

Evaluating Key Factors Affecting Drone-Based Detection of Ursine Colobus (*Colobus vellerosus*)

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Abstract: Monitoring arboreal primates in dense tropical forests is challenging due to limited visibility and accessibility. This study examines the effectiveness of RGB drone imaging in detecting *Colobus vellerosus* in the Kikélé Sacred Forest in Benin. We conducted 36 flights using a DJI Mini 3 drone during the dry and wet seasons to test various flight parameters (altitude, speed, angle), environmental factors (season, land cover, contrast), and observer-related factors (observer time and observer identity). The visual data were analyzed using a negative binomial generalized linear mixed model (GLMM), incorporating observer effort and temporal variables. The probability of detection decreased significantly with altitude. However, morning flights and rainy season conditions improved detectability. The time taken for observer analysis had a positive influence on detection results. Behavioral responses varied among the three groups, with active flight and disappearance recorded in the group located deeper within the forest. Our results suggest that *C. vellerosus* was more readily detected from drone imagery at lower flight altitudes under the conditions tested. These results support the integration of drone-based protocols into primate monitoring, including for cryptic arboreal species inhabiting dense forest environments. While limitations remain in terms of visibility and observer subjectivity, this approach offers a promising, non-invasive tool for conservation studies that will likely be further enhanced by the future integration of AI-based detection systems.

Key words: white-thighed colobus, sacred forest of Kikélé, drone, wildlife conservation, remote sensing

INTRODUCTION

Tropical forests, although home to some of the richest biodiversity on the planet, remain among the most difficult environments to inventory due to their dense vegetation, vertical structural complexity, and poor accessibility (Bibby *et al.* 2000; Rovero & Spitale 2016). In sub-Saharan Africa, anthropogenic pressure, particularly linked to agricultural expansion and extensive livestock farming, is leading to rapid deforestation (Gibbs *et al.* 2010; Laurance *et al.* 2014), exacerbating the fragmentation of forest habitats. This fragmentation compromises ecological connectivity, particularly affecting arboreal species whose survival depends on canopy continuity (Junker *et al.* 2012; Betts *et al.* 2017).

These threats highlight the need for reliable information on the distribution and population status of arboreal primates, which is essential for assessing population trends and informing conservation planning (Matsuda Goodwin *et al.* 2020). For *Colobus vellerosus*, population estimates and their reliability are particularly important because the species has experienced substantial population declines and occurs in increasingly fragmented habitats (Wong & Sicotte 2006; Wikberg *et al.* 2024).

Detecting wildlife in forested environments, particularly nocturnal, cryptic or canopy-dwelling species, represents a major challenge for ecologists and biodiversity managers (Burton *et al.* 2015).

Although conventional approaches such as line transects, photographic trapping, and acoustic monitoring have led to notable advances (Effiom *et al.* 2013; Wearn & Glover-Kapfer 2019), they have significant limitations in terms of spatial coverage, temporal resolution and logistical cost, particularly in tropical environments.

Primates are among the most threatened mammalian groups globally, with a large proportion of species facing elevated extinction risk, with habitat loss, hunting, and agricultural expansion among the major drivers of population decline (Chapman *et al.* 2010; Campbell *et al.* 2011; Estrada *et al.* 2022; Basabose *et al.* 2024). Primate populations are undergoing widespread declines across their geographic ranges, driven primarily by habitat loss and fragmentation, hunting, and other forms of anthropogenic pressure (Estrada *et al.* 2022; Garber *et al.* 2024). The white-thighed colobus (*C. vellerosus*), also known as the ‘magistrate colobus’ or ‘Ursine colobus’, exemplifies this conservation concern. The species is currently classified as Critically Endangered on the IUCN Red List, with an inferred population decline of more than 80% over the past three generations, driven primarily by habitat destruction, habitat degradation, and hunting (Matsuda Goodwin *et al.* 2020; Wikberg *et al.* 2024).

Despite this critical status, information on the species’ distribution, population density and population dynamics remains spatially limited (Wong & Sicotte 2006; Wikberg *et al.* 2024).

In light of these constraints, the emergence of remote sensing technologies, particularly unmanned aerial vehicles (UAVs or drones), offers innovative prospects. Equipped with red-green-blue (RGB), thermal infrared or multispectral cameras, drones can rapidly survey large areas and acquire high-resolution imagery, including in difficult-to-access environments (Hodgson *et al.* 2018; Rahman *et al.* 2022). Research has demonstrated their effectiveness in detecting various animal species, including deer, seals, koalas, monkeys, rhinos, and birds (Koh & Wich 2012; Koski *et al.* 2014; Mulero-Pázmány *et al.* 2014; Flores *et al.* 2021; Nago *et al.* 2021; Kpatchia *et al.* 2025). Applications of drones in primate research have expanded beyond the detection of great-ape nests to include direct detection, counting, and behavioral monitoring of arboreal primates using RGB and thermal sensors. Recent studies have investigated drone-based detection of spider monkeys, chimpanzees, baboons, and orangutans, while systematic assessments have also evaluated the potential of thermal drones for monitoring a broad

range of primate species (Wich *et al.* 2023; Gazagne *et al.* 2024; Pinel-Ramos *et al.* 2024; Duporge *et al.* 2025).

Direct detection of wild colobus monkeys from RGB drone imagery remains poorly documented, particularly for *C. vellerosus* in dense West African forest canopies. At the regional scale, this study is part of emerging research in West Africa. In other tropical regions, drone-based primate research has included studies of orangutans in Southeast Asia and arboreal mammals, including primates, in Neotropical rainforest canopies using thermal infrared sensors (Koh & Wich 2012; Kays *et al.* 2019).

The present study, therefore, aimed to evaluate the potential of drone-based RGB imagery for detecting *C. vellerosus* and to identify flight, environmental, and observer-related factors influencing its detectability in the Sacred Forest of Kikélé, Benin.

MATERIAL AND METHODS

Study area

The study was conducted in the sacred forest of Kikélé (9°10'N, 2°28'E), a semi-deciduous forest formation in south-central Benin, characterized by a closed, dense canopy reaching heights of between 20 and 30 m. This forest is home to a residual population of black-and-white colobus monkeys, specifically white-thighed colobus (*C. vellerosus*), a priority species for conservation, endemic to the forests of West Africa. Figure 1 shows the Sacred Forest of Kikélé, Benin, where drone-based surveys of the white-thighed colobus (*Colobus vellerosus*) were conducted.

Data collection

Data were acquired using a DJI Mini 3 (<http://www.dji.com>) drone, a lightweight quadcopter weighing less than 250 g and equipped with a 4K RGB camera. The drone was controlled using the DJI Fly app, which allowed manual adjustment of flight altitude, speed, and flight plan.

Data were collected during two contrasting climatic seasons: the rainy season (July-August) and the dry season (February-March), with nine days of observation per season, to incorporate seasonal variations in primate behavior (Ekaye & Ogoanah 2022).

Before the drone surveys, the entire Sacred Forest of Kikélé was systematically explored on the ground to locate *C. vellerosus* groups and identify their



Figure 1. Geographical location of the Kikélé Sacred Forest in Benin.

resting and foraging areas. This survey identified three groups that were subsequently selected for the drone experiments. Locating the animals before the experimental flights ensured that the target species was present in the surveyed areas and provided a consistent field setting for evaluating the effects of different flight configurations on detectability. A similar approach has been used in recent drone-based primate research, in which flights were conducted over known sleeping sites of spider monkey groups to facilitate the evaluation of flight speed, height, and camera angle (Pinel-Ramos *et al.* 2024). The objective of the present study was not to estimate total population size of *C. vellerosus* in the forest.

The key parameters tested directly in the field were altitude (UA), flight speed, and approach angle of the drone, all factors that may influence animal detection and behavioral responses (Ditmer *et al.* 2015; López & Mulero-Pázmány 2019).

We tested five classes of altitude: 10 m, 20 m, 30 m, 40 m, and 50 m above the canopy. Altitude was calculated for each flight using the equation:

$$UA = AD - HC$$

where AD represents the altitude of the drone relative to the ground, and HC represents the local canopy height, estimated using a laser rangefinder, a method used in similar contexts (Van Andel *et al.* 2015; Christie *et al.* 2016). The protocol always began at the highest altitude, with a gradual descent, to minimise initial disturbances.

Two speeds were tested: hovering (0 m/s) and slow flight at 2 m/s, simulating standard prospecting (Koh & Wich 2012). Two approach angles were applied: a vertical angle (90°) perpendicular to the canopy and an oblique lateral angle (~45°), in order to assess lateral visibility and behavioral responses under different flight profiles (Koh & Wich 2012; Van Andel *et al.* 2015).

For each combination of parameters (altitude, speed, angle), a one-minute video and ten photographs were taken using the on-board camera. Recordings were conducted during two predefined daily observation periods (06:30–09:00 and 16:00–18:00), chosen to represent morning and late-afternoon conditions and to encompass periods when *C. vellerosus* could be observed in the canopy. Previous observations indicated that ursine colobus use sleeping trees during the morning and may

subsequently move to lower canopy strata or the ground as the day progresses (Teichroeb *et al.* 2012).

Each group of colobus monkeys was exposed to several flight configurations, spaced at least 30 minutes apart to limit behavioral bias (Ditmer *et al.* 2015). The flyover sites were identified in advance during ground surveys focused on roosts and foraging areas.

Contrast between *C. vellerosus* and the surrounding canopy was assessed visually from the drone imagery during laboratory annotation. It was categorized into three ordinal levels: 0 = low contrast, when the animal was difficult to distinguish from the surrounding vegetation; 1 = medium contrast, when the animal was distinguishable but partially blended with the background; and 2 = high contrast, when the animal was clearly distinguishable from the surrounding vegetation.

In this study, the variable 'Land cover' refers specifically to the degree of canopy obstruction within the drone imagery, rather than to land cover at the landscape scale. It was assessed visually from the images used for observer analysis and represented the proportion of the viewed canopy area occupied by vegetation that could obstruct the visibility of colobus individuals. Four ordinal categories were used: 1 = 0–25%, 2 = 25–50%, 3 = 50–75%, and 4 = 75–100% canopy obstruction. This index was used to characterize the degree of visual obstruction potentially affecting the detection of colobus individuals in the imagery.

Four observers with experience in visual wildlife identification independently reviewed the drone-acquired images and video sequences. Before the annotation process, all four observers participated in a standardized calibration session using images showing different postures and viewing conditions of *C. vellerosus*. The purpose of the calibration was to harmonize species-identification criteria and reduce observer-related variation during subsequent independent annotations. Each observer then independently examined the same image and video sequences using Timelapse Image Analysis software, without access to the classifications made by the other observers. Additionally, for each image or video sequence, the time of day was categorized as morning or afternoon. Observer time was recorded separately for each observer as the time spent reviewing each image or video sequence, from the beginning of the assessment until the observer completed the review.

To assess the behavioral responses of *C. vellerosus* to drone approaches, responses were recorded during the experimental flights across different flight altitudes. Responses were classified

using a simplified ethogram adapted from Rahman *et al.* (2022) and van Andel *et al.* (2015). Five categories were considered: (1) no reaction, (2) attention directed toward the drone, (3) passive flight (slow movement without vocalization), (4) active flight (rapid movement with agitation), and (5) disappearance (visual loss of individuals). The occurrence of each response was recorded under the different flight altitudes to describe variation in behavioral responses.

To limit biases related to observer subjectivity, a standardized procedure inspired by established protocols, notably those used at the Nazinga hunting ranch by Vermeulen *et al.* (2013) and on avian fauna by Kpatchia *et al.* (2025), was adopted.

Data analysis

We evaluated the influence of Altitude, Contrast, Land cover, Observer time, Time of day, and Season on animal detection, while observer identity was accounted for as a random effect. Table 1 summarises the variables considered in the detection models.

All statistical analyses were conducted in R software (R Core Team 2023).

Multicollinearity among the candidate explanatory variables was assessed using variance inflation factors (VIFs), following Fox & Weisberg (2019). Because Land cover and Contrast were strongly associated with Altitude, these two variables were excluded from the final detection model, while Altitude was retained because it represented the primary flight parameter experimentally manipulated in the study.

A negative binomial generalized linear mixed model (GLMM) was then fitted using the glmmTMB package (Brooks *et al.* 2017) to account for overdispersion in the detection data. Observer identity was included as a random effect to account for between-observer heterogeneity and the repeated assessment of the same imagery by the four observers. Altitude, Observer time, Time of day, and Season were included as fixed effects.

Associations among categorical variables were assessed using Pearson's chi-square tests of independence. These analyses were used to examine associations among the categorical variables recorded during image assessment, including Contrast, Land cover, Season, and Time of day. These tests were conducted separately from the detection model and were used to describe relationships among the recorded environmental and temporal variables.

Potential two-way interactions were considered only when there was an *a priori* ecological or methodological rationale for their inclusion. Given

Table 1. Summary of Predictor Variables for Generalized Linear Mixed Models (GLMM).

Variable	Nature	Levels/Units	Type	Characteristics
Altitude	Continuous	Meter (m)	Independent	Flight parameters
Observer	Categorical	Observer1 - Observer4	Random effect	Observer bias
Observer time	Continuous	Second (s)	Independent	Operational
Times of day	Categorical	Morning and Afternoon	Independent	Temporal
Season	Categorical	Wet, Dry	Independent	Environmental
Contrast	Categorical	High, Low, Middle	Independent	Environmental
Land cover	Categorical	Percentage %	Independent	Environmental
Animal detection	Count	Number of Detection	Dependent	Ecological

the available sample size, models containing a larger number of interaction terms resulted in convergence problems and unstable parameter estimates. The candidate model set was therefore restricted to a limited number of biologically justified two-way interactions, which were subsequently evaluated within the model-selection framework.

Candidate models were compared using an information-theoretic approach based on Akaike's Information Criterion corrected for small sample size (AICc) (Burnham & Anderson 2004; Johnson & Omland 2004). The dredge() function from the MuMIn package (Bartoń 2012) was used to compare the candidate model combinations. Models with $\Delta\text{AICc} < 2$ were considered to have comparable support and were retained for model averaging. To account for model-selection uncertainty, parameter estimates were averaged across these supported models using the model.avg() function from MuMIn, with conditional averaging.

In addition to detection probability, we assessed the behavioral responses of *C. vellerosus* to drone approaches using the predefined ethogram.

Behavioral responses were examined descriptively in relation to flight altitude, speed, and approach angle. Flight speed and approach angle were not included as predictors in the final GLMM; their potential influence on behavioral responses was explored descriptively by summarising the observed responses under the different flight configurations.

RESULTS

Assessment of detection probability as a function of flight and environmental variables

Model comparison based on Akaike's Information Criterion corrected for small sample size (AICc) identified the most parsimonious models explaining variation in detection probability (Table 2). The effects of the retained predictors are presented below. More specifically, observer time had a significant positive effect on detection probability ($\beta = 0.182$, $p < 0.001$), indicating that longer assessment times were associated with a higher probability of detection.

Table 2. Model selection results based on AICc values for the GLMMs evaluating the effects of observer time, altitude, time of day, and season on detection probability of Colobus vellerosus.

	Estimate	Std. Error	Adjusted SE	z value	Pr(> z)	
Intercept	2.33633	0.08299	0.08324	28.066	< 2e-16	***
Observer time	0.18214	0.04072	0.04083	4.461	8.16e-06	***
Altitude20	-0.16654	0.09157	0.09185	1.813	0.06981	.
Altitude30	-0.44715	0.09566	0.09596	4.660	3.16e-06	***
Altitude40	-1.00351	0.10221	0.10253	9.788	< 2e-16	***
Altitude50	-1.48234	0.11020	0.11053	13.411	< 2e-16	***
Times of day Morning	0.45469	0.06283	0.06303	7.214	< 2e-16	***
Season Rainy	0.20154	0.07657	0.07681	2.624	0.00869	**

In contrast, altitude had a significant negative effect on detection probability ($\beta = -0.447$, $p < 0.001$). This effect was most pronounced at 40 m (Estimate = -1.003 , $p < 0.001$) and 50 m (Estimate = -1.482 , $p < 0.001$), indicating that higher altitudes reduce the detectability of black-and-white colobus. Regarding time of day, observations conducted in the morning were associated with a significantly higher probability of detection ($\beta = 0.455$, $p < 0.001$). Detection probability was also significantly higher during the rainy season ($\beta = 0.202$, $p = 0.0087$) (Figure 2).

In addition to the regression analyses, Pearson's chi-square tests of independence were used to examine associations among the categorical variables. First, a strong dependence was recorded between contrast and land cover ($\chi^2 = 71.53$, $df = 6$, $p < 0.001$). This significant association indicates that the observer-assessed contrast between the colobus and the surrounding canopy was related to the degree of canopy obstruction recorded in the drone imagery. In addition, a significant association was found between contrast and season ($\chi^2 = 21.33$, $df = 2$, $p < 0.001$), indicating that contrasts vary according to the season. Another marked dependence was detected between land cover and season ($\chi^2 = 59.2$, $df = 3$, $p < 0.001$). Finally, no significant association was found between the time of day and contrast ($\chi^2 = 0.997$, $df = 2$, $p = 0.608$).

Behavioral reactions of colobus to drone flight configurations

A total of 36 drone flights were conducted over three groups of *C. vellerosus* in the sacred forest of Kikélé, including 21 vertical flights and 15 horizontal flights. Five types of behavioral responses were considered *a priori*: no reaction, attention directed toward the drone, passive flight (slow movement without vocalization), active flight (rapid movement with agitation), and disappearance (loss of visual contact with individuals). No reaction was recorded among the 31 individuals assessed during the experimental flights (0%).

Among the 31 individuals assessed, 15 (48.4%) directed their attention toward the drone, characterized by a cessation of activity and visual orientation toward the drone. This behavior was observed at altitudes ranging from 25 to 35 m, at a flight speed of 2 m/s and an approach angle of 90°, with recorded response times ranging from 3 to 5 s.

Passive flight was observed in 8 individuals (25.8%), who moved slowly or changed position without apparent agitation. This response was

observed at an altitude of 18 m, a flight speed of 2 m/s and an approach angle of 45°, with recorded response times of 2–3 s.

Active flight was observed in 5 individuals (16.1%). These responses occurred at altitudes below 20 m and at a flight speed of 2 m/s under both approach angles, with a recorded response time of approximately 2 s.

Disappearance from the camera field of view was recorded for 3 individuals (9.7%). These responses occurred at altitudes below 20 m, at a flight speed of 2 m/s and under both approach angles.

DISCUSSION

Our study aimed to explore the combined effects of several drone flight, environmental and operational parameters, including altitude, speed, approach angle, contrast, land cover, time of day, season and observer effects on the visual detection and behavioral responses of the black-and-white colobus monkey (*C. vellerosus*) in the sacred forest of Kikélé, Benin. By combining visual observations from experimental flights with standardized behavioral analysis, we identified flight and observational conditions associated with variation in detection probability and described behavioral responses to drone approaches. This study is part of a broader trend in developing non-invasive tools for primate conservation, where drones offer a promising compromise between accessibility, accuracy, and ecological impact.

We found that altitude was inversely correlated with the probability of visual detection of individuals. This finding is consistent with the general relationship between increasing sensor-target distance and reduced detection performance reported in drone-based wildlife surveys (Hodgson *et al.* 2018). At an altitude of 10 to 20 m above the canopy, the contrasting morphology of colobus monkeys (black-and-white coat) remains relatively visible. At higher altitudes, the smaller apparent size of individuals and increasing visual obstruction may reduce their detectability in the imagery.

The seasonal effect, although more subtle, was also significant: detection probability was higher during the rainy season. Food-resource distribution and its implications for feeding behavior have been studied specifically in *C. vellerosus* (Saj & Sicotte 2007). Seasonal changes in food availability or canopy use may have contributed to the higher detection probability observed during the rainy season in our study. Differences in illumination between seasons may also have affected the visual

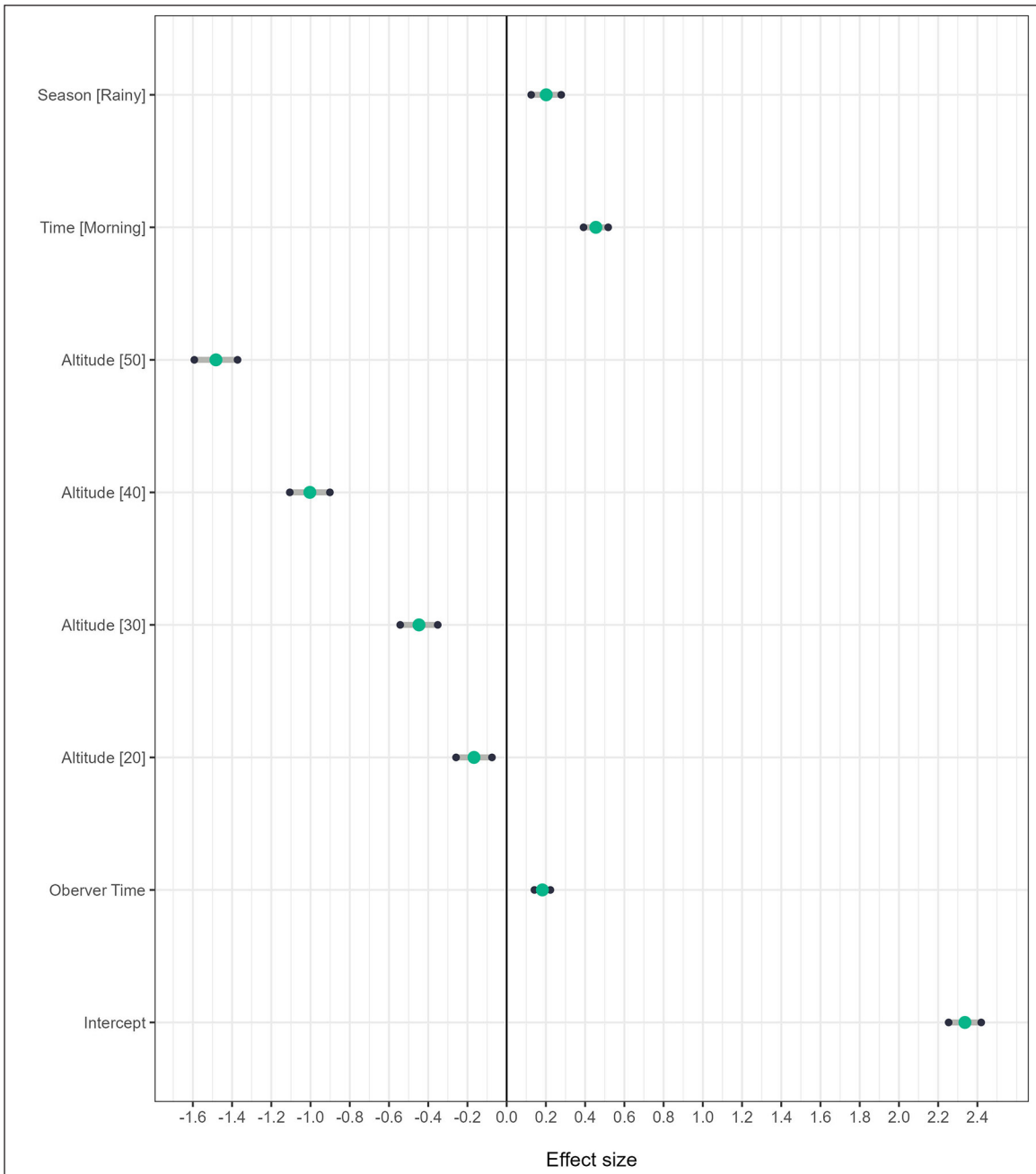


Figure 2. Estimated effect sizes of the predictors influencing the detection probability of *Colobus vellerosus*, as obtained from the GLMM.

contrast between individuals and the surrounding canopy. However, because food availability, canopy use, and illumination were not measured directly, these explanations remain tentative.

The behavioral observations also indicated variation in responses under the different approach angles. Because approach angle was not included as a predictor in the final detection GLMM, these observations should be interpreted descriptively rather than as evidence of a statistically tested effect

on detection probability. Oblique shots ($\sim 45^\circ$) may provide complementary views of individuals in areas with irregular canopy structure, although this potential advantage was not tested statistically in the present study.

With regard to flight speed, behavioral observations were recorded under hovering and slow-flight conditions. Because flight speed was not included as a predictor in the final detection GLMM, its potential influence on detection cannot

be inferred statistically from the present analysis. The observed behavioral responses under the tested flight configuration nevertheless provide descriptive information that can inform future experiments designed specifically to test the effects of flight speed. This is consistent with observations reported by Rahman *et al.* (2022), showing that slow movement speeds could be used effectively, relative to still shots, without significant loss of information, while reducing the flight time needed to cover large areas.

Time of day was also associated with detection probability. Observations made between 06:30 and 09:00 had a significantly higher probability of detection than those made at the end of the day. This higher detectability may be related to the daily activity and ranging pattern of *C. vellerosus*. Teichroeb *et al.* (2012) reported that groups generally remained in their sleeping trees for a period after sunrise before moving toward feeding areas. Individuals remaining in the upper canopy during the early morning may therefore be easier to detect from drone imagery than later in the day, when groups may become more dispersed or move into denser vegetation.

From a behavioral point of view, the responses of the colobus to drone approaches varied among individuals and flight conditions. Attention toward the drone and passive flight were the most frequently recorded responses, accounting for 15 (48.4%) and 8 (25.8%) of the 31 individuals assessed, respectively. These responses indicate that attention and movement responses were more frequently recorded than disappearance from the camera field of view. Similar variation in primate responses to drone approaches has been reported by Rahman *et al.* (2022), highlighting the importance of flight conditions and species-specific behavioral responses when assessing potential disturbance. However, because behavioral responses in the present study were assessed descriptively, these patterns should be interpreted cautiously.

Behavioral responses also differed among the three groups. The two groups located near the forest edge and human dwellings showed predominantly attention and passive-flight responses, whereas active flight and disappearance were recorded in the group located deeper within the forest. These differences may reflect variation among groups in their previous exposure to human activity, habitat context, group-specific behavior, or other unmeasured factors. However, because previous exposure to humans was not quantified in this study, we cannot attribute the observed differences specifically to habituation.

Recent advances in drone-based image analysis also offer promising opportunities for improving

the scalability of primate monitoring. Duporge *et al.* (2025) for example, developed the BaboonLand dataset to support automated detection and behavioral recognition of baboons from drone videos. Similarly, Delplanque *et al.* (2022) demonstrated the potential of convolutional neural networks for detecting and identifying African mammals in aerial imagery. These developments suggest that the image and video datasets generated through drone surveys could eventually support semi-automated or automated detection of arboreal primates. However, in structurally complex forest canopies, human interpretation remains important for validating detections and dealing with partially obscured individuals.

For future RGB-drone surveys of arboreal primates, our findings highlight the importance of standardizing flight altitude, survey timing, observer procedures, and image interpretation. Under the conditions tested in the present study, lower flight altitudes were associated with higher detection probability, while morning surveys were associated with higher detection probability. Flight speed and approach angle should also be considered when designing future behavioral studies, although their effects on detection probability were not evaluated in the final GLMM in the present study. Behavioral responses should be monitored during drone operations so that flight protocols can be adapted when strong responses occur. Recent work on RGB-camera drones for monitoring arboreal mammals in tropical forests similarly highlights the importance of canopy structure and flight design for detection success (Pinel-Ramos *et al.* 2025).

More broadly, RGB drones may be most useful when integrated with complementary approaches, such as thermal sensors or automated image analysis, to improve the monitoring of threatened arboreal mammals in structurally complex forests.

CONCLUSION

Our study demonstrates the potential of drone-based surveys for detecting *C. vellerosus* in dense tropical forest under the conditions tested. Flight altitude was an important predictor of detection probability, with detection decreasing at higher altitudes. Detection probability was also higher during morning observations and during the rainy season, although these effects should be interpreted in relation to the environmental and behavioral conditions of the study site. Behavioral responses to drone approaches varied among individuals and flight conditions, with attention and passive flight

being the most frequently recorded responses, while active flight and disappearance were observed at lower altitudes.

These findings highlight the importance of carefully selecting flight altitude and timing when designing drone-based surveys of arboreal primates. Although our results were obtained from *C. vellerosus* in a single forest, they provide a methodological basis for further studies of this species and may inform future surveys of other black-and-white colobus species. Further studies across species, habitats, and seasons are needed to determine how generalisable these relationships are and to refine flight protocols for primate monitoring.

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REFERENCES

- Basabose, A. K., E. M. Mihingano, M. B. Myakabeji, M. K. Bibentyo, S. M. Bazibuhe & M. B. Mambo. 2024. Confirmed presence of a small, isolated population of *Cercopithecus mitis* on Idjwi Island, Democratic Republic of Congo. *African Primates* 18: 9–18.
- Bartoń, K. 2012. *MuMIn: Multi-Model Inference*. R package version 1.7.7.
- Betts, M. G., C. Wolf, W. J. Ripple, B. Phalan, K. A. Millers, A. Duarte, S. H. M. Butchart and T. Levi. 2017. Global forest loss disproportionately erodes biodiversity in intact landscapes. *Nature* 547: 441–444.
- Bibby, C. J., M. Jones & S. Marsden. 2000. *Expedition Field Techniques: Bird Surveys*. BirdLife International.
- Brooks, M. E., K. Kristensen, K. van Benthem, A. Magnusson, C. W. Berg, A. Nielsen, H. J. Skaug, M. Mächler & B. M. Bolker. 2017. glmmTMB balances speed and flexibility among packages for zero-inflated generalized linear mixed modeling. *R Journal* 9: 378–400.
- Burnham, K. P. & D. R. Anderson. 2004. Multimodel inference. *Sociological Methods & Research* 33: 261–304.
- Burton, A. C., E. Neilson, D. Moreira, A. Ladle, R. Steenweg, J. T. Fisher, E. Bayne & S. Boutin. 2015. Wildlife camera trapping: a review and recommendations for linking surveys to ecological processes. *Journal of Applied Ecology* 52: 675–685.
- Campbell, G., H. Kuehl, A. Diarrassouba, P. K. Ngoran & C. Boesch. 2011. Long-term research sites as refugia for threatened and over-harvested species. *Biology Letters* 7: 723–726.
- Chapman, C. A., T. T. Struhsaker, J. P. Skorupa, T. V. Snaith & J. M. Rothman. 2010. Understanding long-term primate community dynamics: implications of forest change. *Ecological Applications* 20: 179–191.
- Christie, K. S., S. L. Gilbert, C. L. Brown, M. Hatfield & L. Hanson. 2016. Unmanned aircraft systems in wildlife research: current and future applications of a transformative technology. *Frontiers in Ecology and the Environment* 14: 241–251.
- Delplanque, A., S. Foucher, P. Lejeune, J. Linchant & J. Théau. 2022. Multispecies detection and identification of African mammals in aerial imagery using convolutional neural networks. *Remote Sensing in Ecology and Conservation* 8: 166–179.
- Ditmer, M. A., J. B. Vincent, L. K. Werden, J. C. Tanner, T. G. Laske, P. A. Iaizzo, D. L. Garshelis & J. R. Fieberg. 2015. Bears show a physiological but limited behavioral response to unmanned aerial vehicles. *Current Biology* 25: 2278–2283.
- Duporge, I. et al. 2025. BaboonLand dataset: tracking primates in the wild and automating behaviour recognition from drone videos. *International Journal of Computer Vision* 1: 1–8.
- Effiom, E. O., G. Nuñez-Iturri, H. G. Smith, U. Ottosson & O. Olsson. 2013. Bushmeat hunting changes regeneration of African rainforests. *Proceedings of the Royal Society B: Biological Sciences* 280: 1–8.
- Ekaye, S. A. & S. O. Ogoanah. 2022. Seasonal variation, diversity and population dynamics of four species of monkey in Okomu National Park. *Journal of Research in Forestry* 14: 1–10.
- Estrada, A. et al. 2022. Global importance of Indigenous Peoples, their lands, and knowledge systems for saving the world's primates from extinction. *Science Advances* 8:1–19.
- Flores, D., I. González-Hernández, R. Lozano, J. M. Vazquez-Nicolas & J. L. H. Toral. 2021. Automated agave detection and counting using a convolutional neural network and unmanned aerial systems. *Drones* 5: 1–17.
- Fox, J. & S. Weisberg. 2019. *An R Companion to Applied Regression*. 3rd ed. Sage Publications, Davis.
- Garber, P. A. et al. 2024. Global wildlife trade and trafficking contribute to the world's nonhuman primate conservation crisis. *Frontiers in Conservation Science* 5: 1–17.
- Gazagne, E., R. J. Gray, S. Wich, A. Hambuckers & F. Brotcorne. 2024. Development of a global thermal

- detection index to prioritize primate research with thermal drones. *Scientific Reports* 14: 1–12.
- Gibbs, H. K., A. S. Ruesch, F. Achard, M. K. Clayton, P. Holmgren, N. Ramankutty & J. A. Foley. 2010. Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. *Proceedings of the National Academy of Sciences of the United States of America* 107: 16732–16737.
- Hodgson, J. C. *et al.* 2018. Drones count wildlife more accurately and precisely than humans. *Methods in Ecology and Evolution* 9: 1160–1167.
- Johnson, J. B. & K. S. Omland. 2004. Model selection in ecology and evolution. *Trends in Ecology & Evolution* 19: 101–108.
- Junker, J. *et al.* 2012. Recent decline in suitable environmental conditions for African great apes. *Diversity and Distributions* 18: 1077–1091.
- Kays, R., J. Sheppard, K. Mclean, C. Welch, C. Paunescu, V. Wang, G. Kravitz & M. Crofoot. 2019. Hot monkey, cold reality: surveying rainforest canopy mammals using drone-mounted thermal infrared sensors. *International Journal of Remote Sensing* 40: 407–419.
- Koh, L. P. & S. A. Wich. 2012. Dawn of drone ecology: low-cost autonomous aerial vehicles for conservation. *Tropical Conservation Science* 5: 121–132.
- Koski, W. R., T. A. Thomas, D. W. Funk & A. M. Macrander. 2014. Marine mammal sightings by analysts of digital imagery versus aerial surveyors: a preliminary comparison. *Journal of Unmanned Vehicle Systems* 1: 25–40.
- Kpatchia, E. J., S. G. A. Nago, O. A. H. Gado, F. Bahleman & H. Oebel. 2025. Potential of drones for avian ecological monitoring in West African mangrove ecosystems. *Open Journal of Ecology* 15: 359–373.
- Laurance, W. F. *et al.* 2014. A global strategy for road building. *Nature* 513: 229–232.
- López, J. J. & M. Mulero-Pázmány. 2019. Drones for conservation in protected areas: present and future. *Drones* 3: 1–23.
- Matsuda Goodwin, R., S. Gonedelé Bi, G. Nobimè, I. Koné, D. Osei, G. Segniagbeto & J. F. Oates. 2020. *Colobus vellerosus*. *The IUCN Red List of Threatened Species* 2020: e.T5146A169472127. <https://doi.org/10.2305/IUCN.UK.2020-2.RLTS.T5146A169472127.en>
- Mulero-Pázmány, M., R. Stolper, L. D. Van Essen, J. J. Negro & T. Sassen. 2014. Remotely piloted aircraft systems as a rhinoceros anti-poaching tool in Africa. *PLoS ONE* 9: 1–10.
- Nago, S. G. A. *et al.* 2021. Utilisation de drone pour le suivi écologique de la faune dans un ranch au Nord Bénin. *International Journal of Innovation and Applied Studies* 32: 291–302.
- Pinel-Ramos, E. J., F. Aureli, S. Wich, S. Longmore & D. Spaan. 2024. Evaluating thermal infrared drone flight parameters on spider monkey detection in tropical forests. *Sensors* 24: 1–19.
- Pinel-Ramos, E. J., F. Aureli, S. Wich, F. Rodrigues de Melo, C. Rezende, F. Brandão, F. C. S. Alves de Melo & D. Spaan. 2025. An assessment of the effectiveness of RGB-camera drones to monitor arboreal mammals in tropical forests. *Drones* 9: 1–23.
- R Core Team. 2023. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria.
- Rahman, D. A., A. B. Y. Sitorus & A. A. Condro. 2022. From coastal to montane forest ecosystems, using drones for multi-species research in the tropics. *Drones* 6: 1–31.
- Rovero, F. & D. Spitalé. 2016. Camera trapping for biodiversity assessment in tropical forests: A review of field methods and results. *Biodiversity Monitoring and Conservation* 6: 100–128.
- Saj, T.L. & P. Sicotte. 2027. Predicting the competitive regime of female *Colobus vellerosus* from the distribution of food resources. *International Journal of Primatology* 28: 315–336. <https://doi.org/10.1007/s10764-007-9124-x>
- Teichroeb, J. A., T. D. Holmes & P. Sicotte. 2012. Use of sleeping trees by ursine colobus monkeys (*Colobus vellerosus*) demonstrates the importance of nearby food. *Primates* 53: 287–296.
- van Andel, A. C., S. A. Wich, C. Boesch, L. P. Koh, M. M. Robbins, J. Kelly & H. S. Kuehl. 2015. Locating chimpanzee nests and identifying fruiting trees with an unmanned aerial vehicle. *American Journal of Primatology* 77: 1122–1134.
- Vermeulen, C., P. Lejeune, J. Lisein, P. Sawadogo & P. Bouché. 2013. Unmanned aerial survey of elephants. *PLoS ONE* 8: 1–7.
- Wearn, O. R. & P. Glover-Kapfer. 2019. Snap happy: camera traps are an effective sampling tool when compared with alternative methods. *Royal Society Open Science* 6: 1–13.
- Wich, S. A., N. Bonnin, A. Hutschenreiter, A. K. Piel, A. Chitayat, F. A. Stewart, L. Pintea & J. T. Kerby. 2023. Using drones to determine chimpanzee absences at the edge of their distribution in Western Tanzania. *Remote Sensing* 15: 1–11.
- Wikberg, E. C., E. Glotfelty, B. Adu Yeboah, R. Koranteng, C. Kodom, B. Owusu Antwi & A. Boahen. 2024. Predictors of population estimates of the Critically Endangered white-thighed black-and-white colobus *Colobus vellerosus*. *Primate Conservation* 38: 83–94.
- Wong, S. N. P. & P. Sicotte. 2006. Population size and density of *Colobus vellerosus* at the Boabeng-Fiema Monkey Sanctuary and surrounding forest fragments in Ghana. *American Journal of Primatology* 68: 465–476.

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