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Potential of Drones for Avian Ecological Monitoring in West African Mangrove Ecosystems

Essoham Joël Kpatchia[1,2*], Sedjro Gilles Armel Nago[1,2,3], Oumar Abdul Haddy Ayodélé Gado[1,3], Farid Bahleman[1,4], Horst Oebel[5]

[1]Laboratory of Ecology, Botany and Plant Biology, University of Parakou, Parakou, Benin
[2]Doctoral School of Agronomy and Water Sciences, University of Parakou, Parakou, Benin
[3]Faculty of Agronomy, University of Parakou, Parakou, Benin
[4]SOS Savane NGO, Tanguiéta, Benin
[5]Programme RBT-WAP/GIZ, Natitingou, Benin
Email: *kpatchia2015@gmail.com

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Abstract

Bouche du Roy, a community mangrove ecosystem in the RAMSAR 1017 site in Benin, is important for bird conservation. However, it faces many anthropogenic threats. Conservation efforts have been made since its inception, but managers face major constraints. Ecological monitoring is costly and material resources are constantly in short supply, making repeated operations difficult. Recently, drone technology has emerged as an effective tool for wildlife monitoring, particularly in inaccessible areas. The aim of this study was to assess the potential of drones for ecological monitoring of avian biodiversity in the mangrove ecosystems of the Bouche du Roy in Benin. In order to maximize the chances of detecting avian species by drone, an optimization of the flight parameters made it possible to recommend a flight altitude of 10 to 20 m, a flight speed of (2 to 4 m/s), a varied approach angle including vertical approaches for nesting birds of (20˚ to 60˚) and horizontal approaches for flying or moving birds of (90˚), an optimal visual contrast (morning or late afternoon) and the need for observer training to minimize observer bias. By applying the parameters identified in this study, our results show that the use of drones can be an effective methodological approach for monitoring avian biodiversity in West African mangrove ecosystems. This innovative approach provides a practical and cost-effective solution to the challenges posed by traditional monitoring methods, thus ensuring better conservation of biodiversity in mangrove ecosystems.

Keywords

Avian Biodiversity, Drone Technology, Ecological Monitoring, Wetlands, Conservation Efforts

1. Introduction

Wetlands are recognized worldwide as one of the most productive ecosystems [1]. They represent approximately 4% to 6% of the Earth's surface and offer enormous opportunities for sustainable development [2]. In Benin, wetlands are characterized by a diversity of nutrient-rich natural habitats that support the establishment and growth of many animal species [3]. These areas are critically important as feeding, shelter, nesting and wintering areas for many bird species [4] [5]. Bouche du Roy, one of the wetlands in Benin, is an area of importance for bird conservation [4]. Located in the Mono Delta Biosphere Reserve, Bouche du Roy is an exceptionally rich mangrove ecosystem, home to a remarkable array of bird species. As an integral part of Ramsar site 1017, it plays a valuable role as a feeding, nesting and resting area for many resident and migratory species, some of which are rare or threatened [3]. This ecosystem also supports a variety of other taxa (fish, reptiles, mammals) and provides essential ecological services such as flood regulation and carbon sequestration [4].

However, they are threatened by degradation and overexploitation related to human activities such as fishing, agriculture, logging and salt production [6] and uncontrolled settlement and occupation of coastal areas [4]. A study by Azonningbo *et al.* [3] on the specific diversity of avifauna in the wetlands of southwestern Benin, revealed the presence of 217 species of resident and migratory birds [3]. About 41.47% of the species recorded in this area are associated with open habitats. As birds are considered reliable indicators of environmental change in wetlands [7], this abundant presence of birds adapted to open environments reflects the increasing environmental degradation associated with urbanization and agricultural practices [3]. As a result, their condition is strongly affected by this degradation. Therefore, there is a need for accurate and effective monitoring of bird populations and wetland ecosystems. Then, the Bouche du Roy Community Biodiversity Conservation Area was created in 2016 and classified under IUCN Management Category VI, whose main objective is the sustainable use of ecosystems based on local management initiatives.

Despite the conservation efforts often made by managers in these ecosystems, there is still a problem with monitoring, as traditional methods based on line surveys and point counts carried out with the naked eye, binoculars or telescopes [8] are quite time-consuming, tedious and infrequent due to the logistics and high costs associated with these activities, which are difficult to repeat [9]-[12]. These inventory methods are subject to observation bias due to various factors, such as eco-ethological factors [13]. It is therefore important to develop new conservation methods that are effective, affordable and versatile in order to facilitate data collection and gain a better understanding of the processes involved in the conservation of these resources.

In recent years, technological advances have opened up new possibilities for more effective monitoring and management of ecosystems. Among these advances, the use of drones has attracted increasing interest [14]-[16]. Unmanned aerial vehicles (UAVs) have proven to be effective tools for collecting remote sensing data at precise spatial and temporal scales in the study of flora and fauna [17] [18]. Their ability to rapidly cover large areas and collect high-resolution imagery makes them promising tools for ecosystem and wildlife monitoring [19] [20].

In addition, their use allows access to areas that were previously difficult for traditional methods [12] [21] [22]. Compared to helicopters and microlights, UAVs are considered a cheaper and safer option with a minimal environmental footprint [23] [24]. Small-scale experimental studies carried out by these authors [8] [12] have demonstrated the applicability of an unmanned aerial vehicle and mapping software for monitoring fauna and their habitats.

The work of Hodgson and Koh [25] demonstrated that drones enable accurate monitoring of seabird colonies in Australia, outperforming ground-based counts through accumulated resolution, highlighting their potential for ecosystems such as West African mangroves. Similarly, Linchant *et al.* [18] synthesised the successes and challenges of drones in African wildlife monitoring, highlighting their low cost and ability to overcome logistical constraints in remote areas. Furthermore, De Almeida *et al.* [26] used UAVs equipped with hyperspectral and LiDAR sensors to monitor tropical forest restoration, demonstrating their versatility for biodiversity analysis in complex habitats.

The drone is therefore seen as a new, efficient approach that could enhance studies in areas of interest such as wetlands, which are suffering from degradation and where studies are rare due to lack of suitable logistics [13] [27]. This study, entitled "Potential of drones for avian ecological monitoring in West African mangrove ecosystems", aims to assess the effectiveness of this technology for the conservation of waterbirds. Specifically, it aims to assess the key parameters that influence the detection of waterbirds by drones.

2. Material and Methods

2.1. Study Area

The study was carried out in southern Benin, in the Bouche du Roy protected area, which is an integral part of the Mono Delta Biosphere Reserve. It is located between 6˚16' and 6˚17' north latitude and 1˚54' and 1˚57' east longitude. Consisting of part of the coastal lagoon, a barrier beach and two estuaries, one natural (06˚17.694'N, 001˚54.935'E) and the other artificial (06˚17.879'N, 001˚55.937'E), this area is located in the western complex between Djondji and Avlo in the commune of Grand-Popo (Mono department). It is part of Ramsar site 1017. **Figure 1** shows the geographical location of the Bouche du Roy.

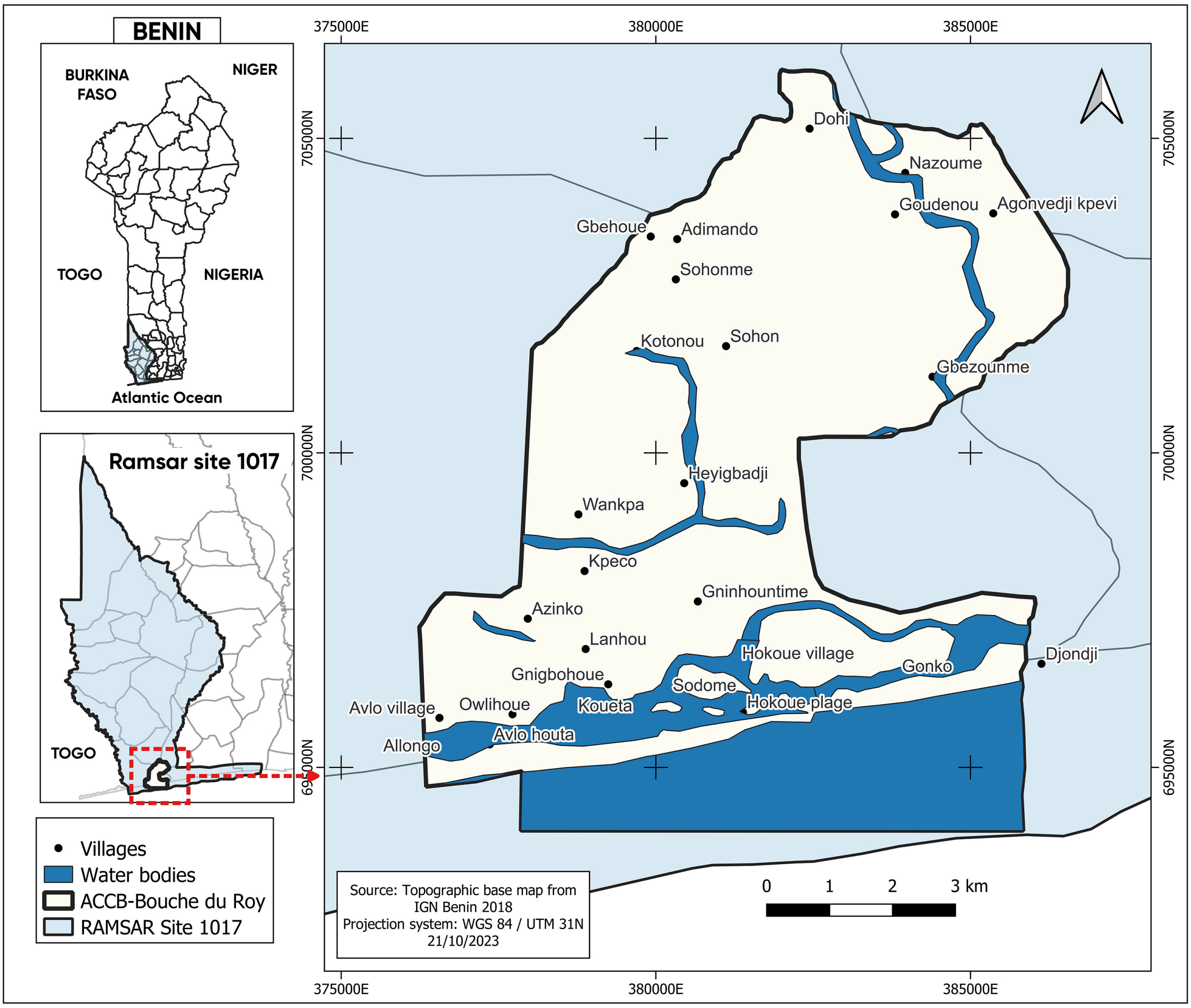

Figure 1. Geographical location of the Bouche du Roy.

2.2. Material

The main device used in this study is the DJI Phantom 4pro (http://www.dji.com), a popular civilian drone widely used for its stable flight characteristics and advanced features. It has a compact design with a sturdy body and carrying case. Equipped with a high-resolution 12-megapixel camera capable of filming in 4 K, it guarantees sharp, stable images thanks to a three-axis stabilizer. The drone has vision sensors to avoid obstacles and several intelligent flight modes, including Follow Me and ActiveTrack. Its intelligent battery provides about 28 minutes of autonomy, and its remote control gives precise control with a live view. Compatible with the DJI GO application for easy mission planning and software integration.

2.3. Methods

2.3.1. Data Collection

We began our study with an exploratory survey aimed at identifying avian hotspots biodiversity. The selection of bird biodiversity hotspots was carried out in two complementary stages to ensure representative coverage of habitats and optimal species coverage. First, a preliminary analysis was carried out by combining data from the existing scientific literature on the distribution of birds in Ramsar site 1017 [5] [28] with recent satellite imagery (from Google Earth) to identify areas of dense mangroves, lagoon margins and flooded habitats known to support high concentrations of birds [3]. Criteria used included: 1) reported presence of nesting or feeding sites in local reports, 2) dense vegetation cover indicating habitat potential for target species, and 3) relative accessibility for drone overflights, with concern for overly urbanised or hazardous areas. Secondly, exploratory field observations were carried out to validate these pre-selected areas. During these visits we looked for visual and auditory signs of bird activity (nests, songs, gatherings) to confirm the presence of hotspots. This exploratory phase allowed us to select representative areas for drone flights.

Once the hotspots were identified, we planned a series of hover flights over these areas. We used a DJI Phantom 4pro drone equipped with high-resolution cameras to maximize bird detection, a method already used by some authors [12] [29] for drones ecological wildlife monitoring [12] [29]. Each flight lasted between 1 to 3 min, and we covered a variety of habitats, including mangrove edges, above mangroves, and flooded areas.

The altitude and approach distance of the drone in relation to the birds were the key parameters of our study, tested directly in the field. We tested a range of altitudes, starting at 100 meters and gradually descending to the optimum altitude for counting. This altitude was chosen within the range of 60 to 100 meters, which is the usual counting altitude using light aircraft [30] for wildlife monitoring. At the same time, we varied the approach distance with an interval of 10 meters. During this flight, a video was started and a photo was taken at each interval. The aim was to approach the birds to determine the minimum distance at which they would react. In addition to altitude and distance, we tested different approach angles (vertical and horizontal) (20˚, 60˚, 90˚) and flight speeds (2 $m \cdot s^{-1}$, 4 $m \cdot s^{-1}$, 6 $m \cdot s^{-1}$) to determine the most discrete approach and speed for tracking birds in isolated situations or in colonies during nesting or not.

Bird responses were classified into three categories: (0) no response, (1) flight movements without flight, and (2) flight.

The contrast parameter, based on the intensity of the luminosity of the landscape and the colour of the species' plumage, was assessed in the laboratory directly on the images by observers, based on the effect of contrast on the observers' vision for the detection of birds. This intensity was also classified into three categories: (0) low intensity, (1) middle intensity, (2) high intensity. For this study, the wind speed (up to 18 km/h), which was recorded at one nanometer, did not interfere with flight operations or bird detection.

2.3.2. Data Analyses

To minimize the bias associated with the observer effect, we followed an approach similar to that described in Nazinga Game Ranch [15]. Four experienced observers, all professionals in the field, were selected to participate in this study. These observers were given prior training, consisting of the projection of images of the different bird species encountered in different postures. The aim of this training was to test and improve their visual recognition skills and to standardise their species recognition. This step helped to reduce inter-observer variation and ensure consistency in bird identification.

The images and videos collected at different altitudes and during different approaches (vertical and horizontal) were analysed using low-bandwidth time-lapse software. This software provides an intuitive interface for viewing and directly documenting observations by altitude and approach distance. Each observer worked independently to avoid confirmation bias, and results were compared to check interobserver agreement.

To assess the influence of altitude and contrast on the number of species recorded, we used a Poisson generalised linear regression (GLM) model. This type of model is particularly suitable for analysing count data, such as the number of species observed, as it takes into account the discrete, non-negative distribution of these data [31]. The explanatory variables included in the model were elevation and contrast (divided into three levels: low, medium and high).

The model was validated by checking the basic assumptions of GLMs, in particular the overdispersion of the data using Pearson's dispersion test, which revealed a slight overdispersion, suggesting greater variability than would be expected from a pure Poisson model. To correct for this, a quasi-Poisson model was fitted, which provided robust estimates of the effects. An analysis of variance (ANOVA) was then performed to determine the significance of the effects of elevation, contrast and their interaction on the number of species detected. The results were visualised using graphs generated by the ggplot2 function in R software (version 4.2.3).

The average distances and heights recorded during the approaches (vertical and horizontal) of the species in isolated situations or in colonies (during the nesting period or not) were calculated.

3. Results

3.1. Effect of Drone Altitude on Detection Rates

The results of the analysis of the collected data (**Figure 2**) illustrate the effect of drone altitude on detection rates for different bird species, with altitudes ranging from 10 m to 100 m. For each species, detection rates are highest at the lowest altitudes (10 m and 20 m) and decrease significantly at higher altitudes. At altitudes above 20 m, detections are low or non-existent for all species. However, the number of species identified decreases with increasing altitude (**Figure 2**). For each species, the p-value indicates that altitude has a statistically significant effect on detection rates. All p-values are extremely low (close to zero), confirming that the differences in detection rates between altitudes are statistically significant.

This strong dependence on low altitudes (10 - 20 m) reflects the vertical stratification of habitats in mangroves, where many species, such as *Anastomus lamelligerus* and *Ardea alba*, occupy dense or low microhabitats that are generally masked at higher altitudes. This suggests that degradation of the lower layers of mangroves could reduce the detectability and viability of these populations, highlighting the importance of accurate monitoring to assess anthropogenic impacts.

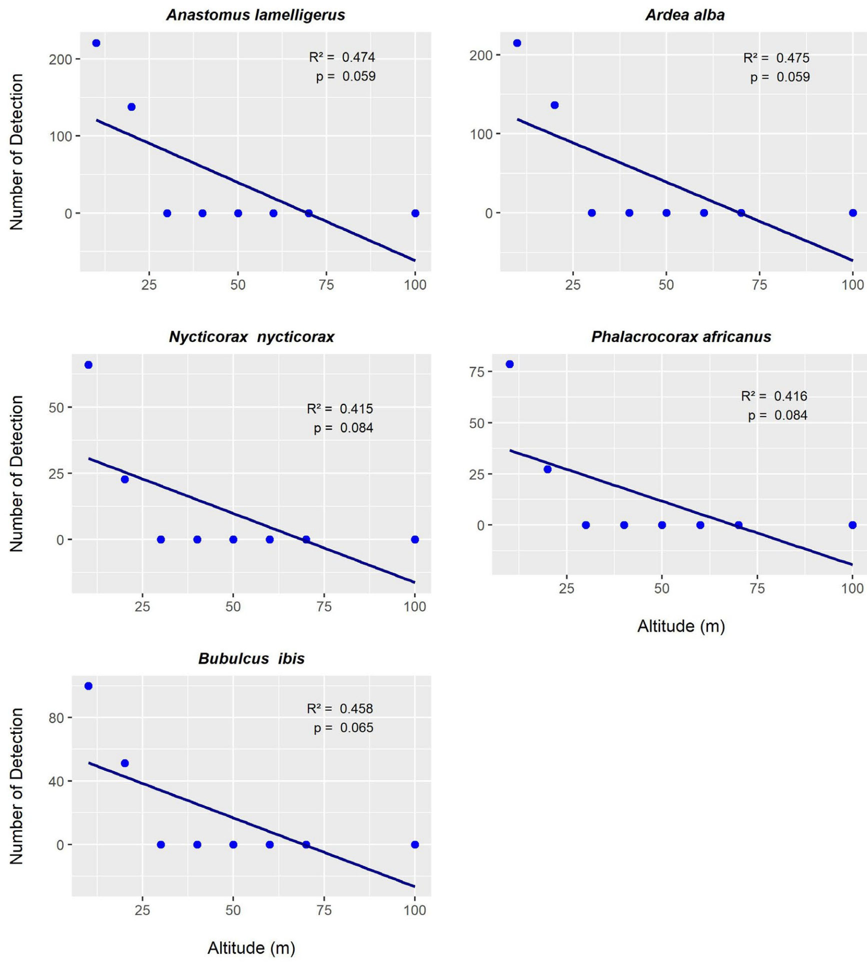

Figure 2. Effect of altitude on number of detections.

Anastomus lamelligerus and *Ardea alba* had the highest number of detections at 10 m, with a still significant number at 20 m. *Nycticorax nycticorax*, *Phalacrocorax africanus* and *Bubulcus ibis* also show a similar trend, with high detection rates at 10 m, moderate at 20 m, but almost no detection at higher altitudes. Figure 2 shows the results of the effect of altitude on the number of detections.

Figure 3 shows an aerial photograph taken during hovering at different altitudes.

3.2. Contrast Parameters Effect on Detection Rates

The results show the effect of visual contrast (divided into three levels: high, medium and low) on the number of detections of five bird species: *Anastomus lamelligerus*, *Ardea alba*, *Nycticorax nycticorax*, *Phalacrocorax africanus* and *Bubulcus ibis*.

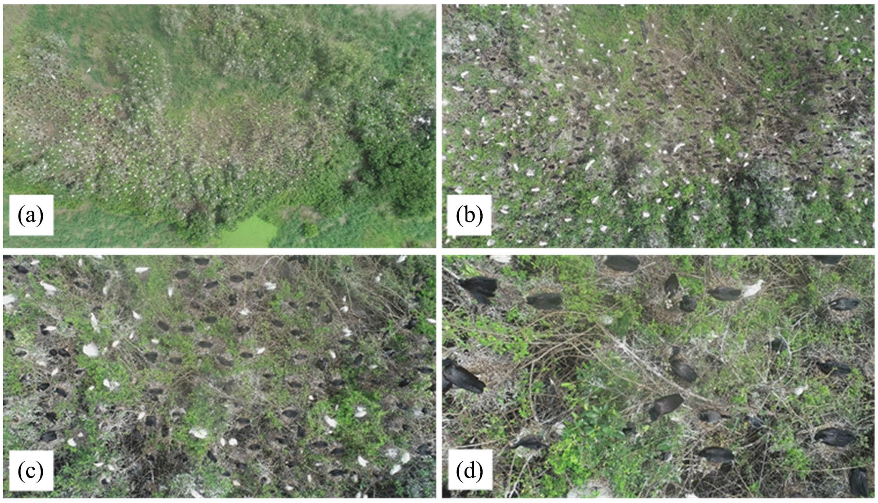

Figure 3. Aerial photographs taken during vertical hover: (a) 70 m; (b) 30 m; (c) 20 m; (d) 10 m.

For each species, the number of detections is highest at high level of contrast. The number of detections decreases significantly at low and medium contrast and tends to zero for each species at low contrast.

The p-values are extremely low ($p < 0.001$), confirming that the effect of contrast is statistically significant for each species. Sensitivity to high contrast indicates an interaction between environmental conditions, such as luminosity, and the behaviour of birds, which are generally more active during periods of high visibility (morning or late afternoon).

For the species *Anastomus lamelligerus*, the majority of detections occurred at high contrast, with low and medium contrast having virtually no effect.

For the species *Ardea alba*, the behaviour is similar, with many more detections or large colonies in high contrast conditions, and for *Nycticorax nycticorax*, *Phalacrocorax africanus* and *Bubulcus ibis*, the trend is the same for these species, although the absolute number of detections varies, with the majority of detections occurring in high contrast conditions.

These results therefore show that visual contrast has a significant effect on the detection of all species studied. High contrast significantly improves detection ability, while low or medium contrast reduces the number of detections, sometimes to zero in the case of low contrast.

Figure 4 shows the results of the analysis of the effect of visual contrast (divided into three levels: high, medium and low) on the number of detections.

3.3. Observer Skills on Detection Rates

The results of the observer effect parameter are shown in Figure 5.

These results indicate that the observer effect does not significantly affect the number of detections for these bird species. This is important for the reliability of the data. In other words, the skills or perceptions of different observers do not appear to bias the collection of detection data for these species.

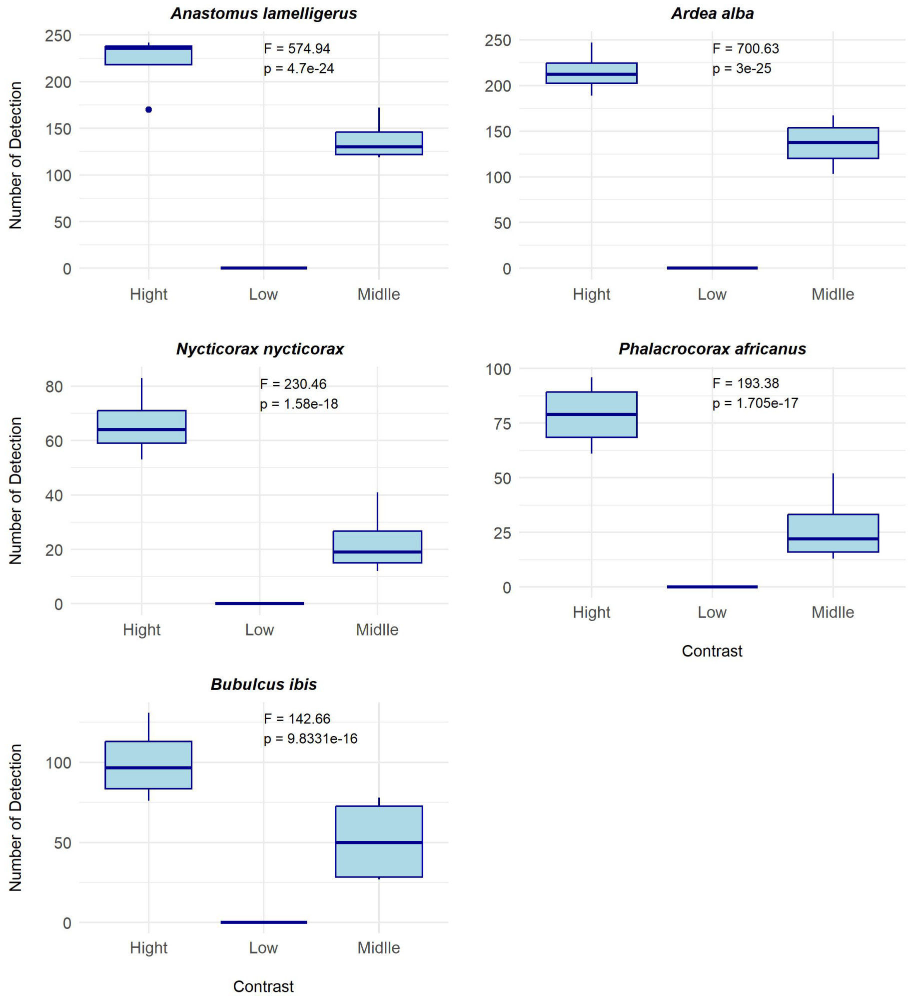

Figure 4. Number of species detected as a function of contrast.

3.4. Bird Behaviour Face Drone Uses

A total of 41 approaches were made, including 20 vertical approaches and 21 horizontal approaches. Of the 20 vertical approaches, the species *Ardea alba* (06 individuals), *Egretta garzetta* (03 individuals) and *Phalcrocorax africanus* (02 individuals) were approached in isolation. They responded at average heights of 13 m, 12 m and 11 m respectively. For the 21 horizontal approaches, the species *Ardea alba* (13 individuals) and *Egretta garzetta* (05 individuals) were approached in isolation, both responding at an average distance of 5 meters. The same species reacted similarly when approached in groups, but not when they were nesting. On the other hand, when they were in a group and nesting, covering their young or eggs, they showed no visible reaction to drone approaches (vertical or horizontal), even when the drone descended to very close altitudes, sometimes below 5 meters. Despite the buzzing of the drone and the obvious disturbance caused by the wind from the propellers, these species seem to tolerate the presence of the drone in such circumstances. **Figure 6** shows some of the reactions in different approach situations.

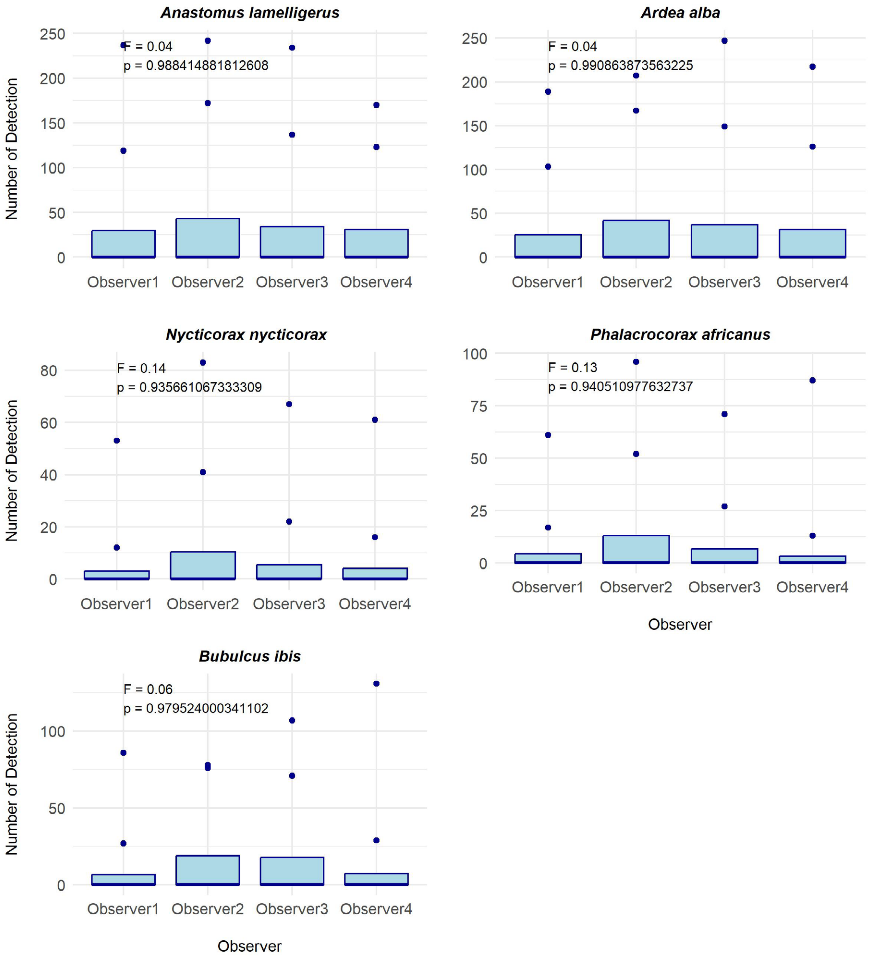

Figure 5. Number of species detected as a function of observer.

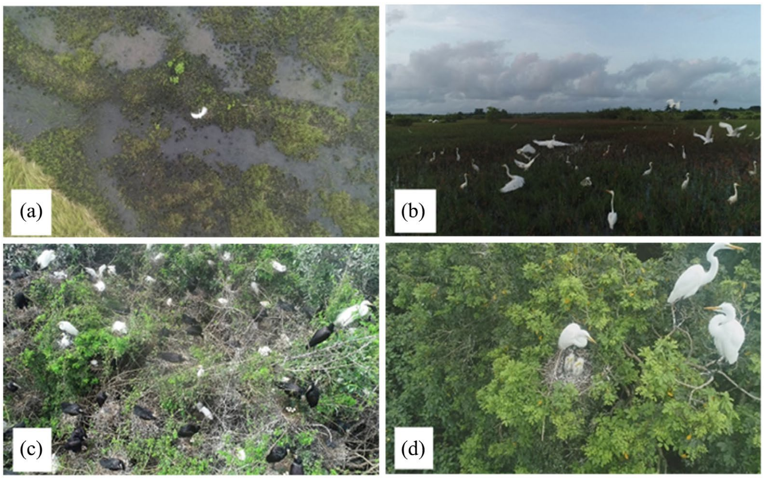

Figure 6. Species reactions in different approach situations: (a) Isolated *Ardea alba* reacting to the drone at 13 m during a vertical approach; (b) Isolated *Ardea alba* individuals reacting to the drone at 5 m during a horizontal approach; (c) Nesting individuals of *Anastomus lamelligerus*, *Ardea alba*, *Egretta garzetta*, and *Bubulcus ibis* showing no reaction during a vertical approach at less than 8 m; (d) Nesting *Ardea alba* individuals showing no reaction during a horizontal approach at less than 5 m.

4. Discussion

Traditional bird monitoring methods based on naked eye or binocular observations are often limited by observation bias and logistical constraints, as highlighted by previous researchers [32] [33]. Our results confirm that UAVs can overcome these limitations by providing more accurate and reproducible data, while reducing cost and effort in the field. Nago *et al.* [12] also demonstrated that drones can cover large areas in record time, which is particularly useful in hard-to-reach mangrove ecosystems. However, it is important to note that drones do not completely replace traditional methods, but complement them, especially for cryptic species or in dense habitats.

The results of this study demonstrate that drones can be an effective tool for monitoring avian biodiversity in West African mangrove ecosystems, particularly in areas such as Bouche du Roy in Benin. Our results also confirm that drones allow accurate and reproducible data collection while minimizing disturbance to birds, particularly during nesting.

Study results show that bird detection rates are significantly higher at lower altitudes (10 - 20 m), which is consistent with previous studies. The study on tern colony by Chabot *et al.* [34] also found that drones equipped with high-resolution cameras provide optimal bird detection at altitudes below 30 m. However, in contrast to our study, Hodgson *et al.* [35] reported that higher altitudes (50 - 100 m) could also be effective for detecting colonies of large birds, such as pelicans or flamingos. This discrepancy could be explained by differences in the species and habitats studied. In our case, the target species (such as *Anastomus lamelligerus* and *Ardea alba*) are often smaller and more discrete, requiring lower altitudes for optimal detection.

Visual contrast plays a key role in bird detection, as also highlighted by previous studies [18] [20]. Our results show that high contrast conditions significantly improve bird detection, especially for species such as *Anastomus lamelligerus* and *Ardea alba*. This is consistent with the work on elephants by Vermeulen *et al.* [15], who demonstrated that UAVs equipped with multispectral sensors can improve fauna detection in complex environments such as mangroves. However, in contrast to our study, Mulero-Pázmány *et al.* [36] suggested that the use of polarization filters could reduce the effect of contrast in variable light conditions, which could be an avenue to explore for future research in West African wetlands.

One of the most interesting results of our study is the tolerance of birds to UAV approaches, especially during the nesting period. In contrast to previous studies in semi-captive situation and in wetland [19] [29] which reported significant flight responses of birds to drone approaches, our observations show that birds during nesting do not respond, even at very low altitudes (less than 5 m). This could be explained by the fact that birds nesting in mangroves are used to frequent natural disturbances such as tides and winds, making them less sensitive to disturbance from drones, or this tolerance is probably due to the priority given to protecting their eggs or chicks. This increased tolerance provides a unique opportunity to monitor breeding colonies without disturbing their natural behaviour.

The use of drones in wildlife research, while effective, raises ethical questions and concerns about its long-term impact. The priority is to minimise any disturbance to birds, particularly during sensitive periods such as nesting. Our results show a high tolerance of nesting species to drones at close range (<5 m), suggesting little immediate stress. However, repeated or poorly calibrated overflights could lead to cumulative effects, such as nest abandonment or altered breeding behaviour, as highlighted by [36]. These risks would be a prudent approach in line with ethical guidelines, such as those of the International Union for Conservation of Nature (IUCN), which recommends protocols limiting the frequency and proximity of overflights in protected areas.

In the long term, the impact of drones on mangrove ecosystems depends on their large-scale use. Although their environmental footprint is smaller than traditional methods (e.g. helicopters), noise and visual disturbance could affect more sensitive species or species not studied in this work, such as small mammals or reptiles. In addition, increased reliance on drones could lead to excessive data collection without appropriate management, which could challenge the confidentiality of nesting sites in the face of non-scientific uses (e.g. tourism). To balance these risks, frameworks such as the "Guidelines for the use of drones in conservation" [25] advocate operator training, prior impact assessments and the inclusion of species-specific tolerance thresholds. In the context of Bouche du Roy, the adoption of such practices would ensure that the conservation benefits of drones (accurate monitoring, reduced costs) do not compromise the sustainability of bird populations and their habitats.

5. Conclusions

Despite the obvious advantages of drones, there are a number of limitations that need to be considered. Firstly, the limited flight time of UAVs (often less than 30 minutes) may limit their use over large areas. In addition, weather conditions such as strong winds or rain can affect the quality of the data collected, as reported in Indonesia rainforests [21]. Finally, legislation on the use of drones in protected areas may vary from country to country, which may limit their use on a large scale.

The results of this study provide valuable information for improving bird inventory methods. The main recommendations based on these results could guide future bird inventory studies:

The best detection rates are higher at lower altitudes (10 - 20 m). For inventory studies, it is recommended to favour low altitude flights to maximize species detection, especially for small or cryptic birds.

Use moderate flight speeds (2 - 4 m/s) to minimize disturbance to birds while ensuring effective coverage of the survey area. Too high a speed could reduce image quality and the ability to detect birds.

Vary the approach angles (vertical and horizontal) to adapt the method to bird behaviour. Vertical approaches may be less disruptive to nesting birds, while horizontal approaches may be more effective for birds in flight or on the move.

Maximize visual contrast by scheduling flights at times of day when light is at its best (morning or late afternoon). This improves bird recognition, especially for species with cryptic plumage.

Training observers in species recognition and image analysis to minimize observation bias is necessary to ensure data consistency for best results.

For future research, it would be interesting to explore the use of drones equipped with thermal or infrared sensors, which could improve bird detection in low-light conditions or in dense habitats. In addition, the integration of artificial intelligence for automatic image analysis could reduce biases related to the observer effect and speed up data processing.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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