drones

Article

An Assessment of the Effectiveness of RGB-Camera Drones to Monitor Arboreal Mammals in Tropical Forests

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Abstract

The use of drones for monitoring mammal populations has increased in recent years due to their relatively low cost, accessibility, and ability to survey large areas quickly and efficiently. The type of drone sensor used during surveys can significantly influence species detection probability. For arboreal mammals, thermal infrared (TIR) sensors are commonly used because they can detect heat signatures of canopy-dwelling species. However, drones equipped with TIR cameras are more expensive and thus less accessible to conservation practitioners who often work with limited funding compared to drones equipped exclusively with standard visual spectrum cameras (Red, Green, Blue; RGB drones). Although RGB drones may represent a viable low-cost alternative for wildlife monitoring, their effectiveness for monitoring arboreal mammals remains poorly understood. Our objective was to evaluate the use of RGB drones for monitoring arboreal mammals, focusing on Geoffroy's spider monkeys (*Ateles geoffroyi*) and southern muriquis (*Brachyteles arachnoides*). We used pre-programmed flights for spider monkeys and manual flights for muriquis, selecting the most suitable method according to the landscape characteristics of each study site; flat terrain with relatively homogeneous forest canopy height and mountainous forests with highly variable canopy height, respectively. We detected spider monkeys in only 0.4% of the 232 flights, whereas we detected muriquis in 6.2% of the 113 flights. Considering that both species are highly arboreal, use the upper canopy, and share similar locomotion patterns and group size, differences in detectability are more likely related to the type of drone flights used in each case study than to species differences. Preprogrammed flights allow for systematic and efficient area coverage but limit real-time adjustments to environmental conditions such as wind, canopy structure, and visibility. In contrast, manual flights offer greater flexibility, with pilots being able to adjust speed, height, and flight path as needed and spend more time over specific areas to conduct a more exhaustive search. This flexibility likely contributed to the higher detection rate observed in the muriqui study, but detectability was still low. The findings of the two studies suggest that RGB drones are better suited as a complementary tool rather than a primary method for monitoring arboreal mammals in dense forest habitats. Nonetheless, RGB drones offer valuable opportunities for other applications, and we highlight several examples of their potential utility in arboreal mammal research and conservation.

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1. Introduction

The use of drones for monitoring wildlife has rapidly grown in recent years, becoming an increasingly important tool for research and conservation of species in natural environments [1–6]. The ability of drones to access remote areas and collect data quickly and efficiently has driven their adoption in a wide range of ecological studies [7–9]. From detecting species and estimating population measures [10–14] to tracking animal movements and behaviors [15–18], drones have become a valuable tool in ecological research, allowing researchers to monitor wildlife across large or inaccessible areas while generating minimal disturbance to the animals [4,19,20].

Depending on the objective of the study, drones can be equipped with different types of sensors that optimize the detection and study of species in their natural environment [9]. Visible spectrum cameras are imaging devices that capture light within the visible range of the electromagnetic spectrum, specifically in the red, green, and blue (RGB) channels [21]. Thermal infrared (TIR) cameras detect radiation in the 8–14 µm range emitted by objects and living organisms, enabling the creation of thermal images based on temperature differences without relying on ambient light. Thermal images allow for effective detection of heat-emitting bodies in low visibility conditions [22]. Multispectral and hyperspectral cameras are imaging devices that capture data across multiple regions of the electromagnetic spectrum, extending beyond the visible range. Multispectral cameras typically collect imagery in a limited number of discrete bands (such as red, green, blue, red-edge, and near-infrared), while hyperspectral cameras acquire data in hundreds of narrow, contiguous spectral bands [23–25]. The selection of the most appropriate type of sensor allows for greater detectability, more accurate estimation of population size, identification of behavioral patterns, and/or the assessment of the impact of environmental changes, providing key information for decision making and the development of effective conservation strategies.

The selection of the appropriate sensor type also depends on the specific characteristics of the species of interest and the habitat in which it occurs [26]. For instance, drones equipped with RGB cameras (hereafter RGB drones) have been widely used in open or sparsely vegetated habitats. In these environments, RGB drones allow for the collection of high-resolution photographic and videographic data, supporting the effective detection, identification, and counting of individuals [3,26–30]. Their success in these ecosystems is due to the absence of significant visual obstructions, which allows for precise and detailed image capture from the air. In addition, in open habitats, natural lighting facilitates the acquisition of high-quality images, improving the identification of species and individuals [31]. Their application to habitats that are more densely vegetated, where arboreal mammals are common, is much more limited (Table S1, Supplementary Materials). This is mainly due to the structural complexity of forest canopies, which obstructs the line of sight between the drone and the individuals [12], and to the cryptic behavior and coloration of many arboreal mammals that further reduce detectability [32]. In addition, variability in lighting within the forest, with shadows cast by vegetation, can reduce contrast in images, further complicating the identification of individuals [24].

As a result, most studies focusing on arboreal mammals have relied on drones equipped with thermal infrared (TIR) cameras (hereafter TIR drones). TIR drones are an especially valuable tool for species that are particularly difficult to detect, such as cryptic species, those occurring at low densities, inhabiting forest canopies, or exhibiting nocturnal activity [33–38]. TIR cameras detect temperature differences between animals and other elements in their surroundings, facilitating the localization of individuals even under conditions of low visibility [22]. Although TIR cameras cannot penetrate through physical obstacles such as leaves or branches, they can detect animals in different vegetation strata when parts of their thermal signature are exposed, for instance, through gaps in the canopy [39]. Consequently, the use of drones equipped with TIR cameras has become more common for monitoring arboreal mammals compared to RGB-only drones (Table S1, Supplementary Materials).

However, there is a considerable cost difference between commercially available drones equipped solely with RGB cameras and those that integrate both RGB and TIR sensors; drones with standard RGB cameras are generally more affordable. For instance, a commercially available RGB drone typically costs less than half as much as a comparable TIR drone. This price difference can significantly constrain research and conservation efforts, especially for projects operating on restricted budgets. The substantial price difference between the RGB and TIR models highlights the financial barriers to incorporating TIR sensor technology into wildlife monitoring, especially in tropical forests, where the majority of arboreal mammals are concentrated, but funding is often limited. As a result, using drones equipped solely with RGB cameras may represent a more practical and accessible option for researchers or organizations with limited resources.

To date, only a few studies have directly compared the effectiveness of RGB and TIR cameras in detecting arboreal mammals [40,41]. The first study was conducted in Vietnam, in semi-wild enclosures composed of dense secondary tropical rainforest with emergent trees up to 30 m in height. Although they found that the detection rate in RGB images was high for two of the evaluated species (47% for Delacour's langur: *Trachypithecus delacouri* and 40% for yellow-cheeked gibbon: *Nomascus gabriellae*), TIR cameras consistently outperformed RGB cameras in detection rate [40]. This was particularly the case with the species that were difficult to detect due to their cryptic pelage and their tendency to remain immobile in the face of disturbances (Hatinh langur: *Trachypithecus hatinhensis*; grey-shanked douc langur: *Pygathrix cinerea* [40]). While species differentiation in TIR footage was facilitated by the species-specific movement patterns and body shapes [40], identification from TIR images alone remained challenging, as ambient heat could obscure individual monkeys or body parts, thereby making it difficult to detect these characteristic movement patterns.

Similar results were reported with 163 Japanese macaques (*Macaca fuscata*) living in semi-free conditions within a 4-hectare enclosed area in Austria, designed to simulate natural habitat and composed of Central European Forest with trees reaching up to 30 m in height [41]. In this case, 25% of the 94 TIR images captured during the study contained clearly visible individuals, resulting in the detection of 278 monkeys, whereas the corresponding 94 high-resolution RGB images revealed 235 individuals [41]. Despite these results, the comparison also highlighted key limitations in both imaging methods. Specifically, 8.9% of monkeys were missed in the TIR imagery due to clustering effects (i.e., situations where multiple individuals are in close proximity to each other, often in direct physical contact or overlapping positions). Additionally, 11.5% of individuals were only visible in the RGB images and not detected by the TIR sensor due to situations where monkeys were on warm surfaces, such as building roofs or paths, or in shaded areas, which limited thermal contrast and reduced the effectiveness of the TIR imagery. Conversely, 76 monkeys were exclusively observed in the TIR images, as they were obscured by vegetation in the RGB footage [41]. These findings suggest that while TIR imaging often enhances detectability, the relative effectiveness of TIR versus RGB cameras remains context-dependent. It is important to note that both studies mentioned above were conducted under semi-free conditions within enclosed and relatively controlled environments, which may have influenced the detection rates observed. The limited area, known animal locations, and reduced behavioral variability compared to truly wild populations could potentially favor higher detectability in semi-captive conditions.

Although the use of drones equipped exclusively with RGB cameras for monitoring arboreal mammals is much more limited compared to their use in open habitats, several studies have demonstrated their potential under specific conditions [12,14,32,36,42]. To date, however, primates are the only group of arboreal mammals for which RGB drones have been used as the primary method of detection (Table S1, Supplementary Materials). For example, RGB drones have been used to detect nests of great apes such as orangutans (*Pongo abelii*) in Sumatra, Indonesia [42], and chimpanzees (*Pan* spp.) in dense and heterogeneous forest habitats across multiple locations throughout their range [14,43]. Additionally, Semel et al. [32] were able to capture clear imagery of golden-crowned sifakas (*Propithecus tattersalli*) in the fragmented forests of northeastern Madagascar by flying a low-cost RGB drone at 15–20 m above the canopy. Spaan et al. [12] detected Geoffroy's spider monkey (*Ateles geoffroyi*) individuals in 85% of flights flown directly above groups observed from the ground in tropical forests of the Yucatan Peninsula, Mexico. However, in survey flights across areas of high and low relative spider monkey abundance, detection dropped to 17% and 0%, respectively [12]. The study highlights the potential of RGB drones for detecting spider monkeys under controlled conditions but also emphasizes limitations in using this method for rapid assessments across broad areas due to low overall detection rates and the need for improved survey designs.

RGB drone imagery has frequently been used as a complementary tool in wildlife studies, particularly for species identification following initial detections of heat-emitting animals made with TIR sensors [36,40,41,44]. In these applications, TIR cameras are typically employed to locate heat-emitting animals, especially in challenging conditions such as dense vegetation or low light. Once individuals are detected, RGB cameras can then provide high-resolution visual confirmation of species identity, group composition, or behavior.

Collectively, the above studies illustrate that, despite the inherent challenges posed by dense foliage and variable lighting conditions, it is feasible to detect and observe arboreal mammals using RGB drones under certain conditions. However, the potential of RGB cameras as a primary method for detecting arboreal mammals remains poorly understood, and studies specifically evaluating their effectiveness are still limited. Therefore, our objective was to evaluate the effectiveness of RGB drones as a primary tool for monitoring arboreal mammals in dense canopy forests through the use of preprogrammed and manual flight modes. To do so, we conducted two case studies: a landscape-scale survey with preprogrammed flights to monitor Geoffroy's spider monkeys in the Yucatan Peninsula, Mexico, and a local-scale survey with manual flights to detect the presence of the southern muriqui (*Brachyteles arachnoides*) in the Serra da Mantiqueira region, Brazil. In addition, we developed three hypothetical scenarios to explore how the distribution and grouping patterns of spider monkeys could influence the detection rates in preprogrammed flights, with the aim of contextualizing our empirical results and evaluating the practical limitations of RGB images taken with drones in complex forest environments.

2. Methods

2.1. Case Study: Preprogrammed Flights to Monitor Geoffroy's Spider Monkey Populations

Geoffroy's spider monkeys are fast-moving, diurnal, highly arboreal primates that exhibit a high degree of fission-fusion dynamics, meaning that group members divide themselves into subgroups that frequently change in size and composition throughout the day [45]. These behavioral and ecological traits pose significant challenges to traditional ground-based monitoring methods [46]. As the species is currently classified as Endangered on the IUCN Red List primarily due to habitat loss and fragmentation throughout its distribution [47], monitoring of its populations is paramount. Reliable and frequent population monitoring is crucial to detect trends in abundance, understand the impacts of environmental change, and implement targeted conservation actions in a timely manner. In this context, RGB drones represent a promising alternative to conventional survey methods.

To evaluate the effectiveness of RGB drones to monitor Geoffroy's spider monkey populations, we conducted a study in an area of approximately 1500 km^2 located in the northern part of the Yucatan Peninsula (Figure 1). We selected this area because it falls within their geographical distribution [48] and presents the necessary ecological conditions to host spider monkey populations, but there is no information on their presence and abundance outside the Otoch Ma'ax Yetel Kooh protected area [49] and Los Arboles Tulum (a sustainable residential development within a 400-ha forest [50]). The study area is mainly composed of mature forests (>50 years old) and regenerating forests in different stages of succession.

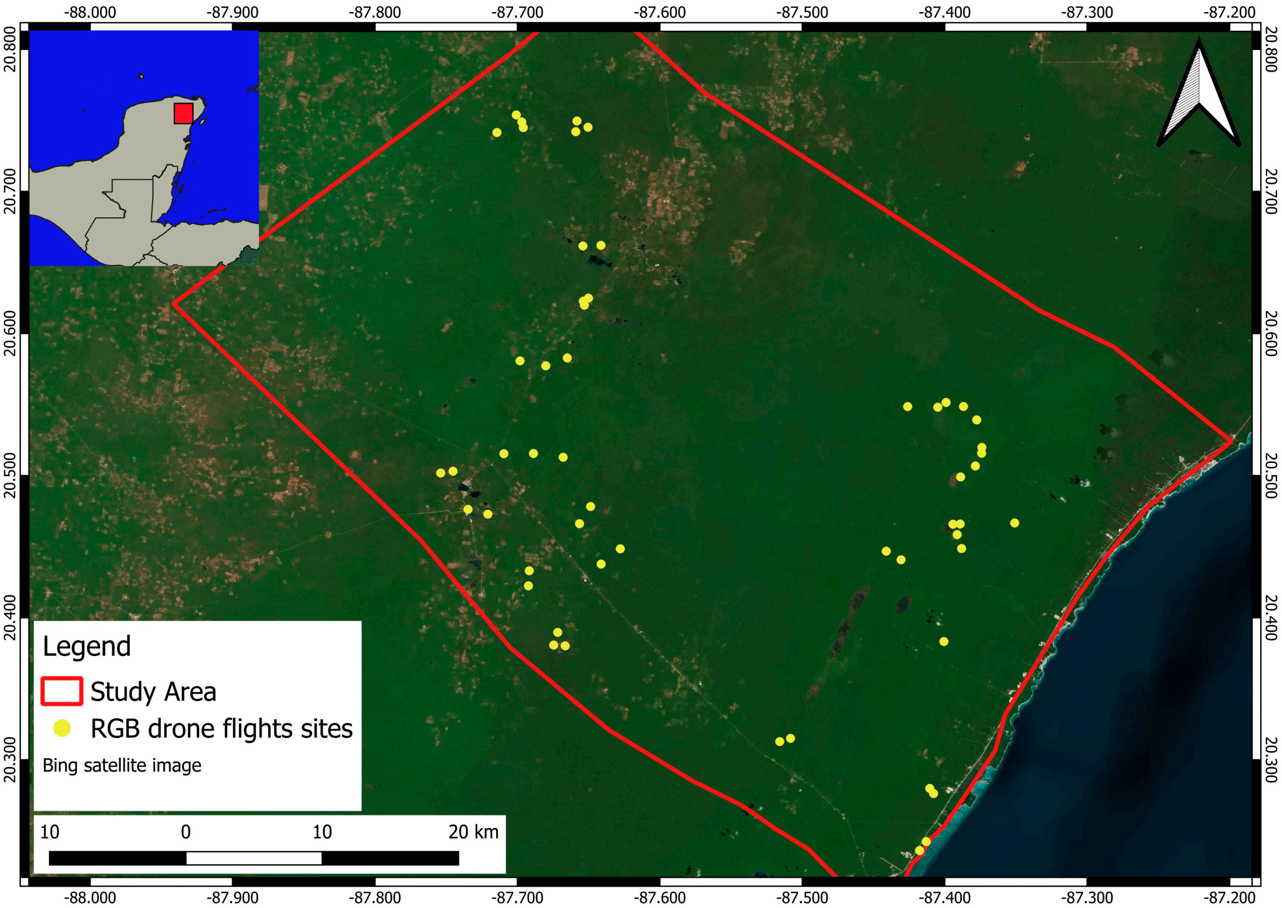

Figure 1. Location of the study area in the northeast of the Yucatán Peninsula, Mexico. The red polygon outlines the boundaries of the study area, and the yellow dots indicate the locations where we established 5-hectare polygons and conducted the preprogrammed RGB drone flights to detect spider monkeys. The background image shows varying shades of green, where darker tones correspond to forested areas (including both mature and regenerating forests), and light brown patches indicate agricultural fields, pastures, or human settlements.

To determine spider monkey presence, we performed drone flights with a Mavic 2 Pro drone (SZ DJI Technology Co., Shenzhen, China) equipped with a 216 Hasselblad L1D-20c

RGB camera. The camera has a 3-axis gimbal with a 1″ CMOS (20M 217 effective pixels) sensor, and the lens has a 28 mm focal length with an image size of 5472 × 3648 pixels. The drone weighs 906 g, has a maximum flight time of 31 min, a maximum operating distance of 10 km, and reaches a maximum speed of 72 km/h (SZ DJI Technology Co., Shenzhen, China). The drone was operated using an Android cell phone. This drone model has been used successfully to detect spider monkeys in previous studies [12].

We conducted preprogrammed drone-flight surveys in 5-ha polygons (Figure 2) in 59 sampling sites. The 5-ha area was sampled on a single day during two consecutive flights, with each flight covering an area of approximately 2.5 ha. We created the 5-ha flight polygons in Quantum GIS 3.18 and imported and pre-programmed them in Mission Planner V1.3.64 (ArduPilot). The flight grids were configured in Litchi Mission Hub 4.24.0 (VC Technology Ltd., London, UK) in a lawnmower pattern (Figure 2). We performed the flights in the early morning (8:00–10:30) and late afternoon (16:00–18:30) to prevent the intensity of the light and the reflection produced by the sun at midday from interfering with the detection efficiency of the monkeys [51]. In addition, it is during these hours that spider monkeys are most active [52], which could increase the probability of detecting them.

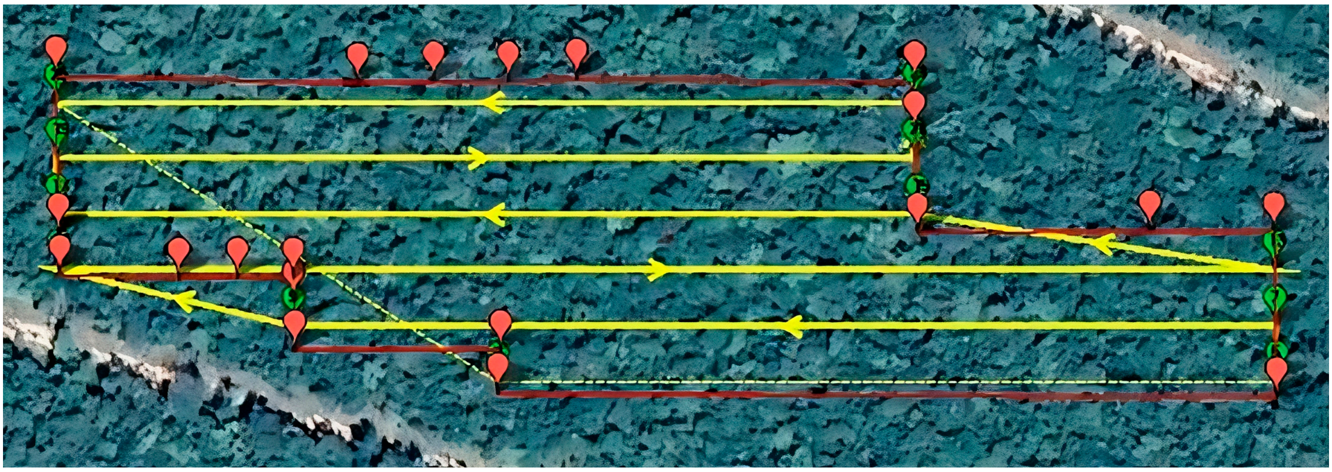

Figure 2. Example of the planned flight path of the RGB drone (yellow line) in a 5-ha sampling site as seen in the Mission Planner software. Yellow arrows show the flight direction. The red balloons and red lines represent the boundaries of the sampling site. The yellow dashed line indicates the path followed by the drone to reach a new point of the route after completing a section, while the green balloons represent the order in which the route was carried out during the flight.

Based on the results of a pilot study that we conducted prior to the data collection flights, and following the methodological improvements proposed by Spaan et al. [12] for detecting spider monkeys using RGB drones, we designed the flight protocol as follows: flights were carried out at a constant speed of 2.0 m/s with 40% forward and side overlap at canopy level, flying at an altitude of 50 m above ground level (i.e., approximately 25 m above the tree canopy). This height was selected after a comparative evaluation during the pilot study of three flight heights (50, 60, and 70 m.a.g.l.), where 50 m was found to be the most effective height for covering larger areas in a single flight while maintaining sufficiently high image resolution to detect spider monkeys in the footage when present. In addition, based on previous research indicating minimal behavioral responses of spider monkeys to drone flights conducted at 35 and 50 m.a.g.l [53], we considered that our pre-programmed flights conducted at 50 m would likewise minimize disturbance to the monkeys. This flight configuration yielded a ground sampling distance (GSD) of 0.83 cm/pixel at ground level and 0.41 cm/pixel at canopy level, with the camera positioned at a nadir angle of −90°. Under these parameters, the swath width (Dw; i.e., the horizontal distance covered by the drone's field of view at canopy level during each flight line, determining the ground area captured in the video footage) was 27 m, and the spacing between flight lines was 23.18 m, ensuring full coverage of the 5-ha sampling area. Given that Spaan et al. [12] reported a high detection rate of 85% for spider monkeys in RGB drone footage when flying directly over previously located monkeys, we did not collect or compare our results to ground-truthing data. Instead, we prioritized expanding the spatial coverage for each flight and the number of monitored sites. This approach allowed us to assess detection rates under conditions more representative of real-world applications, where prior knowledge of the location of the target animals is not usually available.

We conducted two survey replicates per sampling site (one during the dry season and one during the rainy season) to account for potential environmental variation between seasons. During each survey flight, we recorded a high-resolution 4K video (3840 × 2160 FOV), which we manually reviewed to assess spider monkey detectability [12]. When reviewing the videos, we looked for specific details that might indicate spider monkey presence. The primary indicator was the characteristic movement of tree branches when spider monkeys move [12], which typically involves sudden, irregular shaking of upper-canopy branches as individuals leap or swing between trees, often in a horizontal direction and without wind-related swaying. When such signs were detected, we used the digital zoom and slow-motion functions of the VLC 3.0.17.4 (Video LAN Organization, Paris, France) program to perform a more thorough examination and confirm the presence at that sampling site only if we detected at least one spider monkey. We did not directly equate the characteristic movement of the branches to spider monkey presence. Drone video footage lasted 24.1 ± 3.6 min (mean ± SD; range: 18.3–33.5 min). All videos were reviewed by E.J.P.-R., who had experience in detecting spider monkeys in the wild and in detecting spider monkeys in drone footage. When spider monkeys were identified in the videos, the reviewer took screenshots of the individuals and extracted video segments where they were visible. Due to the duration of the videos and the need to review several segments multiple times to confirm the presence of spider monkeys, the review process took approximately 1 h per video. The manual review process of all the videos took approximately 260 h.

2.2. Case Study: Manual Flights for Southern Muriqui Population Monitoring

Southern muriquis are the largest Neotropical primate and are endemic to the Brazilian Atlantic Forest [54]. Like the Geoffroy's spider monkeys, they are highly arboreal diurnal primates that move fast through brachiation and exhibit a high degree of fission-fusion dynamics [55]. The species is classified as Critically Endangered on the IUCN Red List primarily due to habitat loss, fragmentation, and poaching associated with the illegal extraction of palm hearts [56]. In the state of São Paulo, the species is primarily found in mountainous protected areas [57–59], making population surveys difficult using traditional ground-based methods. Despite their occurrence in protected areas, muriquis remain vulnerable to persistent threats [59], highlighting the critical need for continuous population monitoring and conservation assessments.

We conducted the study on the Fazenda São Sebastião do Ribeirão Grande, a private property covering approximately 16 km^2 in the Serra da Mantiqueira region, in the municipality of Pindamonhangaba, São Paulo, Brazil (Figure 3). The area harbors a confirmed population of Southern muriquis and has been the focus of previous monitoring efforts [59]. However, the team had no previous knowledge of muriqui space use in the area, including their movement patterns, home range boundaries, or preferred habitats. The property ranges from 630 to 1960 m above sea level, which makes it difficult to conduct surveys from the ground. The Atlantic Forest is classified as a tropical high-altitude climate, marked by hot and humid summers, dry and cold winters [60]. The average temperature is 18 °C, and the area receives approximately 1846 mm of rainfall annually [61].

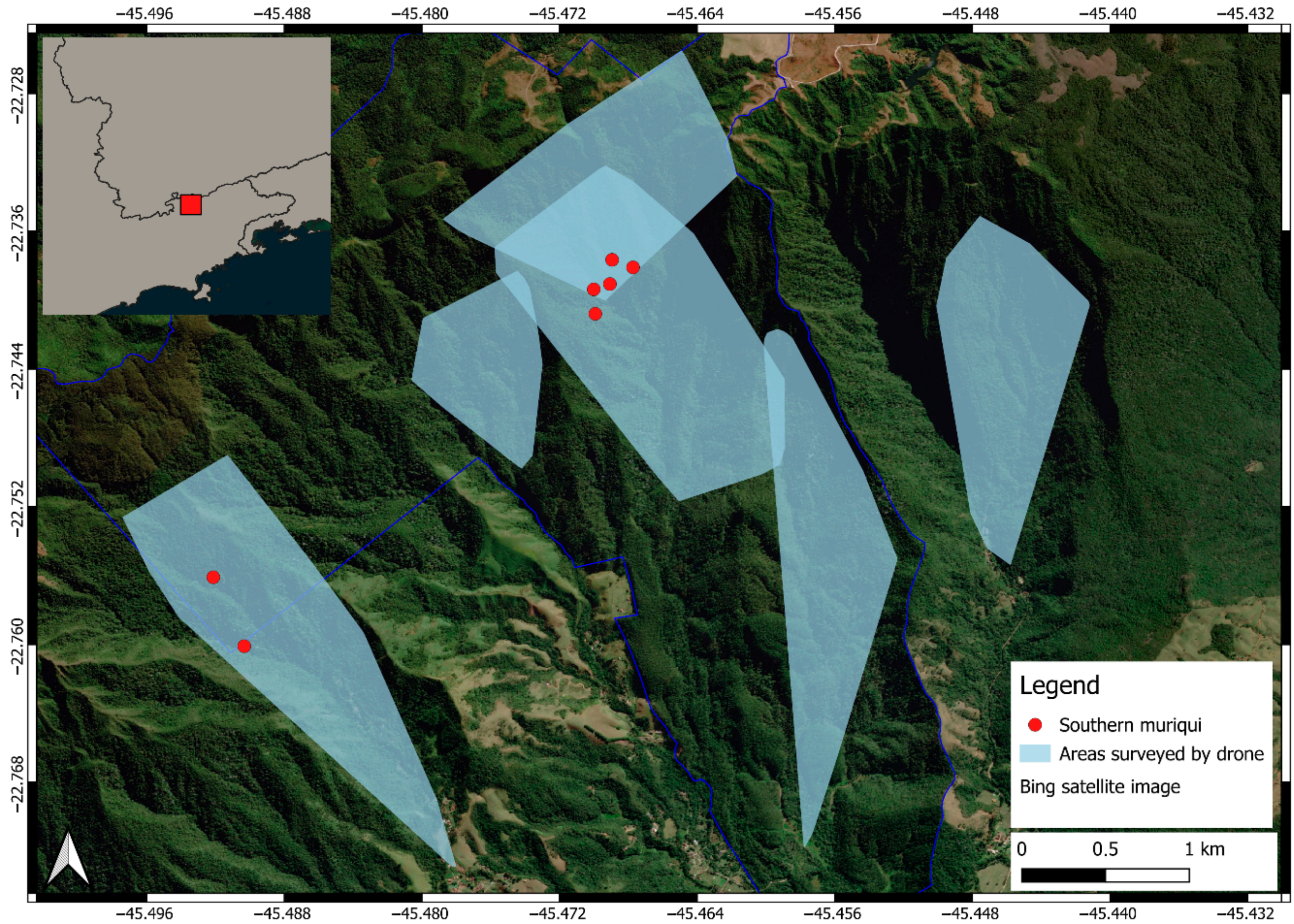

Figure 3. Location of the study area in the state of São Paulo, Brazil. The light blue polygons represent the regions monitored with the RGB drone using manual flights (created in QGIS using the minimum geometry limits tool with the drone flight path for each region surveyed, using "convex hull" geometry type). The red points indicate the locations of muriqui subgroups detected with RGB drone imagery.

To determine the presence of muriquis, we used a DJI Mavic Pro Platinum (SZ DJI Technology Co., Shenzhen, China), which features a 4k (3840 × 2160) resolution RGB camera with a 1/2.3″ (CMOS) sensor (12.35 M effective pixels) mounted on a 3-axis gimbal. The drone weighs 734 g, has a maximum flight time of 30 min, a maximum operating distance of 7 km, and a maximum speed of 40 km/h (SZ DJI Technology Co., Shenzhen, China). We operated the drone using a DJI remote control attached to a tablet (iPad 6th generation—MR7J2LL/A model, display 9.7 inches). We conducted manual drone-flight surveys using an active search protocol. The height above the ground, flight speed, flight path, and camera angle varied across flights. We carried out flights mainly in the early morning and late afternoon, when muriquis are most active [62] and when flight conditions allowed good visibility, low wind speed, and no rain. We started recording the video after takeoff and stopped before landing. During the flight, we looked for the animals themselves (considering the muriquis' color, size, and movement patterns) and any sign of potential muriqui-associated movement in the canopy. These visual cues guided the optimal positioning of the drone and allowed for reliable species identification. During real-time detection of muriquis (i.e., while the drone was flying), we performed the flight to record the largest number of individuals, such as detecting locations where multiple individuals tend to move in a single file. By detecting the direction of group movement and identifying a point where many animals pass, we could momentarily hover the drone at that spot to maximize the number of individuals detected. This strategy was especially effective when the muriquis were in motion.

We conducted our flights at heights between 30 and 50 m above canopy level, based on an average canopy height of around 25 m. Once we detected at least one individual, we maintained a safe distance between the drone and the muriquis, with a mean flight altitude of 67 m.a.g.l. during the encounters. It was possible to observe that the muriquis sometimes reacted to the noise of the drone by looking in the direction of the aircraft, but no panic or escape behavior was recorded.

Two coders, F.B. and C.R., independently reviewed the post-flight videos using 4K TV monitors. When needed, they used the zoom tool in Adobe Premiere CC 2015 (Adobe Inc., California, United States) to confirm the species. We reviewed complete videos at least twice, and some segments were reviewed several times as necessary. Inter-observer reliability for the presence/absence of muriquis was 100%, and the videos showing presence were analyzed jointly by both researchers to determine the individuals' count.

In each case study, we calculated monkey detectability by dividing the number of flights in which monkeys were detected by the total number of flights and then multiplying the result by 100 to express the value as a percentage.

2.3. Hypothetical Detection Scenarios Using Preprogrammed Flights

To better understand how the detection rate can be influenced by different flight parameters as well as by the ecological characteristics of the study species, we contrasted three hypothetical scenarios to estimate the probability of detecting spider monkeys using RGB drone flights. We considered a home range of 80 hectares (ha), which represents the average size reported for the species throughout its distribution [49,63–65] with a square shape and sides that measured approximately 900 m to facilitate calculations. Additionally, we considered a group size of 31 individuals, which is the average group size reported for the species in the Yucatan Peninsula [46,49,50]. Thus, we assumed that a group of 31 spider monkeys lived in an 80-ha square home range, representing a density of 0.387 monkeys per ha. Each survey flight lasted about 20.7 min, with the drone covering a total of 5 ha, flying at a height of 50 m above ground level, with a 40% overlap and sidelap, the camera positioned at an angle of $-90°$ and at a speed of 2 m/s, capturing successive images, each covering 0.03458 ha (23×15 m). With these parameters, we estimated that each flight included approximately 145 successive images, with a duration of 7.5 s of travel time per image. In all cases, we assumed perfect detection if at least one individual or subgroup was within the drone's field of view.

In the first scenario, which we consider as the best possible scenario for the RGB drone to detect at least one individual per flight, the 31 monkeys were in 31 subgroups (each composed of a single individual) distributed throughout the home range. In the second scenario, which we considered to be the closest to the actual conditions we might encounter for spider monkey populations in the wild, the 31 monkeys were in eight subgroups of approximately four monkeys each, which is the average subgroup size of spider monkey reported for Mexico [66–68]. In the third scenario, which we consider the worst-case scenario for monkey detection, all 31 monkeys were together without subgroup formation. Thus, there is only one possible target, and the probability of detection depends exclusively on the drone passing above the single location of the 31-monkey group.

First, for each scenario, we estimate the probability of each image capturing at least one monkey (*Pimage*) by multiplying the area of an image by the number of subgroups and dividing by the total area:

$$Pimage = \text{number of subgroups} \times \frac{0.03458}{80}$$

We then applied the complementary probability to calculate the probability of detecting at least one monkey in the entire flight [69]. Complementary probability (*Pdetection*) is a method used to calculate the likelihood of an event happening by subtracting the probability that it does not happen from 1 [69]. Here, it means estimating how likely it is that no monkeys are detected in any of the images and then subtracting that from 1 to get the overall probability of detecting at least one monkey:

$$Pdetection = 1 - (1 - Pimage)^{145}$$

3. Results

3.1. Case Study: Preprogrammed Flights to Monitor Geoffroy's Spider Monkey Populations

Between 7 April 2022 and 10 January 2023, we carried out 232 flights to determine the presence of spider monkeys with the RGB drone in the Yucatan Peninsula. Of these 232 flights, 118 corresponded to the first survey replicate performed in each of the sampling sites, and the other 114 flights corresponded to the second survey replicate. The total number of sites surveyed in the second replicate decreased from 59 to 57 due to logistic constraints out of our control. After reviewing the 232 videos, we were only able to determine the presence of spider monkeys in one of the videos (Figure 4), which corresponds to a detectability of 0.4%.

Figure 4. Example of a Geoffroy's spider monkey detected (inside the red circle) during an RGB drone flight at 50 m above ground level using the Interactive Zoom Tools in VLC Media Player.

3.2. Case Study: Manual Flights for Southern Muriqui Population Monitoring

We conducted a total of 111 RGB drone flights between 6 February 2021 and 17 December 2022, detecting at least one muriqui individual in 7 of those flights (Figure 5). Two detections occurred during the drone flight, and 5 during the post-flight video review. These results yield an overall detectability rate of 6.3%.

Figure 5. Muriquis detected (inside the red circles) during an RGB drone flight at the Fazenda São Sebastião do Ribeirão Grande, Pindamonhangaba, São Paulo, Brazil.

The maximum number of monkeys detected in a single flight was 30 individuals. This occurred when muriquis were brachiating quickly, resulting in a noticeable swaying in the trees, which, together with the absence of wind, meant that we were able to detect the individuals easily. The maximum count on any other flight was 7 individuals, drawing attention to potential undercounting when muriquis are resting or moving slowly.

3.3. Hypothetical Detection Scenarios Using Preprogrammed Flights

To evaluate how different spatial configurations of spider monkeys could influence detection outcomes when using RGB drones with preprogrammed flights, we explored three hypothetical scenarios based on varying levels of individual dispersion. In Scenario 1, we assumed that 31 individuals were in 31 subgroups composed of a single individual distributed in the home range, with an estimated per-individual detection probability of 0.03458. This resulted in an image-level detection probability of approximately 0.0134. When extended across 145 images (the average number per flight), the probability of detecting at least one monkey per flight was 85.5%. In Scenario 2, we modeled a situation with 8 subgroups of approximately 4 individuals, yielding an image-level detection probability of 0.00345 and a flight-level detection probability of 39.4%. Finally, Scenario 3 considered a highly aggregated configuration in which all individuals were together in a single location. This led to a much lower image-level detection probability of 0.00043 and a corresponding detection probability per flight of only 6.1%.

4. Discussion

We evaluated the effectiveness of RGB drones as a primary method for monitoring arboreal mammals by conducting two case studies on two of the largest primate species in the Neotropics, Geoffroy's spider monkey and the southern muriqui, evaluating detectability under three hypothetical scenarios, and reviewing relevant literature. In both case studies, detectability was low: less than 1% for spider monkeys and 6.3% for muriquis. Although previous studies have reported high detectability of arboreal primates using RGB drones (85% for spider monkeys, 47% for Delacour's langur, and 40% for yellow-cheeked gibbons; [12,40]), flights were performed over groups that had been previously located from the ground [12] or within semi-captive enclosures [40]. Flying directly over the monkeys made it easier to detect them in the videos recorded during the flights [14], as confirmed by detections of muriquis during consecutive flights using the coordinates of an earlier detection. However, the same studies that report high detectability also document low detectability when flights are not conducted over groups previously located from the ground, as well as for other species. In fact, only 17% of the 18 flights resulted in detections of Geoffroy's spider monkeys in areas of high relative abundance, and 0% of the 39 flights in areas of low relative abundance when flights were conducted without prior knowledge of the group's location [12]. Similarly, Gazagne et al. [40] reported a detection rate of 20% for grey-shanked douc langurs and 0% for Hatinh langurs using RGB drones. These findings underscore that detection rates can vary widely, potentially due to factors such as previous knowledge of the monkey location, the position of the individuals within the canopy, their level of activity during the flight (i.e., whether individuals were resting or moving), lighting conditions, and the presence of wind or dense vegetation obstructing the view.

In the spider monkey case study, we did not detect monkeys at the Otoch Ma'ax Yetel Kooh protected area and Los Arboles Tulum, where spider monkeys have been studied since 1997 and 2017, respectively [49,50]. Thus, it is unlikely that the monkeys did not occur at these sampling sites. Instead, these non-detections are more plausibly explained by a combination of ecological, behavioral, and technical limitations inherent to RGB drone surveys. A key factor is the limited spatial coverage of each flight: with spider monkeys typically occupying home ranges of 80 ha and our surveys covering only 5 ha per site, we sampled merely 6.5% of the potential area used by the group. This restricted coverage significantly reduces the probability of encountering individuals during short flights, especially when combined with the monkeys' large and variable daily movement distances. Moreover, dense canopy structure further constrains detection, as overlapping branches, vertical stratification, and foliage severely limit visibility from above [70]. This visual obstruction is exacerbated by the grey/brown coloration of spider monkeys, which tends to blend in with tree bark and shaded areas, especially in natural light conditions that create irregular shadows.

Similar challenges are likely to occur for other arboreal mammals that rely on camouflage or have cryptic coloration, such as sloths, whose slow movements and pelage tones make them particularly difficult to detect in dense canopy environments using RGB imagery [71]. The interplay between light incidence, canopy density, and pelage coloration likely resulted in many missed detections, as monkeys may have been present but effectively camouflaged within the structural complexity of the canopy. Conversely, species with lighter or more contrasting fur coloration relative to the surrounding vegetation may be easier to detect with RGB drones [32]. For instance, arboreal mammals with white, orange, or red pelage that stands out against the predominantly green and brown tones of the canopy are more likely to be visually distinguishable from aerial RGB images [32]. Muriquis, in general, have a lighter coloration than spider monkeys (Figure 5), which may have facilitated the detection of individuals during manual flights, reinforcing that visual contrast can improve detectability and reduce false negatives. However, it is important to note that despite this potential advantage, the overall detection rate of muriquis remained low. This highlights that while pelage coloration may play a role, it is only one of several interacting factors affecting detectability.

In addition, the movement of branches as individuals move is often one of the primary visual indicators for detecting spider monkeys and muriquis in drone RGB footage. However, a recent study assessing the behavioral responses of Geoffroy's spider monkeys to drone flights found that individuals tended to spend more time resting during flights than before or after flights [53]. This tendency to remain still during flights may reflect a passive risk assessment strategy in response to an unknown aerial stimulus [53]. The authors performed flights at the same height as used in our surveys (50 m.a.g.l.) and flew over a spider monkey group living in a similar habitat to that of our study sites, making their findings particularly relevant to our study. This behavioral response has important methodological implications; if monkeys remain immobile during drone flights, their detectability in RGB video footage becomes substantially reduced, as detection is facilitated by the characteristic movement of the monkeys in the canopy. Monkeys resting during flights may partially explain the low detectability of spider monkeys in RGB drone flights. The same may apply to muriquis (although no study on their behavioral responses to drones has been carried out), as the flights with the highest individual counts occurred when the monkeys were moving. Thus, the effectiveness of RGB drone monitoring can vary significantly across species depending on their behavioral traits.

Another factor that can influence detection is wind during drone flights. Wind can cause excessive movement of leaves and branches, which reduces image stability and makes it more difficult to distinguish animals from the surrounding background [32]. In addition, wind-driven branch movement can mask or mimic the movements of arboreal mammals when they move [12]. Consequently, detection of arboreal mammals is more difficult in windy conditions, which may reduce detection rates during aerial surveys. Although we always flew the drone safely, following the instructions indicated for the drone model, wind conditions varied throughout the year in the Yucatan Peninsula and Serra da Mantiqueira. During certain months, stronger winds in both study areas caused significant movement of tree branches and leaves, making it difficult to distinguish the movements of spider monkeys and muriquis when reviewing the video footage. In months when average wind speeds were lower (evident in the videos through reduced vegetation movement), the drone footage was more stable and theoretically improved the chances of detecting individuals. However, despite these favorable conditions, we did not detect any spider monkeys in months with lower wind speed.

When conducting preprogrammed flights, there is an even more critical technical factor that may influence the detectability of spider monkeys with drone RGB cameras: the sampling time of each location during a single flight. The time the drone spends above any single part of the flight path within the sampled area is very short (i.e., a few seconds, depending on the speed at which the flight is performed). In our spider monkey case study, the size of each image captured by the drone was 23 m by 15 m. When flying at a speed of 2 m/s, each point along the flight path was therefore only sampled for 7.5 s. This limited sampling time, combined with spider monkeys' large home ranges, relatively low population density in the study area, and characteristic rapid movements [49,63], makes it difficult that any spider monkey was actually at any point along the flight path for the 7.5 s during which detecting them was possible.

In addition, the results obtained in the three hypothetical scenarios show that the spatial distribution of spider monkeys within the home range has a decisive influence on the probability of detection by RGB drones. Detection was high (85.5%) only in the most favorable scenario, with individuals highly spatially dispersed, a situation not very representative of their natural behavior. In contrast, when monkeys were in subgroups with a more realistic configuration for the species (second scenario), detectability dropped to 39.4% and fell to just 6.1% when all individuals were clustered in a single group. However, even the second scenario remains optimistic compared to realistic field conditions. In reality, spider monkeys are not only organized in dynamic subgroups but are also often partially obscured by dense canopy vegetation and remain immobile for extended periods. These factors, together with the limited visibility of RGB imagery under natural lighting and canopy cover, help explain why the detection in the spider monkey study case (0.4%) was even lower than that of the worst-case scenario (6.1%). The differences in detectability show that, under common operating conditions such as low area coverage per flight (5 ha) and limited flight time per image (7.5 s) using conventional RGB cameras, the probability of recording monkeys is low in ecologically plausible scenarios.

Manual flights, such as those used in the population survey of muriquis, offer important advantages by allowing real-time adjustments to environmental conditions. For example, pilots can adapt flight speed depending on wind intensity, modify the route to avoid areas with low visibility, and spend more time scanning the area if they detect indicators of the target species' presence, as it happened during our muriqui surveys. However, this adaptability came at the cost of jeopardizing standardized coverage, as the irregular flight paths in mountainous terrain and frequent changes in camera direction made it difficult to quantify the actual sampled area. In contrast, pre-programmed flights, as applied to the monitoring of Geoffroy's spider monkeys, followed fixed routes and maintained consistent coverage These flights covered about 5 ha with a camera fixed at $-90°$, likely resulting in a smaller effective sampling area than that of manual flights but providing a repeatable survey design. While manual flights maximize adaptability and time-on-target when animals are detected, pre-programmed flights offer greater standardization, which is particularly valuable for systematic comparisons across sites or time periods. Ultimately, the choice between manual and pre-programmed flights should be guided by the environmental characteristics of the study area, the behavioral and ecological traits of the target species, and the specific research objectives, balancing the need for flexibility in detection with the benefits of standardized, repeatable coverage.

Together, the above-mentioned factors (i.e., canopy obstruction, pelage coloration, light and wind speed conditions, habitat use patterns, and short sampling time) interact in ways that greatly diminish the detection success of arboreal mammals. Our findings suggest that RGB drones are currently limited in their capacity to detect arboreal mammals like Geoffroy's spider monkeys and southern muriquis in dense tropical forests with pre-programmed grid and manual flights. Furthermore, although few studies have statistically evaluated the differences in detectability of arboreal mammals between RGB and TIR cameras [40,41], several authors have pointed out, based on exploratory tests, that the detection of individuals in RGB images or videos is extremely difficult or in some cases almost impossible, due to the lack of contrast between the animals and the background, the presence of fog, as well as their poor movement [40,44]. Therefore, RGB drones should be viewed as a complementary tool rather than a standalone method for monitoring arboreal mammals in complex forest environments. For example, using the combination of TIR and RGB cameras during the same flight, we were 5 times more likely to detect muriquis than using only an RGB camera [72].

It is important to mention that we recognize some limitations of our study, particularly the use of different drone models and the implementation of only one flight strategy per species (pre-programmed flights for Geoffroy's spider monkeys and manual flights for muriquis). These decisions were influenced by logistics and topographic characteristics unique to each study area. The Yucatán Peninsula (Mexico) is characterized by flat terrain and a relatively homogeneous canopy structure, which allowed us to conduct systematic pre-programmed flights for spider monkeys. In contrast, the Serra da Mantiqueira region (Brazil) features rugged terrain, steep slopes, and a highly variable canopy height, making it difficult to design and safely execute pre-programmed flights. Therefore, manual flights were the only practical option. Additionally, although we used two different drone models equipped with different RGB cameras, both of them had the technical specifications required to capture high-resolution imagery, and therefore, we do not believe this factor significantly affected our detection outcomes. Another factor that could influence our results is that the video analysis for the spider monkey study was conducted by a single coder. Nevertheless, this coder has extensive experience in detecting spider monkeys both in the wild using traditional survey techniques such as line transects and in drone footage, ensuring the reliability and accuracy of the detections. Furthermore, whenever the coder identified a potential detection, the video was paused and the corresponding segment was reviewed multiple times to confirm the presence of the monkeys, using the digital zoom function available in the VLC software to enhance visual inspection.

By clearly showing the limitations of RGB drones for monitoring arboreal mammals, our study provides critical guidance for researchers and conservation practitioners. Rather than investing time and resources in methods with low detectability, future studies can build upon our findings to select more effective tools from the outset, such as TIR technology or integrated monitoring frameworks. This evidence-based approach can help avoid unrealistic goals, improve planning efficiency, and ultimately strengthen conservation decision-making in tropical regions where logistical challenges and funding constraints are common. In future studies, the application of machine learning or advanced deep learning methods could help overcome current detectability limitations, such as dense forest canopies, heterogeneous lighting conditions, and partially obscured individuals, by automating species-specific identification in visually complex environments and decreasing false positives and false negatives, thereby increasing both the efficiency and accuracy of data analysis.

4.1. Importance and Applications of RGB Drones in Arboreal Mammal Research

The utility of RGB drones extends far beyond species detection. For example, despite the overall low muriqui detection rate, the use of a drone with an RGB camera led to the first detection of muriquis in that location, enabling the team to open trails and plan ground surveys. Moreover, the real-time detection of 30 individuals during a single RGB drone flight remained the highest recorded count in the region for an extended period of time, underscoring the advantages of aerial monitoring in detecting elusive species that are difficult to observe using traditional ground-based methods.

In recent years, RGB drones have proven to be valuable tools in a wide range of ecological and conservation applications. One of the most widely adopted uses of RGB drones is as a complementary method. While TIR drones are highly effective at detecting heat signatures emitted by mammals in forest canopies [36,44,73,74], the TIR sensors often lack the resolution necessary to identify species or individuals confidently. RGB cameras, when mounted alongside TIR sensors or in survey flights, allow researchers to capture high-resolution visual imagery confirming the detected species identity [36,41,44,75]. This strategy increases data reliability in species detections and counts by reducing false positives and false negatives. To implement this strategy, conducting drone flights during early morning hours appears to be the most effective approach, as natural light levels are already sufficient to support RGB-based species identification, while ambient temperatures are still sufficiently low to ensure strong thermal contrast between animals and their surroundings for TIR sensors [36]. Drones have also become increasingly important in behavioral studies [16,76]. Their ability to capture stable, high-resolution aerial video provides researchers with a unique perspective on animal movement, social interactions, and foraging behavior from above the canopy, a perspective inaccessible through traditional ground-based methods. Since drones are capable of recording from a distance, they may provide a relatively non-invasive way to observe animal behaviors with minimal disturbance [20,53,77]. This potential is further enhanced by the availability of zoom lenses on many recent drone models, which allow detailed observations without the need to fly too close to the study species. Although most behavioral studies involving drones to date have concentrated on species inhabiting open environments or have relied primarily on thermal imaging [18,38], RGB drones also offer significant potential for behavioral monitoring in forested habitats. This applies especially to human-habituated groups whose home ranges are known, allowing drones to be deployed effectively to target areas, thereby increasing the likelihood of successful observations. For instance, when animals are well habituated but difficult to observe when feeding in the upper canopy, RGB drones can be used to record feeding events in canopy trees, thereby providing valuable data on diet preferences, spatial use of feeding sites, and potential seasonal patterns in resource exploitation. Similarly, the aerial perspective provided by RGB drones can offer a unique advantage for recording behaviors that are often difficult to observe from the ground using traditional monitoring methods. This elevated viewpoint allows researchers to document social interactions, movement patterns, and habitat use in the upper canopy, where many arboreal mammal species spend most of their time [44]. This capacity makes RGB drones a powerful tool for expanding behavioral research, even in complex habitats where visibility is often limited from the ground.

In addition to behavioral studies, RGB drones can be valuable tools for defining the sex-age classification of individuals and individual identification [13]. While this is not feasible for all species, certain arboreal mammals display unique visual characteristics such as facial patterns, scars, or fur coloration that can be captured by RGB cameras. In such cases, drone imagery can be used to build photographic catalogs of individuals for demographic monitoring or long-term behavioral research, as has been done for some marine mammals, such as manatees (*Trichechus manatus* [78]) and beluga whales (*Delphinapterus leucas* [79]). Although this application is still developing, it holds promise in improving methods for individual identification, particularly when combined with machine learning tools for individual recognition.

Additionally, RGB drones have been successfully used in the detection and counting of nests built by large-bodied apes such as chimpanzees and orangutans [14,42,43]. These species construct sleeping platforms (i.e., nests) in the upper canopy, which are often visible from the air. Drones flying at appropriate heights (i.e., high enough to capture a broad field of view, yet low enough to ensure sufficient image resolution) can systematically survey forest areas and count these nests, providing an efficient alternative to labor-intensive ground surveys. This method has been validated in multiple studies [14,42,43], showing that nest counts derived from aerial imagery can be reliable indicators of population size and distribution.

Another important application of RGB drones in conservation is their role in habitat mapping and land-cover classification [80]. By stitching RGB images together into orthomosaics and 3D models, it is possible to quantify key structural features of forest habitats, such as canopy height, vegetation density, forest patch size, and connectivity [81–83]. This spatial information is critical for assessing habitat quality and understanding the ecological needs of arboreal mammals. In tropical forests, RGB drones have enabled the identification of emergent trees (i.e., large canopy-dominant trees) that play a vital role in the ecology of many arboreal mammal species. These trees often serve as preferred sleeping sites of a variety of arboreal species, as well as being indicators of forest maturity and structural complexity. In the forests of Sumatra, for instance, researchers used drone imagery to successfully detect such emergent trees, providing valuable insights into gibbon and siamang habitat use while also offering a broader perspective on forest condition [84]. Structural habitat mapping could also provide novel insights into the 3D habitat use of arboreal species, for instance, in terms of the selection of travel routes. Furthermore, the utility of RGB drones extends to habitat suitability assessments. In southwestern China, drone-derived maps of canopy height and vegetation density were used to evaluate habitat quality for the Gaoligong hoolock gibbon (*Hoolock tianxing* [85]). The high-resolution spatial data allowed researchers to identify suitable forest areas for the species and to track habitat changes over time, such as deforestation or natural regeneration, which directly impact gibbon distribution and long-term survival [85].

RGB drones have also been used to detect fruiting trees that are essential food sources for some arboreal mammals. In Gabon, researchers leveraged aerial imagery to identify dominant fruiting tree species used by chimpanzees, facilitating landscape-scale estimates of food availability. This approach proved significantly more efficient than traditional ground surveys and offered new opportunities for understanding spatial patterns of resource distribution and foraging behavior [43].

Finally, an innovative use of RGB drones for studying arboreal mammals lies in the collection of environmental DNA (eDNA) from forest canopies [86,87]. Traditionally, gathering eDNA samples from the treetops has been a logistical challenge due to the inaccessibility of the canopy layer [86,87]. Recent research has demonstrated the potential of drones equipped with specialized probes to collect eDNA from leaves and surfaces in the upper canopy, allowing scientists to monitor biodiversity in these underexplored vertical strata [86,87]. The onboard RGB camera plays a crucial role by helping to identify specific target locations to be sampled and by guiding the drone's navigation through gaps and among branches in the forest canopy. This technique can provide valuable genetic information about arboreal species and ecosystem health without disturbing wildlife.

The above examples underscore the important contribution the use of RGB drones can make to arboreal mammal conservation, offering efficient, non-invasive methods to assess habitat features, monitor availability and distribution of critical resources, and inform landscape-scale management strategies.

4.2. The Role of RGB Drones in Habitat Conservation

RGB drones are not only useful for gathering data to aid arboreal mammal conservation (see above) but also play an important role in conserving the habitats where these species live. RGB drones can quickly capture visual information that helps identify changes in the landscape and supports rapid decision-making. One significant application is the detection and assessment of forest fires [88–90]. RGB imagery enables researchers and authorities to identify burned areas and assess fire severity. For instance, research carried out in the Brazilian Cerrado highlighted the effectiveness of combining RGB drone imagery with vegetation indices to map areas impacted by fire and assess the resulting ecological damage [88]. While satellite imagery is also widely used for fire monitoring and can cover vast areas [91], the resolution of open-access images is typically lower than that of drone-based imagery. Thus, drones can provide higher-resolution data, allowing quicker and more flexible post-fire assessments, especially in extensive or inaccessible landscapes.

Another critical application of RGB drones is the monitoring of illegal deforestation and extractive activities [92]. In the Amazon, indigenous communities effectively use RGB drones to detect and document illegal deforestation within their land [92]. By capturing high-resolution aerial imagery, community monitors were able to identify forest loss, gather visual evidence, and respond rapidly to environmental threats. This participatory approach not only improved surveillance efficiency but also empowered local actors in the defense and management of their community land. Unlike satellite imagery, drones can operate under cloudy conditions and provide frequent updates at a lower cost and higher spatial resolution. RGB drones can also contribute to poacher detection efforts [93], especially during daylight hours. While thermal imaging remains superior for nocturnal detection, RGB footage can still capture human activity during the day, such as the opening of unauthorized trails or the passing of vehicles or individuals through restricted zones, thereby providing valuable evidence for law enforcement and helping to prevent illegal hunting activities.

5. Conclusions

The results of our case studies on spider monkeys and muriquis, two of the largest Neotropical primates, suggest that RGB drones are not an effective primary method for monitoring arboreal mammals. This is largely due to their limited detection power in areas with dense canopy cover and the short time spent surveying any point with preprogrammed flights. Nevertheless, RGB drones still have considerable value for conservation applications. RGB drones can be used to study arboreal mammal behavior, map habitats, and monitor changes in forest structure. Their ability to capture high-resolution images at relatively low cost makes them a powerful tool within integrated monitoring strategies in structurally complex forest environments, where the use of other methods may be difficult. As drone technology advances, the integration of RGB imagery with other sensors and analytical approaches will likely increase its utility in efforts to protect and conserve arboreal mammals and their habitats.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/drones9090622/s1, Table S1: Type of camera used, and the application of red-green-blue (RGB) cameras in studies conducted with drones for monitoring arboreal mammals.

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