CAMILA REZENDE GUIMARÃES

THERE’S SOMETHING OUT THERE WAITING FOR US: DRONES WITH THERMAL CAMERAS AS REVOLUTIONARY TOOLS IN POPULATION MONITORING

Dissertation submitted to the Animal Biology Graduate Program of the Universidade Federal de Viçosa in partial fulfillment of the requirements for the degree of *Magister Scientiae*.

Adviser: Fabiana Cristina S. Alves de Melo

Co-adviser: Fabiano Rodrigues de Melo

VIÇOSA - MINAS GERAIS
2023

Ficha catalográfica elaborada pela Biblioteca Central da Universidade Federal de Viçosa - Campus Viçosa

T
G963t
2023

Guimarães, Camila Rezende, 1995-

There's something out there waiting for us: drones with thermal cameras as revolutionary tools in population monitoring / Camila Rezende Guimarães. – Viçosa, MG, 2023.

1 dissertação eletrônica (31 f.): il. (algumas color.).

Texto em inglês.

Orientador: Fabiana Cristina Silveira Alves de Melo.

Dissertação (mestrado) - Universidade Federal de Viçosa, Departamento de Biologia Animal, 2023.

Inclui bibliografia.

DOI: https://doi.org/10.47328/ufvbbt.2023.367

Modo de acesso: World Wide Web.

1. *Brachyteles arachnoides*. 2. Drone. 3. Primatas - Monitorização. I. Melo, Fabiana Cristina Silveira Alves de, 1976-. II. Universidade Federal de Viçosa. Departamento de Biologia Animal. Programa de Pós-Graduação em Biologia Animal. III. Título.

CDD 22. ed. 599.858

Bibliotecário(a) responsável: Alice Regina Pinto Pires CRB-6/2523

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APPROVED: March 23, 2023.

Assent:

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Author

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Fabiana Cristina Silveira Alves de Melo
Adviser

To my mom.

ACKNOWLEDGEMENTS

Special thanks to my mother who always believed in me and supported me in my decisions. You are my greatest inspiration and life example. Thanks also to all my family members who were in some way with me.

Thanks to Fabiana and Fabiano for masterfully guiding me on my journey through academic life. And a special thanks to Fabiano for introducing me to the most charming primate species in the world, the muriquis.

Thank you to the funders Suzano S.A. for financing field logistics.

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001.

"One individual cannot possibly make a difference, alone. It is individual efforts, collectively, that makes a noticeable difference - all the difference in the world!".

(Jane Goodall)

ABSTRACT

GUIMARAES, Camila Rezende, M.Sc., Universidade Federal de Viçosa, March, 2023. **There's something out there waiting for us: drones with thermal cameras as revolutionary tools in population monitoring**. Adviser: Fabiana Cristina Silveira Alves de Melo. Co-adviser: Fabiano Rodrigues de Melo.

Population monitoring is crucial for the conservation of endangered species, but the most commonly used methods are time-consuming and resource-intensive. This work proposes the use of drones equipped with thermal and RGB sensors (color sensors) for population monitoring of the southern muriqui (*Brachyteles arachnoides*) as an alternative tool in challenging study areas. We tested the effect of sunlight and period of day on detection efficiency and detection distance for a better data collection design. Our results pointed to an effect of sunlight on detection efficiency, but not on detection distance. Considering the period of day, we found no effect on our results. The work also presents our methodology and results in population monitoring with drones in Serra da Mantiqueira and Serra do Mar. We suspect that there are 3 social groups of muriquis that use the study area in the Serra da Mantiqueira at a minimum counting of 39 individuals in just one flight. In the Serra do Mar we recorded 1 social group of muriquis with a minimum count of 10 individuals that use the surroundings of the study area and can use the inside area of the property. Also, by analyzing the high quality images generated by the drone, it was possible to make a sex and age classification of 19 and 6 individuals in Serra da Mantiqueira and Serra do Mar respectively. Moreover we discuss here the limitations that still exist regarding the use of this technology and possible future ways to make it even more efficient in population monitoring and in other areas of study.

Keywords: Brachyteles arachnoides. UAV. Primates. Endangered Species. Population Monitoring.

RESUMO

GUIMARAES, Camila Rezende, M.Sc., Universidade Federal de Viçosa, março de 2023. **Há algo lá esperando por nós: drones com câmeras térmicas como ferramentas revolucionárias no monitoramento de populações**. Adviser: Fabiana Cristina Silveira Alves de Melo. Co-adviser: Fabiano Rodrigues de Melo.

O monitoramento populacional é crucial para a conservação de espécies ameaçadas, mas os métodos mais comumente utilizados são demorados e consomem muitos recursos. Este trabalho propõe o uso de drones equipados com sensores térmicos e RGB (sensores coloridos) para monitoramento populacional do muriqui-do-sul como uma ferramenta alternativa em áreas desafiadoras de estudo. Testamos o efeito da luz solar e do período do dia na eficiência de detecção e na distância de detecção para um melhor planejamento de coleta de dados. Nossos resultados apontaram para um efeito da luz solar na eficiência de detecção, mas não na distância de detecção. Considerando o período do dia, não encontramos efeito em nossos resultados. O trabalho também apresenta nossa metodologia e resultados no monitoramento populacional com drones na Serra da Mantiqueira e Serra do Mar. Suspeitamos que existem 3 grupos sociais de muriquis que utilizam a área de estudo na Serra da Mantiqueira em uma contagem mínima de 39 indivíduos em apenas um voo. Na Serra do Mar registramos 1 grupo social de muriquis, com contagem mínima de 10 indivíduos, que utilizam o entorno da área de estudo e podem utilizar a área interna da propriedade. Além disso, analisando as imagens de alta qualidade geradas pelo drone, foi possível fazer uma classificação sexo/etária de 19 e 6 indivíduos na Serra da Mantiqueira e Serra do Mar, respectivamente. Além disso, discutimos aqui as limitações que ainda existem no uso dessa tecnologia e possíveis caminhos futuros para torná-la ainda mais eficiente no monitoramento populacional e em outras áreas de estudo.

Palavras-chave: Brachyteles arachnoides. UAV. Primatas. Espécies Ameaçadas. Monitoramento Populacional.

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LIST OF ACRONYMS AND ABBREVIATIONS

RGB	Red Green and Blue.
UAV	Unmanned Aerial Vehicles.
FSSRG	Fazenda São Sebastião do Ribeirão Grande.
S	South.
W	West.
mm	Millimeters.
SNUC	Sistema Nacional de Unidades de Conservação da Natureza.
PN	Parque das Neblinas.
RPPN	Reserva Privada do Patrimônio Natural.
DD	Detection Distances.
SISBIO	Sistema de Autorização e Informação em Biodiversidade.
CEUA	Comitê de ética no uso de animais.
ANAC	Agência Nacional de Aviação Civil.

LIST OF SYMBOLS

° Degree.

’ Minutes.

“ Seconds.

°C Degrees Celsius.

~ Approximation.

< Less.

% Percentage.

SUMMARY

1. INTRODUCTION

Population monitoring of endangered species is extremely important to define the conservation status of the species and draw up conservation policies (Strier et al. 2017). Currently, widely used methods such as linear transects, often demand a lot of time, financial and human resources to occur (Spaan et al. 2019; Wich et al. 2021; Tabacow et al. 2021). To overcome that limitation, we describe here the use of technology to ensure the best results in the population monitoring of a critically endangered species in Brazil.

The southern muriquis (*Brachyteles arachnoides*) are the largest non-human primates in the Americas and occurs exclusively in the Atlantic Forest of the Brazilian States of Paraná, São Paulo and Rio de Janeiro (Talebi et al. 2021). Unlike its sister taxon, the northern muriquis (*Brachyteles hypoxanthus*), southern muriquis do not commonly have facial and genital depigmentation, which makes their individual identification more difficult (Strier et al. 2017). Its current population is estimated at no more than 1200 individuals (Talebi et al. 2021) and are concentrated in fragments of the mountainous regions of Serra da Mantiqueira and Serra do Mar (Talebi et al. 2021; Tabacow et al. 2021).

Considering the high degree of altitude variation in these two geological folds, and considering the home range of a group of 39 southern muriquis, which is estimated at 1200 hectares (Petroni 2000), population monitoring by land in these areas requires a great effort to create trail infrastructure. In addition, intensive population monitoring by land generates a level of habituation of the individuals, and may pose a risk to populations in areas with illegal hunting activities (Strier et al. 2017). This is the case of two private properties in the State of São Paulo, in the city of Pindamonhangaba, Mogi das Cruzes and Bertioga. Muriquis have been registered inside these properties since 1996 (Oliveira, Manzatti 1996), and since 2007 (Ecofuturo 2020), both populations are considered as priority for demographic monitoring using criteria listed by Strier et al. (2017).

Unmanned Aerial Vehicles (UAV), or drones, appear as an alternative method for data collection in these areas of difficult access. It is not today that drones have been identified as revolutionary tools in fauna research, but the rapid development of this technology has allowed the expansion of the use of this tool and the detailed development of new methodologies. Rango et al. (2006) predicted that the use of this technology would be widely used for improved data collection and to make appropriate management decisions.

Jones et al. (2006) shows the potential of drones with records of white ibis (*Eudocimus albus*), alligators (*Alligator mississippiensis*) and manatee (*Trichechus manatus*). Drone surveys compared to manned aerial surveys have shown similar results in the study of whales (Koski et al. 2009). There's also studies using drones in tropical forests and for studying primates and other arboreal species (Van-Andel et al. 2015; Burke et al. 2019; Kays et al. 2019; Spaan et al. 2019; Melo 2021; Santos et al. 2023). Drones can also be used for mapping habitats and detecting changes in ecosystems (Wich et al. 2021). There are many possibilities for using drones in scientific research, regardless of the use, the fact is that the drone is now an indispensable tool for conservation biology.

Drones can be combined with different camera types, such as color (RGB) and thermal and sensors. The thermal sensor has been used to differentiate between the body heat of the animals and the ambient heat and Melo (2021) demonstrated its effectiveness in detecting muriquis. On the other hand, cameras with RGB sensors and high resolutions, like 4k cameras, can be used to classify individuals by sex and age, contributing to detailed demographic information (Camila Rezende, *unpublished data*).

We tested the efficiency of data collection and sampling design using drone thermal sensors under distinct environmental circumstances. Direct sunlight can increase the ambient temperature, resulting in many false positives and may make it difficult to detect species, furthermore, the period of the day can influence the retention of heat in the environment. Our aim is to test whether the sunlight and period of day can influence the detection efficiency and detection distance of the muriquis. We hypothesize that the detection efficiency and detection distance will be influenced by the sunlight and the period of day. We predict that the detection efficiency and detection distance will decrease with increasing sunlight. Likewise, we predict that the detection efficiency and detection distance is higher in the morning compared to the afternoon.

We also describe here the methodology used to count and classify muriquis by sex and age and discuss the limitations that still exist regarding the use of drones in population monitoring considering the reality in our study areas.

2. MATERIALS AND METHODS

2.1 Study Area

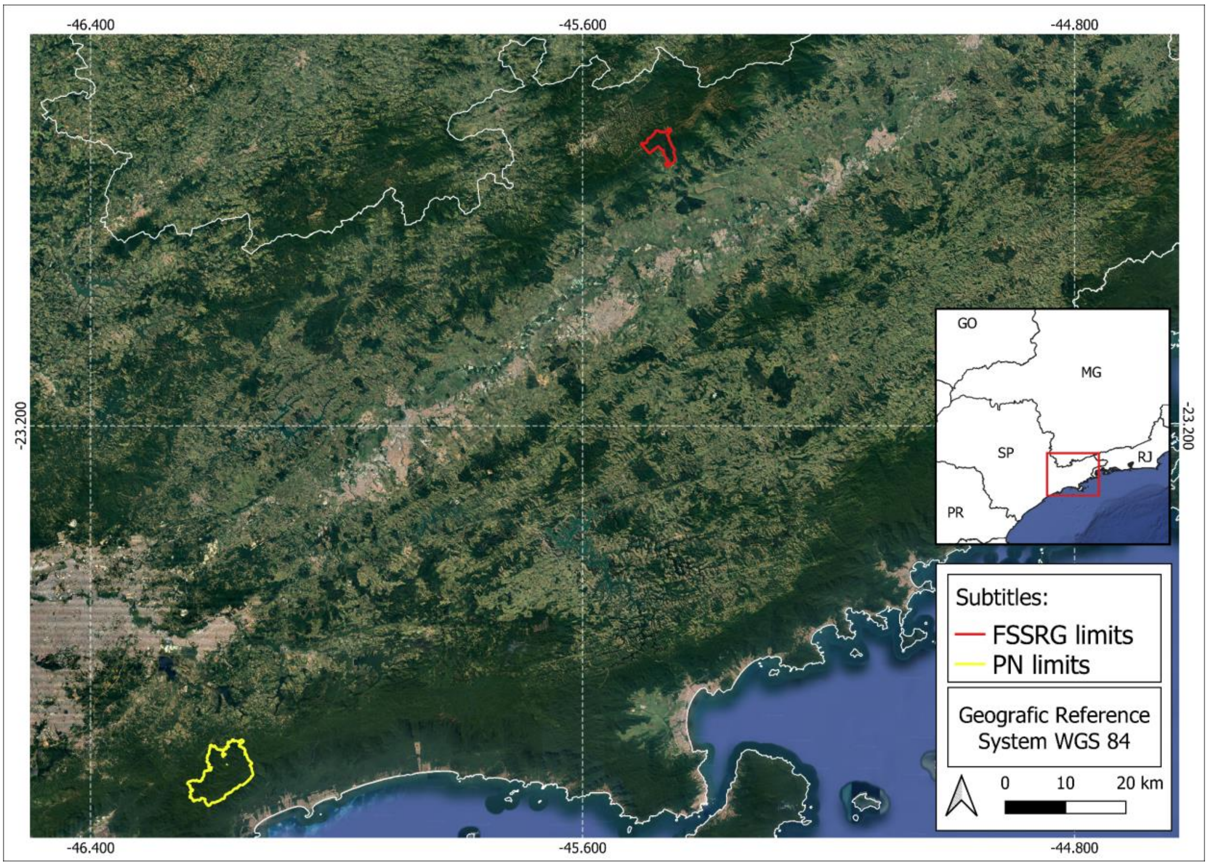

Figure 1 - Map of the two study areas in the São Paulo State, southeastern Brazil. Fazenda São Sebastião do Ribeirão Grande (FSSRG) and Parque das Neblinas (PN).

Our study was carried out in two areas in the state of São Paulo, Brazil, both areas in mountain regions of the Atlantic Forest (Figure 1). One of these areas is the Fazenda São Sebastião do Ribeirão Grande (FSSRG), located in the Serra da Mantiqueira (22°45’S, 45°28’W), city of Pindamonhangaba. The property has a total area of 1617 hectares, 364 hectares of which are *Eucalyptus* spp. plantation, and altitude ranges from 630 to 1960 meters. The Atlantic Forest in the property is classified as Upper Montana Dense Ombrophilous Forest with an average annual temperature of 18°C and rainfall of ~1500 mm (INMET 2019).

The locality is inside a protected area that allows the sustainable use of its resources, named “Environmental Protection Area” (in portuguese: Área de Proteção Ambiental - APA), according to the Brazilian “National System of Protected Areas” (in portuguese: Sistema Nacional de Unidades de Conservação da Natureza - SNUC) (Brasil 2000). This protection category is extremely general and even includes urban areas, being a category in which the objective of animal protection is secondary (Rylands, Brandon 2005; Brasil 2000). Despite this, the region represents an important continuum of forest in a mosaic with other protected areas that allow the occurrence of the species. Talebi and Soares (2005) indicated a minimum of 32 muriquis in the area, and Strier et al. (2017) estimated 47 individuals with about 23 individuals of mature age.

The second study area is the Parque das Neblinas (PN), located in the Serra do Mar (23°46'S, 46°11'W), between the cities of Mogi das Cruzes and Bertioga, the total area is 7000 hectares, 3518 hectares of *Eucalyptus* spp. and *Pinus* spp. plantation. The altitude ranges from 600 to just over 1000 meters in the area. The forest is classified as Dense Montana Ombrophilous Forest with an average of 16°C to 18°C and rainfall ranging from 2600 mm to 3200 mm annually (Ecofuturo 2019).

The property is not a Protected Area in the model of the Brazilian “National System of Protected Areas”, despite being named as a Park (in Portuguese: Parque), but there is a protected area inside the limits of PN, a “Private Natural Heritage Reserve” (in Portuguese: Reserva Particular do Patrimônio Natural - RPPN) in a total area of 518 hectares, named RPPN Ecofuturo. The area is inserted in a continuum of 330000 hectares of Atlantic Forest with Serra de Paranapiacaba and Serra do Mar State Park, the last sharing boundaries with the PN.

Talebi and Soares (2005) pointed the PN as a target area for the study of muriquis, and Strier et al (2017) points out that despite the small size of its population (<50 individuals) it is the only one that has been monitored in the Serra do Mar, but this is the first study using drones to monitor muriquis in both areas.

Both areas have a record of illegal activities inside their limits or their surroundings, such as the extraction of juçara palm hearts (*Euterpe edulis*) and hunting. These activities may threaten muriquis and justifies the search for a monitoring methodology that does not involve the habituation of individuals over the monitoring period.

2.2 Drone and video analyses

We used a DJI Mavic 2 Enterprise Advanced (Figure 2) that has a RGB camera with 3840 x 2160 pixels maximum resolution and the option to zoom 4 times in the 1920 x 1080 pixels resolution, and a thermal camera with 640 x 512 pixels resolution (Table 1 to detailed specifications), using the grayscale to contrast the temperature differences, where the whitest points are the hottest. This model holds a maximum of 36km/h or 10m/s of wind, and cannot fly in the rain (DJI 2021).

Table 1 - Specifications of the cameras in the model of DJI Mavic 2 Enterprise Advanced (DJI 2021)

	RGB sensor	**Thermal sensor**
Sensor	CMOS de 1/2”	Uncooled vanadium oxide (VOx) microbolometer
Resolution	3840 x 2160 pixels	640 x 512 pixels
Focal Length	24mm	9mm
Digital zoom (video mode - max. resolution)	1x	1x
Digital zoom (video mode - low resolution)	4x	4x
Digital zoom (photo mode)	32x	16x

Figure 2: DJI Mavic 2 Enterprise Advanced drone, in frontal view. Photographed in Fazenda São Sebastião do Ribeirão Grande, Pindamonhangaba, São Paulo, Brazil.

Muriquis were filmed and photographed by flying over the canopy stratum of the forest. The distance from the drone to the canopy may vary according to the terrain and the control transmission signal. The equipment does not calculate the distance from the canopy, only the height from the take-off point and the altitude from the sea, but, by visual estimation, we set a distance of 50 meters from the canopy, on average. We only fly in the morning and afternoon, considering our goal of counting individuals, the night period is not ideal, as it is difficult to differentiate individuals when in a sleeping position.

We calculated the detection distance by considering the coordinate of the drone in the first sight of heat points, the coordinate of the muriquis and the difference of altitude between these coordinates, as we can see in Figure 3. The coordinates of muriquis were the drone coordinates when above the individuals with the gimbal placed on an angle of 90º degrees down. When it was not possible to approximate the exact point of the muriquis, like when they were out of the range of the drone, we estimated the coordinates by considering the geography, visual distance and compass orientation (detection number 28 and 29 in FSSRG). There are some flights with more than 1 detection, as the muriquis were divided into subgroups. These extra detections were used only for the calculation of detection distances. To calculate the detection efficiency, we used the number of flights with the presence of muriquis.

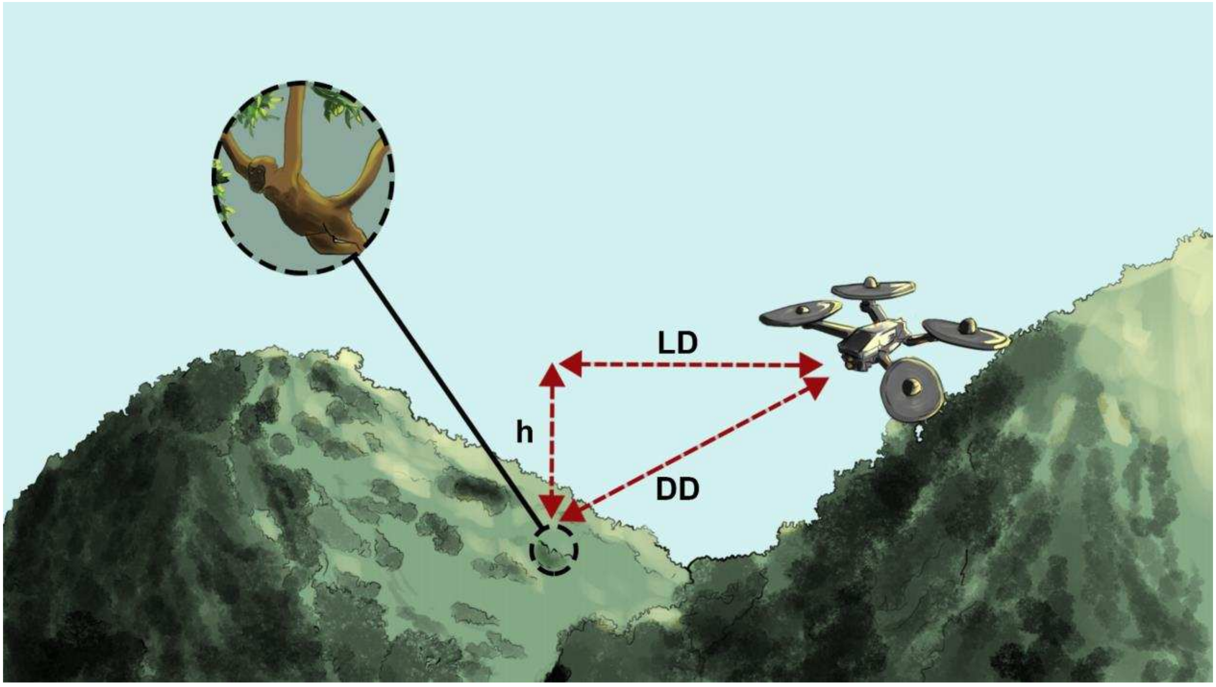

Figure 3: Calculation of detection distance (DD) considering the terrain. **LD** is the straight line distance between the coordinate of the drone in the first sight of hot points and the coordinate of the drone right above the muriquis, **h** is the difference in altitude between the point of first sight of heat points and the altitude above ground of the muriquis coordinate. We used the formula to calculate the hypotenuse: $LD^2 + h^2 = DD^2$

The incidence of sunlight was separated into categories. The "low" category was considered when there is no light incident on the canopy because there was dense cloud cover or, when the sun has not yet risen or has already gone. The “medium” category was considered when the light was incident in some parts of the area flown because of the partial cloudy cover, or when the light was incident partially behind the mountain. And the “high” category was considered when the light was incident directly in the canopy.

Normally, we can define whether the heat point is a species and identify the species detected, or if they are false positives during flights. For that, we move the drone down in relation to the ground or use the RGB camera zoom. When necessary, we also analyzed videos on the computer display to confirm or check for other details. If the heat point does not move or we are not able to confirm the muriquis in the color video, we do not consider them as individuals, even if there is confirmed muriquis close. The video analysis made *a posteriori* is essential to count individuals and classify them in sex and age categories, when possible.

Some muriquis' characteristics are essential to facilitate the detection of the species, locomotion being the main one. Even on the thermal camera we can recognize the muriquis because of the typical semi-brachiation locomotion (Ashton and Oxnard, 1964). When necessary, we used the size, color and other phenotypic characteristics, but normally on the RGB images we can see in detail the individuals, leaving no doubt which species was sighted.

The flights were active searches (manual flights) or, when the muriquis were already located, subsequent flights were directed to the previous detection coordinate. We used a resolution of 1920 x 1080 pixels to survey for muriquis, as we can use the 4 times optical zoom to confirm the species. When muriquis were confirmed, we stopped recording and switched to 3840 x 2160 pixels resolution.

When muriquis were in locomotion or traveling, we prioritized drone positioning to count individuals, with a wider angle of the camera and searching for a place where all the individuals were passing by. We counted muriquis passing considering the direction of their movements to avoid double counting of an individual. When they were not moving, like when foraging or resting, we did the counting and classification of sex and age by approximating the drone from the individuals and looking for more individuals in the proximity. All counts had double concordance between researchers.

To classify sex and age, we tried to approach an open tree that could be better to visualize muriquis in the RGB camera and we always used 3840 x 2160 pixels resolution. We also used the software Adobe Premiere CC and its tools for zooming and changing the speed of the video to help classify the muriquis by sex and age. Parameters used for the sex and age classification were in accordance with Strier et al. (2017) (Table S1 in Supplementary Materials).

The highest count in a video by region and the highest number of individuals classified by sex and age in a video were considered. However, the highest counting and highest classification by gender and age are not necessarily from the same video. Some videos that were better for counting were not necessarily better for classifying individuals.

Permits to study the animals in the areas were duly provided by the Brazilian federal agency SISBIO (authorization number 80503-1), the São Paulo state license (authorization number SIMA.008489/2022-79), and the ethics committee of the University CEUA (authorization number 106/22). The equipment is registered according to the Brazilian National Civil Aviation Agency ANAC.

2.3 Statistical analysis

We used the software R version 4.2.0 for all the statistical analysis and considered p<0,05 as the significance level. To test if there is any difference in the detection efficiency (presence or absence of muriquis in the flights) considering the sunlight incidence (low, medium and high) and the period of the day (morning and afternoon) we did a chi-square test. To test if there is difference in the detection distance according to the sunlight incidence and the period of the day, we did a two-way ANOVA. We also used the *t*-test to verify whether the result including the two coordinates of the muriquis in the FSSRG that were estimated had any influence on the mean number of detection distances.

3. RESULTS

3.1 Detection efficiency and detection distances

We had a total of 53 flights from October 15th 2022 to December 18th 2022 in the FSSRG and 65 flights in the PN from April 09th 2022 to December 10th 2022, in a total of 118 flights, 33 hours and 46 minutes and 482.65 kilometers flown. The average time of flight were 17 minutes and 10 seconds (+/- 3 minutes and 20 seconds) and 4.09 kilometers per flight (+/- 1.57 kilometers).

In FSSRG we had 28 flights with detection of muriquis, resulting in one flight with muriquis every 1.9 flights; one flight with muriquis every 7.9 kilometers traveled; one flight with muriquis every 32 minutes in the air; and 52.8% of the flights with detection of muriquis. In PN we had 6 flights with detections of muriquis, which results in one flight with muriquis every 10.8 flights; one flight with muriquis every 43.7 kilometers traveled; one flight with muriquis every 186 minutes and 45 seconds in the air; and 9.23% of the flights with detection of muriquis.

We ran a chi-square to analyze whether there are differences in muriquis' detections considering the incidence of the sunlight and the period of day in both areas of study. The result demonstrated that there is an association between the incidence of sunlight and the detection of muriquis in flights ($x^2_{(2)}$=7.1889; p=0.02748). The analysis of the adjusted standardized residuals showed that there is a lower detection of muriquis during flights with high incidence of sunlight, while there is a greater detection of muriquis on flights with low incidence of sunlight. Considering the period of the day, there was no differences between detections in morning and afternoon flights ($x^2_{(1)}$=2.7492; p=0.0973).

We tested whether there is a difference in the average detection distance with and without the two estimated values in the FSSRG, as there was no significant difference (t=0.24187, p=0.8097), we kept these two values in the next analysis. We had an average detection distance of 177.24 meters (σ 76.47) in the FSSRG, 178.24 meters (σ 60.59) in the PN and 177.39 meters (σ 73.61) considering both areas. The maximum detection distance was in FSSRG (383 meters).

To test if there is difference in the detection distance considering the sunlight and period of the day during the flights with muriquis' detections in both areas, we did a two-way ANOVA and had no statistically significant results in the interaction between these two variables (F(1,35)=1.072, p=0.3076), there was also no significant result considering only the incidence of sunlight (F(2,35)=2.820, p=0.0732) and period of the day (F(1,35)=0.441, p=0.5110).

3.2 Demographic monitoring

With our drone flights at FSSRG and surroundings we have identified three main regions with records of muriquis (Figure 4), we suspect that there are three distinct social groups, or subgroups, in the region, but a longer monitoring time is still needed to confirm this suspicion. Our highest individual count in a single flight was 39 individuals, this counting was made on the flight of 10/15/2022 at 6:29 a.m. in the central region of FSSRG. If we include the maximum counting in the other two regions (9 individuals, west of FSSRG and 6 individuals, east of FSSRG) we reached a number of 56 individuals in the region of FSSRG. Our highest classification by sex and age on a single flight was in 10/18/2022 at 3:53 p.m. with classification of 19 individuals, 8 with sex and age classification and 11 with just an age classification, as shown in Table 2.

Table 2 - Classification by sex and age during flight in 10/18/2022 at 3:53 p.m.

Sex/Age	Female	Male	Undetermined sex	Total
Infant	-	-	3	3
Juvenile	-	-	3	3
Sub-adult	-	1	-	1
Adult	5	2	5	12
Non Identified	-	-	-	-
Total	5	3	11	19

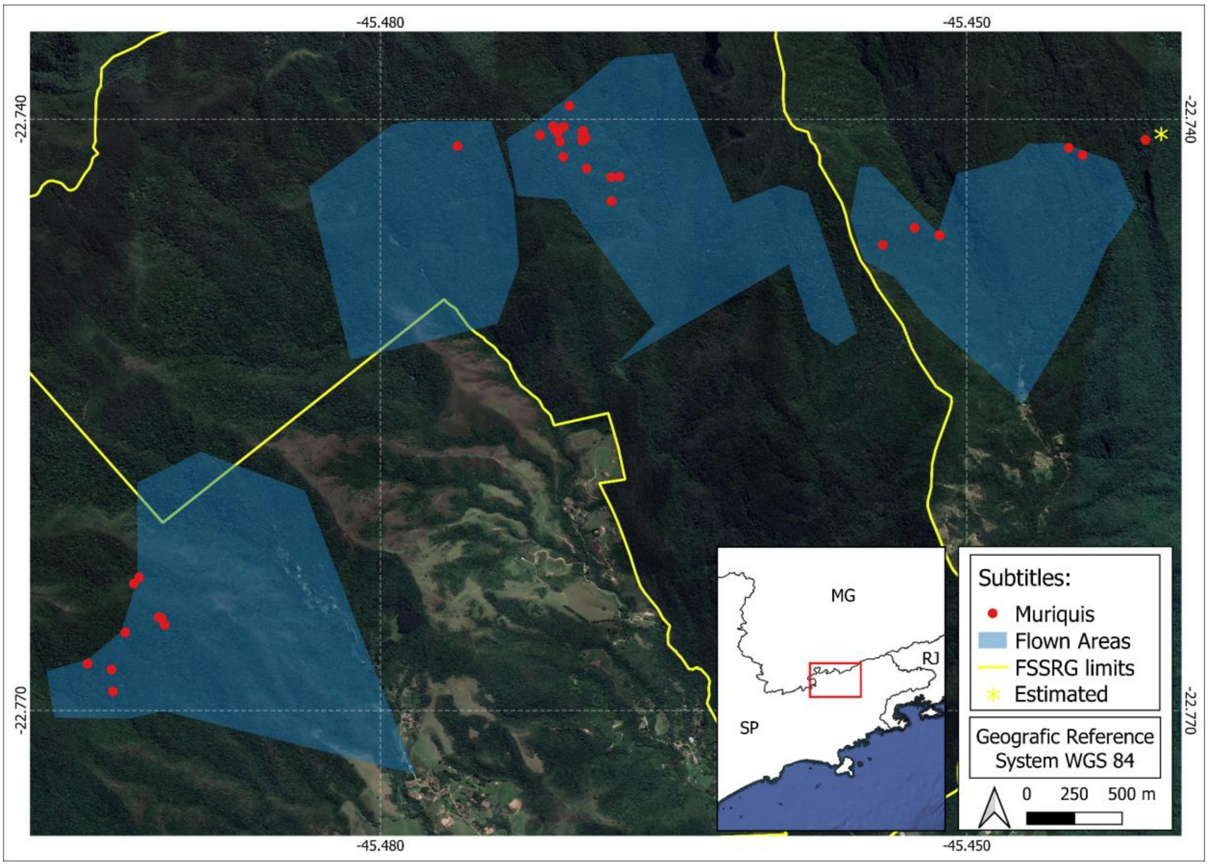

Figure 4 - Map of the FSSRG with the total detections of muriquis by the drone (red dots) made in 53 flights from October 15th 2022 to December 18th 2022. The blue polygons are the flown areas by the drone and the asterisk represents the estimated detection coordinate which was necessary because of the drone range limit.

In the west region of FSSRG our highest count was of 9 individuals in 3 flights, two in 10/16/2022, at 6:55 a.m. and at 5:02 p.m., and another in 10/17/2022 at 6:09 p.m.. The sex and age classification was made using two flights, one in 10/16/2022 at 5:02 p.m. as shown in Table 3 and other in 12/17/2022 at 6 a.m. as shown in Table 4.

Table 3 - Classification by sex and age during flight on 10/16/2022 at 5:02 p.m.

Sex/Age	Female	Male	Undetermined sex	Total
Infant	-	-	1	1
Juvenile	2	-	-	2
Sub-adult	-	-	-	-
Adult	-	2	-	2
Non Identified	-	-	-	-
Total	2	2	1	5

Table 4 - Classification by sex and age during flight on 12/17/2022 at 6 a.m.

Sex/Age	Female	Male	Undetermined sex	Total
Infant	-	-	-	-
Juvenile	-	-	-	-
Sub-adult	-	1	-	1
Adult	-	4	-	4
Non Identified	-	-	-	-
Total	-	5	-	5

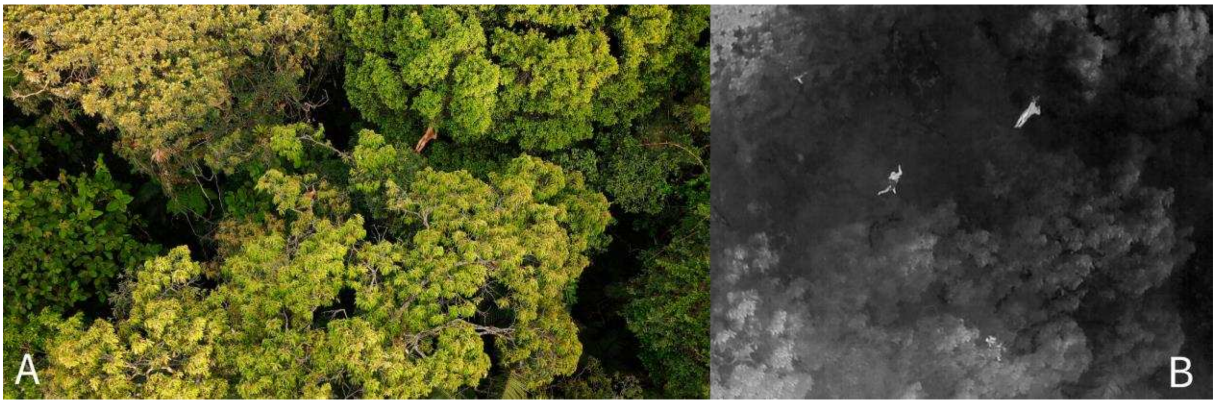

Figure 5: The same frame of the video on color sensor (A) and thermal sensor (B) in the FSSRG in 12/17/2022 at 14:40, showing the difference in detection between the two types of sensors.

In the east surroundings of FSSRG we could register on the same day (12/17/2022) 2 subgroups on opposite ends of the valley. One of them was registered on a flight at 5:19 p.m. with 6 individuals resting, and another was registered passing the FSSRG limits at 2:40 p.m. with 14 individuals (Figure 5). The subgroup that was filmed crossing the FSSRG boundaries could be a subgroup of the FSSRG central group, a subgroup of the individuals found on the opposite of the valley, or even a fourth social group. Therefore, to be conservative, we considered only 6 individuals in this region. The sex and age classification of the 6 individuals spotted on the drone flight performed at 5:19 p.m. was not possible because the muriquis were out of the range of the drone.

At PN we were able to identify muriquis in just one region in the surrounding area of the property, inside the Itatinga hydroelectric power plant which is inside the

Serra do Mar State Park (Figure 6). We counted 10 individuals in one flight in 10/11/2022, at 8:41 a.m. and we could classify 6 individuals in the flight performed in 10/11/2022 at 4:15 p.m., as shown in Table 5.

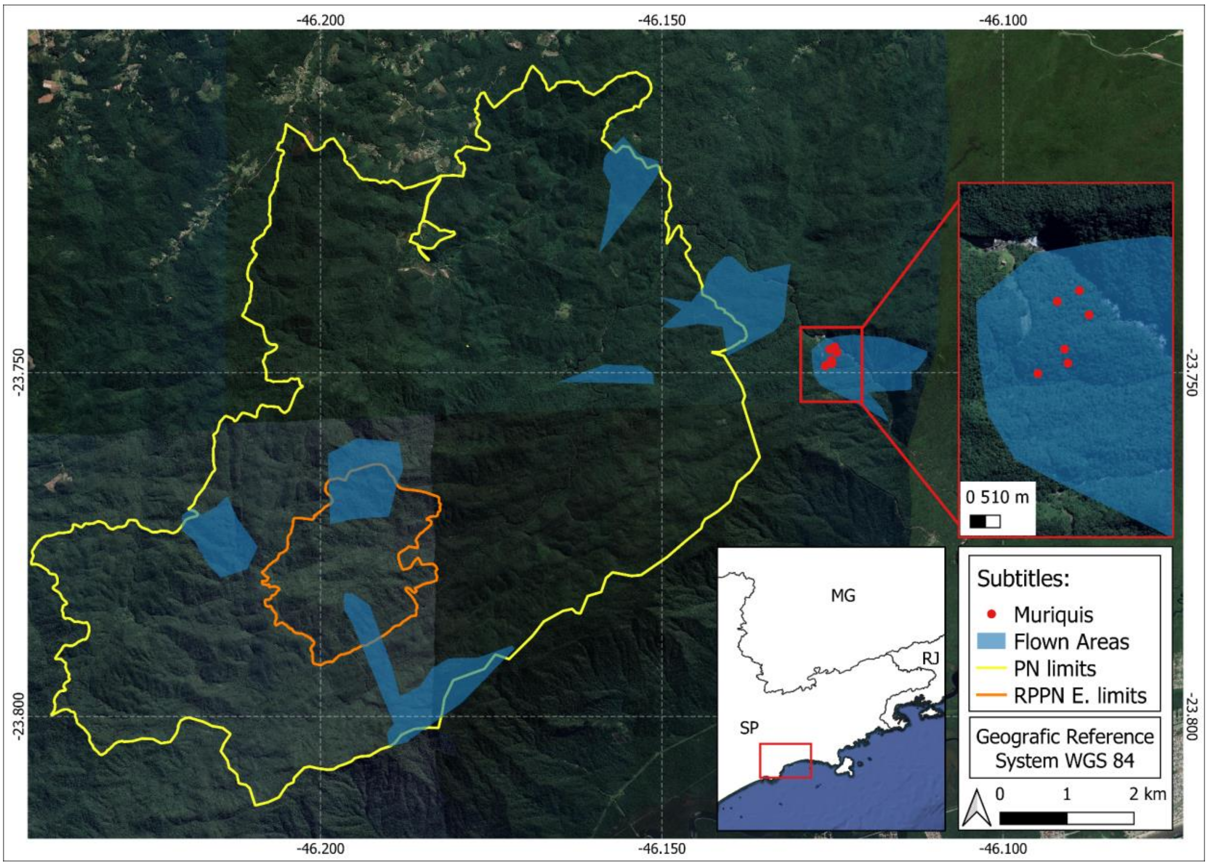

Figure 6 - Map of the PN and RPPN Ecofuturo with the total detections of muriquis by the drone (red dots) in the surroundings of PN in a total of 65 flights from April 09th 2022 to December 10th 2022. The blue polygons are the flown areas by the drone.

Table 5 - Classification by sex and age during flight on 10/11/2022 at 4:15 p.m.

Sex/Age	**Female**	**Male**	**Undetermined sex**	**Total**
Infant	-	-	2	2
Juvenile	-	-	-	-
Sub-adult	-	-	1	1
Adult	2	-	1	3
Non Identified	-	-	-	-
Total	2	-	4	6

We hypothesized that this group could be using the area inside the PN, but considering constant reports from employees of the Itatinga hydroelectric power plant, it is possible that the area they use most is where they were recorded here in our sampling.

4. DISCUSSION

We tested whether the incidence of sunlight and period of the day during the flights influences the detections of muriquis and the detection distance with the purpose of identifying better flight conditions. We had no significant result of the period of the day, both in the detections of muriquis as well as in the detection distance, differently from what was found in Whitworth et al. (2022), which observed the influence of the hour of flight on the detection of several species of animals. We also did not find differences in the effect of sunlight incidence in the detection distance considering the p value < 0.05, but we had a significant effect of the sunlight incidence in the detection of muriquis, where conditions with low sunlight incidence were best to detect the species.

This result is probably related to the difficulty in separating the body heat of the species from the heat of the environment under high sunlight incidence, which is a characteristic directly related to technical factors of the equipment. But this result may also be related to thermoregulation's behavioral, that had already proven for other species of primates (Clutton-Brock 1973; Paterson 1981; Takemoto 2004; Gestich, Caselli and Setz 2014) and may be present in the muriqui's specie.

Prior to using the drone coupled to a thermographic camera, we tried using a simple RGB drone to find muriquis. Although we had a great result with 30 individuals in a flight, this result depended on specific conditions to happen. We needed a day without wind, with the muriquis moving quickly and the drone flying closer to the canopy, so we can see the sway of the trees and detect the muriquis during the flight, allowing the positioning of the drone in the best way for counting.

We also counted muriquis by land; we had 9 encounters with muriquis during the active search from June 2021 to December 2022, but our maximum count was 13 individuals. Non habituated muriquis, when in the human presence, have the behavior of alerting other individuals through their alarm vocalization, and then moving away quickly (Aguirre 1971). Added to the still lack of individual identification of the southern muriquis, counting the number of individuals in the area by land results in an estimated number.

Drones have proven to be technologies capable of contributing to arboreal fauna studies, but it is undeniable that they still have their limitations. Most studies that seek to calculate the density and abundance of a species using drones use standardized and autonomous flights. This allows the development of analyzes similar to those used for other methodologies, such as linear transects. One example is in Brack et al. (2023) study, which used the N-mixture model to calculate species abundance. In our study area and with our study species, autonomous and linear flight are not the best options. We have a terrain with great variation in altitude that makes linear flights and with constant altitude of the canopy difficult.

The species also has a social behavior and normally stays in groups during its daily activities. Thus, with an autonomous and linear flight we would have a reduced ability to count individuals, since normally after finding the first individuals, following them and looking for a better drone positioning for a count, it is possible to make a count much higher than it would be a count on a linear flight. It is the case of our results using the drone only with a RGB sensor: the detection of the muriquis during the flight only occurred on one day in its first flight, in a total of 172 flights performed, being possible to return to the detection coordinate with the other 2 batteries, position the drone and count 30 individuals, another 9 flights the muriquis were only detected in the later analysis of the videos, having a maximum count of 7 individuals in a flight.

The challenge of the active search flights that we carry out in our areas is to choose the sampling unit for this kind of research. Using time and kilometers of the flights seems to be a good alternative, but the area sampled would be the best. Some simple functions and softwares could be developed to facilitate the calculation of the sampled area in mountainous areas.

Linchant et al. (2015) have developed a software to calculate the sampling area for each drone flight, but the software assumes a constant drone altitude throughout the entire flight and also a fixed camera angle, which is not our case. In our flight's type, we need a software in which we can include information such as a topographic map of the area, the drone's altitude from the take-off point, the angle of the drone and the camera, as well as the camera view, throughout all the flight time, would solve this issue of calculating the sampled area.

Another considerable limitation for the use of drones in mountainous and dense forests is the signal of the remote control. The control uses a radio frequency that does not allow obstacles between the control and the drone, so, in some areas we have difficulty finding take-off points, as is the case in the PN. A drone that uses an internet network can facilitate piloting, as in our mountainous research areas it is usually possible to use 4G networks, but a portable signal replicator might be an alternative for all kinds of areas.

It is also interesting to point out that Brazilian legislation on drone flights, which is very general concerning their uses, often limits us in terms of altitude and distance from the take-off point, needing a greater number of takeoff points to cover areas with large terrain differences. Ideally, a specific authorization category could be created for the use of drones in scientific research in remote and mountainous areas.

Conflicts with owners of neighboring properties can also represent a difficulty in the work. Often, the drone's access to the target area requires flying over a neighboring property or using a take-off point from within it. In Brazil, the access to airspace is the responsibility of the National Civil Aviation Agency (ANAC - in Portuguese acronym), but many owners are not comfortable with drone flights on their property. We always get in touch with neighboring owners and explain the study, but we do not always get access to these areas. This is the example of an area in the center of the FSSRG that we are not authorized to access.

Our results in population monitoring show us that drones could be an indispensable tool for future studies with arboreal species, especially the muriquis. In our study area, the use of drones can avoid an unwanted habituation of the individuals, avoiding a possible increase in their hunting risk, as appointed by Strier (2010) and Strier et al (2017).

Considering the spatial distribution of all muriquis detections in the FSSRG area and the time interval between these detections, we have a strong suspicion that there are 3 distinct social groups on the property. We hope that with the constant monitoring of these regions and also with the help of other monitoring technologies, such as camera traps, it will be possible to confirm the number of social groups existing within the FSSRG and in its surroundings. Considering that drones allow not only a higher individual count, but also a sex and age classification, it has proved to be an important tool in population monitoring.

The number of total individuals, the total area available for the muriquis in FSSRG, the existence of groups in proximity with sufficient habitat to guarantee a bidirectional flow between areas, allows us to consider the FSSRG's muriquis population as a viable population in the long term, considering Lanna et al. (2021). In addition, with the previous surveys in the area and our results demonstrated here, the population in FSSRG seems to be in stability or even growing. While the population around the PN still needs monitoring for a longer time to confirm its population size and then its population viability.

In addition to surveys and demographic monitoring, drones can be the first steps in research with arboreal animals, playing an important role to survey potential areas for opening strategic trails, considering locations with more records of muriquis. Drones can also be used for behavioral studies, as with the innovation in zoom quality of the equipment's it is possible to maintain a distance that does not disturb the animals (DJI 2023a; DJI 2023b). In addition, drones are getting quieter (Frąckiewicz 2023) and there is also the potential that the animals can become habituated to the sound of drone propellers.

5. CONCLUSIONS

We conclude that sunlight incidence is an important factor to consider when designing data collection using drones with thermal sensors, as it influences the detection capacity of muriquis. We show here the importance of monitoring muriquis using drones in remote areas that are difficult to access by land and areas where we want to avoid the habituation of individuals. In addition, we demonstrate the effectiveness of thermal sensors coupled with drones for a more precise individual count when compared to the count by land and the count using simple RGB drones, as well as the possibility of using color images for the sex and age classification of individuals.

Although there are still doubts regarding the use of drones for the population monitoring of arboreal species and limitations considering the geography of the areas, the tool demonstrated a revolutionary potential in our study area, facilitating the work with endangered arboreal species that live in areas of difficult access and which use a large home range. The drone can still facilitate the initial work of defining the hot areas to open the trails by considering the places where the species' detections are concentrated and can facilitate the detection of species by land through the coordinate of detection of the drone.

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7. SUPPLEMENTARY MATERIALS

Table S1 – Criteria for sex and age classification modified from Strier et al., 2017

Age category	Characteristics
Infant	Infants are carried ventrally or dorsally by their mother, at 0 to 2 months they are nursing frequently, by 6 months they can play and move next to your mothers. By 12 months they increase their independence in feeding and traveling. They are carried until the weaning, which occurs between 12 and 24 months, but mothers still help their infants in difficult crossing after weaning.
Juvenile	Juveniles are completely independent and weaned but can still travel next to their mothers. The most outstanding characteristic for the classification of juveniles is their body size.
Subadult	Subadults are smaller in body size compared to adults. The female's genitalia are smaller and less pendulous, and they have small and visible nipples. Males have testes larger than juveniles but smaller than adults.
Adult	Female adults have clitoris and labia elongated and females' nipples that have already nursed infants are elongated too. Males have testes equivalent, in size, of "softballs".

Table S2 – Flights in Fazenda São Sebastião do Ribeirão Grande, Pindamonhangaba

Flight	Date	Hour	Period of the day	Time of flight	Km flown	Incidence of sunlight	Muriqui's detection	Detection distance	Number of individuals
1	10/15/22	06:29	a.m.	19:41	3.045	high	yes	127.10	38
2	10/15/22	06:50	a.m.	16:58	4.339	high	no	-	-
3	10/15/22	07:08	a.m.	16:39	3.580	high	no	-	-
4	10/15/22	02:34	p.m.	20:04	4.211	low	no	-	-
5	10/15/22	04:19	p.m.	19:15	3.115	low	yes	166.72	12
6	10/15/22	04:40	p.m.	18:34	3.114	low	yes	210.28	12
7	10/16/22	06:32	a.m.	16:32	8.494	low	no	-	-
8	10/16/22	06:55	a.m.	19:22	3.561	low	yes	159.00	9
9	10/16/22	07:17	a.m.	18:54	3.484	low	yes	245.02	7
10	10/16/22	00:10	p.m.	16:47	6.183	medium	no	-	-
11	10/16/22	00:28	p.m.	16:34	3.545	medium	no	-	-
12	10/16/22	00:46	p.m.	10:55	3.687	low	no	-	-
13	10/16/22	05:02	p.m.	18:15	3.660	low	yes	87.36	8
14	10/16/22	05:21	p.m.	17:50	3.934	low	yes	282.06	8
15	10/16/22	05:40	p.m.	16:14	6.483	low	yes	155.02	7
16	10/17/22	06:22	a.m.	14:43	3.349	high	yes	171.40	1
17	10/17/22	06:37	a.m.	18:03	4.708	high	no	-	-
18	10/17/22	06:56	a.m.	19:30	5.294	high	no	-	-
19	10/17/22	04:51	p.m.	05:40	1.838	low	no	-	-
20	10/17/22	06:09	p.m.	19:10	3.806	low	yes	101.04	9
21	10/18/22	10:28	a.m.	13:24	3.626	low	no	-	-
22	10/18/22	01:53	p.m.	17:12	5.398	low	yes	239.02	35
23	10/18/22	02:11	p.m.	08:49	2.561	low	yes	231.03	28
24	12/13/22	08:32	a.m.	11:58	2.950	low	yes	212.39	4

25	12/14/22	04:45	p.m.	18:10	3.089	medium	yes	146.36	8
26	12/14/22	05:05	p.m.	19:24	2.738	medium	yes	129.47	9
27	12/14/22	05:56	p.m.	16:48	3.013	low	yes	291.53; 171.42; 50.45	15
28	12/15/22	06:14	a.m.	16:30	2.942	low	yes	96.57; 137.37	4
29	12/15/22	06:44	a.m.	18:30	3.369	high	no	-	-
30	12/15/22	07:06	a.m.	20:05	3.873	high	no	-	-
31	12/15/22	02:58	p.m.	18:55	4.223	low	no	-	-
32	12/15/22	04:06	p.m.	18:07	5.543	low	no	-	-
33	12/15/22	06:46	p.m.	15:48	6.559	low	no	-	-
34	12/16/22	10:01	a.m.	15:52	3.610	high	no	-	-
35	12/16/22	10:19	a.m.	17:09	4.755	high	no	-	-
36	12/16/22	10:41	a.m.	19:35	5.693	high	no	-	-
37	12/17/22	05:43	a.m.	15:57	4.596	low	yes	267.76	5
38	12/17/22	06:00	a.m.	17:58	3.703	medium	yes	175.14	5
39	12/17/22	06:19	a.m.	19:04	5.903	medium	yes	272.00	5
40	12/17/22	01:56	p.m.	18:03	3.357	low	yes	382.88	7
41	12/17/22	02:18	p.m.	18:20	2.613	low	yes	138.58; 139.85	18
42	12/17/22	02:40	p.m.	17:07	3.047	low	yes	215.38	14
43	12/17/22	04:04	p.m.	17:07	3.836	low	no	-	-
44	12/17/22	05:19	p.m.	14:03	3.017	low	yes	264.33	6
45	12/17/22	06:35	p.m.	16:10	4.429	low	yes	235.93	3
46	12/18/22	05:55	a.m.	17:34	5.561	medium	no	-	-
47	12/18/22	06:35	a.m.	18:22	6.150	medium	no	-	-
48	12/18/22	06:54	a.m.	19:25	3.885	high	yes	57.49; 52.33; 128.14	10
49	12/18/22	11:50	a.m.	18:42	6.329	low	no	-	-
50	12/18/22	00:10	p.m.	18:19	4.645	low	no	-	-
51	12/18/22	04:48	p.m.	19:07	5.351	low	no	-	-
52	12/18/22	05:09	p.m.	18:05	3.532	low	yes	121.08	9
53	12/18/22	05:29	p.m.	17:00	3.081	low	yes	164.11	10

Table S3 – Flights in Parque das Neblinas, Mogi das Cruzes and Bertioga

Flight	Date	Hour	Period of the day	Time of flight	Km flown	Incidence of sunlight	Muriqui's detection	Detection distance	Number of individuals
1	04/09/22	11:12	a.m.	10:00	0.622	medium	no	-	-
2	04/10/22	00:42	p.m.	09:22	5.949	low	no	-	-
3	04/10/22	01:17	p.m.	18:09	4.056	low	no	-	-
4	04/11/22	08:57	a.m.	15:55	3.053	high	no	-	-
5	04/11/22	09:28	a.m.	18:16	5.149	high	no	-	-
6	04/11/22	10:50	a.m.	18:06	3.754	low	no	-	-
7	04/11/22	11:11	a.m.	20:36	1.992	low	no	-	-
8	04/11/22	00:38	p.m.	20:33	6.011	low	no	-	-
9	04/11/22	04:53	p.m.	21:21	3.636	low	no	-	-
10	04/12/22	08:26	a.m.	19:08	2.462	high	no	-	-
11	04/12/22	09:19	a.m.	17:56	3.702	high	no	-	-
12	04/12/22	09:38	a.m.	18:37	2.396	high	no	-	-
13	04/12/22	10:19	a.m.	20:22	3.278	medium	no	-	-
14	06/14/22	04:12	p.m.	20:23	3.913	low	no	-	-
15	06/15/22	08:54	a.m.	16:38	1.350	medium	no	-	-
16	06/15/22	11:53	a.m.	22:14	0.946	medium	no	-	-
17	06/15/22	04:43	p.m.	21:10	2.091	low	no	-	-

18	06/16/22	07:50	a.m.	16:41	1.826	medium	no	-	-
19	10/06/22	06:28	a.m.	17:43	4.967	low	no	-	-
20	10/06/22	06:48	a.m.	20:39	4.563	low	no	-	-
21	10/06/22	07:11	a.m.	16:12	4.822	low	no	-	-
22	10/06/22	05:17	p.m.	18:49	2.442	low	no	-	-
23	10/06/22	05:27	p.m.	17:50	3.820	medium	no	-	-
24	10/06/22	05:49	p.m.	23:57	5.785	low	no	-	-
25	10/08/22	05:58	a.m.	16:16	3.908	low	no	-	-
26	10/08/22	06:23	a.m.	17:24	5.195	medium	no	-	-
27	10/08/22	02:46	p.m.	10:55	2.634	low	no	-	-
28	10/08/22	03:25	p.m.	06:47	2.733	low	no	-	-
29	10/08/22	03:36	p.m.	17:12	4.342	low	no	-	-
30	10/08/22	04:20	p.m.	15:08	4.446	low	no	-	-
31	10/09/22	07:47	a.m.	14:56	5.152	low	no	-	-
32	10/09/22	08:19	a.m.	20:34	7.887	low	no	-	-
33	10/09/22	08:41	a.m.	16:01	5.931	low	no	-	-
34	10/11/22	06:47	a.m.	18:00	2.569	low	yes	294.19	9
35	10/11/22	07:20	a.m.	17:05	2.042	low	yes	134.83	8
36	10/11/22	08:41	a.m.	11:46	0.667	low	yes	189.18	10
37	10/11/22	03:55	p.m.	18:42	1.334	low	yes	161.03	3
38	10/11/22	04:15	p.m.	19:01	1.613	low	yes	159.45	6
39	10/11/22	04:37	p.m.	17:39	3.031	low	yes	130.74	3
40	10/12/22	02:59	p.m.	18:45	6.162	low	no	-	-
41	10/12/22	04:48	p.m.	20:13	6.221	low	no	-	-
42	10/12/22	05:10	p.m.	09:44	5.178	low	no	-	-
43	10/13/22	06:03	a.m.	16:48	5.465	low	no	-	-
44	10/13/22	06:21	a.m.	17:00	5.665	low	no	-	-
45	10/13/22	06:40	a.m.	16:40	5.237	low	no	-	-
46	10/13/22	05:05	p.m.	07:12	2.196	low	no	-	-
47	10/14/22	05:55	a.m.	10:25	3.316	low	no	-	-
48	10/14/22	06:31	a.m.	06:41	2.748	low	no	-	-
49	12/07/22	06:34	a.m.	14:07	3.200	low	no	-	-
50	12/08/22	06:20	a.m.	18:16	3.699	low	no	-	-
51	12/08/22	07:28	a.m.	19:29	6.005	high	no	-	-
52	12/08/22	07:49	a.m.	20:19	5.906	high	no	-	-
53	12/08/22	05:32	p.m.	17:58	6.115	high	no	-	-
54	12/08/22	05:52	p.m.	16:38	5.332	high	no	-	-
55	12/09/22	06:34	a.m.	17:15	3.752	high	no	-	-
56	12/09/22	06:53	a.m.	19:54	3.998	high	no	-	-
57	12/09/22	07:15	a.m.	19:14	4.908	high	no	-	-
58	12/09/22	05:11	p.m.	19:10	4.062	high	no	-	-
59	12/09/22	05:32	p.m.	21:28	5.268	medium	no	-	-
60	12/09/22	05:55	p.m.	18:58	5.102	medium	no	-	-
61	12/10/22	06:56	a.m.	21:24	8.502	high	no	-	-
62	12/10/22	07:20	a.m.	20:35	8.148	medium	no	-	-
63	12/10/22	05:55	p.m.	16:16	3.558	medium	no	-	-
64	12/10/22	06:12	p.m.	19:29	3.908	medium	no	-	-
65	12/10/22	06:32	p.m.	18:11	2.504	low	no	-	-

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