transects, with lengths varying according to bay length, were required per bay so that real-time visualization and image acquisition covered the entire predefined area (the full planimetric area of each bay), regardless of the size of the water surface. We conducted manually operated flights via a Phantom 4 Pro Plus V2.0 drone with an integrated camera (1” 20 MP CMOS sensor, 84° FOV, 8.8 mm [24 mm equivalent] lens) to count individuals in real time and record images for cross-checking counts and estimating individual total length (Figure 3). Flights were conducted at 15 m altitude and a speed of 8–10 km/h.

After each sampling event, the water depth and temperature were measured at five random points in the middle of each bay. For depth measurements, a Fish Finder portable fishing sonar (model SN-01) was used in the deepest locations (>60 cm), and a 100 cm ruler was used for shallower locations. A Greisinger GTH175 PT-T meter was used to measure the water temperature at a depth of approximately 10 cm. These measurements could not be taken when

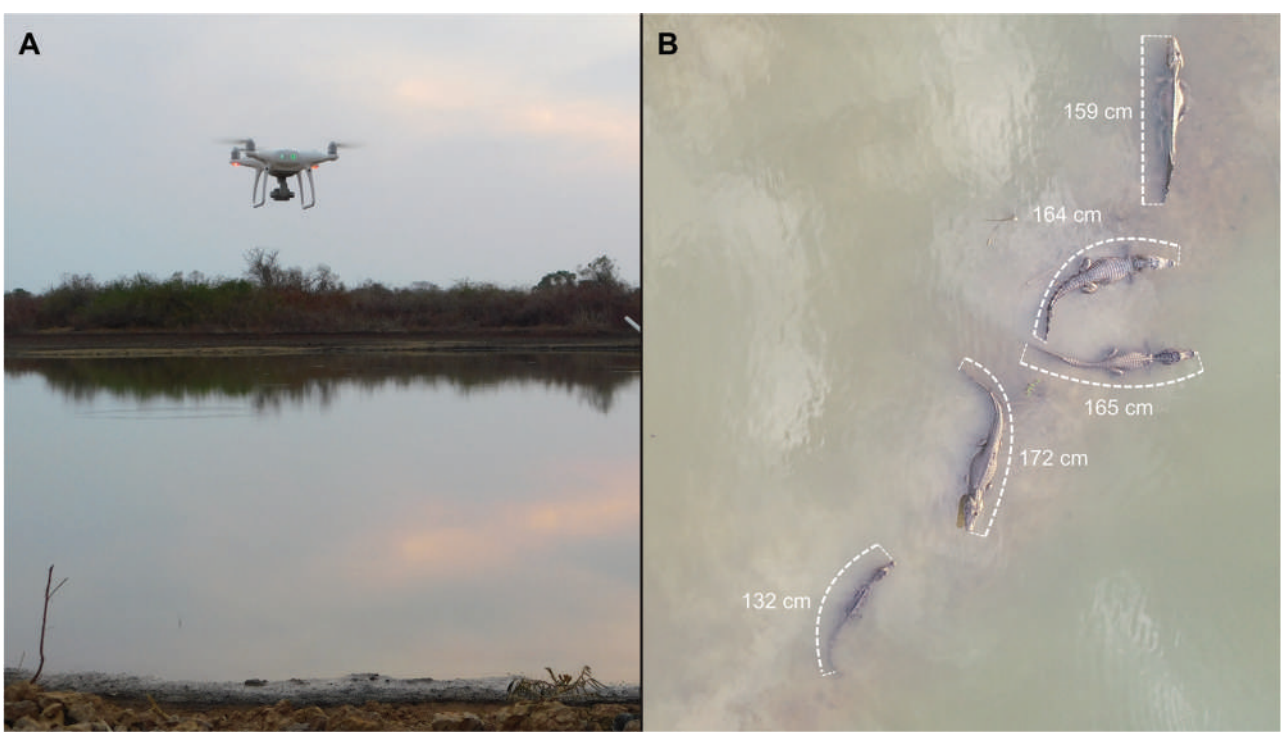

Figure 3. (A) Drone Phantom 4 Pro Plus V2.0 with an integrated camera; (B) Body size measurements taken via ImageJ software.

standing water was absent during the dry season in the Cambarazal, Barrosa, and Ilhazinha bays or during the rising season in Ilhazinha Bay, or when flooded conditions limited access to inner-bay areas in the Barrosa and Ilhazinha bays.

Data analysis

Two drone surveys (morning and afternoon) were conducted in each bay within each hydrological season. Counts recorded in the field were cross-checked against the archived images to resolve uncertain detections and minimize the risk of double counting within a single survey.

For estimates of abundance (N), we retained a single representative count per bay and season: the higher of the two surveys (morning vs afternoon), as proposed by Castillo et al. (2021). This choice assumes that, over the short interval separating the paired surveys in each season, movement of *C. yacare* between bays is negligible and that differences between morning and afternoon counts primarily reflect within-bay variation in detectability driven by short-term environmental conditions (*e.g.* temperature and sun exposure) rather than true changes in abundance. Accordingly, N is treated as the survey that most closely approximates the number of individuals present in each bay in each season. The morning and afternoon counts were neither summed nor treated as independent replicates; instead, the second survey served to capture short-term variability in detectability. To estimate overall density, the number of individuals counted in each season was divided by the total area of the studied bays, assuming that the bays functioned as a connected system during the flood pulse (i.e. periods of widespread inundation and connectivity).

When fully visible in the images obtained by the drone, the total length (TL) of individuals was measured via ImageJ (Schneider et al. 2012) (Figure 3). The measurement scale was calibrated in ImageJ using the 'Set Scale' function on the basis of the known distance between two fixed reference points visible in the imagery. Given that flights were standardized (15 m altitude) and that the drone camera specifications were fixed, this pixel-metric conversion factor (256.6 pixels = 1 m) was then applied to the set of images acquired under the same survey conditions. The TL was traced from the snout tip to the tail tip using the segmented line tool and recorded using the 'Measure' function.

Individuals were classified into size classes based on TL: hatchlings/neonates (≤50 cm), juveniles (51–120 cm), subadults (121–180 cm), and adults (>180 cm), following Aguilera et al. (2008). These labels are used here as operational TL-based size classes rather than direct proxies for age or reproductive status. The reproductive thresholds reported for the southern Pantanal are typically expressed as snout–vent length (SVL); for example, females may experience onset of vitellogenesis at ~55 cm SVL, but nesting is typically reported only at larger sizes (~80 cm SVL), and males reach functional sexual maturity at even larger sizes (~90 cm SVL) (Coutinho 2000). Because SVL excludes the tail, which can represent a substantial fraction of TL (often approaching half of the individual length), we expect SVL-based maturity thresholds to correspond broadly to the upper TL classes; however, we do not convert SVL to TL without dedicated calibration. Accordingly, we use these references only to contextualize the TL-based size classes adopted here, which remain operational categories defined by the measured total length.

The seasonal variation in Caiman counts was evaluated via a generalized linear mixed model (GLMM) with a negative binomial error distribution (nbinom2) and a log link. For each bay and hydrological season, we retained as the representative seasonal count the higher of the two within-season surveys (morning vs afternoon) under the assumption that differences are driven primarily by visibility/detectability rather than movement between bays. The hydrological season was included as a fixed effect, and bay identity was included as a random intercept to account for repeated measurements across seasons. Model adequacy was assessed via simulation-based residual diagnostics (DHARMa), including tests for dispersion and zero inflation (Hartig 2024). Post hoc pairwise comparisons among seasons were derived from estimated marginal means on the response scale with Holm adjustment (Lenth 2025). Analyses were conducted in R (v4.3.3; R Core Team 2024) via the R packages glmmTMB (Brooks et al. 2017), DHARMa (Hartig 2024), and emmeans (Lenth 2025).

To explore whether local environmental conditions were associated with variation in observed counts, we fitted negative binomial GLMMs to counts from all drone surveys (morning and afternoon), including the bay as a random intercept and the hydrological season as a fixed effect, using glmmTMB (Brooks et al. 2017). We then evaluated either the mean water depth or the mean water temperature as an additional standardized continuous predictor. Because environmental measurements were unavailable for some surveys (absence of measurable standing water or limited access to inner-bay areas during flooded conditions), environmental models were fitted to the subset of surveys with nonmissing covariates and should be interpreted cautiously as exploratory, conditional analyses.

The first environmental analysis script initially failed because it relied on optional packages with unmet dependencies and package-update conflicts in the running R session. We used ChatGPT (GPT-5.2 Thinking) to identify and resolve this error. We also used Grammarly to check English grammar and improve clarity during the final manuscript revision. All AI-assisted outputs were reviewed and edited by the authors, who take full responsibility for the final content of the manuscript.

All field data are stored at the INAU Pantanal BioData Center (IPBC), located at the Laboratory of Arthropod Ecology and Taxonomy (LETA), of the Biosciences Institute of the Federal University of Mato Grosso, Cuiabá campus, Mato Grosso, Brazil.

Results

A total of 1,118 *Caiman yacare* individuals were counted throughout the study. The dry season had the highest number of individual records ($N = 598$ individuals; 53.49% of all individual records), followed by the rising ($N = 280$; 25.04%), receding ($N = 238$; 21.29%), and wet ($N = 2$; 0.18%) seasons (Table 1). In all the sampled bays, the presence of the species was detected. Across the hydrological seasons combined, the highest number of individuals recorded was in Baião Bay ($N = 486$; 43.47%), followed by Baiinha Bay ($N = 375$; 33.54%), Pelada Bay ($N = 137$; 12.25%), Cambarazal Bay ($N = 43$; 3.85%), BAPP Bay ($N = 42$; 3.76%), Ilhazinha Bay ($N = 31$; 2.77%), and Barrosa Bay ($N = 4$; 0.36%) (Table 1).

The estimated *C. yacare* density in the sampled bay system was highest in the dry season (34.8 individuals/ha), followed by the rising (16.3 individuals/ha) and receding seasons (13.8 individuals/ha), and was lowest in the wet season (0.1 individuals/ha), as calculated using the total area of the seven sampled bays.

It was possible to measure total length (TL) for 249 individuals who were fully visible in the archived drone images (Table 2). Most TL measurements were obtained during the dry season ($n = 239$), with fewer in the rising season ($n = 10$). Among the measured individuals, 134 (53.8%) were classified as subadults, 105 (42.2%) as juveniles, and 10 (4%) as adults (Table 2), and no hatchlings/neonates were observed. The measured TLs ranged from 56 cm to 254 cm.

The counts varied across the hydrological seasons as shown in Figure 4. The negative binomial GLMM provided a substantially better fit than the Poisson model (AIC 196.1 vs 1071.5) and showed no evidence of residual dispersion (DHARMa dispersion test $p = 0.648$) or zero inflation ($p = 1$). According to the fitted model, the counts in the wet season were markedly lower than those in the dry season (estimate = −5.565 on the log scale; $z = -4.185$; $p < 0.001$), whereas those in the rising and receding seasons did not differ significantly from those in the dry season ($p > 0.18$). On the response scale, the estimated marginal mean count was lowest in the wet season (0.085; 95% CI: 0.005–1.496) and higher in the other seasons (dry: 22.22; rising: 6.48; receding: 74.13), with wide confidence intervals indicating strong

Table 1. Maximum *Caiman yacare* counts per bay and hydrological season from drone surveys with bay areas.

		Season			
Bay	Area (ha)	Dry	Rising	Wet	Receding
Baião	2.44	275	199	1	11
Baiinha	0.32	294	77	1	3
Pelada	2.05	1	4	0	132
Cambarazal	6.57	11	0	0	32
BAPP	1.36	17	0	0	25
Ilhazinha	3.98	0	0	NA*	31
Barrosa	0.47	0	0	0	4

*NA: data not available (bay not surveyed in that season).

Table 2. Number of *Caiman yacare* individuals by body size class* and hydrological season from drone images (2021–2022) collected in Parque SESC Baía das Pedras, northeastern Pantanal, Brazil.

		Seasons			
Body size class	Total length (TL)	Dry	Rising	Wet	Receding
Hatchlings/neonates	TL ≤ 50 cm	0	0	0	0
Juveniles	51 cm ≤ TL ≤120 cm	103	2	0	0
Subadults	121 cm ≤ TL ≤180 cm	130	4	0	0
Adults	181 cm ≤ TL	6	4	0	0
Total		239	10	0	0

*TL-based body size-class thresholds follow Aguilera et al. (2008).

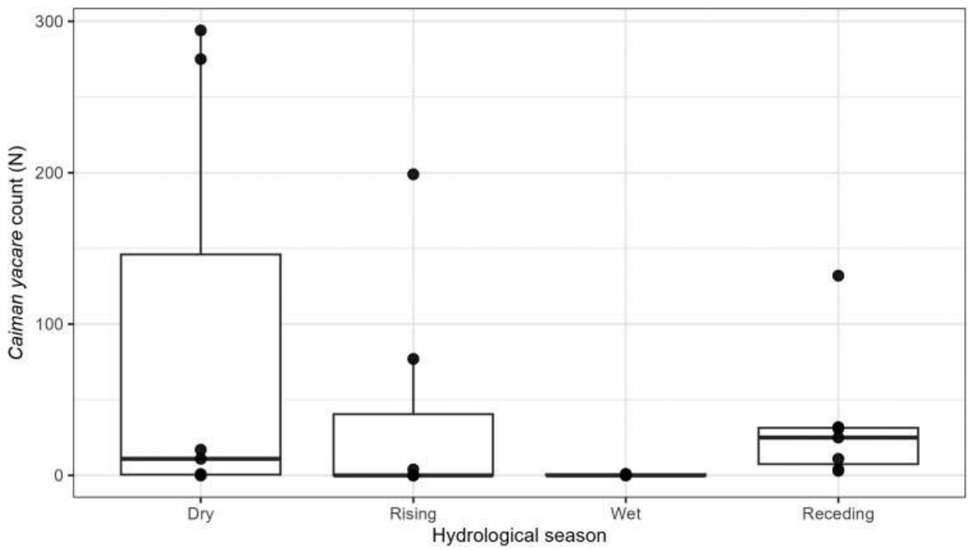

Figure 4. Variation in the number of *Caiman yacare* individuals recorded across hydrological seasons in Parque SESC Baía das Pedras, northeastern Pantanal, Poconé, Mato Grosso, Brazil (2021–2022).

among-bay heterogeneity. This heterogeneity was also captured by the bay-level random intercept in the GLMM (SD = 1.73).

Water temperature was not associated with variation in *C. yacare* counts (estimate = −0.070 on the log scale; SE = 0.184; z = −0.378; $p = 0.705$). In contrast, counts showed a weak positive association with water depth (estimate = 0.439; SE = 0.204; z = 2.155; $p = 0.031$). These results should be interpreted cautiously because environmental covariates were not available for all surveys due to field conditions (e.g. in Cambarazal Bay during the dry season, 11 caimans were recorded, but depth and temperature could not be measured because only mud or a very thin water layer was present) and because missing data are likely not random across seasons and bays.

Discussion

There was marked variation in the number of individuals among the bays, suggesting strong bay-level heterogeneity in habitat suitability and/or detectability. Across all seasons, most records came from Baião and Baiinha. During the dry season, this pattern was especially pronounced, with Baião and Baiinha concentrating most of the records (275 and 294 individuals, respectively), whereas several bays held few or no individuals. This strong spatial concentration is consistent with drought-period aggregation reported for *C. yacare* (Coutinho and Campos 1996; Campos and Mourão 2020), here observed within a small and discrete bay network, in which individuals may remain in (or redistribute toward) bays that retain standing water for longer periods. Because we did not quantify seasonal changes in the water-covered surface area of each bay, we cannot determine whether the dry-season concentration primarily reflects a reduced available habitat area, changes in within-bay detectability, short-distance redistribution among nearby bays, or a combination of these processes. Nonetheless, the substantial bay-level random effect in the seasonal GLMM (SD = 1.73) indicates pronounced and persistent among-bay heterogeneity beyond seasonal differences.

The density of *Caiman yacare* observed in the studied bays during the dry season was greater than that reported in other studies. In two permanent plots of 100 km^2 each, one in an intermittent river area and one in a lake area, Coutinho and Campos (1996) estimated densities through repeated aerial surveys with an ultralight aircraft at different times of the annual cycle (March, early July, late August, and December 1993, and March 1994) conducted in the morning (07:00–09:00) and/or late afternoon (15:00–17:00). They reported densities ranging from 4.3 to 147 individuals/km^2 in river areas and from 1.0 to 26.0 individuals/km^2 in lake areas. Mourão et al. (2000) estimated densities ranging from 5.0 to 61.34 individuals/km^2 across 10 subregions of the Pantanal. Their surveys were conducted during what they classified as the dry season (September–October, 1991–1993), which, under our hydrological season scheme, corresponds to the late dry/early rising transition, using fixed-wing aerial strip transects flown at 60 m altitude and 200 km/h, with a 200-m strip width. Aguilera et al. (2008) estimated densities in oxbow lakes of the Ichilo

River in Bolivia on the basis of nocturnal spotlight counts (October–December 1999 and December 2000), a period that broadly corresponds to the onset of the rainy period, and reported 0.5–10.5 individuals/km of shoreline in 1999 and 0–7.3 individuals/km of shoreline in 2000.

In contrast, our dry-season density estimate (34.8 individuals/ha, i.e. 3,480 individuals/km^2 when expressed on the same area unit) was derived from low-altitude drone surveys (15 m) that produced high-resolution photographic records, allowing postflight verification of uncertain detections and cross-checking against archived images. This difference in survey platform and data verifiability, together with differences in habitat type and spatial scale (a small, discrete, anthropogenic bay system rather than broad river-lake landscapes), likely contributes to the magnitude of the discrepancy. However, direct comparisons of density across studies should still be interpreted cautiously because our surveyed system represents a smaller and environmentally distinct set of water bodies (Figure 2), and methodological differences among studies (e.g. aerial vs spotlight vs drone, time of day, and size classes effectively detectable) may substantially affect detectability and density estimates.

The higher density observed in this study is likely a result of the limited availability of water bodies in the area, the intermittent nature of many of these aquatic habitats, and the relatively long geographical distance of the studied bays from larger, more permanent rivers (approximately 3.6–6.5 km from the Cuiabá River). On the basis of our findings, along with previous estimates, we see that the densities of *C. yacare* vary significantly across their geographical distribution and the types of aquatic habitats they occupy. The elevated concentration of individuals during periods of drought, in contrast with their lower densities in all other seasons in the Pantanal, is well documented (Coutinho and Campos 1996). We note, however, that we did not quantify seasonal changes in the surface extent of each bay and therefore cannot disentangle whether the dry-period concentration reflects a reduced available habitat area, changes in within-bay detectability, or both.

Although water temperature showed no detectable associations with counts in our exploratory analyses, water depth showed a weak positive relationship with the number of individuals recorded. This inference should be treated cautiously because environmental covariates were unavailable for a subset of surveys because of field conditions that were intrinsically linked to hydrology and access (e.g. bays with little or no measurable standing water during the dry season or limited access to inner-bay areas during flooded conditions). Notably, in Cambarazal Bay during the dry season, 11 caimans were recorded under muddy or extremely shallow-water conditions that precluded *in situ* measurements, highlighting that the analyzed subset may not fully represent the full range of environmental states experienced by the bays. It therefore remains plausible that water level, together with other unmeasured factors such as aquatic vegetation cover, surrounding vegetation structure, and food availability, contributes to local density and/or detectability (Ouboter and Nanhoe 1988; Da Silveira et al. 1997; Pereira and Malvásio 2014). Evidence from studies on the congener *Caiman crocodilus* suggests that hydrological conditions and aquatic vegetation cover can be linked to more stable thermal microenvironments, increased refuge availability, and potentially higher prey abundance, which may influence detectability and/or habitat use and, consequently, inferred density (Ouboter and Nanhoe 1988; Da Silveira et al. 1997; Pereira and Malvásio 2014). While these studies address *C. crocodilus*, they provide plausible mechanisms that may also be relevant for *C. yacare*.

The TL-based size structure derived from aerial images was dominated by juveniles and subadults, with few adults and no hatchlings/neonates recorded (Table 2). A similar pattern, where intermediate size classes comprise most detected individuals and large adults are less frequent, has been reported in a previous study of *C. yacare* (Aguilera et al. 2008), suggesting that this may reflect a common demographic and/or detectability pattern for the species. This interpretation is consistent with evidence that aerial survey methods can be size-selective in crocodilians; for example, Mourão et al. (2000) noted limited detectability of smaller individuals in aerial counts of *C. yacare*, highlighting that observed size composition may partly reflect detection constraints rather than true population structure. Importantly, our TL dataset is conditional on aerial visibility: reliable measurements require individuals to be fully exposed and sharply delineated in the images, a condition that occurs predominantly during the dry season, when animals concentrate in the remaining shallow water and are more detectable. In contrast, under higher water-level conditions, individuals tend to disperse and may remain in deeper water or within vegetation, reducing the probability that the whole body is visible for accurate length estimation (Coutinho 2000). In addition, during flood pulses, the water may become darker and more turbid because of decomposing aquatic vegetation and allochthonous inputs, further limiting visual contrast and the feasibility of TL measurements from aerial imagery (Oliveira et al. 2013, 2019). Therefore, the observed body-size composition should be interpreted cautiously as the size structure of detectable individuals under the conditions in which measurements were feasible rather than as a complete, season-independent representation of the population's true size distribution.

The results presented here have the potential to guide research on *C. yacare* by enabling population and behavioral assessments using drones and reducing field effort, time, and operational costs. In our surveys, both counts and body measurements were more effective in the dry season, when individuals were more readily detectable in shallow remaining water. However, dry-season estimates may also be biased by drought-related behaviors, including burying in mud and the use of forested areas as shelters (Campos et al. 2003; Campos and Mourão 2020), which may reduce detectability and alter the observed size composition. In addition, visibility constraints in bays with extensive macrophyte cover can limit both counting and measurement from RGB imagery; in such contexts, complementary approaches such as thermal sensors (*e.g.* microbolometer thermal infrared, TIR) have been proposed to improve detection in difficult habitats (Gray and Gazagne 2023).

Importantly, pilot tests were also performed prior to data collection to verify image quality and assess whether the target species would be disturbed by drone operations. In flights conducted at 15 m altitude, we did not observe stress behaviors in *C. yacare*, which contrasts with the disruptive responses reported for saltwater crocodiles in UAV-based surveys (Bevan et al. 2018). These findings suggest that responses to drone use may depend on factors beyond flight height, including the UAV model and operational profile, as well as species-specific ecology (e.g. foraging mode and sensory cues used during hunting). Overall, although drones are highly useful tools for surveying crocodilians, their effectiveness varies with technical constraints, the behavioral traits of the target species, the habitat structure (including vegetation cover), and the seasonal climatic/hydrological conditions, all of which should be explicitly considered when designing surveys and interpreting results.

Final considerations

This study indicates that low-altitude UAV imagery is a practical and minimally intrusive approach for surveying *Caiman yacare* in bay systems in the Pantanal, with the potential to reduce field effort and costs while enabling standardized monitoring of abundance, density, and body-size structure. To our knowledge, this is among the first UAV-based surveys focused on this species in the Brazilian Pantanal. The performance is season-dependent, as detectability and measurement feasibility are generally higher when animals concentrate in the remaining water during the dry season. Accordingly, UAV-based monitoring should be designed with explicit consideration of hydrological conditions, habitat structure, and species-specific behavior and may benefit from complementary tools (e.g. thermal sensors) where visual detection is constrained. Overall, UAV surveys can support repeated assessments in remote wetlands, provided that technical constraints and seasonal variation in detectability are incorporated into sampling design and interpretation.

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KLS, IAAR, CZF, MIM: Conceptualization; KLS, IAAR, CZF, AST, MIM, MGR: Methodology, Data curation; KLS, IAAR, CZF: Formal analysis, Writing – original draft, Visualization, Investigation; KLS, IAAR, CZF, AST, MIM, MGR: Writing – review & editing; MGR, CZF: Formal analysis (statistical revision and reanalysis); KLS, MIM: Funding acquisition; KLS, MIM: Supervision. All the authors actively participated in the discussion of the results and reviewed and approved the final version of the paper.

Author contributions

CRediT: **Carolline Zatta Fieker:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing; **Italo Afonso Alves Rondon:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing; **Matheus Gonçalves dos Reis:** Data curation, Formal analysis, Methodology, Writing – review & editing; **Ana Silvia Tissiani:** Data curation, Methodology, Writing – review & editing; **Marinez Isaac Marques:** Conceptualization, Data curation, Funding acquisition, Methodology, Supervision, Writing – review & editing; **Karl-L. Schuchmann:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Supervision, Visualization, Writing – original draft, Writing – review & editing.

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Disclosure statement

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ORCID

Carolline Zatta Fieker http://orcid.org/0000-0003-0491-3520
Italo Afonso Alves Rondon http://orcid.org/0009-0003-2187-1657
Matheus Gonçalves dos Reis http://orcid.org/0000-0002-3861-2032
Ana Silvia Tissiani http://orcid.org/0000-0002-5128-2592
Marinez Isaac Marques http://orcid.org/0000-0002-9890-8505
Karl-L. Schuchmann http://orcid.org/0000-0002-3233-8917

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