Aplicación de drones en la conservación de la vida silvestre del hotspot Cerrado
Drone application for wildlife conservation in the Cerrado hotspot

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Programa de Doctorado en Biodiversidad

Aplicación de drones en la conservación de la vida silvestre del hotspot Cerrado

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Memoria presentada por **Geison Pires Mesquita** para optar por el grado de Doctor por la Universidad Autónoma de Barcelona 2021

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A mi familia,

A mi abuela,

Y a todas las personas que luchan por la conservación de la biodiversidad.

“*La mente que se abre a una nueva idea, jamás volverá a su tamaño original*”

Albert Einstein

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Además de los diversos problemas que tuve en el desarrollo del trabajo de campo en Brasil, que fueron en parte responsables de los diversos cambios a lo largo de la tesis, es imposible no comentar las consecuencias que la pandemia del Covid 19 trajo al desarrollo de la tesis y a mi vida. Tras haber transcurrido poco más de la mitad de la tesis, emergió este triste momento de la historia, que lamentablemente fue mucho más trágico aquí en Brasil, principalmente por los diversos errores cometidos por los dirigentes del país. Hacer un doctorado en medio del caos que se ha producido en el país, contraer Covid durante el pico de la pandemia, sin ninguna vacuna disponible todavía, ver morir a amigos por esta enfermedad que hoy ha superado los 610.000 muertos en Brasil, es algo para lo que no estaba preparado y que casi me hizo renunciar a mi doctorado. Por haber pasado por todo esto y haber superado todos estos percances, quiero agradecer eternamente a mi familia, mi refugio y mi base, que siempre me apoya en todos los sentidos y en todas mis decisiones, sean o no equivocadas. Muchas gracias, familia, sin vosotros nada de esto hubiera sido posible.

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Resumen

La tecnología de drones, emergente en el siglo XXI, se ha convertido en una de las principales herramientas tecnológicas en el campo de la biología de la conservación. Los estudios de identificación, seguimiento, análisis poblacional y comportamiento de la vida silvestre con el uso de drones están creciendo exponencialmente en los últimos años debido a su capacidad para obtener datos de alta resolución espacial y temporal, empleando un menor esfuerzo logístico en comparación con las metodologías convencionales. Sin embargo, los estudios y proyectos de conservación que utilizan drones aún son escasos en algunas regiones geográficas como es el bioma Cerrado, un “hotspot” y uno de los ecosistemas de sabana más amenazados del mundo. El objetivo de esta tesis consiste en ampliar las posibilidades de uso de drones dentro del bioma Cerrado analizando el potencial y las limitaciones de esta tecnología para el estudio de la vida silvestre.

El uso de drones en biología de la conservación, aunque está en constante crecimiento debido a varias ventajas metodológicas y de disponibilidad de datos, todavía se limita a grupos de investigación con cierta capacidad financiera. Debido a esto, el primer capítulo de esta tesis aborda la principal limitación en el uso de drones en materia de conservación, el coste de adquisición de los equipos, proporcionando una solución económica para su construcción (“hazlo tú mismo”, Do It Yourself, DIY) accesible al usuario no especializado, ya que no requiere conocimientos avanzados de electrónica. El segundo y tercer capítulo tratan sobre el impacto que los drones tienen sobre dos grupos de fauna, aves y mamíferos,

analizando los factores específicos (estímulo visual y auditivo) que lo causan y las consecuencias de dicho impacto (efectos en la reproducción, cambios comportamentales). Concretamente, el segundo capítulo demuestra que el estímulo visual provocado por los drones sobre especies de avifauna puede afectar negativamente a su proceso de reproducción en las áreas de anidación. El tercer capítulo aborda el estudio del impacto del estímulo acústico de los drones, demostrando en experimentos realizados “ex situ” que el nivel de presión y la frecuencia de los sonidos generados por estos aparatos provocan diferentes cambios de comportamiento en especies de megafauna terrestre. Finalmente, en el cuarto capítulo, se presenta un dron equipado con dispositivos comerciales de seguimiento de bajo coste para localizar blancos que pueden usarse para marcar fauna terrestre.

Los capítulos de esta tesis, además de abordar el potencial del uso de drones en el Cerrado, aportando el conocimiento para la construcción de drones específicos y de bajo coste para estudios en grandes áreas, así como la viabilidad de usar drones de plataforma multirotor para estudios de rastreo de vida silvestre, también abordan las limitaciones de los mismos al mostrar las posibles perturbaciones que los estímulos visuales y sonoros pueden generar en diferentes especies de aves y mamíferos. Estas informaciones son fundamentales para ampliar el uso de drones y mejorar los estudios futuros de la vida silvestre en el bioma del Cerrado, además de ayudar en el desarrollo de protocolos para el uso de esta tecnología tanto por la comunidad científica como por la sociedad civil, especialmente en áreas protegidas.

Abstract

The emerging drone technology has become one of the leading technological tools in the field of conservation biology in the 21st century. Studies of identification, monitoring, population analysis and behavior of wildlife with the use of drones are growing exponentially in recent years due to their ability to obtain high spatial and temporal resolution data while requiring less logistical effort as compared to conventional methodologies. However, studies and conservation projects using drones are still scarce in some geographic regions such as the Cerrado biome, a hotspot and one of the most threatened savanna ecosystems in the world. The objective of the thesis is to expand the possibilities of using drones within the Cerrado biome by analyzing the potential and limitations of this technology for the study of wildlife.

The use of drones in conservation biology, although constantly growing due to various methodological and data availability advantages, is still limited to research groups with some financial capacity. For this reason, the first chapter of this thesis addresses the main limitation of the use of drones in conservation, the cost of acquiring the equipment; it provides an economic solution "DIY " (Do It Yourself) accessible to the non-specialized user, as it does not require advanced knowledge in electronics. The second and third chapters analyze the impact that drones have on two groups of fauna, birds and mammals respectively, by analyzing the specific factors (visual and auditory stimulus) that cause perturbations and analyzing the consequences of these (effects on reproduction, behavioral changes). Specifically, the second chapter shows that the visual stimulus caused by drones on bird species can negatively affect their reproduction process in nesting areas located in waterfalls. The third chapter deals with the study of the impact of the acoustic stimulus of drones, demonstrating in ex situ experiments that the pressure level and the frequency of the sounds generated by the drones cause different behavioral changes in terrestrial megafauna species. Finally, in the fourth chapter, I introduce a drone equipped with a system consisting of low-cost commercial tracking devices in order to locate targets that can be used to mark terrestrial fauna.

The chapters of this thesis also address the potential of the use of drones in the Cerrado, providing knowledge for the development of specific and low-cost drones for studies in large areas as well as demonstrating the feasibility of using multirotor platform drones for studies of wildlife tracking. The chapters also address the limitations of their use by uncovering the potential disturbances generated to different species of birds and mammals, which are caused by either visual or sound stimuli from drones. This information is essential to expand the use of drones and improve future studies of wildlife in the Cerrado biome, in addition to helping in the development of protocols for the use of this technology by both the scientific community and the civil society, especially in protected areas.

Abbreviations

ANAC – Agência Nacional de Aviação Civil

BVLOS – Beyond Visual Line-Of-Sight

DIY – Do It Yourself

EASA – European Union Aviation Safety Agency

FAA – Federal Aviation Administration

GCS – Ground Control Station

HTOL - Horizontal Take Off Landing

ICAO – International Civil Aviation Organization

MAV – Micro Aerial Vehicle

MTOM - Maximum Take Off Mass

NASA – National Aeronautics and Space Administration

NAV – Nano Aerial Vehicle

PAV – Pico Aerial Vehicle

RPA – Remotely piloted aircraft

RPAS – Remotely piloted aircraft system

RC – Radio Controller

SD – Smart Dust

sUAV – small UAV

UAV – Unmanned Aircraft Vehicle

UAS – Unmanned Aircraft System

UFMA – Universidade Federal do Maranhão

UWB – Ultra-Wide Band

VHF – Very High Frequency

VLOS - Visual Line-Of-Sight

VTOL – Vertical Take Off and land

DIRECTORS' REPORT

DIRECTOR'S REPORT

Dr. José Domingo Rodríguez-Teijeiro, researcher and professor of the Department of Evolutionary Biology, Ecology and Environmental Sciences, University of Barcelona, Dra. Margarita Mulero-Pázmány, researcher and lecturer in Drone applications in Natural Sciences of School of Biological and Environmental Sciences, Liverpool John Moores University, and Dr. Serge A. Wich, researcher and professor of School of Biological and Environmental Sciences, Liverpool John Moores University, as directors of the PhD. Thesis authored by M.S. Geison Pires Mesquita and entitled Application of drones in wildlife conservation of the Cerrado hotspot (Aplicación de drones en la conservación de la vida silvestre del hotspot Cerrado),

INFORM

That the results and conclusions achieved in the research developed by M.S. Geison Pires Mesquita as part of his PhD Thesis have been organized in 4 chapters, which correspond to 4 papers (2 published, 1 under revision and 1 to be submitted). We attach the list of published manuscripts, together with the impact of each journal (2020 Journal Citation Reports, ISI Web of Knowledge)

1. Mesquita, G. P., Rodríguez-Teijeiro, J. D., de Oliveira, R. R., & Mulero-Pázmány, M. (2021). Steps to build a DIY low-cost fixed-wing drone for biodiversity conservation. PLOS ONE, 16(8), e0255559. https://doi.org/10.1371/journal.pone.0255559

   Journal Impact Factor 2020 = 3.240, in Q1 of "Multidisciplinary" group

2. Mesquita, G. P., Rodríguez-Teijeiro, J. D., Wich, S. A., & Mulero-Pázmány, M. (2021). Measuring disturbance at swift breeding colonies due to the visual aspects of a drone: a quasi-experiment study. Current Zoology, 67(2), 157–163. https://doi.org/10.1093/cz/zoaa038

   Journal Impact Factor 2020 = 2.624, in Q1 of "Animal Science and Zoology" group

And CERTIFY that

the contribution of M.S. Geison Pires Mesquita has been very active as demonstrated by his first co-authoring of all manuscripts that confirm this PhD Thesis. Concretely, his participation included the following task:

- Definition of the focus and objectives of the derived manuscripts
- Development and execution of experimental designs for field work
- Compilation of data, analysis and interpretation of results
- Main writing of the manuscripts, preparation and design of the figures and tables and responsible for the submission.

Finally, we certify that none of the co-authors of the manuscripts detailed above has used nor is going to use, implicitly or explicitly, the information produced and presented here with the purpose of elaborating another PhD Thesis.

Barcelona, 22 November 2021

wich

José Domingo Rodríguez-Teijeiro | Margarita Mulero Pázmány | Serge A. Wich

GENERAL INTRODUCTION

GENERAL INTRODUCTION

What is a drone?

Created in the 30s in the military field as a tool of war (Newcome, 2004), drones have evolved and diversified in recent years, currently including a variety of unmanned aircrafts that range from toys to weapons. Once incorporated into the civilian society in 2006, when the first commercial drone use license was issued by the FAA (Federal Aviation Administration), there has been an exponential increase in drone use, currently reaching more than 1.5 million registered drones for commercial and recreational purposes in the United States only, the main drone market in the world (FAA, 2020).

The term “drone” has been adopted over different technical nomenclatures and acronyms that have emerged in recent years (Table 1), which attempt to conceptualize a remotely-controlled unmanned autonomous system. As shown in Table 1, many of the acronyms created use the term "aircraft" or "aerial", since the historical and current majority of remotely controlled autonomous unmanned vehicle systems, that is, drones, are aerial vehicles. However, it is worth mentioning that several other systems used in terrestrial or aquatic environments, such as the Russian Status-6 military system, an "unmanned underwater vehicle", or the Perseverance civil system of the National Aeronautics and Space Administration - NASA, "unmanned ground vehicle" are also considered drones as they have the same conceptual prerequisites (Lațici, 2019; Obura et al. 2019).

Table 1: Main acronyms and terms used to refer to Drones. Terms in bold are those that have had some official recognition from the main international civil aviation agencies (ICAO, FAA, EASA). Adapted from Granshaw (2018).

Acronyms	***Description***	***Meaning***
AA	**Autonomous Aircraft**	Unmanned aircraft that operates autonomously without pilot intervention in flight management.
APV	Automatically Piloted Vehicle	Vehicle controlled automatically by instructions on board the vehicle.
ROA	Remotely Operated Aircraft	Unmanned aerial vehicle that complies with the applicable parts of 14 CFR (Code of Federal Regulations) and has its operation approved based on the requirements of manned aircraft of the same class and category (AIAA, 2014)
RPA	**Remotely Piloted Aircraft**	Unmanned aircraft controlled remotely by a pilot
RPAS	**Remotely Piloted Aircraft System**	Remotely piloted unmanned aircraft system, and all other components necessary to carry out the operation: its ground control station (s), pilot (s) and command and control links.
RPV	Remotely Piloted Vehicle	Unmanned aerial vehicle controlled via a communication link by a distant person. This term was previously used for RPAS.
sUAS/ SUAS	**Small Unmanned Aircraft System**	Autonomous aircraft system composed of a vehicle weighing less than 25 kg, station (s), pilot (s), and command and control links.
UA	**Unmanned Aircraft**	Aircraft that operates autonomously without a pilot on board.
UAS	**Unmanned Aircraft System**	Autonomous aircraft system composed of vehicle, station (s), pilot (s) and command and control links.
UAV	**Unmanned Aerial Vehicle**	Remotely or Autonomously Controlled Pilotless Air Vehicle

Although the term drone can refer to different systems used in different environments besides the aerial one, most of the existing models, especially in the civil society, are aircrafts, as are the models used in this study. In this sense, the main nomenclatures that we can find in the literature regarding the mentioned aerial systems, and even recognized by the main international civil aviation agencies

(ICAO - International Civil Aviation Organization; EASA - European Union Air Safety Agency; FAA) are: RPA - Remotely piloted aircraft, RPAS - Remotely piloted aircraft system, UAV - Unmanned Aircraft Vehicle and UAS - Unmanned Aircraft System (Table 1).

While the acronyms RPA and UAV are synonymous, as are the acronyms RPAS and UAS, there is a significant difference between RPA and RPAS or UAV and UAS. RPA or UAV, only refer to the vehicle, which in this case is the “piloted aircraft” or “aerial vehicle”, while the S in RPAS or UAS refers to the system, thus including all the components necessary to operate them, such as the Ground Control Station (GCS), C2 Link – “Command and Control" (C2), Radio Controller (RC) and the aircraft (Mesquita et al. 2021a; Figure 1)

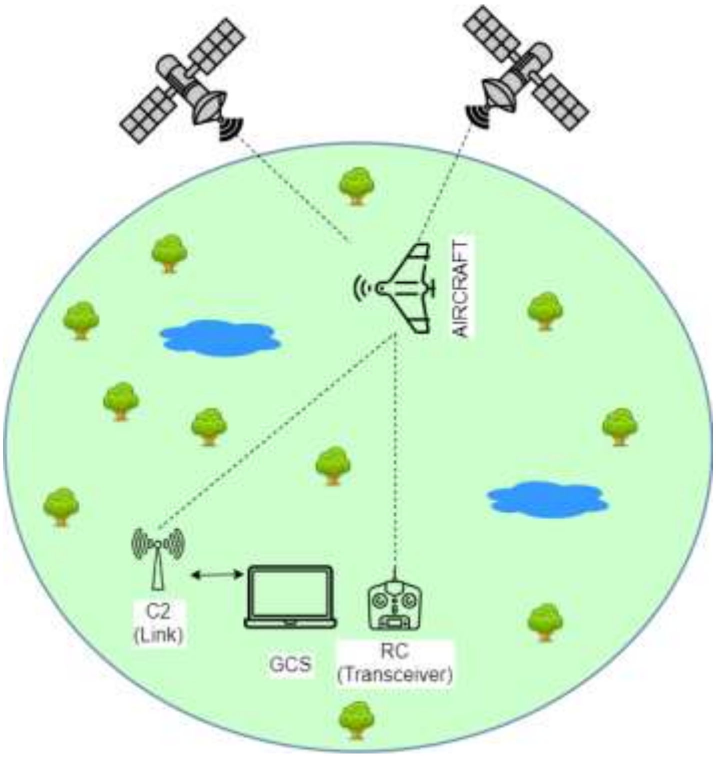
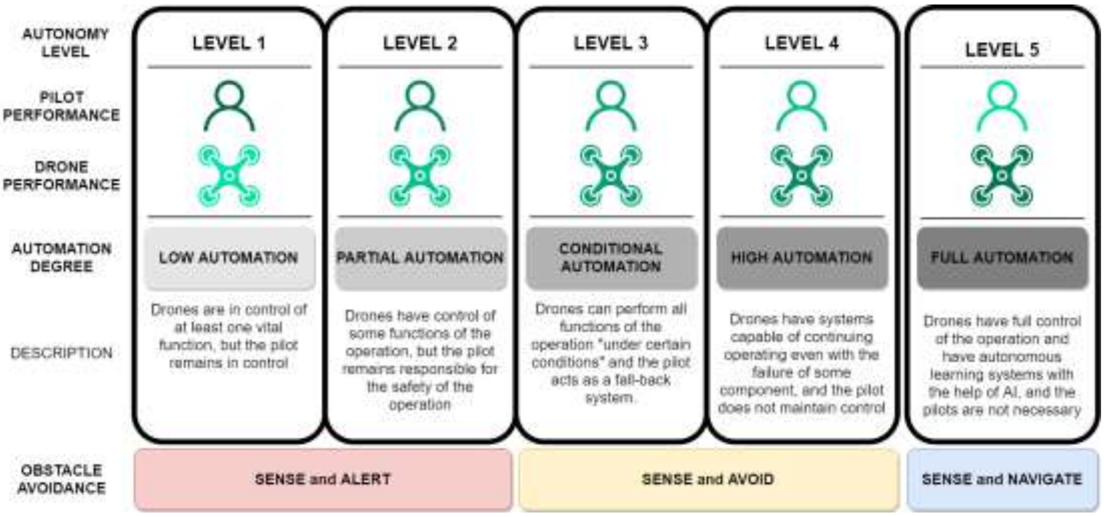


Figure 1. Diagram of the main components of an Unmanned Aircraft System - UAS. Adapted from Mesquita et al. 2021a

While we acknowledge that the most appropriate technical nomenclature to refer to these systems is RPAS or UAS, we adopted the term “drone” due to its generalization in scientific and media contexts.

As the drone market is diverse, so are drone components, which range from simple mobile apps (e.g. DJI recreational drone models) to complex GCS (including operational control rooms for military drones). Likewise, the C2 link ranges from WI-FI with a few meters of range to long-range links with dedicated satellites. In drones, the degree of automation of the system is directly influenced by the level of complexity of its components (Floreano and Wood, 2015; Droneii, 2019), that is, the more functions and more complex the drones are, the greater their autonomy and degree of automation and the less the need for manual control by the pilot (Figure 2).



AUTONOMY LEVEL	LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4	LEVEL 5
AUTOMATION DEGREE	LOW AUTOMATION	PARTIAL AUTOMATION	CONDITIONAL AUTOMATION	HIGH AUTOMATION	FULL AUTOMATION
DESCRIPTION	Drones are in control of at least one vital function, but the pilot remains in control	Drones have control of some functions of the operation, but the pilot remains responsible for the safety of the operation	Drones can perform all functions of the operation "under certain conditions" and the pilot acts as a fall-back system.	Drones have systems capable of continuing operating even with the failure of some component, and the pilot does not maintain control	Drones have full control of the operation and have autonomous learning systems with the help of AI, and the pilots are not necessary
OBSTACLE AVOIDANCE	SENSE and ALERT		SENSE and AVOID		SENSE and NAVIGATE

Figure 2. Drone autonomy levels. Adapted from Droneii (2019)

Types, Classification and Regulation of Drones

There are different types of drone classifications based on different criteria combinations, such as weight; range and duration of the flight; wing loading;

maximum altitude and engine type (Arjomandi et al. 2006); size; flight duration and capabilities (Watts et al. 2012) or more comprehensive ones such as the Hassanalian and Abdelkefi (2017) classification that considers all the previous characteristics plus range, speed, costs and performance. Considering that the drone market is dynamic, we opted here to use the most up-to-date classification by Hassanalian and Abdelkefi (2017), which groups drones into six main categories, subsequently divided into 17 main types of platforms (Figure 3). The categories are: UAV - Unmanned Aerial Vehicle; sUAV - small UAV; MAV - Micro Aerial Vehicle; NAV - Nano Aerial Vehicle; PAV - Pico Aerial Vehicle; and SD - Smart Dust. The main aspects that differentiate the different models within the six categories are the size, the purpose of operation, the complexity and the cost of the control system.

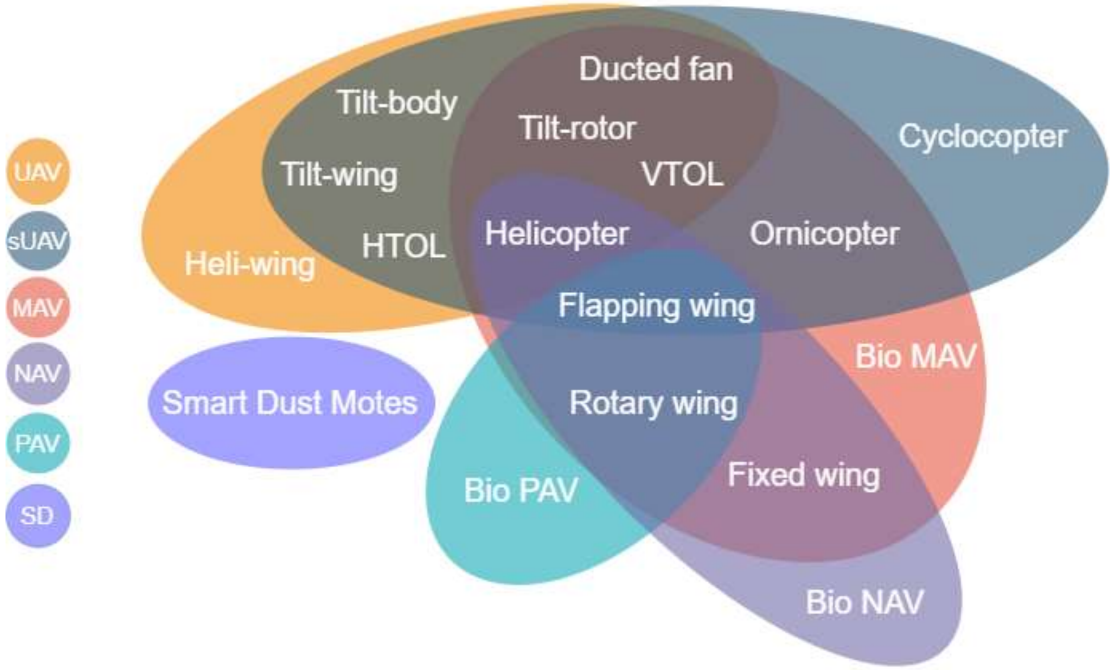


Figure 3. Classification and types of drones. Adapted from Hassanalian and Abdelkefi (2017).

Within this great diversity of types of drones, most of the commercial models, including the most used ones in environmental studies, fall into the sUAV category.

The sUAV are portable and generally don’t require launch and landing structures. These are the best suited drones for large-scale use in the civil environment, including wildlife research and conservation (Watts et al. 2012; Goebel et al. 2015).

The diversity and speed at which drones evolve pose a challenge for the regulation of their use, both locally and internationally. Each country adopts its own regulations, although they are generally based on recommendations from the main international aviation agencies such as ICAO, EASA and FAA.

Considering that the various drone flights performed in this thesis were implemented in Brazil, the regulations of the National Civil Aviation Agency (ANAC) of Brazil were followed. In Brazil, all drone operations must follow the Brazilian Special Civil Aviation Regulation No. 94/2017 (RBAC-E No. 94/2017; ANAC, 2022), which classifies drones into three main classes: Class 1 (with a maximum takeoff weight greater than 150 kg); Class 2 (with maximum takeoff weight greater than 25kg and up to 150kg); Class 3 (maximum takeoff weight of up to 25 kg). For each of these classes there are different requirements and operating standards that are more restrictive for drones from classes 1 and 2 and less restrictive for drones from class 3, with class 3 drones weighing less than 250 g not requiring registration or several operational requirements. Most class 3 drones are generally equivalent to models in the sUAV category by Hassanalian and Abdelkefi (2017). However, in this type of classification, it is important to consider that drones from a given class may have operational requirements belonging to a more restrictive class depending on the type of operation in which it will be used. Based on these requirements, the model developed in this thesis, the HTOL Asa-Branca-I, could fit into class 3 if used away from crowds of people, at altitudes below 120 m and within the line of sight, VLOS - Visual Line of Sight, or, alternatively, it could fall into class 2 if any of the above requirements are not met.

Drones for biodiversity conservation

Drones have recently become popular tools for biodiversity research and conservation (Manfreda et al. 2018; López and Mulero-Pázmány, 2019; Nowak et al. 2019), although their potential to solve environmental problems had already been identified more than 35 years ago (Tomlins, 1983). Drone applications comprise monitoring and identification of fauna (Van Andel et al. 2015; Hodgson et al. 2016; Han et al. 2017; Lyons et al. 2019), flora (Zahawi et al. 2015; Baena et al. 2017; Woellner and Wagner, 2019; Williams et al. 2020), forest fire analysis (Twidwell et al. 2016; Fernández-Guisuraga et al. 2018; Burke et al. 2019), degradation and deforestation (Paneque-Gálvez et al. 2014), ethological analyzes (Brisson-Curadeau et al. 2017; Mesquita et al. 2021b), ecological analyses (Anderson and Gaston, 2013; Mulero-Pázmány et al. 2015; Baxter and Hamilton, 2018) and epidemiological studies (Hardy et al. 2017; Laguna et al. 2018). Reviewing 256 studies on drones used in conservation, López and Mulero-Pázmány (2019) highlighted that drone can increase the effectiveness of conservation actions, especially within protected areas.

The main advantages of drones in conservation are: greater precision and accuracy of the data as compared to ground-based methods, as proved by Hodgson et al. (2018) estimating seabirds population numbers; better spatial and temporal resolution as compared to satellite images, as shown in the different studies compiled by Pajares (2015); possibility of obtaining data in inaccessible or difficult-to-access areas by other means, such as plant inventories in areas with high forest density (Ivosevic et al. 2017), or in areas without direct access such as bird colonies on cliffs or uninhabited islands (Mcclelland et al. 2016); lower operational risk for researchers as compared to manned vehicles (airplanes and ships) or land routes, mainly in polar (Sasse, 2003; Crocker et al. 2012), marine (Fiori et al. Al. 2017) and terrestrial (Rey et al. 2017) environments; and, in many cases, better cost/benefit trade-off in economic terms as compared to the use of manned vehicles (Tang and Shao, 2015; Villa et al. 2016; Colefax et al. 2017). On the other hand, there are also limitations that, despite being increasingly overcome, are still present in most drones used in the scientific community, making them in some situations less efficient in obtaining data than other already known methodologies. The impossibility of covering large areas due to the low autonomy in most models and the high cost of some models that partially overcome this low autonomy problem, are in general the greatest limitations of drone use in biodiversity conservation studies (Watts et al. 2012; Zahawi et al. 2015; Singh and Frazier, 2018). In addition to the possibility of causing disturbances to wildlife (Mesquita et al. 2021b, chapter III), the difficult access to this technology by researchers in many countries, the unavailability of maintenance schedules for several models, the need for a basic knowledge concerning technology, operations, regulation and data analysis, makes it even more difficult for researchers to use this technology.

Wildlife and drones

In wildlife studies, drones have played an important role in obtaining data, (Chabot and Bird, 2015; Hodgson et al. 2016 -2018; Lyons et al. 2019). Most of the studies that use drones are conducted with large size animals, whether aquatic or terrestrial, and mainly gregarious, since these species possess characteristics (body size, habitat type, and behavior type) that favor aerial and remote visualization as compared to other traditional methodologies (Chabot and Bird, 2015). From a compilation of studies from the Web of Science, Scopus, Scielo and Google Scholar databases, involving drones and wildlife since 2006, the year in which civil drones began to be used, it was found that 218 species were studied among the 143 compiled papers, being birds around 54% of them, generally gregarious, and 33% of them mammals, generally large (Complementary Table 1: Appendices), considering the classification of Wilson and Reeder (2005). Other classes of animals, such as chondrichthyans and reptiles, despite comprising fewer species studied with drones, are increasingly being explored in the context of population and behavioral assessments, as is the case for sharks and turtles (Schofield et al. 2017; Hensel et al. 2018; Colefax et al. 2020). The literature contains examples on the use of drones ranging from measuring the length and body condition of the largest animal on the planet, the blue whale (Durban et al. 2016), to studies that measure the different echolocation sound patterns of bats about 4 cm in size (Kloepper and Kinniry, 2018). The type of environment where these animals are found is also another essential factor when choosing to use drones. In general, environments that are difficult or dangerous to access are the most conducive to drone use (Chabot and Bird, 2015; Manfreda et al. 2018). 31% of the drone studies on wildlife were conducted in marine environments where data collection is facilitated by this technology.

There are several examples of drone studies for mammalian research. Hodgson et al. (2010) and Johnston et al. (2017) demonstrated the capacity and potential use of these systems for research in marine mammals as compared to methods based on direct observations; Vermeulen et al. (2013) analyzed elephants’ density in Ghana; and Barasona et al. (2014) estimated the spatial pattern of various ungulate species in order to predict the risk of tuberculosis. Birds are also often studied using drones, as drones allow monitoring populations with greater precision than traditional counts (Hodgson et al. 2016), particularly for large and complex bird aggregations (Lyons et al. 2019). New advances in drone technology allow studying smaller species. Drones equipped with thermal cameras are used to detect small threatened species such as the brown hare, Lepus europapeus, in areas with low or medium vegetation cover (Karp, 2020); koalas, Phascolarctos cinereus, using deep convolutional neural algorithms, with greater probability of detection and precision than terrestrial surveys (Corcoran et al. 2019); Northern lapwing nests, Vanellus vanellus, and other species nesting in agricultural land, also facilitating data analysis with artificial intelligence (Santangeli et al. 2020).

As for other emergent technologies, drones present challenges such as the lack of standardization for the application and the optimization of the data analysis techniques (Buters et al. 2019). Standardizing drone use is particularly relevant for wildlife studies in order to avoid causing disturbances to the animals exposed to the flights (Mulero-Pázmány et al. 2017). There is substantial work focusing on different types of drone disturbance on different animal species. For example, Arona et al. (2018) studied the effects of small fixed-wing drones on colonies of breeding seals, Bennit et al. (2019) quantified the disturbance levels of VTOL drones on different species of herbivorous mammals, and Weston et al. (2020) analyzed the influence of the flying distances of the drones on the behavior of several species of aquatic birds. Several works have suggested ways to standardize methodologies and propose protocols for drone use over wildlife (Ratcliffe et al. 2015; Barnas et al. 2020).

Drones and the Cerrado hotspot

Considered the most biodiverse tropical savanna in the world, the largest "hotspot" in the Western Hemisphere and the second largest biome in Brazil, the Cerrado is currently a highly threatened biome, with only about 47% of its original area unchanged and only 8% of its extension legally protected consisting of areas generally smaller than 100,000.00 hectares, being therefore a highly fragmented ecoregion (Sawyer et al. 2017). Although it is generally considered a biome, the Cerrado or Cerrado Sensu Lato is a complex formed by three phytophysiognomic categories (Ribeiro and Walter, 2008) or even biomes (Batalha, 2011): forest formations or tropical fields, savanna formations or savanna, and field formations or fields (Figure 4). Forest formations, which can be riparian forest, gallery forest, dry forest, also known as Cerradão, are vegetative formations where larger trees with canopy formation and a growth pattern associated with wet and dry seasons predominate. The savanna formations, which can be palm groves, trails, the cerrado park also known as the typical cerrado stricto sensu, consist of an almost continuous herbaceous layer interrupted by shrubs and trees in different densities and present alternated wet and dry seasons. The field formations that can be dirty fields, rock fields and clean fields, are formations with continuous herbaceous strata and low density of shrubs, with an insignificant presence of shrub vegetation.

Figure 4. Different phytophysiognomic types in the Cerrado biome: a) Clean field; b) Dirty field; c) Rock field; d) Cerrado park; e) Veredas; f) Palmeiral; g) Cerradão; h) Dry Forest. Adapted from Janišová et al. (2016) and Embrapa (2020).

2,373 species of vertebrates have been registered in the Cerrado considering all its formations, around 20% of which are endemic (Sawyer et al. 2017). Sorted by biological groups, birds comprise the majority of vertebrate species in this biome, with 856 species, followed by fish, reptiles and mammals, the latter with 251 registered species (Sawyer et al. 2017). Iconic species such as the giant armadillo, Priodontes maximus, the giant anteater, Myrmecophaga tridactyla, the maned wolf, Chrysocyon brachyurus, the tapir, Tapirus terrestris and the jaguar, Panthera onca, considered the “Big Five” of the Cerrado are some examples of threatened species in this biome.

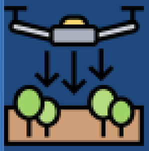
From a bibliographic search in the Web of Science (WoS), Scopus, Google Scholar and Scielo databases, since 2006 and considering keywords such as "Cerrado", "UAS", "UAV "," RPAS, "unmanned aircraft system" and “drone”, we found 18 studies with drones in the Cerrado biome (Table 2).

Table 2. Environmental studies made with drones in the Cerrado biome from 2006 to 2021.

Cerrado-Drone Studies	Type	Referencia
Mapeamento da cobertura vegetal a partir de imagens de alta resolução obtidas por VANT	Conference Proceedings	Felix et al. 2007
Estimativa do material combustível em área de Cerrado campo sujo a partir de imagens do sensor RGB	Journal Article	Souza et al. 2018
Utilização De Drones Para Preservação Da Biodiversidade Do Cerrado No Jardim Botânico de Brasília	Thesis	Soares, 2018
Zoning the fire-risk in protected areas in Brazil with drones: a study case for the Brasilia National Park	Journal Article	Ferreira et al. 2019
RPAS aplicado na detecção de plantas invasoras em hábitat de áreas úmidas	Conference Proceedings	Nascente et al. 2019
Estimating Pasture Biomass and Canopy Height in Brazilian Savanna Using UAV Photogrammetry	Journal Article	Batistoti et al. 2019

Utilização de índices de vegetação baseados na porção visível do espectro eletromagnético para monitoramento de fitofisionomias do Cerrado	Thesis	Filho, 2019
Mistura Espectral em Áreas de Cerrado: Abordagem Multisensor e Multiresolução	Conference Proceedings	Petri et al. 2019
Hidrodinâmica em área úmida de cerrado na chapada sedimentar do oeste mineiro	Thesis	Furlan, 2019
Sensoriamento remoto e anáise espacial na determinação de processos hidrológicos no bioma cerrado	Thesis	Salles, 2019
Análise hidro-pedológica com multisensores embarcados em aeronaves remotamente pilotadas para vertentes do Cerrado Mato-Grossense	Thesis	Jesuz, 2019
Geotecnologias aplicadas à análises e delimitação de área de preservação permanente (APP) de cursos D'água	Thesis	Melo, 2020
Extraction of Mauritia flexuosa in Orthophotos Obtained by UAV	Journal Article	Faxina and Silva, 2020
Avaliação geomorfométrica de campo de murundus no Chapadão do Diamante, Serra da Canastra, Minas Gerais, Brasil	Journal Article	Silva et al. 2020
Aeronave remotamente pilotada de baixo custo no estudo de plantas invasoras em áreas de cerrado	Journal Article	Pessi et al. 2020
Dinâmica e classificação fitogeomorfológica de veredas em diferentes bacias hidrográficas no cerrado	Thesis	Santos, 2020
Estimating invasive grasses heights with images from a unmanned aerial vehicle in brazilian Cerrado: accuracy of global navigation satellite system from Phantom 4	Journal Article	Pessi et al. 2021
Beyond trees: Mapping total aboveground biomass density in the Brazilian savanna using high-density UAV-lidar data	Journal Article	Da Costa et al. 2021

As shown in Table 2, the first studies conducted with drones in the Cerrado have been published since 2018, that is, only during the last three years. These are only focused on drones use as a tool to obtain abiotic data in the biome, such as hydro-pedological and geomorphometric characteristics (Jesuz, 2019; Silva et al. 2020) or vegetation analysis (Nascente et al. 2019; Santos, 2020: Faxina e Silva, 2020; Pessi et al. 2021), while drone use for animal studies in the biome remains unexplored. Therefore, one of the outcomes of this thesis "Measuring disturbance at swift breeding colonies due to the visual aspects of a drone: a quasi-experiment study" carried out within the Cerrado is the first to study animals within the biome. Although there are still no published results connecting the use of drones and wildlife in the Cerrado biome, some initiatives and projects can already be found, such as the Ecodrones Brasil project of the WWF Brazil organization - World Wide Fund for Nature in Brazil, which has the objective of evaluating the use of drones for different applications in nature conservation, or even in experimental monitoring work in protected areas managed by ICMBio - Chico Mendes Institute for Biodiversity Conservation.



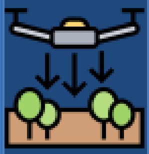
OBJECTIVES

OBJECTIVES

The overall aim of this thesis is to explore the potential and limitations of drone use for wildlife conservation in the Cerrado hotspot, especially for vertebrates' monitoring and behavior analysis.

To achieve the main objective, the following specific objectives have been established, which correspond to each thesis chapter.

1. Development of low-cost drones for researchers in biodiversity conservation projects within the Cerrado biome, especially for projects that require analysis on large spatial and temporal scales;
2. Identification of sources of disturbance caused by drones that can interfere with bird species' behavior in colonies in the Cerrado biome in order to develop rules for drone use in these environments;
3. Understanding of the different characteristics of the drone noise that cause behavioral changes in different species of mammalian fauna in order to facilitate the development of guidelines to minimize possible disturbances;
4. Development of new easy-to-use adaptive approaches for monitoring wildlife using drones and smartphones.



CHAPTERS

CHAPTER 1

Steps to build a DIY low-cost fixed-wing drone for biodiversity conservation

This chapter corresponds to the article: Mesquita, G. P., Rodríguez-Teijeiro, J. D., de Oliveira, R. R., & Mulero-Pázmány, M. (2021). Steps to build a DIY low-cost fixed-wing drone for biodiversity conservation. PLOS ONE, 16(8), e0255559. https://doi.org/10.1371/journal.pone.0255559

Steps to build a DIY low-cost fixed-wing drone for biodiversity conservation

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Resumen

A pesar de la probada utilidad de los drones en estudios de biodiversidad, los costos de adquisición y las dificultades para operar, mantener y reparar estos sistemas limitan su integración en proyectos de conservación, particularmente en países de ingresos bajos. Aquí presentamos los pasos necesarios para construir un dron de ala fija de bajo costo para aplicaciones ambientales en grandes áreas, junto con instrucciones para aumentar la fiabilidad del sistema y probar su desempeño. Inspirado en el concepto DIY (Do it Yourself) y los modelos de código abierto, este trabajo prioriza la simplicidad y tiene en cuenta el costo-beneficio para el investigador. El dron DIY de ala fija desarrollado tiene propulsión eléctrica, puede realizar vuelos preprogramados, puede transportar hasta 500 g de capacidad de carga útil con 65 minutos de duración de vuelo y vuela a una distancia máxima de 20 km. Está equipado con un sensor RGB (Red, Green and Blue) capaz de obtener una resolución de 2.8 cm por píxel GSD (Ground Sample Distance) a una altitud constante de 100 m AGL (Above Ground Level). El costo total fue de $ 995, que es sustancialmente menor que el valor promedio de drones comerciales similares utilizados en estudios de biodiversidad. Realizamos 12 pruebas de vuelo en modo automático utilizando el modelo desarrollado en áreas protegidas en Brasil, obteniendo imágenes RGB que nos permitieron identificar puntos de deforestación menores de 5 m2 y animales de tamaño mediano. La construcción de drones DIY requiere cierto conocimiento técnico y requiere más tiempo que comprar un sistema comercial listo para volar pero, como se demuestra aquí, puede ser menos costoso, lo que a menudo es crucial en proyectos de conservación.

Abstract

Despite the proved usefulness of drones in biodiversity studies, acquisition costs and difficulties in operating, maintaining and repairing these systems constrain their integration in conservation projects, particularly for low-income countries. Here we present the steps necessary to build a low-cost fixed-wing drone for environmental applications in large areas, along with instructions to increase the reliability of the system and testing its performance. Inspired by DIY (Do It Yourself) and open-source models, this work prioritizes simplicity and accounts for cost-benefit for the researcher. The DIY fixed-wing drone developed has electric propulsion, can perform pre-programmed flight, can carry up to 500 g payload capacity with 65 minutes flight duration and flies at a maximum distance of 20 km. It is equipped with a RGB (Red, Green and Blue) sensor capable of obtaining 2.8 cm per pixel Ground Sample Distance (GSD) resolution at a constant altitude of 100 m above ground level (AGL). The total cost was $995 which is substantially less than the average value of similar commercial drones used in biodiversity studies. We performed 12 flight tests in auto mode using the developed model in protected areas in Brazil, obtaining RGB images that allowed us to identify deforestation spots smaller than 5 m2 and medium-sized animals. Building DIY drones requires some technical knowledge and demands more time than buying a commercial ready-to-fly system, but as proved here, it can be less expensive, which is often crucial in conservation projects.

Key-words: drone; biodiversity; conservation; cost-benefit; DIY; low-cost; RPAS; UAS

Introduction

In the last decade, drones (known as Unoccupied Aircraft Systems–UAS, or Remotely Piloted Aircraft Systems–RPAS) have been adopted as a new tool for the monitoring and conservation of protected areas [1]. These systems are used for identifying deforestation and fragmentation processes [2, 3], searching for illegal hunters [4] and conducting forest inventory and biodiversity assessments [5, 6] as well as wildlife surveys [7, 8]. The success of drones for biodiversity monitoring is primarily due to the high spatial and temporal resolution of the data obtained as well as to a reduction in time, cost and logistical challenges as compared to other means of obtaining aerial imagery, such as satellite or manned aircrafts [9, 10]. The majority of biodiversity studies conducted with drones use Small Unoccupied Aircraft Systems (sUAS) weighting 2–5 kg with a wingspan smaller than 3 m and payloads below 1 kg, they are generally electrically powered and operate at low altitudes [7, 8]. Despite the growing popularity of drones, their acquisition cost along with high maintenance and training costs are the main factors constraining their use in research. In the current scenario, where the greatest loss of biodiversity is concentrated in low-income tropical countries [11], low-cost prototyping is a new way of helping local agents to preserve biodiversity [12]. Low-cost drone development initiatives (conservationdrones.org; diydrones.com) and open-source software (ardupilot.com; opendronemap.org) are gaining popularity in the drone and scientific community. DIY (Do It Yourself) models offer unlimited opportunities for researchers who need tailor-made solutions while optimizing cost-benefits [13]. ArduPilot, an open-source project combining software and hardware-plus-sensors for drones (copter, plane, rover and sub), is a positive example where sharing knowledge through DIY concepts can generate significant technologies in the scientific environment.

Along with the significant growth in the use of drones in biodiversity conservation in the past 10 years [1, 14] some studies on building DIY fixed-wings drones for conservation purposes have been published [9, 15–19]. While these contain descriptions of the systems, they do not provide detailed information of the building process, which precludes their replication by other potential users. In the next sections we describe step-by-step the development of a low-cost, fixed-wing drone specifically designed for conservation purposes in large protected areas. It is inspired by the conservationdrones.org and diydrones.com websites, prioritizing simplicity, a positive cost-benefit balance and an open source model in the manufacturing process (Fig 1). We provide the basic construction and parameterization details in order to allow replication by individuals without prior experience in electronic works. The budget is kept to a maximum of$ 1000. We describe how we tested the performance of the model, in terms of flight autonomy, coverage and data collection with high spatial resolution. In addition, we dis- cuss the potential uses of this model in applications aimed at monitoring protected areas and deforestation activities.

Materials and methods

Step 0: Choosing drone type

The first important step to integrate drones in conservation research is deciding the drone type. The drone type has to be aligned with the flight mission profile and, in order to define the mission, the scientific objectives need to be previously defined, at least regarding operation range, terrain characteristics, mission duration and payload needs. Drones can be mainly classified into two types according to the principles of flight and aerodynamics: fixed-wing (planes) and rotary-wing (helicopters and multicopters). Fixed-wing models depend on forward motion for lift; they need to be constantly moving forward at a certain speed that can support them in the air, so that they tend to have more efficient aerodynamics. This allows longer flight durations, which makes them appropriate for working at large scales such as intended in this study. However, they require open terrain to take off and land, which may limit their use in dense vegetation scenarios. In the Rotary-wing models the engine propellers are responsible for both lift and thrust, hence the vertical component of the engine force is lift, and the horizontal component is the thrust [20]. They can support them- selves in the air without a need for constant movement, which allows them to take-off and land vertically from a small patch of open terrain, and to hover in stable ways above a fixed spot in the air, generally facilitating stable data acquisition. These features make them the most popular choice for small scale (<1km2) biodiversity studies [21] that track specific targets or obtain data at fixed points. A few hybrid models exist, although they are generally expensive.

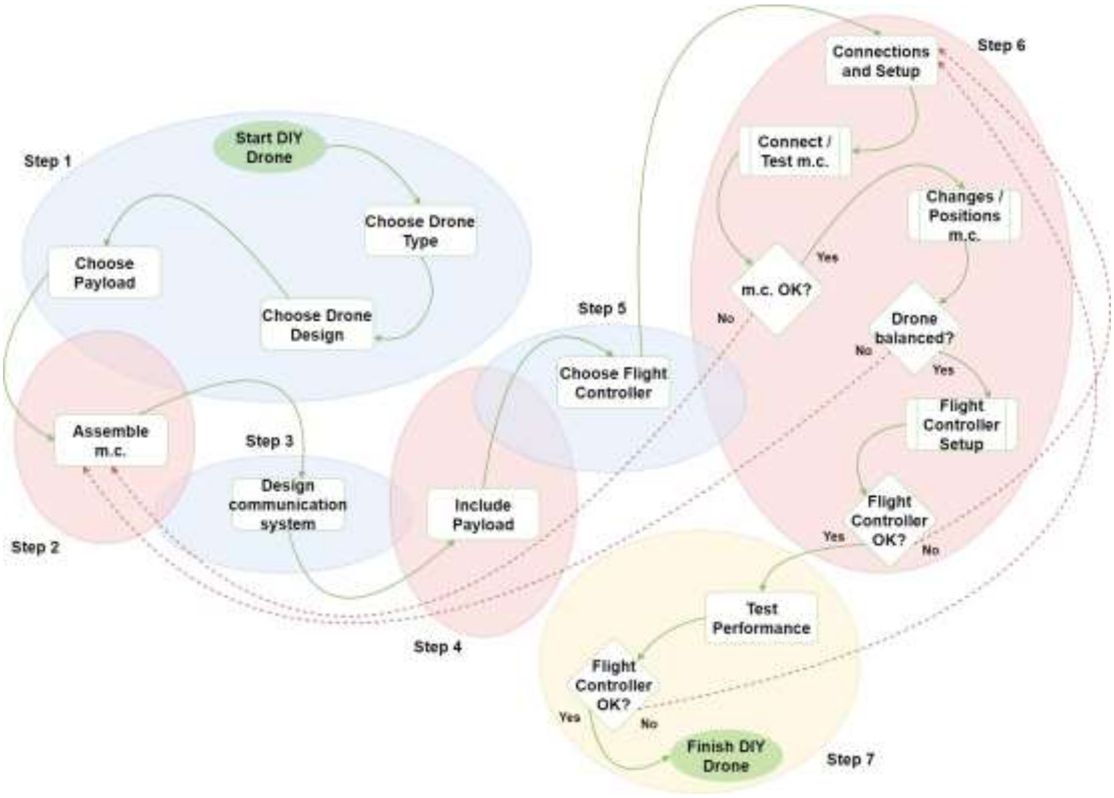

Fig 1. General DIY workflow. m.c. means main components. Blue balloons are pre-development phase, Red balloons are development phase and the yellow balloon is post-development phase.

Regardless of the drone type, previous studies suggest that the minimal requirements for drones in conservation works are: 1) ability to fly in manual and Global Navigation Satellite System (GNSS)-aided modes as well as in pre-programmed mode; 2) easy transportation and pre-flight assembly; 3) payload capacity of up to 500 g; 4) 30 minutes minimum flight duration; 5) and at least 5 km telemetry range [7, 9, 21, 22]. Most drones used for conservation purposes that need to perform pre-programmed flights have four main components: Ground Control Station (GCS), Telemetry (T), Radio Controller (RC) and the drone platform (Fig 2).

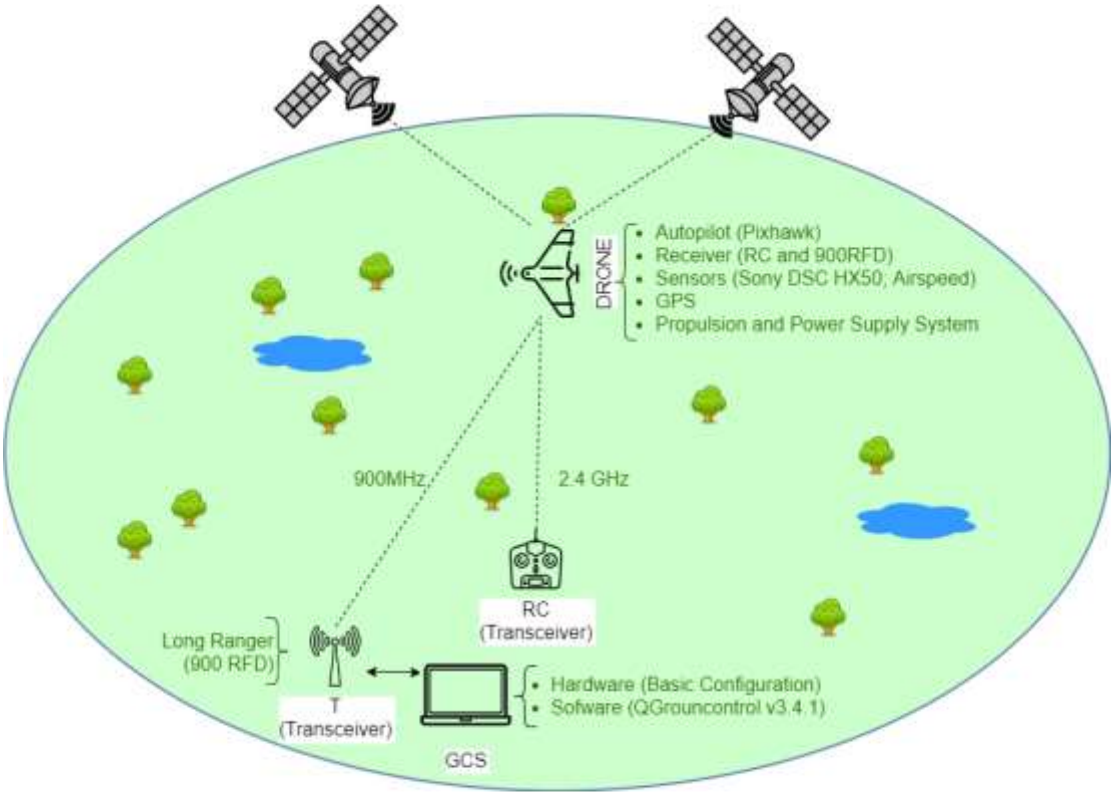

Fig 2. Schematic ofthe system's four main components.

Step 1: Choosing fixed-wing airframe design

Within the fixed-wing drone there is a variety of models, sizes and shapes with different maneuverability, performance and advantages [23]. Among the commercial, most used fixed- wing airframes in conservation studies available on the market, we highlight the tailless or delta-wing (eBee, SenseFly; UX5, Trimble; UX11, Delair; Batmap II, CloudUAV; Maptor, Horus) and the typical gliders (Maja, Bormatec; HBS Skywalker, HornbillSurveys; RQ-11, AeroVironment; E384, EVENT38 Unammaned Systems). While glider-type models generally possess more control surface configuration options thanks to a tail (aileron, flaps, elevator, rudder), delta-wing or tailless models have less control surface options as these features are absent (elevon, rudder or equivalent). These different airframe configurations, along with other factors (size, payload weight, propulsion system) directly influence the velocity needed to maintain flight, flight duration and maneuverability. In fixed-wing models, the wing aspect ratio is one of the factors that increases the aerodynamic efficiency. High wing aspect ratio confers a smaller induced drag component that results in an enhanced gliding, leading to energy saving. In general, the lower the lift-to-drag ratio is proportional to the size of the airframe. Therefore, it requires a higher thrust needed to overcome aerodynamic drag at a given lift and this associated drag and power penalty causes a reduction in total energy efficiency [20]. On the other hand, a smaller airframe can bring some benefits for maneuverability, which can be important to facilitate eventual pilot interventions. Portability is another important aspect when choosing airframes for conservation works. While smaller airframes are easy to take off and transport, larger airframes generally require more space and logistics to take off, landing and transportation. Taking into account the wing aspect ratio, size, portability and also the price, we chose the airframe of a typical glider, characterized by a high wing aspect ratio, a slender fuselage and a fully-faired narrow cockpit. This model is one of the most efficient aerodynamic designs and its features minimize induced drag for any given amount of lift [24]. The airframe model used was the fixed-wing Ranger 2000 (Volantex-RC, CO., International) with the following features: 2000 mm wingspan, 1100 mm length, 1083 g empty weight (See Item 1.1 in S1 Text). The fuselage is made of hard, flexible plastic, the wings are composed of expanded polyolefin (EPO) and the control set includes four servos (ailerons, flaps, rudder and elevator). Due to the limited internal space of the fuselage, and in order to reduce RGB (Red, Green and Blue) sensor stability problems, we modified the internal fuselage structures in order to fit the electronic components and sensors, as well as to fit the lens of the RGB imaging sensor at the bottom of the fuselage (See Item 2 in S2 Text). This allowed us to carry any payload fitting in a volume of 12 x 5 x 7 cm3. This model is easily launched by hand and recovered by “belly landing”, avoid- ing the need for complex systems such as catapults or skyhooks. Another aspect considered important in the choice of this model was its portability: it is modular and can be disassembled into three smaller parts (fuselage, wings and elevator, and rudder) that allow transportation inside one compact case (110 x 30 x 30 cm^3).

Step 2: Assembling primary electronic components

There are three possible options for purchasing an airframe: 1) Almost Ready-to-Fly (ARF), where the airframe is purchased without the primary electronic components (motor, servos, ESC, battery, etc.); 2) Plug-N-Play (PNP), where the airframe comes with all the primary com- ponents installed, except for the battery, receiver and transmit; and 3), Ready-to-Fly (RTF), where all the primary components are already installed on the airframe. The choice of the airframe version, in addition to being directly related to the intended purpose of the drone, must take into account the knowledge level of those involved in the process of assembling the drone, the degree of customization that is intended to be performed on the model and the time avail- able for the process. In our case, we opted for the airframe model PNP version, since we intended to use differentiated batteries and communication system. It included a brushless electric engine, six servos, a brushless Electronic Speed Control (ESC) and 8 x 4 propellers (See Item 1 in S1 Text). For simplicity, we used the default configuration of the engine, ESC, servos and propeller. The recommended battery for the pre-installed motor was a 3S 2200 mAh / 25C / 11.1 V LiPo battery, but we replaced it for a higher capacity 4S 5000 mAh / 25C / 14.8 V LiPo battery in order to increase flight time (See Item 1.6 in S1 Text). There is no standard formula defining the balance between battery capacity, weight and flight time, but it is necessary to con- sider several factors (type of flight, airframe model, wing load, engine and propeller) to find an optimal compromise. Currently, the majority of drones used in conservation-related works use an electric propulsion system [23].

Step 3: Designing the communication system

There are several types of drone communication systems, from short-range, unidirectional communication through a simple RC, to more complex long-range communication systems with robust GCS. The DIY system we designed includes three different communication links: one unidirectional (GNSS) and two bidirectional ones (RC and telemetry). The Ublox M8N GNSS module (See Item 1.9 in S1 Text) is indispensable to autopilot flight and geo-referencing because it determines the drone’s real time location in 3D by means of triangulation, the RC FlySky model (See Item 1.12 in S1 Text) with an approximate range of1 km, features a 2.4 GHz transmitter and server to perform manual control of the drone when necessary, and the telemetry with the RFD 900 long-range radio modem model (See Item 1.10 in S1 Text) at 915 MHz has an approximate range of40 km. Considering the minimum configurations above, we chose the link models on the market with the best cost-benefit ratio.

Step 4: Selecting the payload

The usefulness of research drones is determined by their payload [25]. The payload of the model described here is formed by one sensor, a compact RGB camera that we used to acquire high resolution images. We opted for a Sony model DSC-HX50 that can gather images in the visible spectrum with high resolution and records Full HD 1080p video (See Item 1.13 in S1 Text). We used the Seagull #MAP2 UAV camera trigger to connect the Sony camera to the flight controller and the RC receiver (See Item 1.14 in S1 Text).

Step 5: Selecting the flight controller

The Flight Controller or Autopilot is considered the “drone brain”. There are two types of commercial autopilot solutions available: closed-hardware and open-hardware. Following the open-source and low-cost solution in this study, we chose an open hardware autopilot (See Item 11 in S5 Text). Aiming at the most favourable cost-benefit ratio and possibilities of updating the core code in the future, we chose the mRo Pixhawk 2.4.6 (mRobotics.io) open hard- ware flight controller board (See Item 1.8 in S1 Text). This model is an enhanced version of the discontinued Pixhawk 1 (3DR Robotics Inc) that uses the firmware (FMUv3) with twice the flash memory of the Pixhawk 1. The mRo Pixhawk is a microcontroller with several internal sensors (gyroscope, accelerometer/compass; magnetometer and barometer) that serves as a communication center and connection of sensors (speed sensor, cameras, lasers, among others). In order to increase the efficiency of pre-programmed flight we incorporated an airspeed sensor. The airspeed sensor we used was the pitot tube airspeedometer model, that measures differences in air pressure and helps the autopilot to control the drone under different flight conditions as well as for autonomous landings (See Item 1.11 in S1 Text). The flight controller board can be used on different platforms (fixed-wing, rotary-wing, rover, boats, submarines and others). We chose an open source flight control, the PX4 software that enables the programming and execution of fully autonomous drone flights and is fully compatible with the mRo Pixhawk 2.4.6 model. The entire system is divided into two parts: 1) the hardware and on-board firmware installed on the drone; and 2) the software installed on the GCS. Different flight controllers can be controlled by different GCS software packages that have different interfaces.

There are about 10 different GCS software that can be installed on desktops or tablet / smartphones (See Item 12 in S5 Text). Among these, we limited our-selves to 4 GCS open-source licenses (Mission Planner, APM Planner 2.0, MAV Proxy, QGroundControl) that have more configuration and analysis tools, important features for DIY users. Although the Mission Planner is the GCS recommended by Ardupilot, as it was the first to be created and has more features, we opted for QGroundControl because it is the only one with the possibility to run on all platforms (Windows, Mac OS, Linux, Android and IOS), it has an intuitive interface, allows automatic download of the correct firmware for a connected autopilot (based on its firmware) and provides a full flight control and vehicle setup for Pixhawk and ArduPilot. The QGroundControl interface Pixhawk allows creating flight missions with waypoints and per- forming other flight commands via radio and telemetry. However, the pilots’ choice of GCS software is a matter of preference since the features of GCS software are similar.

Step 6: Connections and setup

Once all hardware and software has been decided in the previous steps, it is necessary to start the configuration process while considering the premise of simplicity, that is, the fewer modifications, the better. At this step we suggest configuration sequences that should follow the order presented here. For each of these sequences, we provide detailed information in the (S2 and S3 Texts), according to the DIY concept.

I. Configuring and testing the main components. Considering that the PNP airframe version was purchased, the motor, servos and ESC components are already pre-installed on the airframe, so there is no need for any modifications. However, it is necessary to check if all these components are working correctly as well as to eliminate possible problems during parameterizations of the flight controller or even during the flight (See Item 1.1 in S2 Text).

II. Component positioning and modifications. The position of the internal components will directly influence the drone balance and, consequently, the flight performance. Therefore, it is necessary to define the positioning of all components and possible modifications of the airframe considering the drone balance from the center of gravity. The modifications we made to the airframe (hole at the bottom for passing the camera lens, hole at the top for passing the GNSS cable and elimination of some internal structures for positioning the battery and flight controller) were carried out taking into account the balance of the drone (See Item 2 in S2 Text). Some fixed-wing airframe models have markings that indicate the center of gravity where the drone can be balanced and are usually found below the wings. We recommend that the center of gravity of each airframe is found and the modifications and positioning of the components are carried out from there (See Item 13 in S5 Text).

III. Setup flight controller. The mRo Pixhawk 2.4.6 flight controller is the command center of the drone that makes the link between the main components, the sensors and the GCS, so its configuration is one of the most important parts in the drone development. Initially we must make the connections on the Pixhawk of all the components necessary for its operation (See Item 1.2 in S2 Text). Then we must perform the installation of the GCS software to start the update, calibration and setup of the internal and external sensors of the flight controller (See Item 2 in S3 Text).

Once the components are connected and the GCS software is installed, we start the following steps (Fig 3): Firmware update (See Item 3 in S3 Text); Airframe setup (See Item 4 in S3 Text); Sensor setup (See Item 5 in S3 Text); RC setup (See Item 6 in S3 Text); Flight modes configuration (See Item 7 in S3 Text); Power calibration (See Item 8 in S3 Text); Safety configuration (See Item 9 in S3 Text); and Camera setup (See Item 10 in S3 Text) within the QGroundcontrol software. We recommend that the processes mentioned above are performed in the same order in which they appear, since in some test configurations some problems occurred when performed differently.

During the execution of each of these processes, we may encounter some unusual situations concerning the configuration of the flight controller (See S4 Text).

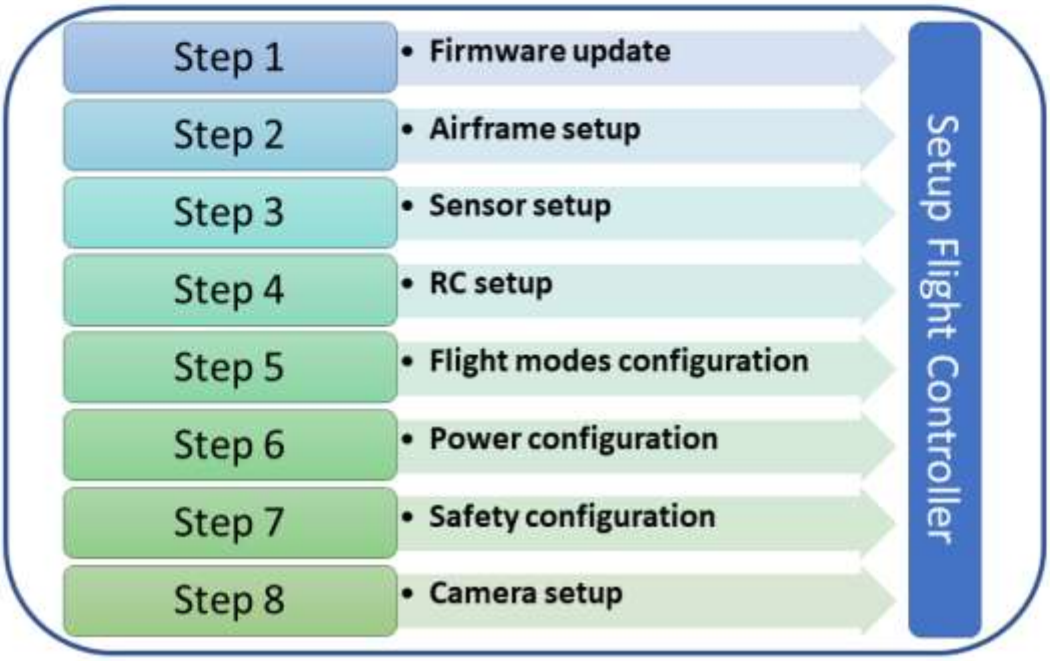

Fig 3. Steps for setup flight controller.

Step 7: Performance tests

Performance tests were carried out for proving the drone’s ability to cover an area of up to 1 km2 with a minimum spatial resolution of3 cm / px with only one battery. The drone flight tests were performed in July 2018, 15:00–18:00 h local time in different areas within the northern region of Maranhão state, Brazil. We performed 16 test flights (four conducted in manual mode and 12 in auto mode) to assess flight autonomy, communication range and resolution of aerial images. Before flight missions we followed safety procedures regarding the operator, drone stability and the protection of others involved (See S1 Checklist).

During the four flights in manual mode, we tested the aerodynamics, control surfaces (ailerons, flap, rudder and elevator) and engine. All manual flight manoeuvres were performed in VLOS (Visual Line of Sight), <500 m from GCS, and the take-off and landing were performed manually. The 12 flights in auto mode aimed to check the autopilot, pre-programmed flights, the telemetry RFD 900, GNSS and the other external sensors (compact RGB camera and 3DR Digital Airspeed). All auto mode flights were performed in VLOS or EVLOS (Extended Visual Line of Sight).

For EVLOS flights to test RFD 900 long-range telemetry, it was necessary to have a second pilot with a second RC connected (binding) to the drone's transmitter. In these flights, this pilot followed all trajectories of the drone beyond the visual line of sight of the main pilot, by moving parallel to the drone's trajectory by car. For this, we strategically choose an open field adjacent to the road outside an urban area that allowed the second pilot to travel by car as well as to watch the drone during the entire flight path. In direct communication with the main pilot, the second pilot was able to manoeuvre the drone with the second RC in case of any eventual problem. This type of logistics on EVLOS flight tests was necessary both to avoid the loss of the drone due to possible connection and failsafe failures and to comply with local civil aviation legislation. Although the second RC signal was always within the range of500 m throughout the trajectory of the EVLOS test flights, we disabled the Failsafe action in QGroundControl in case of RC loss signal, to avoid the automatic return to home of the drone in long-range flights and we enabled the Failsafe action in case of long-range telemetry signal loss. We opted for the execution of "Return mode" action in situations of telemetry RFD 900 loss for more than 10s (See Item 9 in S3 Text).

For comparison with other DIY drones, we performed a simple transect flight and lawnmower flight pattern simulating methodologies employed in studies using DIY drones [9, 17]. For transect flights, within the QGroundControl, we programmed a "Corridor Scan" flight pattern consisting of a straight-line flight with a maximum length and telemetry distance of20 km. The drone was programmed to fly at a constant altitude of100 m (AGL) and at a speed of 15 m/s. The "Corridor Scan" flight pattern was performed twice within the same area and with the same parameters (See flight-plan-corridor-scan in S1 Plan). In these flights, we mainly tested the flight range and the maximum telemetry range (Table 1).

For the lawnmower flight we programmed a "Circular Survey" flight pattern covering 10 ha (lat: -2.524484˚ / long: -44.208837˚) at 100, 75, 50 and 25 m AGL (See flight-plan-lawnmower in S1 Plan) which was performed in VLOS in order to identify the best flight altitude for dis- tinct objectives (monitoring of anthropic activities, vegetation analysis, fauna and flora identification). The camera was triggered automatically using the “Survey Mode” (See Item 10 in S3 Text) and based on a predefined flight plan to produce at least 70% overlap and side lap among each image. We performed two test flights for each altitude in the same area applying the same parameters, totaling eight flights (Table 1).

Table 1. Main pre-programmed flights features. All flights were performed with a 70% overlap (front and side) and 15m/s drone speed. Wind speed was obtained using the UAV Forecast app.

Pre-programmed Flights Mode							
Flight	Pattern	Flight Type	Altitude (m)	Wind speed (m/s)	Range (km)	Flight time (min)	GSD (cm/px)
1	Corridor Scan	EVLOS	100	10	15	65	2,8
2	Corridor Scan	EVLOS	100	9	17	50	2,8
3	Circular Grid	VLOS	25	11	0,1	13	0,7
4	Circular Grid	VLOS	25	8	0,1	13	0,7
5	Circular Grid	VLOS	50	10	0,1	8	1,4

6	Circular Grid	VLOS	50	9	0,1	7	1,4
7	Circular Grid	VLOS	75	12	0,1	6	2,1
8	Circular Grid	VLOS	75	10	0,1	6	2,1
9	Circular Grid	VLOS	100	9	0,1	5	2,8
10	Circular Grid	VLOS	100	9	0,1	4	2,8
11	Specific Grid	EVLOS	120	8	2	25	3,3
12	Specific Grid	EVLOS	120	9	2	27	3,3

All flights were performed with a 70% overlap (front and side) and 15m/s drone speed. Wind speed was obtained using the UAV Forecast app.

For the last two test flights, we programmed a lawnmower flight with a grid pattern covering around 1 km2 in a specific area inside the “Area de Proteção Ambiental do Itapiracó” (lat: -2.523079˚, long: -44.202738˚). The flights were carried out at 120m AGL, maximum altitude permitted by the local civil aviation legislation, and at 15 m/s (Table 1). The camera was also triggered automatically using the “Survey Mode” and with 70% overlap and side lap among each image. These flights were planned to support the “Secretaria de Meio Ambiente do Maranhão–SEMA” in identifying degraded areas, opening of trails and unauthorized access within part of the “Area de Proteção Ambiental do Itapiracó”. In addition to identifying trails in these flights, we tested the drone ability to generate useful data for creating orthoimages, georeferenced maps and other products. For these flights, two observers with direct communication with the pilot were positioned at opposite extreme points within the flight plan grid for constant observation of the drone (EVLOS flights).

Ethical statements

The flight tests followed Brazilian Civil Aviation Special Regulations (RBAC-E No. 94). The local civil aviation legislation does not allow BVLOS flights (Beyond Visual Line of Sight) without prior special registration and authorization of the drone, the flight and the pilot. Therefore, all flight tests were performed in VLOS or EVLOS mode as reported above. The individual shown in Fig 4 has given written informed consent (as outlined in PLOS consent form) to publish his picture in this study.

Results

We completed the development of the DIY model named "Asa-Branca-I" (Fig 4) in five months, with 30 hours of weekly dedication for development, plus another month for all performance tests and final adjustments. The purchase process and delivery time of the components corresponded to 20% of the development time, considering that the majority of the components were shipped from China and delivered to Spain.

Fig 4. Asa-Branca-I model and main components.

The model developed in this project had a material cost of$995 (details in Table 2). The average price of small fixed-wing commercial drones used in conservation studies that could perform similar functions to the model developed is around $15797 and, for equivalent DIY drone models where cost information is available, this figure is around $1440 (S1 Table).

Table 2. Asa-Branca-I costs (USD) based on prices available on the internet in November 2019. Ground station laptop cost not included. * Included in the airframe cost.

Specifications model UAS "Asa-Branca-I"			
Component	**Model/Brand**	**Quantity**	**Cost ($)**
Airframe	Volantex Ranger 2000 (PNP version)	1	135
Motor	Motor 2215 1400 Kv	1	*
Servos	Servos 9 g	6	*
Propeller	8 x 4	1	*
Electronic Speed Control	ESC 30 A 2-4S XT60 Volantex	1	*
Battery	Turnigy 5000 mAh 4S 14.8 V	1	25
Charger	SkyRC IMAX B6 Digital	1	36
Autopilot	Pixhawk PX4 2.4.6	1	130
GNSS	Ublox NEO-M8N GPS Module	1	16
Telemetry	900 RFD 915 MHz	1	176
Sensor	Pitot Tube Airspeedomoter	1	38
RC	Flysky FS-i6X 2.4 GHz 10CH RC Transmitter	1	51
Camera	Sony DSC-HX50	1	310
Camera trigger	Seagull #MAP2 + cable Sony	1	38
Accessories	Connectors and cables	-	50
TOTAL			995

The manual and pre-programmed flight tests allowed us to adjust manoeuvrability, payload capacity, flight duration and range so that we could confirm they were suitable for being used for biodiversity studies in large areas. We accomplished pre-programmed flights with a maxi- mum flight time of65 minutes, including take-off and autonomous landing. With simple transect pre-programmed flights as made in other conservation studies [9, 17], the model was able to fly for 50 minutes, covering a total distance of42.4 km round trip, at a speed of15 m/s, at a constant altitude of100 m AGL and a maximum telemetry range of around 20 km, covering an area of1.7 km2 with 2.8 cm px-1 GSD. As a reference, the model in circular survey pre-programmed flights was able to survey 10 ha in four minutes flying at 100 m AGL (2.8 cm px^{-1} images); six minutes flying at 75 m AGL (2.1 cm px^{-1} images); seven minutes flying at 50 m AGL (1.4 cm px^{-1} images); and 13 minutes, flying at 25 m AGL (0.7 cm px^{-1} images) always including take-off and landing (Table 1).

For both specific and circular grid for the lawnmower flight at 100 and 120 m AGL it was possible to identify deforestation spots smaller than 5 m2, opening of small trails and vegetation clearings that are difficult to detect by satellite images (Fig 5). We could also easily detect and identify medium size animals (such as a domestic dog, 1 m size) on the images obtained in flights with the embarked camera at 25 m AGL, which were less easily detectable although still noticeable at around 50 m.

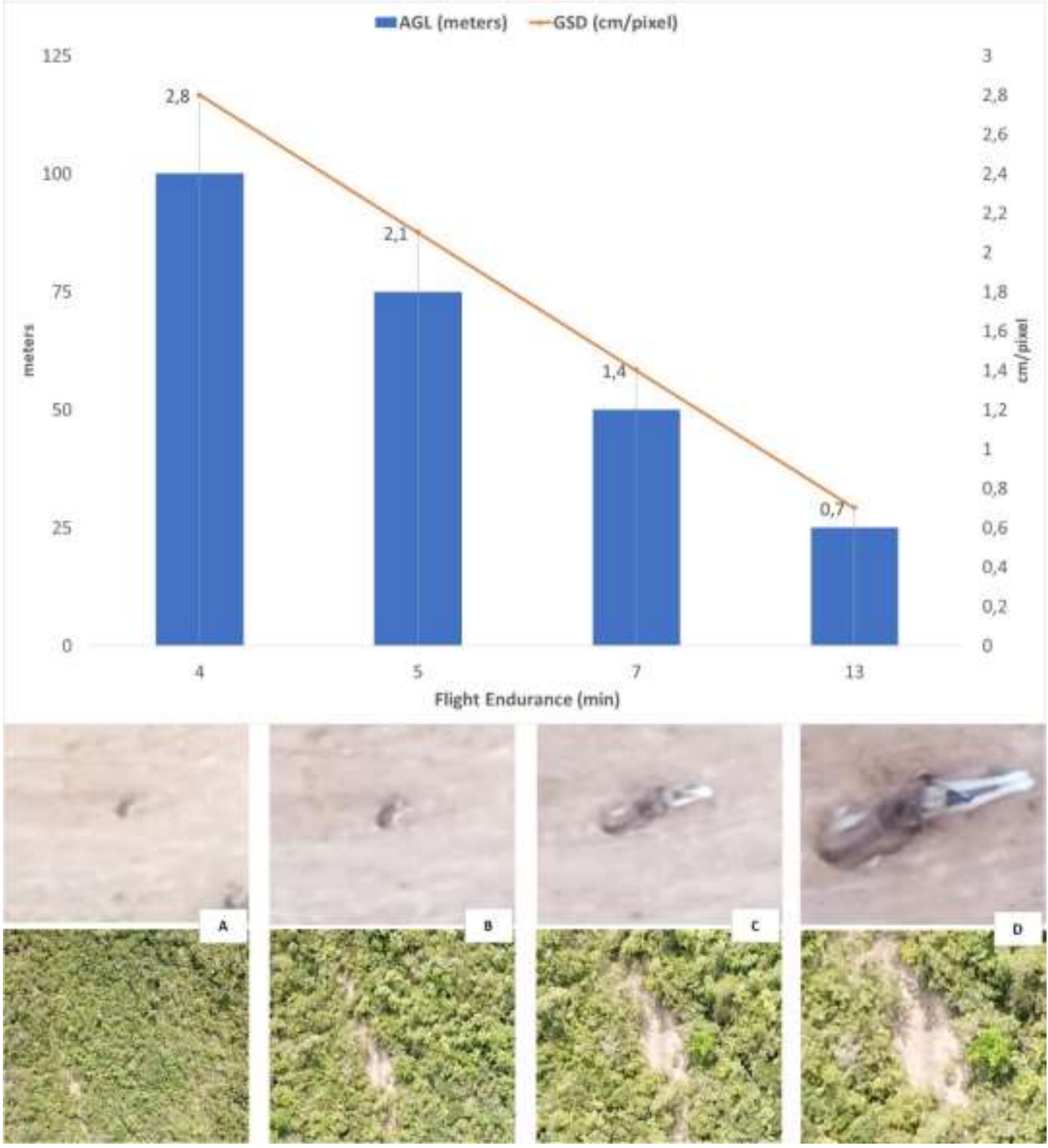

Fig 5. Comparison between Above Ground Level (AGL), Ground Sample Distance (GSD) and flight duration. Images with a 10x zoom ofa dog and a deforestation spot at (a) 100 m; (b) 75 m; (c) 50 m; and (d) 25 m AGL.

For the last two flights with a specific grid pattern and at 120 m AGL it was possible to obtain images with a resolution of 3.3 cm px^{-1} in which we could identify trails in the vegetation and degraded areas inside an area of1 km^2. The drone images were processed in this case to create an orthomosaic map using the Agisoft Metashape (version 1.5.5; www.agisoft.com).

In addition to an orthomosaic map, we also created maps to analyze the quality of vegetation, known as healthy green vegetation or plant health maps. These maps show how green the images are through the Visible Atmospherically Resistant Index (VARI), since this index is used for images obtained from an RGB sensor (Fig 6). The vegetation health map was created from images of the visible spectrum (Red, Green, Blue) obtained by the RGB sensor using the formula: $VARI_{green} = (R_{green} - R_{red}) / (R_{green} + R_{red} - R_{blue})$ [26]. Knowing that the images obtained are from the visual spectrum, we considered the standard CIR Calibration of Agisoft Metashape and filtered the values obtained between 0.06 and 0.39 of each raster.

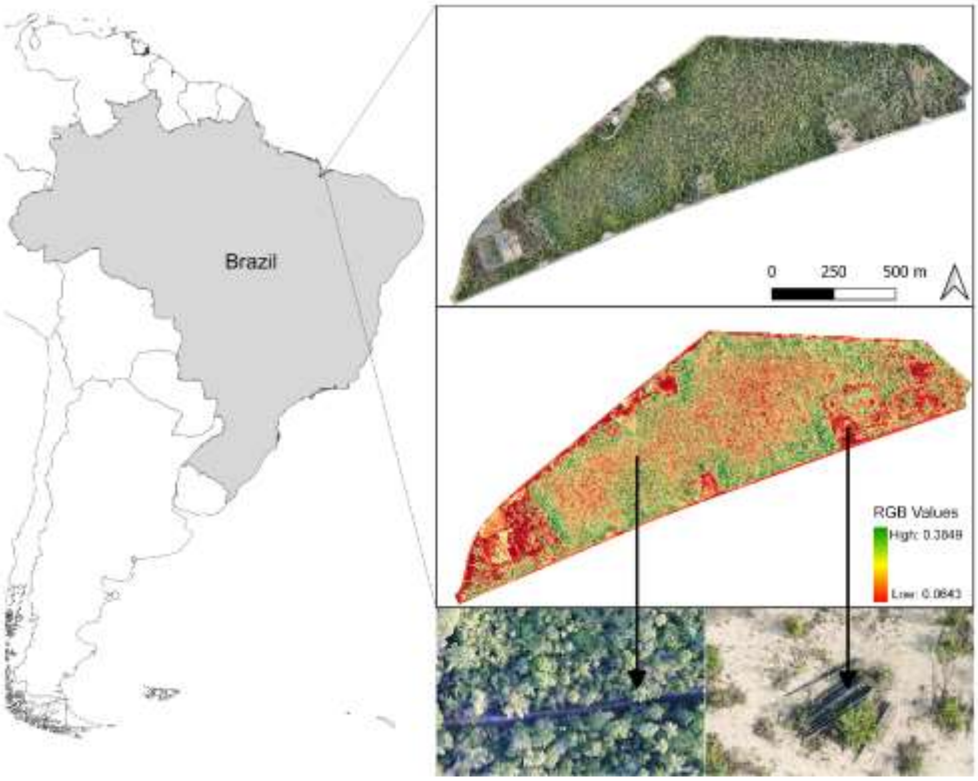

Fig 6. Georeferenced orthomosaic and health vegetation map. Images with a 20x zoom of an open trail in the vegetation and a deforestation area with some irregular structures

Discussion

In this study we describe the step-by-step process for the development ofa DIY low-cost drone that allows performing basic biodiversity-related studies in large areas. We present the steps in a simple and flexible way, aiming to help researchers with basic electronics knowledge and with limited financial resources to develop their own drone system. We describe the drone developed in this project as low-cost since the summed amount of the components was $995, substantially less than the average value of commercial drones, even in relation to other DIY drones used in biodiversity studies [See S1 Table]. The reduction of drone acquisition costs in conservation projects produces a significant saving in the total budget, but there are additional factors to consider when evaluating the DIY option against commercial products. While the material cost of the drone developed here is $14802 less than commercial drones' average, it took us five months to develop it and an additional month to perform the tests presented in this study. Among the few studies that describe the development of a low-cost fixed- wing drone in the last decade [9, 18, 19, 27, 28] there is no information on the average development time, which makes it impossible to compare our results with other studies. This fact makes the development time informed here a useful parameter for the development of future projects. Therefore, when choosing between developing your own drone system and purchasing a commercial RTF system, the time required for development must be considered in addition to the final cost.

As in other studies that use low-cost fixed-wing drones to carry out conservation works [4, 15, 16, 19], we also chose for this project the development of the drone system of the glider type platform due to its better aerodynamic efficiency, portability and competitive cost. Despite the choice of this platform, the development process is not limited to the specific platform model presented here. Once the main components and the way to make their connections and configurations are defined, these can be easily mounted into other fixed-wing platforms without many adjustments or even translated to rotary-wing platforms, although with some more modifications. While the development of the first DIY model requires a substantial initial time investment, thereafter only occasional updates are necessary for building new DIY platforms, even for different goals.

Through simple transect and lawnmower flights tests, we verified that our model served for monitoring large areas within a 20 km radius, covering more than 1 km2 in a single flight at high spatial resolution, which is sufficient to perform standard vegetation analysis [29, 30], fauna identification [10, 31] and deforestation monitoring [2]. Particularly for deforestation monitoring, the ability of this model to flight long distances, enabling large coverage with high spatial resolution, makes it a low-cost technology tool with a great potential for combating ille- gal activities in protected areas, especially in the Cerrado biome, one of the world's biodiversity hotspots [32] which is suffering a drastic loss of native vegetation during the last years [33].

The maximum flight time and coverage capacity ofthis model was similar to that of commercial RTF systems such as the standard version of eBee model (SenseFly), one of the most well-known fixed-wing systems in the drone market, and which presents an average acquisition cost 15 times higher than the model developed in this project. Beyond the economic fac- tor, other important factors, still little considered in the comparisons between the use of drones and manned airplanes, are the environmental impacts and the social costs concerning greenhouse gas emissions. One of the first attempts to analyse these costs showed that monitoring areas of up to 30 km2 using photometry with a resolution of5 cm / px from fixed-wing drones is more economically and socially advantageous than the use of manned aircrafts [34]. Considering that the comparisons in that study were made between the costs of manned aircraft and the eBee model, representing the fixed-wing drones, the economic advantage of DIY drone models as the one developed in this project is emphasized.

Although nowadays there are satellite systems such as DETER [35] used in Amazon and Cerrado biomes monitoring with a greater potential to identify changes in forest vegetation cover in areas measuring between 25 and 100 ha, with a spatial resolution of between 56 and 64 meters, the system developed here can identify changes in vegetation cover at a scale of meters and with spatial resolution at a scale of centimeters. By conducting only two lawnmower flights, it is possible to monitor the entire protected area (3.2 km2) of the “Área de Proteção Ambiental do Itapiracó” where we conducted part of our tests. In addition to this fine resolution scale, the possibility of systematic replication (temporal resolution) and the non-interference of cloud cover are other advantages over monitoring via satellite images that make the use of these types of drones an efficient tool in the inspection and fight against deforestation of large protected areas. The combination of payload and flight procedures developed here also allowed us to identify medium-sized fauna species from 50 m AGL, which suggests that it can also be useful for conducting medium-sized terrestrial wildlife studies [e.g. 4, 31].

The data obtained with the developed drone served to generate products such as orthomosaic maps and vegetation health maps that allowed monitoring the degradation of vegetation in protected areas with a higher resolution than satellite derived ones. The advantages of implementing drones, instead of satellites or manned aircrafts for generating orthomosaic maps with centimeter resolutions and all other subsequent products [27] makes photometry with drones one of the current main resources in the activities of conservation and combating environmental degradation, such as identification [36, 37], mapping [38, 39] and monitoring [6, 40]. In addition to the performance tests, we also validated the functionality of the Asa-Branca-I model in two environmental inspection and monitoring actions carried out by public environmental organizations in Maranhão, Brazil. These actions allowed to identify illegal opening of trails used by hunters within protected areas in the Cerrado biome that were not identified in previous terrestrial inspections due to the difficulty of ground access to the site.

Although the performance tests demonstrated here the suitability of the low-cost drone developed to cover large areas, we note that the local legislation, which generally follows the international legislation, ended up being a limiting factor regarding the use of this model and all other commercial models with similar functions, for the monitoring of large areas beyond the visual line of sight of the pilot, on flights known as BVLOS. Thus, seeking the certifications for the developed model as well as for the pilot, are future steps that should be considered for those who intend to use the full potential of drones capable of long-range flights as the model produced in this work.

Conclusions

Finding solutions that can make environmental monitoring more efficient is a constant challenge for researchers and conservationists. The balance between costs and benefits is one of the key factors for choosing between buying a commercial drone or developing a DIY solution. In this paper, we described a path for the development of a low-cost drone and performed tests to prove its usability.

With a material cost considerably lower than the least expensive model on the market, the knowledge gained from the development of this drone could be an alternative for researchers with limited financial resources. We are aware that the model developed here is just a first version with many possibilities for improvement. In addition, further tests in different situations and with different objectives are necessary to validate large-scale drone capacity. Transforming this model into a vertical take-off and land (VTOL) model, in order to make take-off and landing operations easier, increasing the stability of the camera with gimbal insertion and attaching safety features such as a parachute, are improvements that we intend to incorporate in future versions. Therefore, we believe this DIY model approach can be a valuable alternative for conservation projects.

Acknowledgments

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CHAPTER 2

Measuring disturbance at swift breeding colonies due to the visual aspects of a drone: a quasi-experiment study

This chapter corresponds to the article: Mesquita, G. P., Rodríguez-Teijeiro, J. D., Wich, S. A., & Mulero-Pázmány, M. (2021). Measuring disturbance at swift breeding colonies due to the visual aspects of a drone: a quasi-experiment study. Current Zoology, 67(2), 157–163. https://doi.org/10.1093/cz/zoaa038

Measuring disturbance at swift breeding colonies due to the visual aspects of a drone: a quasi-experiment study

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Resumen

Hay pruebas crecientes que indican que los drones pueden molestar a los animales. Sin embargo, generalmente no está claro si la alteración se debe a señales visuales o auditivas. Aquí, examinamos el efecto de los vuelos de drones sobre el comportamiento de los vencejos de cascada *Cypseloides senex* y los vencejos de collar blanco *Streptoprocne zonaris* en lugares de anidación donde el ruido de los drones estaba tapado por el ruido ambiental de las cascadas y cualquier perturbación debería ser en gran parte visual. Realizamos 12 vuelos experimentales con un dron multirotor a diferentes distancias verticales, horizontales y diagonales de las colonias. De todos los vuelos, el 17% provocó <1% del abandono temporal del lugar de reproducción, el 50% provocó el abandono de la mitad de ellos y el 33% provocó el abandono de más de la mitad. Encontramos que la distancia diagonal explica el 98,9% de la variabilidad del porcentaje de perturbación mientras que a distancias >50 m el porcentaje de perturbación no supera el 20% y a <40 m el porcentaje de perturbación aumenta a >60%. Recomendamos que los vuelos con un dron multirotor durante el período de reproducción se realicen a una distancia de >50 m y que los vuelos recreativos se desaconsejen o se realicen a distancias mayores (por ejemplo, 100 m) en áreas de anidación de aves, como cascadas, cañones y cuevas.

Abstract

There is a growing body of research indicating that drones can disturb animals. However, it is usually unclear whether the disturbance is due to visual or auditory cues. Here, we examined the effect of drone flights on the behavior of great dusky swifts *Cypseloides senex* and white-collared swifts *Streptoprocne zonaris* in 2 breeding sites where drone noise was obscured by environmental noise from waterfalls and any disturbance must be largely visual. We performed 12 experimental flights with a multirotor drone at different vertical, horizontal, and diagonal distances from the colonies. From all flights, 17% caused <1% of birds to temporarily abandon the breeding site, 50% caused half to abandon, and 33%

caused more than half to abandon. We found that the diagonal distance explained 98.9% of the variability of the disturbance percentage and while at distances >50m the disturbance percentage does not exceed 20%, at <40m the disturbance percentage increase to >60%. We recommend that flights with a multirotor drone during the breeding period should be con- ducted at a distance of >50m and that recreational flights should be discouraged or conducted at larger distances (e.g. 100m) in nesting birds areas such as waterfalls, canyons, and caves.

Key-words: Cypseloides senex; disturbance; drones; multirotors; Streptoprocne zonaris; unmanned aircraft systems

Introduction

Multirotor drones are one of the most widely used drone platforms in the civilian environment and with the greatest commercial growth in recent years (Droneii 2019). The main growth factors for scientific, commercial, and recreational drone use are associated with a diversity of models relatively easy-to-use, vertical take-off/landing, and easy transport. The high maneuverability of multirotor drones and their ability to hover in the air make them the preferred option for filming and data collection in hard-to-access places (Bakó et al. 2014; Chabot et al. 2015). For these reasons, along with the affordability of commercial models, they are currently the most popular choice for recreational flyers (Rebolo-Ifrán et al. 2019), commercial services (Droneii 2019), and scientists (Chabot and Bird 2015; Jiménez López and Mulero-Pázmány 2019).

Within the scientific environment, the integration of drones as data-collection platforms has significantly facilitated vertebrate studies, mainly focused on birds and mammals (Wich and Koh 2018) to address a wide variety of topics, such as species monitoring (Rey et al. 2017; Hodgson et al. 2018); behavioral analysis (Canal et al. 2016; Mulero-Pázmány et al. 2017; Cliff et al. 2018); management (Mulero-Pázmány et al. 2014); habitat mapping (Castellanos-Galindo et al. 2019); and spatial ecology and wildlife diseases (Barasona et al. 2014; Mulero-Pázmány et al. 2015; Laguna et al. 2018). Some of the main advantages of using drones to study wildlife are the reduction of logistical difficulties; costs; risks; and disturbance on wildlife when compared with conventional methods such as manned aircraft surveys or researchers on the ground (Dulava et al. 2015; Christie et al. 2016).

The increase in drone use has raised concerns about the potential disturbance these systems can cause on wildlife (Bevan et al. 2018; Bennitt et al. 2019; Weston et al. 2020). There are a number of fac- tors associated with drone characteristics (drone size, motor type, and flight pattern) and animals (species, life-history stage, and level of aggregation) that can be related to the level of disturbance caused by these systems (Mulero-Pázmány et al. 2017). The threshold of disturbance caused by a drone in a given species is often formed by a set of interconnected factors: the sound signature of the drone, the environmental noise level, the visual ability of the species, and the association degree of the drone with a threatening stimulus of the species (Bevan et al. 2018). Birds have acute visual perception, and therefore the visual stimuli generated by the drone can have a greater effect than the noise. Even though some studies that assessed drone disturbance in birds relating flight patterns and distances to the sound and visual aspects of the drone (McEvoy et al. 2016; Rummler et al. 2016; Brisson-Curadeau et al. 2017; Reintsma et al. 2018), so far it has not been possible to analyze separately the disturbances caused by the visual stimuli of the sound stimuli coming from the drones.

Here, we describe an experiment in which we investigate responses from 2 species of swifts, great dusky swift *Cypseloides senex* and white-collared swift *Streptoprocne zonaris*, to drone flights in a scenario where noise is mainly masked by the back- ground noise of waterfalls and the visual stimulus the main disturbance factor. We measured the disturbance caused by a multirotor drone at varying distances from swift colonies located in wet rocks walls next or behind waterfalls where the environmental noise is louder than the drone noise. Our aims were to 1) bring a new perspective of visual disturbance analysis caused by multirotor drones disassociated from the drone noise and 2) facilitate establishing guidelines that allow minimizing disturbance to bird colonies that use places such as rocks walls next or behind waterfalls, canyons, and caves around the world as resting and nesting sites, places with high probability of drone–bird interaction due to the increased recreational drone use and the tourist interest of such places.

Material and Methods

Study area and species

This study was conducted in Chapada das Mesas National Park, Maranhão, Brazil, in October, 2018. The Park covers a total area of 1,600km2 within the Cerrado biome, that has various vegetation types, from “cerradão,” which is a type of seasonal forest with dense tree vegetation to “campos limpos” that are open fields as savannas with few trees (Marques and Amorim 2014). The 2 breeding areas of the study species were: Cachoeira do Prata (6°59’36” S, 47°9’55” W) and Cachoeira de São Romão (7°1’11” S, 47°2’26” W). Both are located in the North of the park along different stretches of the “Farinha” river, a tributary of Araguaia/Tocantins basin, and are ~14km away from each other in a straight line. The breeding areas are the 2 most voluminous waterfalls present within the park.

The Cachoeira do Prata is formed by a set of falls that reach up to 18m in height, and the Cachoeira de São Romão has falls of up to 25m in height (Figure 1). The region has a humid tropical climate characterized by 2 well-defined seasons: dry, which runs from May to October and wet from November to April, with an annual temperature varying between 24°C and 26°C and an annual rainfall varying between 1,200 and 1,600mm (IMESC 2008). The waterfalls are accessible to tourists but the number of visitors is low because the access is currently limited to 50km of dirt road that can only be accessed by 4x4 vehicles.

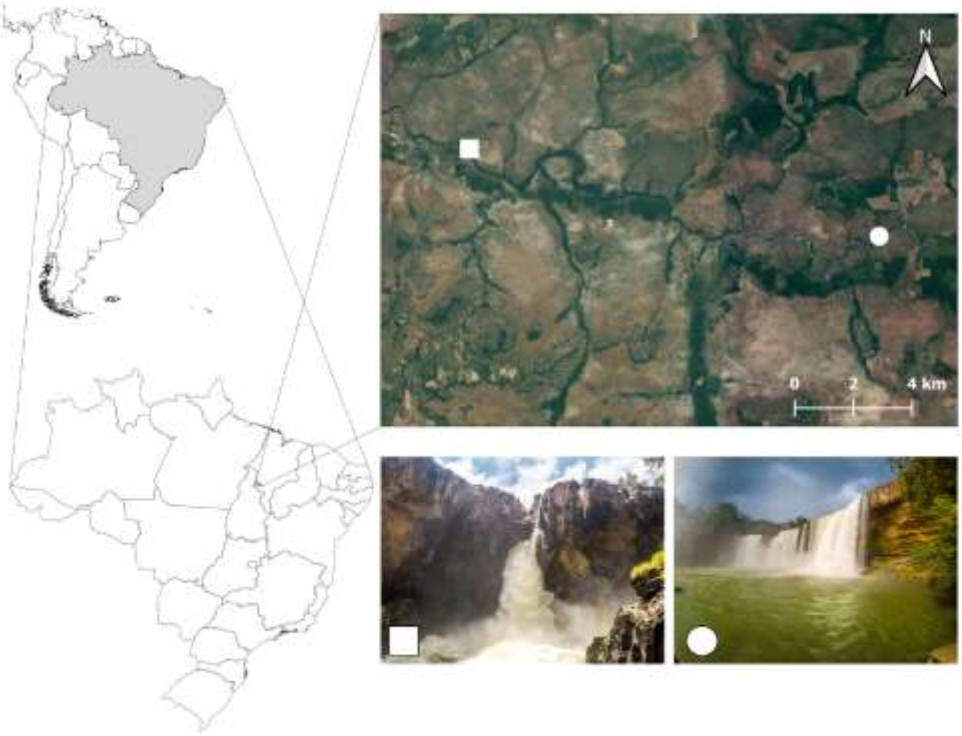

Figure 1. Location of the studied swift breeding sites in Chapada das Mesas National Park, Brazil. Cachoeira do Prata (white square) and Cachoeira de São Romão (white circle)

The 2 study species were the great dusky and white-collared swifts. These are globally considered of least concern according to the Red List (IUCN 2020) with stable population for the great dusky swift and declining population for the white-collared swift population. The great dusky swift distribution is restricted to Argentina, Bolivia, Brazil, and Paraguay (Stopiglia and Raposo 2007) and the white-collared swift is distributed from the United States to Argentina (Chantler 1999). In Brazil, data for both species are sparse, leading to an inaccurate distribution map. Both species are strongly associated to areas with wet rocks walls next or behind waterfalls, canyons, and caves. These sites are used with great fidelity for breeding and nesting that occurs between October and November (Whitacre 1989; Stopiglia and Raposo 2007). The 2 species often share nesting sites (Pearman et al. 2010). In this study, most of the individuals identified in the nesting sites were the great dusky swift and few individuals of the white-collared swift.

Drone and experimental flights

The drone model used was a DJI Mavic Pro quad-copter, black color, with a diagonal size of 335mm, 743 g weight, 677 dB (decibel) noise level, maximum flight speed of 65 km/h, and 20min average flight autonomy, that carried a camera with a 1/2.300 CMOS (complementary metal-oxide semiconductor) and sensor with 12.35 effective megapixels. In each of the 2 swift breeding sites, we per- formed 6 experimental flights at varying heights above the ground and distances to the breeding rocks walls (Table 1).

Table 1. Experimental flights parameters

Flight	Date	Time	Study Site	Height nests	Flight Altitude	Vertical Distance	Horizontal Distance	Diagonal Distance
1	22/10/2018	16:00	Cachoeira do Prata	10	50	40	50	64.03
2	22/10/2018	17:30	Cachoeira do Prata	10	25	15	50	52.20
3	23/10/2018	16:00	Cachoeira de São Romão	15	50	35	50	61.03
4	23/10/2018	17:30	Cachoeira de São Romão	15	25	10	50	50.99
5	24/10/2018	16:00	Cachoeira do Prata	10	10	0	50	50.00
6	24/10/2018	17:30	Cachoeira do Prata	10	50	40	25	47.17
7	25/10/2018	16:00	Cachoeira de São Romão	15	10	-5	50	50.25
8	25/10/2018	17:30	Cachoeira de São Romão	15	50	35	25	43.01
9	26/10/2018	16:00	Cachoeira do Prata	10	25	15	25	29.15
10	26/10/2018	17:30	Cachoeira de São Romão	15	25	10	25	26.93
11	27/10/2018	16:00	Cachoeira do Prata	10.00	10	0	25	25.00
12	27/10/2018	17:30	Cachoeira de São Romão	15.00	10.00	-5	25	25.50

Note: Distances are in meters.

All the swift nests were located in the rock wall at 10±1m above the ground in the Cachoeiras do Prata and 15±1m in the Cachoeiras de São Romão (Figure 2). Flights were conducted between 15 and 18h local time. The drone was launched at a minimum distance of 100m from the breeding site. During a pilot study conducted a week before the actual experiments, we checked that at this distance the drone did not lead to any noticeable reaction from the birds. Between the launch sites and the breeding areas, there was vegetation that prevented birds from viewing the drone's take-off. We approached the nesting sites horizontally at a speed between 14 and 21km/h which in a previous study did not seem to influence bird behavior (Vas et al. 2015) and allows for good control of the drone. Once the drone reached the set point, which corresponds to the diagonal distance of each flight according to Table 1, it remained hovering stationary for a maximum time of 10min or until we detected any swifts' behavioral reaction (flying away or mobbing). Once we detected any reaction, we kept the flight time no >5min to minimize negative effects on the species. An experienced observer using a binocular (10x50) counted the number of birds that were present at the breeding site 5min before the take-off of each flight and after the drone was landed. At both field sites, the observer was positioned between the nesting rocks walls and the drone, with free view to both. Due to the difficulty of approaching the nesting rocks walls and to avoid possible disturbance to the colony, the observer was positioned at a horizontal distance of 15–20m from the base of the rocks walls, hidden from the colony's line of sight. Because of the large number of individuals of the 2-species agglomerated and the low luminosity at the waterfalls, we could not determine the number of individuals of each of the 2 species at the breeding sites and therefore recorded the total number of birds. We established a minimum interval of 30 min after landing of each flight or until the birds regrouped in the breeding sites, and a maximum of 2 daily flights, to avoid major disturbances during the same day.

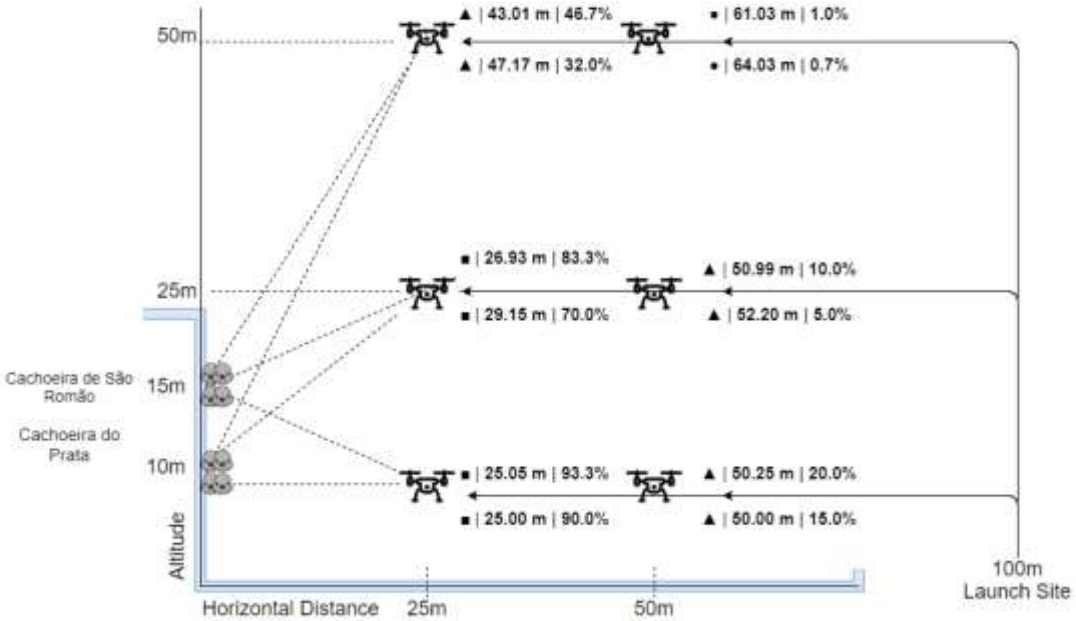

Figure 2. Design of experimental flights. Breeding group from “Cachoeira do Prata” and “Cachoeira de São Romão.” Classification (circle, noticeable disturbance; triangle, moderate disturbance; and square, high disturbance), Diagonal distance (meters) and disturbance (%) for each drone flight.

The visual analysis included an assessment of the spots size on the walls, which were agglomerations of the birds, and were used to define whether the birds had regrouped. This is, if the spot size returned to its original size, we assumed that the individuals had returned. For the visual analysis of spot sizes, we compare the spot sizes with rock wall features as atypical marks, deformations, or some plants. Due to the high environmental noise caused by the waterfalls, in all the experimental flights in the 2 studied places it was not possible to hear the drone noise by the observer who was positioned between the drone and the rock walls at a horizontal distance of 15–20m from the base of the rock’s walls.

Statistical analysis

As drone disturbance we considered the change in swifts’ behavior (flying away or mobbing). We calculated this disturbance for each experimental flight as the percentage of birds present in the breeding colony 5min before drone exposure minus the percentage of birds present after drone landing. Following Chabot et al. (2015), we classified the drone disturbance level in 3 categories based on the percentage of birds reacting: 1) noticeable disturbance, when the percentage does not exceed 1%; 2) moderate disturbance, when the percentage does not exceed 50%; and 3) high disturbance, when the percentage is >50%. For vertical distance, we considered the difference in height between the nest and the drone on each flight. The horizontal was measured from the projection of the drone to the ground to the colony and the diagonal distance (hereafter distance) was obtained through the Pythagorean theorem. We also calculated the return time of the individuals to the breeding sites after the drone had landed on each flight and the average time for each of the 3 categories of disturbance.

A previous descriptive scatter plot showed the possibility of a nonlinear association between variables in the 2 ran models. The first model with diagonal distance as a predictor variable and the disturbance percentage as a dependent variable, and the second model with the disturbance percentage as a predictor variable and the return time as a dependent variable. To choose the best models, we initially consider the nature of the variables and Akaike's information criterion (AIC). For model validation, we tested for normality test (Shapiro–Wilk), heteroscedasticity (Breusch–Pagan) and set the significance level at 0.05. All analyses and charts were made using "car" (Fox 2016), "drc" (Ritz et al. 2015), and "investr" (Greenwell and Schubert 2014) packages in R 3.6.2 with RStudio 1.2.5033 (R Core Team 2019).

Ethics Statement

This project was the authorized No. 64630-1 (scientific purpose) by the System of Authorization and Information on Biodiversity (SISBIO) in Brazil (art. 28 of IN 03/2014) from the Chico Mendes Institute for Biodiversity Conservation (ICMBio), and the flight drone was register certificate No. PP-019272726 by the National Civil Aviation Agency (ANAC).

Results

Twelve drone flights were performed at different distances from 2 swift breeding colonies. A maximum disturbance of 93.3% was recorded when the drone flew at 25.5m distance from a bird’s colony, and a minimum of 0.7% disturbance when the flight was con- ducted at 64.0m distance (Table 2). During the 6 flights that produced moderate disturbance initially, a few swifts, ranging from 5 to 40 individuals, showed a mobbing behavior against the drone. However, the majority of other individuals who showed reactions just left the breeding sites and began to perform circular flights at a distance 2065m above the drone. Flights performed at less than 29m produced high disturbance, causing the departure of most of the colony of the breeding sites with just an average of 15.8% of the individuals remaining. In flights with high disturbance, we also recorded a larger number of individuals performing mobbing behavior toward the drone. In each of these flights, we landed as fast as possible.

Table 2. Percentage disturbed and classification of experimental flight

Classification	**Flight**	**Date**	**Time**	**Study Site**	**Diagonal Distance (m)**	**Total Swifts**	**Disturbed (%)**	**Return Time (min)**

1	1	22/10/2018	16:00	Cachoeira do Prata	64.03	3000	0.7	1
1	3	23/10/2018	16:00	Cachoeira de São Romão	61.03	1000	1.0	1
2	2	22/10/2018	17:30	Cachoeira do Prata	52.20	1000	5.0	9
2	4	23/10/2018	17:30	Cachoeira de São Romão	50.99	3000	10.0	9
2	5	24/10/2018	16:00	Cachoeira do Prata	50.00	1000	15.0	12
2	6	24/10/2018	17:30	Cachoeira do Prata	47.17	2500	32.0	15
2	7	25/10/2018	16:00	Cachoeira de São Romão	50.25	2500	20.0	12
2	8	25/10/2018	17:30	Cachoeira de São Romão	43.01	1500	46.7	16
3	9	26/10/2018	16:00	Cachoeira do Prata	29.15	1000	70.0	20
3	10	26/10/2018	17:30	Cachoeira de São Romão	26.93	3000	83.3	22
3	11	27/10/2018	16:00	Cachoeira do Prata	25.00	1000	90.0	25
3	12	27/10/2018	17:30	Cachoeira de São Romão	25.50	3000	93.3	25

Note: 1, noticeable disturbance; 2, moderate disturbance; and 3, high disturbance.

The nonlinear Gompertz model is the one that presents a lower AIC, 80.16, and the distance from the drone to the colony explained 98.9% of the variability of disturbance percentage. Thus, while at distances >50m the percentage of disturbances does not exceed 20%, at <40m the disturbance percentage increase to >60% (Figure 3). The relationship between the disturbance percentage and the return time, that is, the time it takes for the swifts to return to the colonies is better fitted to a nonlinear power model that explains 97.3% of the variability of return time, and it was the one that presents a lower AIC, 54.5 (Figure 4). On the 4 flights classified as high disturbance it took an average of 23.562.4 min for all individid- uals in the colony to return to the breeding sites after the drone had landed. On flights classified as moderate disturbance this time was reduced to 1262.9 min, whereas on flights with just noticeable disturbance the individuals returned almost immediately after the drone landing.

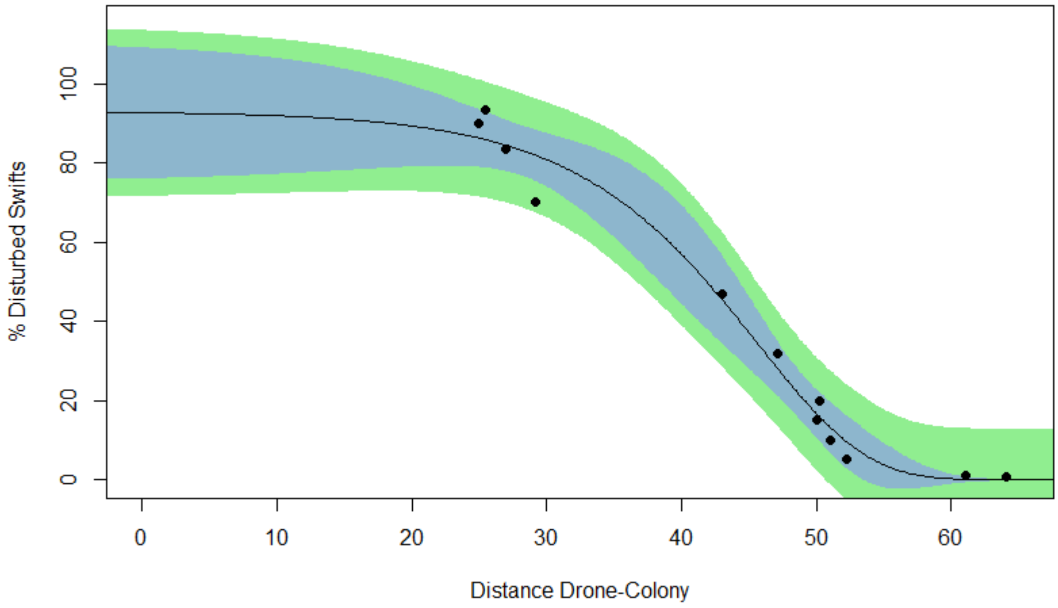

Figure 3. Nonlinear Gompertz regression between diagonal distance and % disturbed of swifts. Blue, 95% confidence band; green, prediction band.

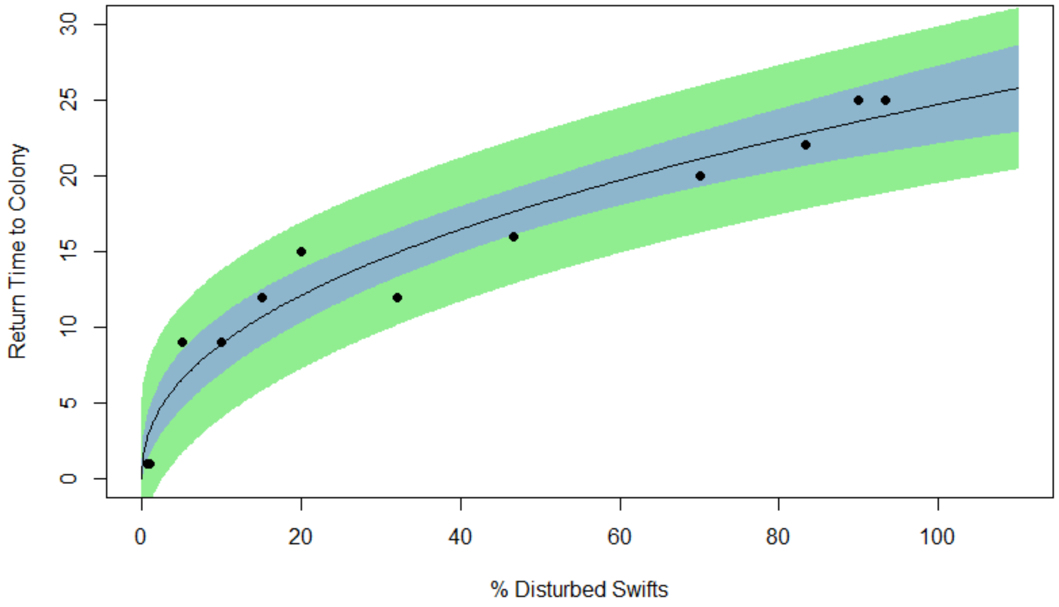

Figure 4. Nonlinear power regression between % disturbed of swifts and re- turn time. Blue, 95% confidence band; green, prediction band.

Discussion

In this study, we measured the drone visual disturbance separate from the drone noise disturbance in birds breeding colonies from a quasi-experiment where the drone’s noise is masked by environment noise, and we found that the response of birds to drone use follows a sigmoidal distribution with the diagonal distance from the drone to the colonies. Although our results are similar to studies that indicate that drone disturbance on birds increases as flight height decreases under different conditions and with different bird species (Rummler et al. 2016; Mulero-Pázmány et al. 2017; van der Vliet et al. 2019), we found that the recommended minimum distance must be >50m to avoid moderate and high disturbance in breeding sites, which is different from other studies, that were 15m by common gulls and other species in the bird reserve island Langenwerder in the Baltic Sea (Grenzdorffer 2013) and at least 20m with drones to survey cliff-nesting seabirds as murres (Brisson-Curadeau et al. 2017). However, unlike all the studies mentioned above, our results show that this reaction to the drone at a greater distance from the colony could be due to the idiosyncrasy of these species but it could also be a consequence of the fact that the drone, without any apparent sound is more similar to a natural situation of approach of a winged predator to the colony and trigger the defensive reaction earlier. The drone's sound could initially prevent the colony's reaction by being an artificial stimulus not associated with a winged predator, and only when the drone is close enough then triggers this defensive reaction.

The median bird hearing thresholds from 49 bird species suggest that the birds hear best at frequency between about 2 and 3 kHz, while humans generally have better auditory sensitivity with lower auditory thresholds and with wider bandwidth than typical birds (Dooling and Popper 2007). Therefore, if an observer was unable to hear the drone at 15m, suppressed or muffled by waterfalls in this experiment, it is assumed that the swifts could not hear the drone at 25m in the flight closest to the colony. This suggests that the drone noise may lose importance for the disturbance, while the visual aspects such as the shape or the flight pattern can be determinant for the swift's behavior change. Indeed, the drone visual stimulation was one of the possible causes of disturbances in colonies of greater crested tern *Thalasseus bergii* in a study that suggested that the noise emitted by multirotor drones may not be audible to colonies of this species (Bevan et al. 2018). However, the drone shape of our study eschews the classic “hawk/goose” rule (Schleidt et al. 2011) because a multirotor does not look like any potential swift predator. The new multirotor shape was one of the explanations for the lack of flight response in waterfowl at low flight altitudes in other studies (McEvoy et al. 2016). In contrast, we found that swifts showed mobbing behavior in flights near the nesting sites and may have recognized the multirotor drone as a potential predator. In the case of the great dusky swift and white-collared swift, the only known aerial predator is the peregrine falcon Falco peregrinus which has been observed near the others colony sites awaiting to catch swifts as they enter or leave the colony to feed and collect nest materials (Whitacre 1989). So even though the multirotor does not have a "hawk" shape, it is possible that the mobbing behavior of the swifts facing the drone can be elicited due to the drone being perceived as an unknown potential predator.

The time that swifts took to return to the colony after multirotor flights classified of high disturbance was about 2 times longer than those classified of moderate disturbance and about 20 times longer than those of low disturbance. This time between departure and return to the original location after the disturbance is also considered a way to measure an animal's response to a disturbance (van der Vliet et al. 2019). These types of responses can have a negative impact on the reproductive process in the case of birds in their breeding season, since it causes the individual to spend more energy, alters the incubation cycle and the care of altricial nestlings, and exposes them to possible predators. This negative impact caused by the return time to the nests was different from others bird studies that measured this time after drone disturbance in breeding colonies: ranging from 1min to common terns *Sterna hirundo* (Reintsma et al. 2018), 1–3min for Iceland gulls *Larus glaucoides*, and 5–10min for thick-billed murres *Uria lomvia* (Brisson-Curadeau et al. 2017), while our experiment demonstrated much longer return time, whether on high disturbance flights, ranging from 20 to 25min, or moderate disturbance flights, 9 to 16min. This variability in return time suggests the need to carry out specific tests to know this effect in different species. Our experiment shows that this delay time in returning to the nesting site can cause very negative impacts on the reproductive process if the presence of these drones is intense over time.

Understanding the minimum operating distance at which drones can cause disturbance, which factors can cause them, and for which species each distance can be tolerated is critical, whether for the preparation of flight missions in scientific studies or to regulate the growing recreational use of drones in such environments. Despite the great diversity of responses to the drone use from different bird species due to the different types of ecological contexts in which they are found, almost always the greater the frequency and intensity of the disturbance, the greater the negative impacts on breeding bird populations. In this sense, the drone use, which is expanding in sites as bird nesting areas, such as this study, should be considered as a possible source of negative effects in certain colony birds. Therefore, we suggest the flight distance with multirotor drone to avoid high disturbance in the great dusky and white-collared swifts during the breeding period in nesting areas should be >50m. We also recommend that recreational flights are generally discouraged or conducted at larger distances (e.g., 100m) in areas where swifts occur such as waterfalls, canyons, and caves. This study serves as a basis both for the elaboration of new protocols for the use of drones over birds by researchers in conservation studies and for possible regulations for the recreational use of drones in areas where these species occur.

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CHAPTER 3

Terrestrial megafauna response to drone noise levels in ex-situ areas

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Terrestrial megafauna response to drone noise levels in ex-situ areas

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Resumen

El uso de drones ha crecido significativamente en los últimos años, pero aún existe poco conocimiento sobre cómo el uso de drones puede afectar negativamente al comportamiento de los animales, especialmente para la megafauna. Investigamos cómo los niveles de presión sonora (dB) y la frecuencia (Hz) de un dron personalizado se asociaban con la perturbación en 16 especies de megafauna y realizamos un hierarchical cluster multivariate analysis para determinar si los cambios en el comportamiento asociados con el ruido del dron son similares entre especies. Los elefantes asiáticos y las jirafas mostraron cambios de comportamiento con los niveles de presión sonora promedio más bajos y el oso hormiguero gigante soportó los más altos. Los bóvidos, cérvidos, suidos y cánidos fueron altamente sensibles al ruido de los drones a altas frecuencias, mientras que los carnívoros de la familia Felidae mostraron un comportamiento vigilante con el ruido de los drones con baja presión sonora en bajas frecuencias. Seis grupos de especies de megafauna terrestre mostraron un cambio de comportamiento similar considerando siete variables: altitude vigilant, altitude move, decibels vigilant, decibels move, frequency vigilant, frequency move and visual contact drone. El cambio de comportamiento debido al ruido de los drones fue causado por diferentes niveles de presión sonora que posiblemente sean notados en diferentes frecuencias por diferentes especies, no necesariamente cercanas en taxonomía. Nuestros hallazgos muestran las características del sonido emitido por el dron y los valores mínimos de nivel de presión sonora en diferentes frecuencias que pueden provocar cambios de comportamiento para cada especie, y señalan que entender estas características es fundamental para evitar perturbaciones adicionales en especies de mamíferos en ambientes ex-situ. Nuestros hallazgos también pueden ayudar a hacer que el uso de drones sea más seguro y con menor impacto para las especies objetivo y servir como estudio experimental para la creación de posibles protocolos futuros para el uso de drones en mamíferos terrestres en áreas ex-situ.

Abstract

The use of drones has grown significantly in recent years but there is gap of knowledge on how drone use can negatively affect the animals' behavior especially for megafauna. We investigated how the sound pressure levels (dB) and frequency (Hz) of a custom-off-the-shelf drone were associated with disturbance of 16 megafauna species and performed a hierarchical cluster multivariate analysis to determine if changes in behavior associated with the drone noise are similar between species. Asian elephants and giraffes showed behavioral changes with the lowest average sound pressure levels and giant anteater supported the highest. Bovidae, Cervidae, Suidae and Canidae were highly sensitive to drone noise at high frequencies, while the felines from Carnivora family showed vigilant behavior with the drone noise in low sound pressure in low frequencies. Six groups of terrestrial megafauna species showed similar behavioral change considering seven variables: altitude vigilant, altitude move, decibels vigilant, decibels move, frequency vigilant, frequency move and visual contact drone. The behavioral change caused by the drone noise was caused by different sound pressure levels that are possibly noticed at different frequencies by different species, not necessarily close in taxonomy. Our findings show the characteristics of the sound emitted by the drone and the minimum values of sound pressure level in different frequencies that can cause behavioral changes for each species, and that understanding these characteristics is fundamental to avoid additional disturbances in mammal species in ex-situ environments. Our findings can also help making the use of drones safer and with less impact for the target species and serve as experimental study for the creation of possible future protocols for the use of drones with terrestrial mammals in ex-situ areas.

Keywords: large mammals; multi-rotor; auditory sensitivity; behavior; sound pressure levels; frequency

Introduction

Drones are becoming more ubiquitous for research and conservation of species and their habitats (Chabot & Bird 2015; Christie et al. 2016; Jiménez & Mulero-Pázmány 2019) due to the several methodological advantages when compared to other conventional techniques. Greater safety for researchers, especially for research of large mammals in large open areas, access to restricted areas by car or river, and more accuracy are some of the main advantages of using drones over wildlife ground surveys (Hodgson et al. 2018; Kellenberger et al. 2018), while the generation of data with high spatial and temporal resolution, low operational costs and easier logistics, and also more security for researchers are some of the main advantages of using drones over aerial surveys by manned airplanes (Anderson & Gaston 2013; Linchant et al. 2015). These advantages have expanded the studies of identification and detection (Rey et al. 2017; Kellenberger et al. 2018), monitoring (Schofield et al. 2019; Schroeder et al. 2020) and habitat assessment (Bonnin et al. 2018; Olsoy et al. 2018) of wildlife using drones. But, on the other hand, drone use for wildlife research or even for recreational use has become a new source of disturbance for many species (Mulero-Pázmány et al. 2017; Vliet et al. 2019).

Among animal groups, megafauna and birds are the main groups studied using drones (Chabot & Bird 2015) and consequently those that are most likely to suffer such disturbance. Several studies have already shown that in certain situations drones can cause disturbances to birds, (Brisson-Curadeau et al. 2017;

Mesquita et al. 2021) and large mammals (Ditmer et al. 2015; Bennitt et al. 2019). As a result of this concern several papers have suggested drone use guidelines to minimize their impact on wildlife (Hodgson and Koh 2016, Mulero-Pázmány et al. 2017). Although megafauna (Moleón et al, 2020) is one of the preferred groups for drone studies (Chabot & Bird 2015; Linchant et al. 2015) and for wildlife images and videos in recreational settings (Rebolo-Ifrán et al. 2019), there are still few works that identify or quantify the precise factors that can negatively affect these animals' behavior.

Bennitt et al. (2019) demonstrated that some large African mammals respond to drones approaches negatively, although the animals varied in their level of response and their tolerance for drone proximity. They also found that even at high flying heights and out of sight of the species, the drone caused some reaction, suggesting that first responses were triggered by auditory rather than visual signals. Similarly, Schroeder et al. (2020) proved that guanacos (*Lama guanicoe)* perceived drones even at 180 m above ground level (AGL), height that makes the animal's visual detection of the drone unlikely. Focusing only on the sound pressure levels, Scobie and Hugenholtz (2016) suggested that drone flights should be performed above 200 m to avoid aural detection by ungulates, dogs, cats, gamebirds, and waterfowl in most environmental conditions. More recently Duporge et al. (2021) comparing the auditory sensitivity of different species of mammals through available audiograms with the drone noise from different models of commercial drones, suggested different minimum advisable altitudes for each type of drone over the different species. Some studies have tried to identify which drone stimulus can cause behavioral change in wildlife either focusing on the sound (Scobie and Hugenholtz 2016), or on the visual stimulus (Mesquita et al. 2021). More research is needed to disentangle the influence of the auditory and visual signals on drone animal disturbance. Despite behavioral audiograms exist for some mammal species, knowledge of mammalian hearing skills in general is still limited. Knowing why the wide range of auditory limits at low frequencies among mammalian species and understanding auditory perception, which includes the ability of animals to recognize objects or other animals by the sounds they emit, are still to be explored (Heffner and Heffner 2014).

The aim of this study is to investigate how the sound pressure levels of a custom-off-the-shelf drone are associated with disturbance on various megafauna species. Our prediction is that species with a higher auditory sensitivity in the low frequencies will show more disturbance related behavior to drone noise. We studied megafauna animal behavior in experiments ex-situ in a zoological park in Brazil where a small multi-rotor drone was operated at different altitudes. To our knowledge, this is the first experiment where drone sound characteristics are related to terrestrial megafauna behavioral changes.

Methods

Study area and species

We studied 16 species of terrestrial megafauna (Moleón et al, 2020), (Table 1), ‘ex-situ’, in the São Paulo Zoological Park with a total area of 82 ha. All animals are in areas created to simulate their respective natural habitats. We carried out the experiments in open environments with the drone in the line of sight of the individuals and the drone pilot. The zoo's technical team verified that none of the studied specimens had been exposed to drones in the last 5 years.

Table 1. Terrestrial megafauna species analyzed.

Common name	Species	Family	Order
Addax	*Addax nasomaculatus*	Bovidae	Artiodactyla
Dromedary	*Camelus dromedarius*	Camelidae	Artiodactyla
Noble deer	*Cervus elaphus*	Cervidae	Artiodactyla
Giraffe	*Giraffa camelopardalis*	Giraffidae	Artiodactyla
Hippopotamus	*Hippopotamus amphibius*	Hippopotamidae	Artiodactyla
Waterbuck	*Kobus ellipsiprymnus*	Bovidae	Artiodactyla
Warthog	*Phacochoerus africanus*	Suidae	Artiodactyla
Maned wolf	*Chrysocyon brachyurus*	Canidae	Carnivora
Jaguar	*Panthera onca*	Felidae	Carnivora
Bengal tiger	*Panthera tigris tigris*	Felidae	Carnivora
Spectacled bear	*Tremarctos ornatus*	Ursidae	Carnivora
White rhinoceros	*Ceratotherium simum simum*	Rhinocerotidae	Perissodactyla
Imperial zebra	*Equus grevyi*	Equidae	Perissodactyla
Tapir	*Tapirus terrestris*	Tapiridae	Perissodactyla
Giant anteater	*Myrmecophaga tridactyla*	Myrmecophagidae	Pilosa
Asian elephant	*Elephas maximus*	Elephantidae	Proboscidea

Control flights

Before experimental flights over the animals, we performed two flights, using a drone DJI Mavic Pro black quad-copter with a diagonal size of 335 mm and maximum take of mass of 743 g (https://www.dji.com/br/mavic), to measure the sound-pressure level (SPL) in decibels (dB) as well as to characterize the frequencies (Hz) received at ground level when the drone was flown at different altitudes. We measured the drone noise using the Instrutherm model DEC-7000 sound meter (https://www.instrutherm.net.br/) following the protocol outlined in

International Organization for Standardization ISO-3746 (ISO 2010). The DEC-7000 has class 1 accuracy, linear precision 0.8 dB, measurement range 22 ~ 136 dB (A), with frequency weights A, B, C and Z and 36 frequency band response from 6.3 to 20000 Hz at 1/3 octave in real time. We carried out the measurements with the DEC-7000 using the slow type weighting time, weighting in dB (A) with 1/3 octave filters, and 30 seconds of measurement at each altitude. Using the Instrutherm software for DEC-7000 sound meter we obtain the exponential average of the sound-pressure level (SPL) values in dB re 20 µPa during the 30 seconds of measurement at each altitude for the 36 frequency bands (6.3 – 20000 Hz). We consider the dB (A) weighting curve to be the standard for the evaluation of continuous and intermittent noise and because it is the most used on sound meters models commonly found on the market. The measurements were made in an open field area with sparse vegetation, between 07:00 – 08:30h and 16:00 – 17:30h, with an average temperature of 28°C (SD 2.9), an average relative humidity of 60% (SD 1.7), and with maximum winds of 3 (gentle breeze) on the Beaufort scale. Before the drone taking off, we measured the background noise following the same international protocol ISO-3746. Then the drone was flown to a maximum of 120 m AGL, considering the recommendations of the national civil aviation regulatory agency from Brazil (ANAC, 2017). From 120 m AGL, we performed the measurement on the ground of the noise generated by the hovering drone every 5 m AGL for 30 seconds, descending at a maximum speed of 3 m/s until reaching a minimum altitude of 5 m AGL. For each altitude, we collected the average values in dB(A), calculated by the DEC-7000 post-processing software of the sound pressure levels with slow response, in addition to the 36 frequency bands in the 1/3 octave mode. We performed the above procedures for each of the two flights and obtained the average values for each altitude.

Experimental flights

We performed 32 experimental flights using the drone DJI Mavic Pro, in February 2021 at the São Paulo Zoological Park. In all take-offs we performed flights against the wind and at a minimum distance of 100 m from the location where the target species was found in cases where there are no physical barriers, or 50 m away when there were barriers, to minimize potential disturbance from drone approaches before the actual flights. We carried out flights between 07:00–08:30h and 16:00–17:30h and under similar environmental conditions as the control flights. After take-off, the drone ascended vertically to a maximum altitude of 120 m AGL and then horizontally directed a maximum speed of 10 m/s until it was above the target animal or group of individuals. From there, the drone descended with a maximum speed of 3 m/s. Simultaneously, an observer from the zoo team, aided with binoculars and outside the line of sight of the target animal, noted the animals' behavior as the drone descended vertically (Figure 1). The behavioral observations followed an adapted classification by Bennitt et al. (2019) which divided the species' behavioral response to the drone as “None”, “Vigilant” or “Move”. Here we do not consider the classification “None” since we descended the drone vertically over the species until some behaviors were registered. We recorded “Vigilant” behavior that is equivalent from Bennit et al. (2019), when the species interrupted its original behavior, and "Move" behavior when the species presented escape behavior or irritation. Different than Bennit et al. (2019), we considered not only the displacement of the animal from its place of origin, but any species-specific sign of irritation such as movement of the head, legs and tail confirmed by the zoo technician. On each drone flight we recorded the altitude where the respective behaviors occurred. After recording the two behaviors types, the drone was ascended back to 120 m AGL and then horizontally flew back to the take-off location and landed. For animals forming groups, a behavioral changed was considered to have occurred when at least one individual changed its behavior. In addition to recording the altitudes where some behavioral change occurred, we also recorded the number individuals that looked directly towards the drone. We performed two flights for each of the 16 study species with an interval of at least one day between each flight to avoid repetitive stimuli on the same species.

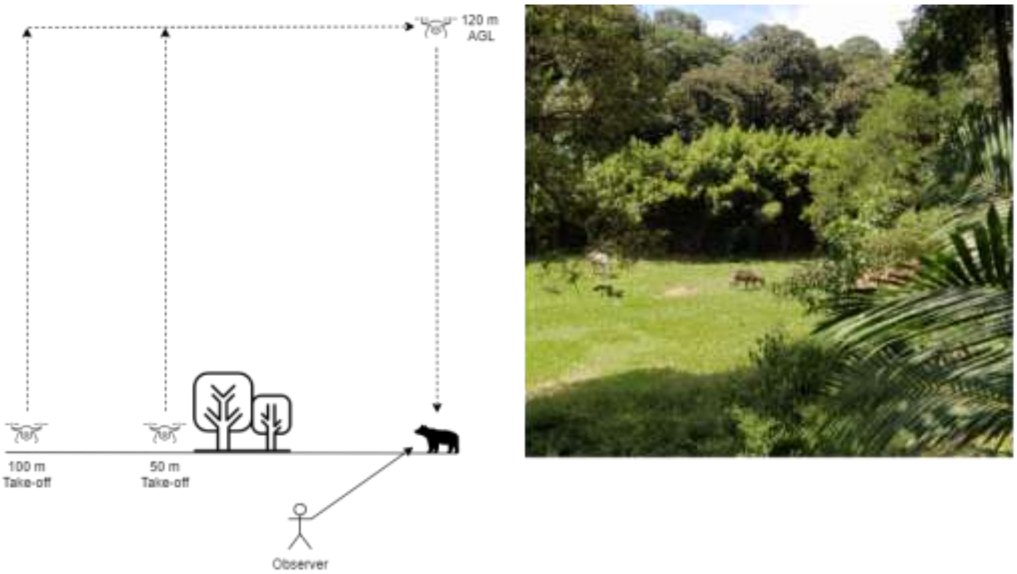

Figure 1. Design of experimental flight on the left and observer’s view to the right

Data Analysis

We compared the behavioral reactions of the observed animals with the drone noise characteristics at the altitudes where they took place. The drone noise characteristics (sound pressure level (dB) and frequency in all 1/3 octave bands (6.3

Hz – 20000 Hz)) were obtained from the control flights at different altitudes flight altitudes. Because each studied species may have a different auditory sensitivity and audiograms are only available for a few, when specific ones were not available, we used those published for same family or order (Table 2).

Table 2. Behavioral audiograms of mammal species used as reference. Approximate range in Hz with average absolute thresholds (in dB re 20 µN/m2).

Orden	Family	Species	Approximate Range (Hz)	Reference
Artiodactyla	Bovidae	Bos taurus	16-40,000	Heffner and Heffner, 1983
Artiodactyla	Bovidae	Ovis aries	100-40,000	Wollack, 1963
Artiodactyla	Bovidae	Capra hircus	63-45,000	Heffner and Heffner, 1990
Artiodactyla	Camelidae	Vicugna pacos	25-40,000	Heffner et al. 2014
Artiodactyla	Cervidae	Odocoileus virginianus	31-64,000	Heffner and Heffner, 2010
Artiodactyla	Cervidae	Rangifer tarandus	63-38,000	Flydal et al. 2001
Artiodactyla	Suidae	Sus scrofa	31-45,000	Heffner and Heffner, 1990
Carnivora	Canidae	Canis familiaris	50-50,000	Heffner, 1983
Carnivora	Felidae	Felis catus	45-91,000	Heffner and Heffner, 1985
Perissodactyla	Equidae	Equus caballus	31-40,000	Heffner and Heffner, 1983
Primates	Hominidae	Homo sapiens	16-18,000	ISO, 2003
Proboscidea	Elephantidae	Elephant	16-14,000	Heffner and Heffner, 1982

To determine if changes in behavior associated with the drone noise (sound pressure and frequency) are similar between species, we performed a hierarchical cluster multivariate analysis (Kaufman and Rousseeuw, 1990) considering seven variables: *altitude vigilant, altitude move, decibels vigilant, decibels move, frequency vigilant, frequency move and visual contact drone*. For the variable *visual contact* *drone*, we considered the value "1" when the animal looked directly towards the drone and "2" when we do not register this behavior. All analyses were performed in Rstudio v 1.3.959 (Rstudio Team, 2020) using the ‘dplyr’, ‘cluster’, ‘tidyverse’, ‘factoextra’ and ‘pheatmap’ package. Initially we standardized the data using the scale () function and we consider the agglomerative hierarchical clustering with a Euclidean distance matrix. We chose the complete linkage method with Ward algorithm (Murtagh et al. 2014) based on the values of agglomerative coefficient through the function ‘agnes’ and ‘map_dbl’ (Kaufman and Rousseeuw, 1990). We considered the average silhouette method from function ‘fviz_nbclust’ to choose the ideal cluster number.

We use the drone that was operated under the license no. PP-019272726 by the National Civil Aviation Agency (ANAC). Considering that all flights were performed within VLOS (Visual Line of Sight Rules) and inside the requirements of the National Civil Aviation Agency (ANAC), prior authorization from ANAC was not required for the execution of drone flights at the São Paulo Zoological Park. All experimental flights followed the recommendations of the American Society of Mammalogists (Sikes and Gannon, 2011) and were approved by the Technical-Scientific Directorate of the São Paulo Zoological Park Foundation under the authorization number project 545.

Results

We analyzed the behavior of 25 individuals from 16 species of terrestrial mammals, with a representation of 14 families and 5 orders. None of the analyzed species was observed looking towards the drone in the first behavior change (vigilant) caused by the drone. In the second behavior change (move) 25% of the species, all from carnivorous order, looked directly towards the drone between the 63-25 m AGL. These species initially turned their heads towards the drone, on average for 5 seconds, followed by sign of irritation, such as growling in the case of Bengal tiger and jaguar, sudden movements with the head in the case of spectacled bear and escape from maned wolf.

Asian elephant and giraffe were the only species that showed vigilant behavior against the drone noise at average sound pressure levels below 40 dB, being 38.7 dB and 39.6 dB respectively, values close to ambient noise without the presence of the drone (36.1 dB), and also presented move behavior with lower sound pressure caused by the drone with 41.3 dB and 42.3 dB respectively (Figure 2). Giant anteater showed vigilant behavior with the highest sound pressure at 48.5 dB (Figure 2). Within felines, Bengal tiger and jaguar only exhibited move behavior once the sound pressure level reached 50 dB. Asian elephant and the giraffe were also the species that showed vigilant behavior with the drone above 100 m AGL, and together with white rhinoceros were the only species that showed move behavior with the drone above 80 m AGL (Figure 2). Felines and giant anteater showed vigilant behavior from 40 m AGL and presented move behavior by the drone only below 30 m AGL.

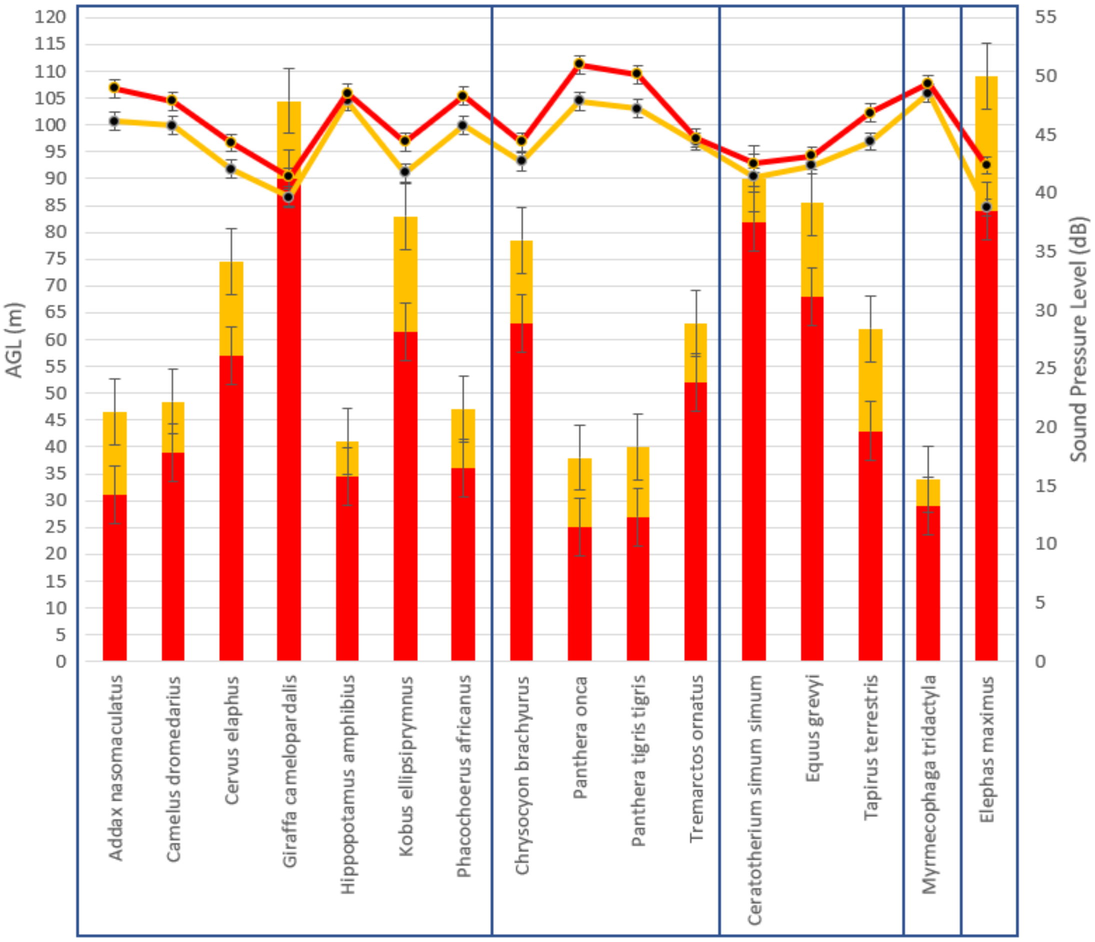

Figure 2. Relationship between altitude (AGL), sound pressure level (dB) and behavioral change in different terrestrial megafauna species. Bars in yellow show the altitude where there were vigilant behavioral change and the in red bars the move behavioral change. Yellow lines show the level in dB where there was vigilant behavioral change and the red lines move behavioral change, all with standard errors. The species were organized according to the taxonomic order, from left to right (Artiodactyla, Carnivora, Perissodactyla, Pilosa, Proboscidea).

All the analyzed species were more sensible to the sound pressure level from the drone noise in the high frequencies, from 2500 to 20000 Hz (Supporting Information), with the exception of the Asian elephant, that considering your audiogram, was unable to hear sound pressure of the drone noise above 4000 Hz, (Figure 3). The elephant's audiogram also showed that it was possibly the only species capable of perceiving the sound pressure emitted by the drone in the 1/3 octave bands of 31.5 and 63 Hz (Figure 3). Among the artiodactyl species, the warthog and addax were the most sensitive ones in low frequency showing vigilant behavior with the drone noise in 34 dB and 125 Hz (Supporting Information). The giraffe was more sensitive to medium and high frequency drone noise (22.7 dB average; 315 – 20000 Hz), and also the species that presented move behavior with the lowest sound pressure level in medium and high frequencies (31.3 dB average; 315 – 20000 Hz) (Supporting Information). Among carnivores, spectacled bear was the most sensitive species in all 1/3 octave bands (32.4 dB average; SD 9.5) and together with maned wolf presented a higher auditory sensitivity in medium and high frequencies (26 dB; 315 – 20000 Hz) (Supporting Information). The two felines showed vigilant behavior with the drone noise in low sound pressure in low frequencies (39.5 dB average; 40–250 Hz). Among the three species of perissodactyl, white rhinoceros and imperial zebra presented practically the same hearing sensitivity considering their vigilant behavior when exposed to the drone and the tapir was the least sensitive. Considering the move behavior caused by the drone noise, tapir presented this behavior with lower sound pressure in the low frequency noises (38.7 dB average; 31.5 – 250 Hz). The only species of the order Pilosa and Proboscidea, giant anteater and Asian elephant make up the two extremes of auditory sensitivities, the first being the least sensitive and the second the most sensitive to the drone noise considering all 1/3 octave bands (29.3 dB average, SD 11.9; 37.1 dB average, SD 7.9 respectively), both especially sensitive to low and medium frequency drone noise (Figure 3).

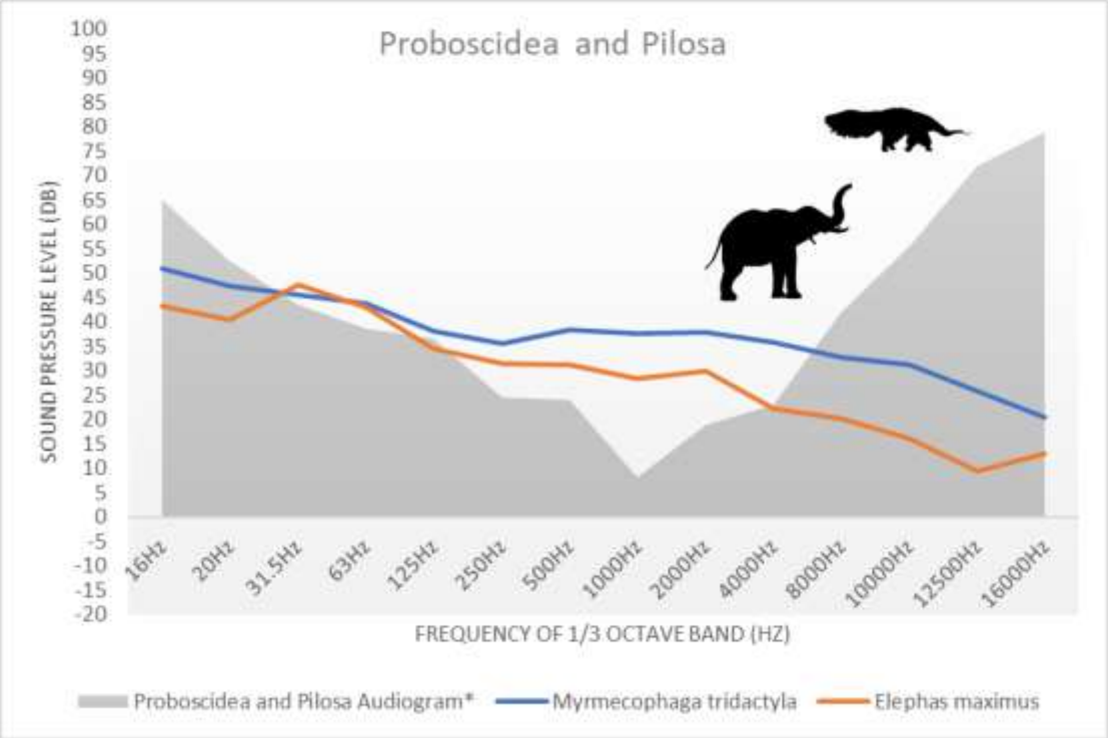

Figure 3. The gray area is the non-detection area of sound by species according the species audiogram. Each colored line corresponds to the drone noise in dB at the different frequencies of 1/3 of an octave (Hz) where there was a behavioral change for each species in the picture.

Considering the agglomerative coefficient (AC = 0.92) and the ideal number of cluster (k = 6), we found six groups of terrestrial megafauna species that showed similar behavioral change considering the seven variables (Figure 4). In one of the extremes, the group formed by the felines (jaguar and Bengal tiger) showed a change in behavior with the drone at low altitudes, and with high decibel values, in addition to show signals of visually perceiving the drone. At the other end, the group formed by the two species most sensitive to drone noise (Asian elephant and giraffe), reacting to the drone at high altitudes, above 100 m AGL, and with low decibel levels at different frequencies. Similar to the group of the most sensitive species, a group with a greater number of species, formed by two artiodactyl species and two perissodactyl species, noble deer, waterbuck, white rhinoceros and imperial zebra, which have lower hearing sensitivity with the drone at high altitudes but under 100 m AGL. The other large group also with four species, addax, warthog, dromedary and tapir, were formed by the species that showed vigilant and move behavior with altitude, decibel and frequency values similar to those of the feline group, however without having shown signals of visually perceiving the drone. Between this group and the feline group, another group was formed with the common hippopotamus and giant anteater that withstand high values of sound pressure, at different frequencies, at low altitudes and did not make visual contact with the drone. And finally, the group formed by two species of carnivores that also having visually perceived the drone, but who were more sensitive in terms of decibel values and who were able to perceive the drone at higher altitudes compared to felines.

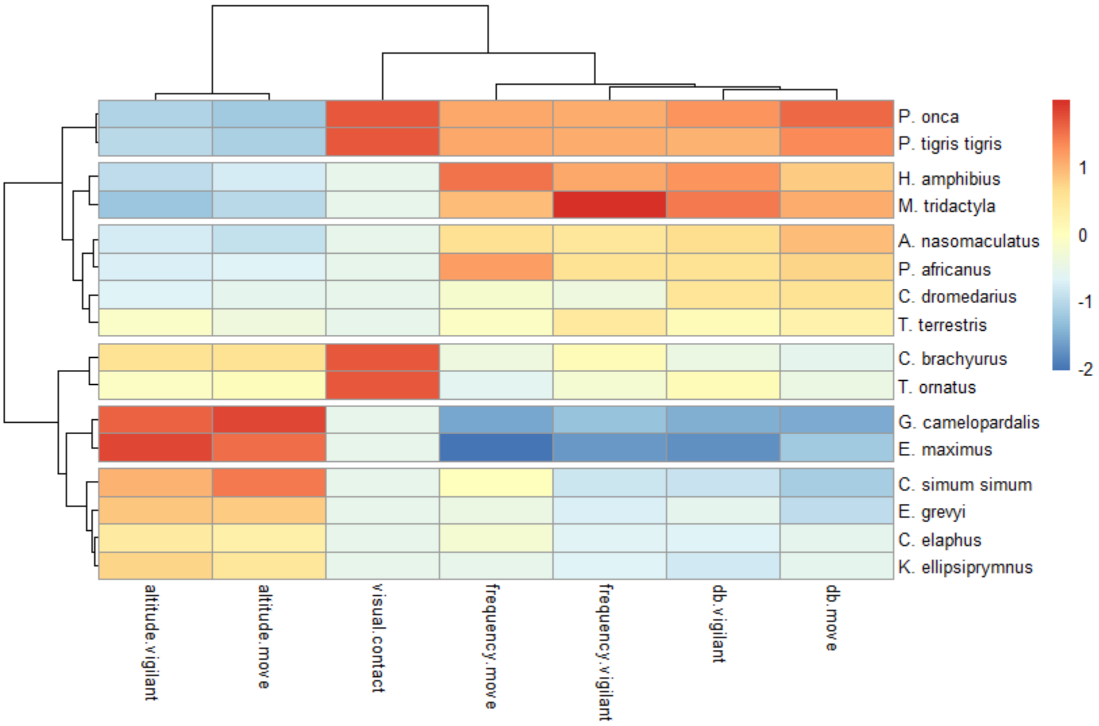

Figure 4. Heatmap with groups of similar species regarding the perception of drone

Discussion

The increase in drone use over wild megafauna for different purposes requires a greater understanding of the disturbance that these can cause on the animals subjected to it. Here, we analyzed the characteristics of a custom-off-the-shelf drone noise against the auditory perception of 16 mammal species from different family and orders, in an 'ex-situ' area, demonstrating that the vigilant behavior and the escape behavior or irritation caused by the drone noise is started by different sound pressure levels that are possibly noted at different frequencies by different species, not necessarily close in taxonomy. To our knowledge, this study is the first to analyze this type of disturbance in a large set of terrestrial megafauna species presenting drone response data for new species. Although we cannot separate here the visual stimulus from the sound stimulus coming from the drone as performed in the quasi-experimental study by Mesquita et al. (2021) with bird species, our results support Bennitt et al. (2019) and Schroeder et al. (2020) in that the drone noise is the first and possibly the main factor of behavioral change in large terrestrial mammals exposed to drone use. As well as the idea that the mammal auditory system, as explained by Turner et al. (2007), responds faster than other sensory systems, causing their neural circuits to be activated more quickly, allowing a faster fight or flight response.

The largest and heaviest species studied, giraffe and Asian elephant, were also the most sensitive regarding the drone noise, showing vigilant behavior with lowest sound pressure. While in game reserve areas in Africa the giraffe has been observed to became vigilant with the drone from 80 m AGL and the African elephant from 50 m AGL (Bennit et al. 2019), here the giraffe and Asian elephant showed a change in behavior with the drone 100 m AGL and noise below 40 dB. Besides the fact that African elephant in the study by Bennit et al. (2019) is a different species in a different environmental context from the one studied here, we highlight some factors such as drone model, size and flight path that were different from those used in this study, which may explain the difference in results. Even in studies with methodology similar to this one and using the same drone model as the one proposed by Duporge et al (2021) the results may be different. While Duporge et al. (2021) suggested as advisable altitude to fly the Mavic Pro model on Asian elephant at an altitude of 10 m AGL, we find that at altitudes above 80 m AGL there has already been an escape behavior or irritation in the species. Possibly another aspect to be taken into account about the greater sensitivity of the giraffe over others species analyzed here is the fact that it is the tallest terrestrial species on the planet, so its auditory system is physically closer to the drone noise about 5 meters compared to others species. Among some unprecedented behavior data obtained in this study was from the giant anteater, the largest species of the order Pilosa and an endangered species. Considering its reduced auditory and visual capacity (Nowak, 1999), we expected that this species would be the least sensitive of drones, what has been proven since it withstood the highest sound pressure before showing vigilant behavior. This is particularly interesting since the giant anteater is one of the few large mammal species in the hotspot Cerrado (Sawyer et al. 2017) that can be identified in open areas on the Cerrado biome using drones. And such data collected in this study added to others data collected in the free field about the giant anteater are serving as preliminary parameters to define the best flight altitude in new studies of monitoring and population analysis of the species under development. Maned wolf is another threatened species analyzed for the first time for drone use, which showed the highest sensitivity to drone noise among the analyzed carnivores' species. This is probably compatible with its biological and ecological characteristics, as a species of canine that has good hearing and has long ears that are disproportionate to the size of its head, which is suggested to help in the hunting of small prey usually hidden in soil vegetation (Paula and Gambarini 2013). White rhinoceros, one of the most endangered species in Africa, was one of the three most sensitive species considering the drone noise. These results were compatible with the recommendations of Mulero-Pázmány et al. (2014) who suggested flights with drones between 100 and 180 m AGL to avoid possible disturbances in the species while allowing the identification of possible poachers of these in the African savannas.

In spite of having identified a sound pressure level for each altitude where there is a change in behavior in each species, we must consider that within the sound pressure level found there are other values for the different frequency bands of the sound. Each species has the ability to identify different sound pressure levels at different frequencies, making them more or less sensitive to sounds in certain frequency ranges. Although among mammals the basis of comparison is the human with capacity to identify sound pressure that varies between frequencies 16 – 18000 Hz with a minimum of 40 dB and a maximum bearable of 70 dB (ISO, 2003), we know that this range can be enlarged or reduced depending on the mammal species (Toledo University 2021). Although the sound meter used in this study is limited to 20000 Hz, some species have the highest audible frequency (in Hz, ultrasounds), reaching up to 68000 Hz with sound pressure above 40 dB in some felines (Heffner and Heffner, 1985), which means that these species may have perceived lower sound pressure at higher frequencies not considered in this study. Ratifying the generalization that highest audible frequency for a given species is negatively correlated with body, head, and ossicle sizes (Rosowski, 1994) and the hearing capacity of elephants (Heffner and Heffner, 1982), here we observed that the Asian elephant was the only species that showed signs of perceiving the drone noise at low frequencies, with the low sound pressure level. Since the attenuation of the sound with the distance in free field is proportional to the frequency, that is, high-pitched sounds propagate only in a few meters, while low-pitched sounds can be heard from kilometers away (Peixoto and Ferreira, 2013), we can infer that the Asian Elephant's ability to perceive the noise drone at high altitudes is due to the perception of sounds at low frequencies emitted by the drone. In contrast, we can highlight the species of the families Bovidae, Cervidae, Suidae and Canidae, which are highly sensitive to drone noise, especially at high frequencies, which inferred greater capacity to hear lower sounds pressures over shorter distances considering the attenuation of the sound. The group of carnivores was the most taxonomically consistent regarding their ability to perceive drone noise, having shown to visually detect the drone after exhibiting vigilance behavior. The species of artiodactyl and perissodactyl were mixed in different groups showing that species of bovines and equines can be more similar to each other in terms of the association between behavior change and drone noise than among other species of the same taxonomic order. While the only two species representing the order Pilosa and Proboscidea were necessarily grouped with other species of other order since for the formation of a cluster there is a need for at least two species. Although we know that taxonomically close species are more likely to be morphologically and physiologically similar, we also know that many other traits (biological, ecological and ethological) can have a greater influence on a species' ability to perceive drones. Even knowing that most studies that analyze behavioral audiogram of large terrestrial mammals are based on analyzes of a few individuals (Heffner and Heffner, 1982, 1983, 2010, 2014), we understand that the greater the number of individuals analyzed, the greater will be the consistency of the results. Therefore, increasing the number of individuals analyzed with different traits and in different environments is a continuous work to be carried out from this study, which will allow better identification of similarities between species, considering the drone's noise behavior.

An important factor that led us to carry out this study is the growing diversity of drone models on the market (Droneii, 2019). As demonstrated by Duporge et al. 2021 Different drone models have different sound profiles, and these profiles have a greater amplitude difference at lower frequencies and more intensely at lower altitudes. Added to this the large number of multi-rotor models drones available in the current market, with different sizes, shapes and capacities of sensors ends up making the flight altitude just one more factor when we consider the ability to generate disturbances in certain species. Therefore, it is essential that in addition to the drone altitude, we also know the characteristics of the drone noise that a given drone model is capable of generating and what are the reactions of the different species to the drone noise. Although we can see in the field that there are several other sources of noise 'in-situ' and specially in 'ex-situ' environments, as zoos, that can negatively affect species in certain situations, such as movement of vehicles, operation of equipment, movement of people, we also know that the drone if not used properly in these locations can become an unnecessary additional disturbance source. It is still a complex issue the subject of animal habituation in 'ex-situ' areas, although in general, we can say that animals in 'ex-situ' environments, such as zoos, tend to get habituated to anthropic noise over time (Hosey, Melfi, & Pankhurst 2013). But at the same time, if we consider that the concept of habituation is form of learning in which the animal reduces its response to a constant or repetitive stimulus (Hosey, Melfi, & Pankhurst, 2013), and that none of the studied animals had previous contact with stimuli from drones, we can infer that none of the animals were habituated to the drone stimulus. The São Paulo Zoo where this study was developed is one of several 'ex-situ' areas where there is no internal policy on the use of drones although in practice it is not allowed to use drones without prior authorization from the managers. In the 'in-situ' areas (Braverman, 2014), especially in remote natural areas, the regulation and inspection of the drone use on wildlife is practically non-existent, which ends up generating several conflicts with wildlife, mainly by recreational drone users as demonstrated in several videos compiled from youtube by Rebolo-Ifrán et al. (2019). Even within the scientific community, where researchers seek to consider in drone operations the best conducts and protocols to reduce disturbance in wildlife, there is still little information regarding specific data of the target species, and among the few studies the majority are only on drone altitude as the main requirement for reducing disturbances in wildlife.

Considering not only the minimum altitudes, but the characteristics of the sound emitted by the drone and the minimum values of sound pressure level in different frequencies that can cause behavioral changes for each species is fundamental to avoid an additional disturbance in mammal species in 'ex-situ' environments besides to increasing efficiency of studies with mammals in 'in-situ' environments. Despite the limitations of this study regarding the environmental context and number of individuals of the species studied, we consider that the information presented here, in addition to bring unpublished data for some species, can help make the use of drones in 'ex-situ' areas safer and with less impact for the target species and serve as experimental study for the creation of possible future protocols for the use of drones with terrestrial mammals. We also suggest that before carrying out drone flights over certain species of mammals should be measured the sound pressure level emitted by the drone model to be used and considered as the minimum flight altitude over a given species the altitude that has the minimum sound pressure value supported by the species, as the values recommended in this study and others similar.

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Supporting Information

The analysis graphs of the dB ratio of the drone's noise and the frequency of 1/3 of an octave (Hz) that caused behavioral changes of the type vigilant (Appendix S1) and move (Appendix S2) of all species are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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CHAPTER 4

A practical approach with drones, smartphone and tracking tags for potential real-time tracking animal

This chapter is under review in the Ecology and Evolution journal

A practical approach with drones, smartphone and tracking tags for potential real-time tracking animal

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Resumen

En este estudio, exploramos la potencialidad de un sistema que consiste en un dron multirotor, “smartphones” y dispositivos de rastreo comercial a través de señales de “Bluetooth” y Ultra-Wide Band (UWB), sencillo y listo para usar, para el seguimiento de fauna silvestre. Presentamos la configuración del sistema, exploramos los parámetros operativos que pueden afectar a la capacidad de detección y probamos la efectividad para localizar blancos simulando animales en ambientes de sabana y forestales. El sistema de seguimiento autónomo se construyó sin necesidad de personalización de hardware o software. En 40 vuelos de rastreo realizados en el bioma del Cerrado (Brasil), obtuvimos una tasa de detección del 90% en sabana y del 40% en áreas forestales. Considerando las pruebas en movimiento (n = 20), las tasas de detección fueron del 90% en la sabana y del 30% en las áreas forestales. La precisión espacial obtenida por el sistema fue de 14.61 m, siendo significativamente más precisa en áreas de sabana (x = 10.53) que en áreas forestales (x = 13.06). Sugerimos realizar estudios adicionales para refinar los parámetros operativos con el fin de mejorar las tasas de detección.

Abstract

In this paper, we explore the potential of wildlife tracking with drones by using a system consisting of a multirotor drone, smartphones, and commercial tracking devices via Bluetooth and Ultra-Wide Band (UWB) off-the-shelf that is easy to use by non-specialists. We present the system configuration, explore the operational parameters that can affect detection capabilities, and test the effectiveness of the system in locating targets by simulating target animals in savanna and forest environments. The self-contained tracking system was built without the need for hardware or software customization. From 40 tracking flights carried out in the Cerrado biome, we obtained a detection rate of 90% in savanna and 40% in forest areas. Considering the moving tests (n = 20) the detection rates were 90% in the savanna and 30% in the forest areas. The spatial accuracy obtained by the system was 14.61 m, being significantly more accurate in savanna areas (x = 10.53) than in forest areas (x = 13.06). We encourage additional studies to refine operational parameters in order to improve detection rates.

Introduction

During the last half century, wildlife tracking has made a major impact in ecology and conservation biology (Kays et al. 2015). Aimed at investigating animals' movement, wildlife tracking is one of the main tools to explore species' behavior and ecology in diverse habitats (Lahoz-Monfort and Magrath, 2021). Over the years, new technologies have been used for wildlife tracking: conventional radio telemetry (Very High Frequency, VHF); Argos Doppler tags (aka platform transmitter terminals, PTTs) based on the satellite network ARGOS System (https://www.argos-system.org), and Global Navigation Satellite Systems (GNSS) tracking tags. Although GNSS- tracking provides the best spatial and temporal resolutions, the small size of many animals limits the use of this technology, as tags are often too large or heavy to be fitted to subject animals (Cooke et al. 2004). The smallest GNSS-tracking device with data download via Bluetooth technology weighs 15 g (Thomas et al. 2011), and considering that tracking devices should not weigh more than 3 – 5% of the animal body mass (Kenward, 2001), the use of GNSS-tracking devices currently available are limited to animals heavier than 500 g. In addition, the high cost of such devices, which can reach approximately $1500 with manual download or $ 4000 with remote download services (Thomas et al. 2011), is another challenge to be overcome by researchers and which currently limits the use of this technology in ecology and conservation studies.

In recent years, the use of drones (Unmanned Aerial Systems, UAS) has gained popularity in wildlife studies (Schiffman, 2014; Jiménez and Mulero-Pázmány, 2019; Duffy et al. 2020). Both on terrestrial and aquatic ecosystems, drones are increasingly used for fauna monitoring (Linchant et al. 2015; Aniceto et al. 2018; Lyons et al. 2019), to study species' spatial distribution (Mulero-Pázmány et al. 2015; Baxter and Hamilton, 2018), and for wildlife tracking (Cliff et al. 2018; Nguyen et al. 2019; Roberts et al. 2020). The main benefits of UAV-based Radio Tracking Systems (also known as UAVRTS) as compared to conventional methods are the reduction of logistical and labor-intensive challenges in the field and the increase of fieldwork operational safety (Linchant et al. 2015; Cliff et al. 2018). In addition, UAVRTS studies have shown that these systems present a significantly stronger signal than ground-based ones, which helps in detecting species such as small forest birds (Tremblay et al. 2017), and may provide localization estimates with 53% less error than those obtained by experienced radiotelemetry users (Shafer et al. 2019).

Currently available UAVRTS use the principle of conventional radio telemetry for wildlife localization in two ways: 1) range-based or 2) bearing-based (Hui et al. 2021). Range-based, such as those developed by Santos et al. (2014) and Nguyen et al. (2019) are less difficult to build than bearing-based systems because the antenna configuration is simpler (Cliff et al. 2018; Dressel and Kochenderfer, 2018). However, for both systems, considerable technical knowledge is still needed both for the development and customization of the hardware and for data analysis, generally based on estimation approaches such as particle, grid and Kalman filters (Nguyen et al. 2019; Dressel and Kochenderfer, 2018; Jensen and Chen, 2013). Thus, the application of drones for tracking wildlife is restricted to those users with the technical capacity to develop such systems.

Here, we explore a practical approach to potential wildlife tracking through the use of a system consisting of a multirotor drone, smartphones and tracking tag off-the-shelf and easy to use by non-specialists. Specifically, we describe the setup of the system, explore operational parameters that can affect detection capability, and test the system's effectiveness in locating targets simulating animals in open and forest-covered environments. To our knowledge, this is the first experiment where drones are associated with off-the-shelf Bluetooth and Ultra-Wide Band (UWB) technologies for wildlife tracking.

Materials and Methods

Off-the-shelf tracking system

The off-the-shelf tracking system we developed is formed by a DJI Mavic Pro multirotor drone (https://www.dji.com/br/mavic), two smartphones (Iphone model 8 and Iphone model 11, Apple Inc.), and tracking tags known as AirTags from Apple.inc (Figure 1). To assemble the system, we created a structure to attach the iPhone 8 to the Mavic Pro drone (Figure 1b) using pre-existing models in 3D printing webpages (https://www.thingiverse.com/). AirTags (https://www.apple.com/airtag/) are Apple tracking tags (diameter = 31.9 mm; thickness = 8.00 mm; weight = 11 g), with IP67 water resistance (IEC 60529), with a built-in speaker, which features Bluetooth technology with a transmission capacity of up to 100 m, an Ultra-Wide Band (UWB) support, an accelerometer sensor and estimated battery life of one year (Figure 1c). UWB is a technology similar to Wi-Fi and Bluetooth but that has a significantly higher bandwidth than most narrowband signals used in communications, with low-power signals, less interference and low energy consumption.

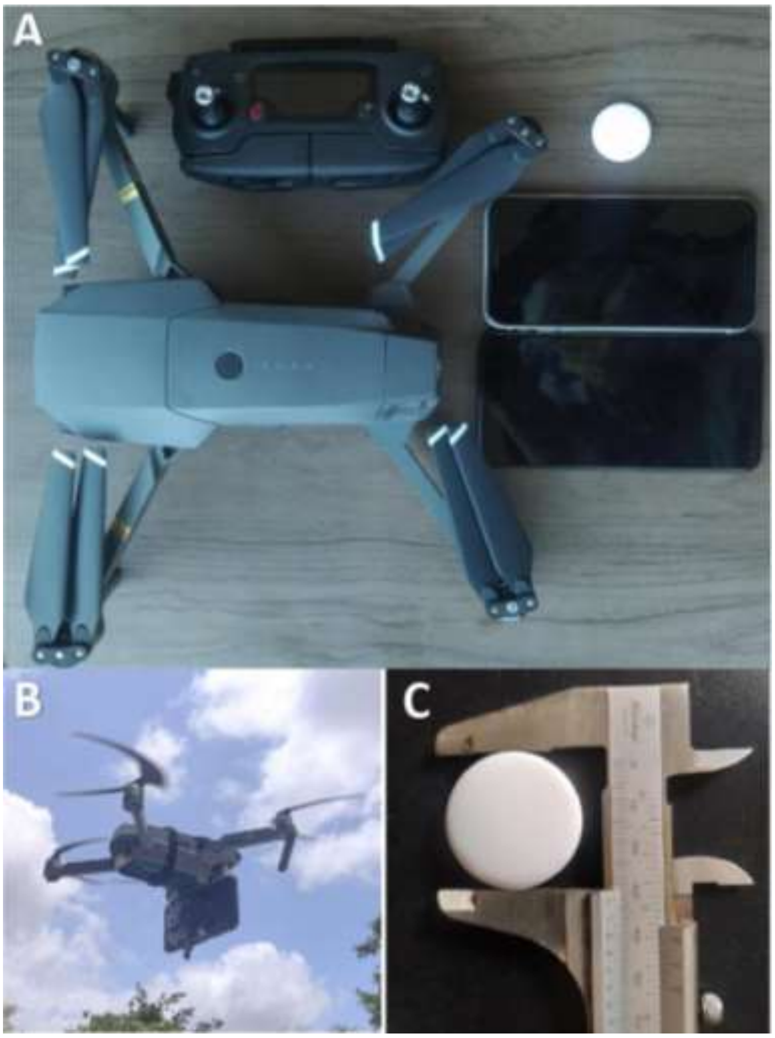

Figure 1. Off-the-shelf tracking system and components. A) off-the-shelf tracking system (Mavic Pro drone with controller, Iphone 8 and 11, one AirTag), B) Mount support for Iphone, C) AirTag

In this system, we set up the AirTag acting as a transmitter of Bluetooth and UWB signals. The Iphone 8 is coupled to the drone and works both as 1) a receiver of the AirTag's Bluetooth signals and 2) a transmitter of the tag coordinates to the cloud. The Iphone 11 works as a receiver retrieving the coordinates from the cloud and also receives the AirTag's Bluetooth and UWB signals (Figure 2). The AirTags do not obtain locations using GPS technology, but working through the network from other anonymous iOS and iPadOS devices nearby. Therefore, the AirTag needs to find the nearest Bluetooth-enabled device and take the device's location data in order to work. The Iphone 8 needs to have a GSM (Global System for Mobile Communications) signal working in order to be able to send the location to the cloud. We chose Iphone model 8 because of the type of Bluetooth incorporated in these models, which is Bluetooth version 5, the latest version of Bluetooth with data transmission speed of up to 50 Mb/s (https://www.bluetooth.com/). To set up the system it is necessary to link the AirTag to an Iphone handled by the researcher. To use the UWB technology (Figure 2; step 5) it is necessary that the Iphone model has the same U1 chip present in the AirTag, so we recommend the use of iphones 11 or newer. Once the AirTag is linked to the Iphone, the “Lost Mode” function must be activated within the “Find” application of the Iphone. After this configuration is set up, the Iphone 11 becomes the device that will receive the coordinates of the AirTag from the cloud. The Iphone 8 attached to the drone will receive the Bluetooth signal transmitted by the AirTag and it will transmit the coordinates to the cloud (Figure 2; Steps 1, 2, 3), which will be retrieved by the Iphone 11 linked to the AirTag.

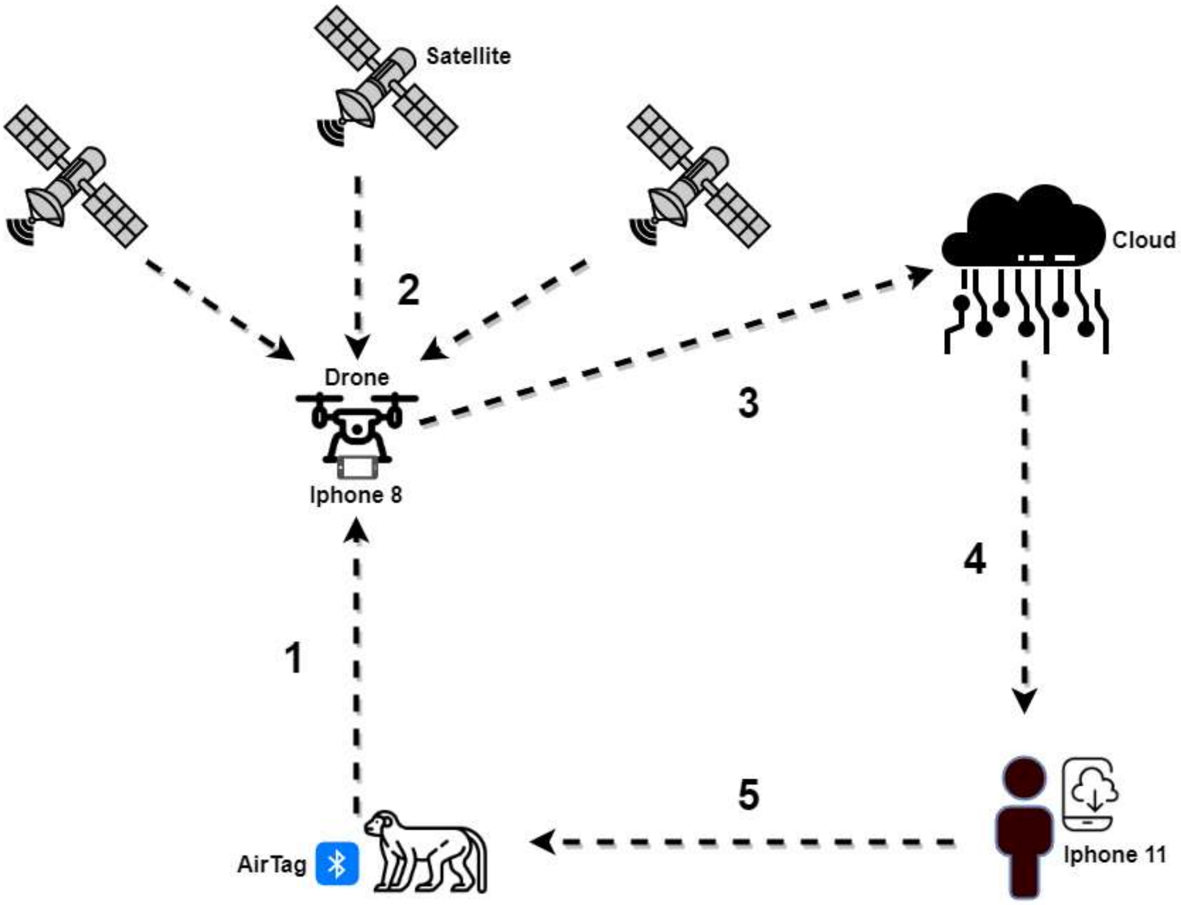

Figure 2. Off-the-shelf tracking system working scheme: 1. Bluetooth signal transmitted by the Airtag; 2. Reception of the Bluetooth signal from the AirTag and the signal from the satellites by the triangulation system; 3 Sending coordinates by triangulation to the cloud; 4. Cloud server sends coordinates to the iphone previously linked to the Airtag. 5. Researcher initiates the searching of the AirTag using bluetooth and UWB

Parameter control flights

Before starting the tracking flights, we carried out 20 flights tests to define the maximum flight altitude allowing the capture of the tag's Bluetooth signal. The first step is checking if both smartphones are receiving a GSM signal, by sending and receiving data between them. At a minimum distance of 200 m from the tag in an open, non-urban area, with no physical barrier between the drone and the tag and with GSM signal in the area, we performed the drone take-off with the Iphone 8 attached. Next to the pilot, an observer with an Iphone 11 linked to the tag confirmed that it was out of range of Bluetooth. Once this was confirmed, we raised the drone to an altitude of 120 m AGL, maximum altitude allowed by the local legislation (ANAC, 2017) and then flew horizontally towards the tag until the drone was positioned over it. We descended the drone vertically at a maximum speed of 1 m/s until the Bluetooth signal sent by the tag was detected by the Iphone 8 and the coordinate information received by the Iphone 11 from the cloud. We performed the above procedures five times and considered the maximum detection altitude the average value obtained (x = 52.8 m). With this average altitude, we performed five horizontal approach flights at a speed of 5 m/s and we also obtained the average value (x = 50.4). Considering the average values obtained, we carried out the drone flight tests in open environments at an altitude of 50 m AGL. We repeated the same procedure in forest environments and obtained average altitudes (x = 32.6) in vertical flights and (x = 30.4) in horizontal flights and chose to perform the drone flight tests at an altitude of 30 m AGL.

Drone flights tracking

We tested the off-the-shelf tracking system design in two habitat types: savanna and forest areas, both within the Cerrado biome. The tests were carried out in August 2021, in two areas adjacent to Chapada das Mesas National Park, Maranhão, Brazil (Figure 3). In the forest area, flights were carried out within the "Cerradão", a physiognomy that has dense vegetation cover and predominant arboreal strata, and in the savanna area within the category "cerrado stricto sensu", typical physiognomy of savanna with forest cover below 30% (Sawyer et al. 2017).

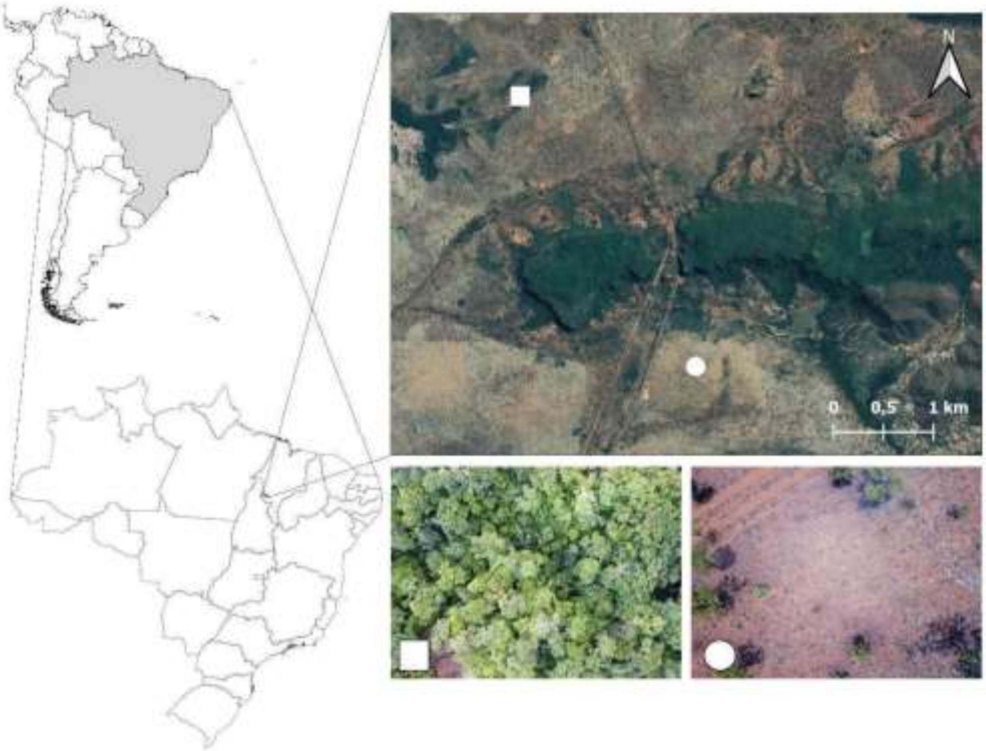

Figure 3. Location of drone tracking flights test areas. Cerradão (white square) and cerrado sensu stricto (white circle).

In both areas we carried out two types of experiments: stationary and in motion. For stationary experiments, we placed the tags randomly on the ground inside the study area. For the test in motion, a researcher walked randomly in the study area holding a tag at 1 m above the ground. In all tests, the take-off was performed 200 m away from the perimeter of the study area, with the pilot unaware of the tags' location. Lawnmower pattern flights were performed covering the 10-hectare using the Dronedeploy free version software (https://www.dronedeploy.com/). In the savanna area, we performed flights at 50 m AGL, with 60% front and side overlap, 5 m/s flight speed and the app function "terrain awareness" activated. In the forest area, we performed flights at 30 m AGL, with 50% front and side overlap, 5 m/s flight speed and terrain awareness activated. On each of the tracking flights, the tags were placed at different locations inside the study area. We carried out flights between 08:00–09:30h and 16:00–17:30h local time and under the same environmental conditions as the parameter control flights. For the execution of the lawnmower pattern flight, once the Bluetooth signal was identified by the smartphone coupled to the drone and we confirmed it was sending the coordinates to the smartphone with the researcher, the pilot disabled the automatic flight mode and enabled the manual flight mode to try keeping the captured Bluetooth signal. At that moment, the researcher, without knowledge of the location of the tag, handling the Iphone 11 previously linked to the tag and with the “Lost Mode” activated, started the process of terrestrial tracking of the tag as instructed by the Maps application in the smartphone (Apple Inc.). During the search process, when entering the coverage radius of the UWB technology, ±10 m, the smartphone automatically changes the tracking form to directional search with accuracy at the centimeter scale (Figure 4).

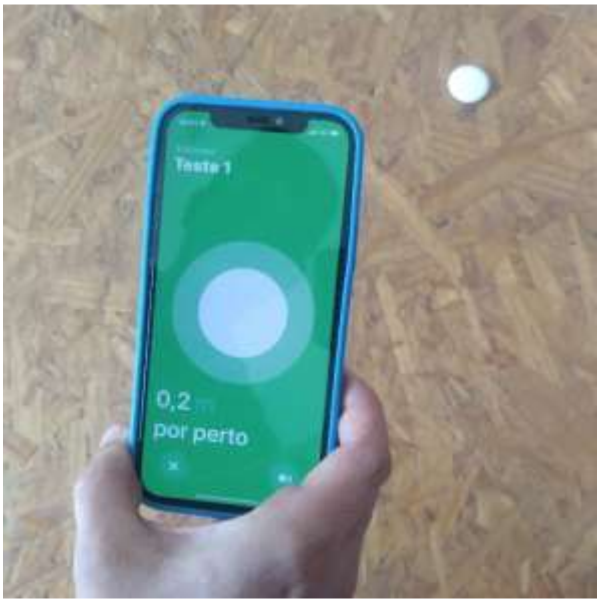

Figure 4. Accurate search process by UWB technology in Iphone application.

Data Analysis

Considering that this off-the-shelf system indirectly involves the use of GNSS, we measured the system's effectiveness based on the two main steps in the overall operation of satellite telemetry units: Fix acquisition and data transfer (Hofman et al. 2019). Adaptively, we consider Fix Acquisition as steps 1, 2, 3 (Figure 2) and Data Transfer as step 4. Acknowledging that there may be a failure or delay between steps 3 and 4 due to the GSM signal of both smartphones, we considered it an effective detection when the sending of coordinates in step 4 was performed while the drone was still in flight. Considering the average fix acquisition rate of 66% found by Matthews et al. (2013), we calculated detection probabilities above 70% using the binomial test considering the proportion of total detection, by type of environment and type of experiment. To find out if there is any significant association between the factors environment and the type of experiment that may influence the system's detection capacity, we performed a general linear model using a binominal distribution and a logit link function with the interaction between the two factors. The model selection process was done using the R ‘drop1()’ command, which drops one explanatory variable at a time and applies an analysis of deviance test each time. The significance of the factors was assessed using command ‘Anova ()’. The heterogeneity of residuals was assessed by visual examination of the figures. GLM models with no random factors were fitted using the ‘glm()’ function. In all stationary tests we recorded the coordinates of the tags using a GPS Garmin eTrex 30x. To calculate the static precision, that is, the distance between the eTrex coordinates and the coordinates obtained by the off-the-shelf tracking system, we used the formula based on the Spherical Law of Cosines:

$$\mathrm{acos}(\sin(\mathrm{lat1}) * \sin(\mathrm{lat2}) + \cos(\mathrm{lat1}) * \cos(\mathrm{lat2}) * \cos(\mathrm{long2} - \mathrm{long1})) * 6371$$

We used the t test to compare the mean values of accuracy obtained in the savanna and forest areas. For model validation, we tested for normality (Shapiro–Wilk) and set the significance level at 0.05. All statistical analyzes were performed using R Studio version 1.4.1 (R Core Team, 2019).

Results

We performed 40 tracking flights with the off-the-shelf tracking system, 20 in the savanna and 20 in the forest, totaling 9.23 flight hours (Table 1). Tracking flight times varied between 5 and 22 min (x = 13.85 ± 6.07), from take-off until obtaining the first tag coordinate. Due to the lower altitude and lower detection rate, the total time of flights in the forest area was 6.45 h, while in the savanna area it was 2.78 h.

Table 1: Drone flights tracking data

Flight	Type	Environment	Detection	flight time (min)	Accuracy (m)
1	stationary	savanna	yes	9	11,60
2	stationary	savanna	yes	13	8,10
3	stationary	savanna	yes	8	11,91
4	stationary	savanna	yes	10	11,87
5	stationary	savanna	yes	7	9,79
6	stationary	savanna	no	13	---
7	stationary	savanna	yes	5	9,84
8	stationary	savanna	yes	7	12,13
9	stationary	savanna	yes	9	8,48
10	stationary	savanna	yes	8	11,12
11	stationary	forest	yes	18	10,48
12	stationary	forest	yes	14	13,19
13	stationary	forest	no	21	---
14	stationary	forest	no	20	---
15	stationary	forest	yes	19	14,67
16	stationary	forest	yes	18	12,38
17	stationary	forest	no	21	---
18	stationary	forest	yes	17	14,58
19	stationary	forest	no	21	---
20	stationary	forest	no	20	---
21	in motion	savanna	yes	10	---
22	in motion	savanna	yes	7	---
23	in motion	savanna	yes	7	---
24	in motion	savanna	yes	5	---
25	in motion	savanna	yes	8	---
26	in motion	savanna	no	13	---
27	in motion	savanna	yes	7	---

28	in motion	savanna	yes	5	---
29	in motion	savanna	yes	10	---
30	in motion	savanna	yes	6	---
31	in motion	forest	yes	15	---
32	in motion	forest	no	21	---
33	in motion	forest	no	21	---
34	in motion	forest	no	21	---
35	in motion	forest	yes	16	---
36	in motion	forest	no	22	---
37	in motion	forest	yes	18	---
38	in motion	forest	no	21	---
39	in motion	forest	no	22	---
40	in motion	forest	no	21	---

Considering the execution of all steps in Figure 2, we obtained an overall detection rate of 65% (90% in the savanna area and 40% in the forest area). The probability of detection above 70% was only significant in the savanna (binominal test, $p = 0.035$). The interaction between environmental and type of experiment factors did not significantly influence the system's detection rate ($x^{2}1 = 0.23$, $p = 0.63$). However, the detection rate of the system was higher in the savanna (90% detection) than in the forest (30% detection, $x^{2}1 = 12.0411$, $p < 0.01$), while no differences were observed between tests in motion (60% detection) and static tests (70% detection, $x^{2}1 = 0.6099$, $p = 0.43$). In the stationary tests where there was detection, we calculated a mean spatial accuracy of 14.61 ± 0.53 m ($n = 14$) based on the R95 parameter (Figure 5). In the savanna area the average spatial accuracy was 10.53 ± 1.53 m ($n = 9$), and in the forest area the average spatial accuracy was 13.06 ± 1.73 m ($n = 5$), and there was a significant difference concerning the spatial accuracy obtained between the two environments ($t_{12}= 2.818$, $p = 0.015$; Figure 5).

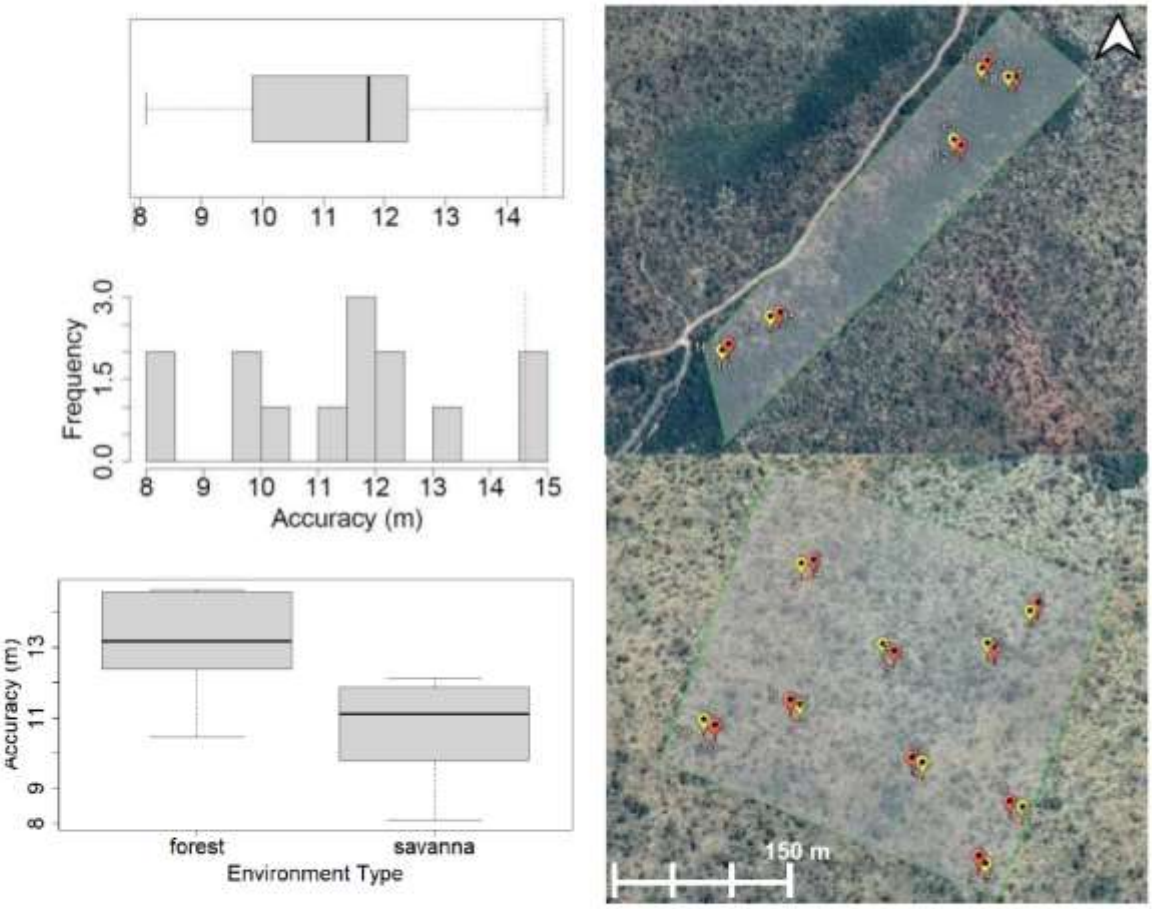

Figure 5. Spatial accuracy of stationary tracking tests in the forest and savanna environments. Flight numbers and location obtained on flights are shown in red tags and real location in yellow tags.

Discussion

Finding ways to make wildlife tracking easier and less expensive is a constant challenge for researchers. In this study we propose a practical approach to potential wildlife tracking using drones, smartphones and tags through Bluetooth and UWB signals to serve as a user-friendly animal tracking system and we tested its detection capability in different types of typical environments from the Cerrado biome. To our knowledge, this is the first attempt to use an off-the-shelf tracking system with drones, Bluetooth and UWB technology.

We found the off-the-shelf tracking system tag detection rate was higher in savanna areas (90%) than the average rate (66%) found by Matthews et al. (2013) for several Australian mammal species and similar to the 85% rate obtained by Hoffman et al. 2019, who analyzed the performance of satellite telemetry units in terrestrial wildlife research across the globe. On the other hand, the detection rate in environments with forest cover in Cerrado biome was low, with a detection rate of 40%. This is likely due to the vegetation biomass of the trees which blocks the transmission of the Bluetooth signal. In step 5 of all tests, after receiving the tag coordinates via cloud, the researchers, in addition to using Bluetooth and UWB technology, used the tag's sound emission function, demonstrating that this technology can offer a differential in the wildlife tracking process in the precision search, mainly for small animals with cryptic behavior and in forest areas where the animal can be camouflaged below vegetation. However, the sound emission by a tag attached to the animal can cause disturbances in behavior that have not yet been analyzed.

The off-the-shelf tracking system accuracy around 12 m is higher than lightweight GPS collars accuracy averaging 30 m, (e.g. used for research on common brushtail in suburban environment (Adams et al. 2013)). When compared with the few studies that developed a tracking system involving UAVRTS such as Nguyen et al. (2019), with an average precision of 22.7 m, Cliff et al. (2018), with 51.4 m and Hui et al. (2021) with 25.9 m, we note that the coordinates of the system assembled in this study were more accurate (14.61 m). Also, as opposed to the UAVRTS from Cliff et al. (2018), Nguyen et al. (2019) and Hui et al. (2021), in this system there is no need for the development or customization of hardware or algorithms since all parts of the system can be purchased commercially ready for use. However, we emphasize that the comparison of accuracy of this system with other tracking systems based on radio frequency (UHF/VHF) is only for the context of the experiment, since the calculation of the position in radio frequency is done through an estimate of quadratic regression based on the number of “pings" and on the shape of the UHF/VHF signal (Desrochers et al. 2018), while the positioning via GNSS works through the triangulation of satellites (Hofman et al. 2019).

This off-the-shelf tracking system, although using Bluetooth and UWB as its differential technology, has application characteristics similar to radio frequency and GNSS telemetry systems. In the same way as in radio frequency tracking systems, there is a need for a field search for the tagged animals, in this case in order to recognize the Bluetooth signal emitted by the tags. And just as in GNSS telemetry systems, the sending of coordinates captured from one smartphone to another depends on the satellite triangulation system and subsequent transmission to the cloud, but with the limiting factor of depending on the need to also use the GSM signal. On the other hand, the field effort needed for this system as compared to the traditional radio frequency technique is relatively lower, as it reduces the need for the researcher to travel by land, allows the collection of data without physically approaching the animal specially necessary in cases of large carnivores- and can also enable an increased search coverage depending on the flight capacity of the drone used. The difference in cost between GPS tags with similar size and the tags used in this system is another aspect to be taken into account when applying this tracking methodology. While an AirTag can be found for $29, GPS-tags of similar sizes can cost up to $2000 (Lahoz-Monfort et al. 2021). In addition, its 1 year battery life and its 10 g weight would allow the tracking of any animal with a minimum weight of 350g, considering the recommended limit of not exceeding 3 – 5% of the animal's weight (Kenward, 2001). The reduced size and weight of Air tags allows attaching them to different types of animals, and can be used as a necklace on mammals or even medium and large birds, or fixed as a backpack on some species of birds and reptiles. Considering that AirTags have IP67 water resistance (IEC 60529) it may not be necessary to include protective structures, although they are recommended for animals with aquatic habits, since the time span that the tag can tolerate water is limited to 30 minutes at a maximum depth of 1 meter. In cases where the tags need to be fixed by protection structures, such structures would not significantly affect the emitted Bluetooth and UWB signals since these technologies do have higher bandwidth than most narrowband signals and are usually only affected by other electromagnetic sources within the same communication channel. Although we used a specific drone model in this off-the-shelf tracking system, the lack of hardware customization allows the use of different parts of the system (smartphones and tracking devices) on different drone platforms, paying attention to the due previous parameterizations of speed and altitude that will allow the connection of the Bluetooth signal. Different multirotor platforms or even fixed-wing platforms such as the Asa-Branca I model (Mesquita et al. 2021), developed for use in the study of biodiversity conservation in large areas, could be incorporated into this system, thus increasing the tracking coverage area. Another potential modification of the system that does not affect the functioning core is changing the types of smartphones and tags, thus paying attention to the latest Bluetooth class and versions. In this study we used Apple branded smartphones and tags due to prior availability of the devices for the researchers. However, other brands like Samsung have smartphones and tags with the same type of operation and capacity. Considering that a single tag of this system can be tracked by different smartphones, since the system works in a type of a network, we envisage the possibility of using more than one drone or even a drone network with attached smartphones in order to locate different targets in an area, making the tracking process possibly even more efficient.

Although we demonstrated the feasibility of this off-the-shelf tracking system on controlled targets in savanna areas, we acknowledge that tests on animals can present variable results, whether due to the complexity of the behavior of different species or the different ways of fixation and positioning of tags on animals. Therefore, carrying out new experiments with this system in real animals will help to understand the actual possibilities of use. In addition, further research is still needed for assessing the effects of other operational parameters (flight speed, altitude, flight types, tag displacement speed) as well as the environmental influence (vegetation types, relative air humidity, arboreal stratum height). Determining which factors may influence the detection capability of this system is likely to make it more useful not only in savanna areas but possibly in other areas with higher forest cover.

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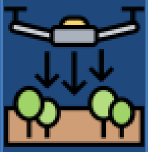

GENERAL DISCUSSION

GENERAL DISCUSSION

The use of drones in biodiversity conservation studies is increasing. Due to the several logistical advantages of using drones over traditional methodologies and the possibility of obtaining data with better spatial and temporal resolution, this technological tool has exponentially grown in ecological research in the last decade (Gallardo-Salazar et al. 2020; Eugenio et al. 2020). However, the application of this tool in different environments is not uniform, being still scarce in biomes such as the Cerrado, one of the most threatened hotspots in the world. This thesis aimed to expand the knowledge of the potential and limitations of drones in studies within the Cerrado Biome while bringing new possibilities for applying this tool in an accessible and practical way for researchers. This thesis provides new information about the potential disturbances that drones can cause on animals, thus demonstrating the limitations and possibilities of using drones within this biome.

In the following paragraphs the key points will be discussed (Summary of the key findings) in addition to the methodological contributions (Methodological and Practical contributions), the implications for policy and management (Policy implications) and the future perspectives that this thesis brings into the field of conservation biology (Future prospects).

Summary of the key findings

The first chapter of this thesis provides the scientific community with a possible solution to the main problem that precludes the use of drones by researchers with difficult access to funds, such as those from developing countries, that is, the acquisition cost (Christie et al. 2016). Commercial fixed-wing drones, similar as the one presented in the first chapter of the thesis, which are generally indicated for studies in large areas, have an average price of $15797 (Mesquita et al, 2021a), what constrains its use. Although there has already been some work conducted on the development of low-cost drones for use in biodiversity conservation studies (Watts and Perry, 2010; Koh and Wich, 2012; Sardà-Palomera et al. 2012; Mulero-Pázmány et al. 2014) or initiatives such as Conservation Drones (conservationdrones.org) that seek to expand the use of drones in the field of conservation, there was no scientific study providing a didactic step by step method to build a low-cost drone without necessarily possessing an advanced knowledge of electronics. This thesis, in addition to making these instructions available to the scientific community, also demonstrated the viability of the DIY low-cost fixed-wing drone developed for application in the conservation of biodiversity in large areas within the Cerrado biome. In addition to the effectiveness proven by the performance tests carried out, the Asa Branca I model is currently used by the Secretariat of Environment of the State of Maranhão, Brazil, in combating deforestation and illegal forest fire and in monitoring and environmental mapping in protected areas of the Cerrado biome in the state of Maranhão, as well as by the Biology department of the Federal University of Maranhão – UFMA in population analysis projects of some species of Cerrado fauna, demonstrating its feasibility both for studies aimed at biodiversity conservation and management of protected areas of the Cerrado.

The second chapter analyzes the disturbances caused by drones on different species. Although it is known that disturbances caused by drones are produced by visual and auditory stimuli, no study was able to analyze these separately. Through a unique quasi-experiment, Mesquita et al. (2021b) demonstrated the effects of visual disturbances that drones cause on bird species in their nesting sites. For the first time, it was possible to separate the visual disturbance from the sound disturbance caused by a multirotor drone in birds. This information proved in this case that the response of birds to the use of the drone follows a sigmoidal distribution with the diagonal distance of the drone to the colonies, being necessary a distance greater than at least 50 m to avoid moderate and high disturbances to the nesting sites.

Chapter III sought to analyze the behavior of species from the other group most studied with drones: mammals. In this case, focusing on the sound stimulus that drones expose animals to, Chapter III analyzed the behavior of a set terrestrial megafauna species from different families and orders. These analyzes evidenced that the disturbance behaviors caused by the drone’s noise are started by different sound pressure levels that are possibly noted at different frequencies by different species, which are not necessarily close in taxonomy. Unlike the birds in Chapter II, which had a behavioral change initiated by the visual disturbance, the mammals studied in Chapter III changed their behavior due to the drone's noise disturbance as visual contact with the drone is unlikely at high altitude. Understanding that sounds with different sound pressure levels and different frequencies can affect species differently is particularly important today, as it is increasingly common to use drones to study these species and there are different models of drones on the market with different sound profiles as demonstrated by Duporge et al. (2021).

The last chapter of the thesis, Chapter IV, is an example of how drones have made wildlife study methodologies more dynamic and practical within the field of conservation biology. In wildlife tracking, where technologies such as Very High Frequency (VHF) tracking system, ARGOS system and GPS-based tracking system are already fully incorporated into its methodologies, the use of drones is increasingly incorporated. Chapter IV presents a new adaptive methodology for tracking wildlife through a simple system consisting of a multirotor drone, smartphones and tracking devices using Bluetooth and Ultra-Wide Band (UWB), and demonstrates its feasibility on the tracking targets in savanna environments within the Cerrado. Although prototypes of drone systems for tracking animals already exist (Cliff et al. 2018; Nguyen et al. 2019; Hui et al. 2021), Chapter IV presents for the first time the use of Bluetooth and Ultra-Wide Band (UWB) in a ready-to-use and easy-to-apply system, capable of obtaining location data intuitively and with high accuracy in active search cases.

Methodological and Practical contributions

The results of this thesis provide the scientific community with valuable methodological and practical information to increase the efficiency of drone use in wildlife conservation studies. At a methodological level, paths for the development of both the tool and the application methodology are provided, considering the different possibilities of visual and sound disturbances of drones in species of the avifauna and mammalian groups. Although the results of this thesis reinforce the idea that for different species there must be operational parameters for the use of specific drones, it also supports the idea that minimum values for distance, altitude, sound level pressure and frequency should be established in advance. While this thesis provides practical information for the development of customizable, low-cost fixed-wing drones focused on monitoring and mapping studies of large areas, it also suggests the adaptive use of commercial multirotor drones for wildlife tracking in order to make the use of this technological tool feasible in different environments and methodological situations.

At a theoretical level, this thesis is relevant to the literature contributing with new data on the behavior of species from the Cerrado biome when exposed to drones, such as the Giant anteater, the Maned wolf and the Tapir. Similarly to the large African mammals that are already detected, identified and monitored by drones (Mulero-Pázmány et al. 2014; Yang et al. 2014; Rey et al. 2017), including a suggested use protocol for some species (Hartmann et al. 2021), large mammal species from Cerrado biome have also the potential to be monitored with drones, and understanding the characteristics of drones' noise that can affect their behavior is essential to establish protocols for these species.

Policy implications

Currently, drone use, whether recreational, commercial or scientific, is governed by rules at the national level although most countries rely on the regulation of large agencies such as the European Union Aviation Safety Agency (EASA) in Europe or the Federal Aviation Administration (FAA) in the United States. In Brazil, where the field tests of this thesis were carried out, the rules established by the National Civil Aviation Agency (ANAC) were followed. Operations with a drone such as the Asa Branca I, developed in this thesis, capable of flying beyond the operator's line of sight (BVLOS flights), are still rare in Brazil due to the scarcity of models and the high acquisition costs of existing commercial models. Therefore, the approval and certification rules involving these drones are still complicated at the local level. Thus, stimulating the development of new models with BVLOS flight capabilities is a way to press for the creation of more consistent rules for the use of this drone type, especially at the scientific level where there is great demand for environmental management in large protected areas.

Considering the increasing recreational and scientific use of drones, the information provided in this thesis about the potential disturbances that drones can cause on certain species is essential for establishing rules within areas where these species are present. The information provided in Chapter II is being considered in establishing local regulations on limiting the recreational use of drones in nesting areas of swift's species inside federally protected areas in Brazil, demonstrating that studies such as this can help in the creation of public policies for species conservation. Likewise, the information obtained in Chapter III, on the drone disturbances on mammal species, is also being considered for the creation of internal rules for drone use at the São Paulo Zoo, which so far does not have any regulations.

Future prospects

The information contained in this thesis brings new perspectives for drone use for biodiversity conservation, especially within the savanna areas from the Cerrado biome, which so far have benefited little from the use of this technology. The didactic information for the development of a low-cost fixed-wing drone model with great flight autonomy and load capacity higher than the average of commercial drones presented in this thesis is essential to increase the chances of using drones by researchers from this location. Since drones are constantly being updated, tests with other types of operation, BVLOS flights, other payloads, thermal or multispectral sensors, or even another platform type, as VTOL, are the next steps that should be taken forward with this model. These future updates may demonstrate more consistently their usefulness in other types of environmental services such as fauna monitoring, biomass calculation and monitoring of forest fires within the Cerrado. In addition, considering that drones are now one of the emerging technologies of the century (PwC, 2021), the knowledge of developing this technology at a low cost and with a focus on biodiversity conservation enables researchers to develop their own platforms.

Drones, in combination with other technologies such as Bluetooth, UWB, 5G and Internet of Things (IoT) will be the next steps that should be tested in the field of environmental monitoring and tracking. New methodological research that can compare the cost-effectiveness of monitoring large areas through the use of drones in relation to conventional methodologies are also future options that can be explored in order to prove the effectiveness of this technology in studies aimed at conservation or management of protected areas.

The information in this thesis related to disturbances caused by drones to species of birds and mammals, in addition to bringing new data from unevaluated species, also offers new insights into how drones can affect the visual and sound senses differently in different species. This information can help not only the operational refinement of drone use in biological and ecological studies, but also serve as a basis for the development of future protocols for use by recreational users in areas where these species are present. Initiatives to create rules for the use of drones in protected areas from Cerrado are already being formulated based on the information contained in this thesis.

CONCLUSIONS

CONCLUSIONS

- This thesis provides the tools to develop customizable low-cost fixed-wing drones capable of carrying out conservation biology studies in large areas.

- Low-cost drones with high flight range can be developed through the DIY concept by researchers without the need for advanced technical knowledge and can be used in projects with few financial resources.

- The visual disturbance caused by drone use at nesting sites of the great dusky and white-collared swifts' species can produce negative impacts on the reproductive process.

- Drones must be operated at a minimum distance higher than 50 m from nesting areas to avoid high disturbance to great dusky and white-collared swifts during the breeding period.

- The sound pressure level and the frequency of the drone's noise affect species of terrestrial megafauna differently.

- Wildlife tracking through an easy-to-use off-the-shelf tracking system using drones, Bluetooth and UWB has shown an acceptable detectability rate and accuracy when used in open environments.

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APPENDICES

Complementary Table 1

n_id_sp	species	Class	Family	ecoregions*	Study	year	main_goal	goal_description	Citation
1	*Acridotheres tristis*	Aves	Sturnidae	terrestrial	124	2020	Behavioral Ecology	Disturbance Analysis	Weston et al. 2020
2	*Aechmophorus occidentalis/clarkii*	Aves	Podicipedidae	terrestrial	14	2015	Animal Population Assessments	Investigate application of	Dulava et al. 2015
3	*Aepyceros melampus*	Mammalia	Bovidae	terrestrial	88	2019	Behavioral Ecology	Disturbance Analysis	Bennit et al. 2019
4	*Aetobatus narinari*	Chondrichthyes	Myliobatidae	marine	76	2018	Animal Population Assessments	Identify and estimate sha	Hensel et al. 2018
4	*Aetobatus narinari*	Chondrichthyes	Myliobatidae	marine	129	2020	Animal Population Assessments	Identification/Detection	Kelaher et al. 2020
5	*Alligator mississippiensis*	Reptilia	Alligatoridae	freshwater	7	2006	Animal Population Assessments	Test the feasibility of usin	Jones IV et al. 2006
6	*Alouatta palliata*	Mammalia	Atelidae	terrestrial	110	2019	Animal Population Assessments	Identification/Detection	Kays et al. 2019
7	*Anas acuta*	Aves	Anatidae	terrestrial	23	2015	Animal Population Assessments and Behaviora	xxxxx	Drever et al. 2015
8	*Anas Americana*	Aves	Anatidae	terrestrial	23	2015	Animal Population Assessments and Behaviora	xxxxx	Drever et al. 2015
9	*Anas crecca*	Aves	Anatidae	terrestrial	23	2015	Animal Population Assessments and Behaviora	xxxxx	Drever et al. 2015
9	*Anas crecca*	Aves	Anatidae	terrestrial	81	2018	Animal Population Assessments	Population analyzes	Pöysä et al. 2018
10	*Anas platyrhynchos*	Aves	Anatidae	terrestrial	23	2015	Animal Population Assessments and Behaviora	xxxxx	Drever et al. 2015
10	*Anas platyrhynchos*	Aves	Anatidae	terrestrial	30	2015	Behavioral Ecology	Test the impact of drones	Vas et al. 2015
10	*Anas platyrhynchos*	Aves	Anatidae	terrestrial	81	2018	Animal Population Assessments	Population analyzes	Pöysä et al. 2018
11	*Anas superciliosa*	Aves	Anatidae	terrestrial	124	2020	Behavioral Ecology	Disturbance Analysis	Weston et al. 2020
12	*Anastomus lamelligerus*	Aves	Ciconiidae	terrestrial	128	2020	Animal Population Assessments	Identification/Detection	Francis et al. 2020
13	*Anser brachyrhynchus*	Aves	Anatidae	terrestrial	100	2019	Animal Population Assessments	Identification/Detection	Lee et al. 2019
14	*Anser caerulescens caerulescens*	Aves	Anatidae	terrestrial	72	2018	Behavioral Ecology	Disturbance Analysis	Barnas et al. 2018
15	*Aptenodytes patagonicus*	Aves	Spheniscidae	terrestrial	68	2018	Behavioral Ecology	Disturbance Analysis	Weimerskirch et al. 2018
16	*Aquila chrysaetos*	Aves	Accipitridae	terrestrial	135	2020	Behavioral Ecology	Disturbance Analysis	Dwyer et al. 2020
17	*Arctocephalus forsteri*	Mammalia	Otariidae	marine	112	2018	Animal Population Assessments	Identification/Detection	Gooday et al. 2018
18	*Arctocephalus pusillus doriferus*	Mammalia	Otariidae	marine	83	2018	Animal Population Assessments and Behaviora	Identification/Detection	McIntosh et al. 2018
18	*Arctocephalus pusillus*	Mammalia	Otariidae	marine	121	2019	Animal Population Assessments	Compare wildlife monitor	Sorrell et al. 2019
19	*Ardea alba*	Aves	Ardeidae	terrestrial	105	2019	Behavioral Ecology	Disturbance Analysis	Collins et al. 2019
19	*Ardea alba*	Aves	Ardeidae	terrestrial	115	2019	Animal Population Assessments	Population analyzes	Zbyryt, 2019
19	*Ardea alba*	Aves	Ardeidae	terrestrial	126	2020	Behavioral Ecology	Disturbance Analysis	Barr et al. 2020
20	*Ardea cinerea*	Aves	Ardeidae	terrestrial	132	2020	Animal Population Assessments	Nest Identification/Detect	Schedl et al. 2020
21	*Ardea herodias*	Aves	Ardeidae	terrestrial	126	2020	Behavioral Ecology	Disturbance Analysis	Barr et al. 2020
22	*Ateles geoffroyi*	Mammalia	Atelidae	terrestrial	93	2019	Animal Population Assessments	Identification/Detection	Spaan et al. 2019
22	*Ateles geoffroyi*	Mammalia	Atelidae	terrestrial	110	2019	Animal Population Assessments	Identification/Detection	Kays et al. 2019
23	*Aythya valisineria*	Aves	Anatidae	terrestrial	14	2015	Animal Population Assessments	Investigate application of	Dulava et al. 2015
24	*Balaena mysticetus*	Mammalia	Balaenidae	marine	26	2015	Animal Population Assessments	Identification/Detection	Koski et al. 2015
25	*Balaenoptera edeni*	Mammalia	Balaenopteridae	marine	42	2010	Animal Morphometrics and Individual Health	Collection of exhaled brea	Acevedo-Whitehouse et al. 2010
26	*Balaenoptera musculus*	Mammalia	Balaenopteridae	marine	38	2016	Animal Morphometrics and Individual Health	Test the feasibility of usin	Durban et al. 2016
26	*Balaenoptera musculus*	Mammalia	Balaenopteridae	marine	42	2010	Animal Morphometrics and Individual Health	Collection of exhaled brea	Acevedo-Whitehouse et al. 2010
26	*Balaenoptera musculus brevicauda*	Mammalia	Balaenopteridae	marine	92	2019	Animal Morphometrics and Individual Health	Establish methods for cor	Burnett et al. 2019
27	*Balaenoptera physalus*	Mammalia	Balaenopteridae	marine	42	2010	Animal Morphometrics and Individual Health	Collection of exhaled brea	Acevedo-Whitehouse et al. 2010
28	*Bos taurus*	Mammalia	Bovidae	terrestrial	3	2017	Animal Population Assessments	Identification/Detection	Longmore et al. 2017
29	*Bubulcus ibis*	Aves	Ardeidae	terrestrial	84	2018	Behavioral Ecology	Disturbance Analysis	Reintsma et al. 2018

30	*Bucephala clangula*	Aves	Anatidae	terrestrial	81	2018	Animal Population Assessments	Population analyzes	Pöysä et al. 2018
31	*Bunolagus monticularis*	Mammalia	Leporidae	terrestrial	118	2019	Animal Population Assessments	xxxxx	Burke et al. 2019
32	*Buteo jamaicensis*	Aves	Accipitridae	terrestrial	113	2015	Animal Population Assessments	Identification/Detection	Junda et al. 2015
33	*Buteo regalis*	Aves	Accipitridae	terrestrial	113	2015	Animal Population Assessments	Identification/Detection	Junda et al. 2015
34	*Cacatua galerita*	Aves	Psittacidae	terrestrial	124	2020	Behavioral Ecology	Disturbance Analysis	Weston et al. 2020
35	*Caiman latirostris*	Reptilia	Alligatoridae	freshwater	99	2019	Animal Population Assessments	Estimate the density of ca	Scarpa et al. 2019
36	*Caiman yacare*	Reptilia	Alligatoridae	freshwater	99	2019	Animal Population Assessments	Estimate the density of ca	Scarpa et al. 2019
37	*Calidris alpina*	Aves	Scolopacidae	terrestrial	23	2015	Animal Population Assessments and Behaviora	xxxxx	Drever et al. 2015
38	*Canis latrans*	Mammalia	Canidae	terrestrial	101	2019	Animal Population Assessments	Identification/Detection	Bushaw et al. 2019
39	*Capreolus capreolus*	Mammalia	Cervidae	terrestrial	95	2019	Animal Population Assessments	Identification/Detection	Cukor et al. 2019
40	*Capreolus pygargus*	Mammalia	Cervidae	terrestrial	1	2011	Animal Population Assessments	Identification/Detection	Israel, 2012
40	*Capreolus pygargus*	Mammalia	Cervidae	terrestrial	5	2017	Animal Population Assessments	Identification/Detection	Witczuk et al. 2017
41	*Carcharhinus leucas*	Chondrichthyes	Carcharhinidae	marine	91	2019	Animal Population Assessments	Identification/Detection	Colefax et al. 2019
41	*Carcharhinus leucas*	Chondrichthyes	Carcharhinidae	marine	129	2020	Animal Population Assessments	Identification/Detection	Kelaher et al. 2020
42	*Carcharhinus melanopterus*	Chondrichthyes	Carcharhinidae	marine	10	2016	Animal Population Assessments	Estimate density	Kiszka et al. 2016
42	*Carcharhinus melanopterus*	Chondrichthyes	Carcharhinidae	marine	59	2018	Animal Population Assessments and Behaviora	Measure local densities ar	Rieucau et al. 2018
42	*Carcharhinus melanopterus*	Chondrichthyes	Carcharhinidae	marine	70	2018	Behavioral Ecology	Movements and behaviou	Raoult et al. 2018
42	*Carcharhinus sp.*	Chondrichthyes	Carcharhinidae	marine	129	2020	Animal Population Assessments	Identification/Detection	Kelaher et al. 2020
43	*Carcharodon carcharias*	Chondrichthyes	Lamnidae	marine	129	2020	Animal Population Assessments	Identification/Detection	Kelaher et al. 2020
43	*Carcharodon carcharias*	Chondrichthyes	Lamnidae	marine	131	2020	Animal Population Assessments	Population analyzes	Colefax et al. 2020
44	*Caretta caretta*	Reptilia	Cheloniidae	marine	48	2017	Animal Morphometrics and Individual Health a	Estimate of changes in the	Schofield et al. 2017
44	*Caretta caretta*	Reptilia	Cheloniidae	marine	116	2019	Animal Population Assessments	Population analyzes	Varela et al. 2019
45	*Castor fiber*	Mammalia	Castoridae	terrestrial	28	2015	Animal Population Assessments	Impact analysis	Puttock et al. 2015
46	*Catharus bicknelli*	Aves	Turdidae	terrestrial	114	2017	Animal Population Assessments	Radio-tracking wildlife	Tremblay et al. 2017
47	*Catharus ustulatus*	Aves	Turdidae	terrestrial	114	2017	Animal Population Assessments	Radio-tracking wildlife	Tremblay et al. 2017
48	*Ceratotherium simum*	Mammalia	Rhinocerotidae	terrestrial	18	2014	Animal Population Assessments	Actions for species conser	Mulero-Pázmány et al. 2014
48	*Ceratotherium simum simum*	Mammalia	Rhinocerotidae	terrestrial	108	2019	Behavioral Ecology	Actions for species conser	Penny et al. 2019
49	*Cervus elephus*	Mammalia	Cervidae	terrestrial	5	2017	Animal Population Assessments	Identification/Detection	Witczuk et al. 2017
49	*Cervus elaphus*	Mammalia	Cervidae	terrestrial	19	2014	Animal Population Assessments	Standard abundance mod	Barasona et al. 2014
49	*Cervus elaphus*	Mammalia	Cervidae	terrestrial	85	2018	Animal Population Assessments	Describe and assess a new	Laguna et al. 2018
50	*Charadrius hiaticula*	Aves	Charadriidae	terrestrial	100	2019	Animal Population Assessments	Identification/Detection	Lee et al. 2019
51	*Chelonia mydas*	Reptilia	Cheloniidae	marine	55	2018	Behavioral Ecology	Disturbance Analysis	Bevan et al. 2018
51	*Chelonia mydas*	Reptilia	Cheloniidae	marine	66	2016	Animal Population Assessments	Identification/Detection	Bevan et al. 2016
51	*Chelonia mydas*	Reptilia	Cheloniidae	marine	76	2018	Animal Population Assessments	Identify and estimate shar	Hensel et al. 2018
51	*Chelonia mydas*	Reptilia	Cheloniidae	marine	116	2019	Animal Population Assessments	Population analyzes	Varela et al. 2019
51	*Chelonia mydas*	Reptilia	Cheloniidae	marine	129	2020	Animal Population Assessments	Identification/Detection	Kelaher et al. 2020
52	*Chenonetta jubata*	Aves	Anatidae	terrestrial	124	2020	Behavioral Ecology	Disturbance Analysis	Weston et al. 2020
53	*Chroicocephalus novaehollandiae*	Aves	Laridae	terrestrial	124	2020	Behavioral Ecology	Disturbance Analysis	Weston et al. 2020
54	*Chroicocephalus ridibundus*	Aves	Laridae	terrestrial	12	2012	Animal Population Assessments	Monitor temporal change	Sardà-Palomera et al. 2012
54	*Chroicocephalus ridibundus*	Aves	Laridae	terrestrial	47	2017	Animal Population Assessments	Monitor the temporal and	Sardà-Palomera et al. 2017
55	*Comluba livia*	Aves	Columbidae	terrestrial	124	2020	Behavioral Ecology	Disturbance Analysis	Weston et al. 2020
56	*Connochaetes taurinus*	Mammalia	Bovidae	terrestrial	88	2019	Behavioral Ecology	Disturbance Analysis	Bennit et al. 2019

57	*Coracina novaehollandiae*	Aves	Campephagidae	terrestrial	124	2020	Behavioral Ecology	Disturbance Analysis	Weston et al. 2020
58	*Corvus sp.*	Aves	Corvidae	terrestrial	29	2015	Animal Population Assessments	Determine utility of drone	Weissensteiner et al. 2015
58	*Corvus mellori*	Aves	Corvidae	terrestrial	124	2020	Behavioral Ecology	Disturbance Analysis	Weston et al. 2020
59	*Craticus tibicen*	Aves	Artamidae	terrestrial	124	2020	Behavioral Ecology	Disturbance Analysis	Weston et al. 2020
60	*Crocodylus niloticus*	Reptilia	Crocodylidae	freshwater	57	2018	Animal Population Assessments	Determine size and age cl	Ezat et al. 2018
61	*Crocodylus porosus*	Reptilia	Crocodylidae	marine	21	2015	Animal Population Assessments	Monitoring methodology	Evans et al. 2015
61	*Crocodylus porosus*	Reptilia	Crocodylidae	marine	55	2018	Behavioral Ecology	Disturbance Analysis	Bevan et al. 2018
61	*Crocodylus porosus*	Reptilia	Crocodylidae	marine	65	2018	Behavioral Ecology	Eating behavior	Gallagher et al. 2018
62	*Cygnus atratus*	Aves	Anatidae	terrestrial	124	2020	Behavioral Ecology	Disturbance Analysis	Weston et al. 2020
63	*Cypseloides senex*	Aves	Apodidae	terrestrial	139	2020	Behavioral Ecology	Disturbance Analysis	Mesquita et al. 2020
64	*Dama dama*	Mammalia	Cervidae	terrestrial	19	2014	Animal Population Assessments	Standard abundance mod	Barasona et al. 2014
64	*Dama dama*	Mammalia	Cervidae	terrestrial	85	2018	Animal Population Assessments	Describe and assess a ne	Laguna et al. 2018
65	*Damaliscus lunatus*	Mammalia	Bovidae	terrestrial	88	2019	Behavioral Ecology	Disturbance Analysis	Bennit et al. 2019
66	*Dasyatis americana*	Chondrichthyes	Dasyatidae	marine	76	2018	Animal Population Assessments	Identify and estimate sha	Hensel et al. 2018
66	*Dasyatidae sp.*	Chondrichthyes	Dasyatidae	marine	129	2020	Animal Population Assessments	Identification/Detection	Kelaher et al. 2020
67	*Delphinapterus leucas*	Mammalia	Monodontidae	marine	107	2019	Animal Population Assessments	Population analyzes	Boyd et al. 2019
68	*Delphinus sp.*	Mammalia	Delphinidae	marine	42	2010	Animal Morphometrics and Individual Health	Collection of exhaled bre	Acevedo-Whitehouse et al. 2010
68	*Delphinus delphis*	Mammalia	Delphinidae	marine	96	2019	Animal Population Assessments	Identification/Detection	Subhan et al. 2019
69	*Diceros bicornis*	Mammalia	Rhinocerotidae	terrestrial	18	2014	Animal Population Assessments	Actions for species conse	Mulero-Pázmány et al. 2014
70	*Diomedea dabbenena*	Aves	Diomedeidae	terrestrial	34	2016	Animal Population Assessments	Population analyzes	McClelland et al. 2016
71	*Diomedea exulans*	Aves	Diomedeidae	terrestrial	68	2018	Behavioral Ecology	Disturbance Analysis	Weimerskirch et al. 2018
72	*Dugong dugon*	Mammalia	Dugongidae	marine	6	2013	Animal Population Assessments	Identification/Detection	Hodgson et al. 2013
73	*Egret sp.*	Aves	Ardeidae	terrestrial	128	2020	Animal Population Assessments	Identification/Detection	Francis et al. 2020
73	*Egretta garzetta*	Aves	Ardeidae	terrestrial	132	2020	Animal Population Assessments	Nest Identification/Detect	Schedl et al. 2020
74	*Egretta novaehollandiae*	Aves	Ardeidae	terrestrial	124	2020	Behavioral Ecology	Disturbance Analysis	Weston et al. 2020
75	*Egretta rufescens*	Aves	Ardeidae	terrestrial	126	2020	Behavioral Ecology	Disturbance Analysis	Barr et al. 2020
76	*Egretta thula*	Aves	Ardeidae	terrestrial	84	2018	Behavioral Ecology	Disturbance Analysis	Reintsma et al. 2018
76	*Egretta thula*	Aves	Ardeidae	terrestrial	126	2020	Behavioral Ecology	Disturbance Analysis	Barr et al. 2020
77	*Elephas maximus sumatranus*	Mammalia	Elephantidae	terrestrial	86	2012	Animal Population Assessments	Identification/Detection	Koh e Wich (2012)
78	*Eolophus roseicapillus*	Aves	Cacatuidae	terrestrial	124	2020	Behavioral Ecology	Disturbance Analysis	Weston et al. 2020
79	*Equus kiang*	Mammalia	Equidae	terrestrial	80	2018	Animal Population Assessments	Population analyzes	Guo et al. 2018
80	*Equus quagga*	Mammalia	Equidae	terrestrial	88	2019	Behavioral Ecology	Disturbance Analysis	Bennit et al. 2019
81	*Eretmochelys imbricata*	Reptilia	Cheloniidae	marine	55	2018	Behavioral Ecology	Disturbance Analysis	Bevan et al. 2018
81	*Eretmochelys imbricata*	Reptilia	Cheloniidae	marine	76	2018	Animal Population Assessments	Identify and estimate sha	Hensel et al. 2018
82	*Eschrichtius robustus*	Mammalia	Eschrichtiidae	marine	42	2010	Animal Morphometrics and Individual Health	Collection of exhaled bre	Acevedo-Whitehouse et al. 2010
82	*Eschrichtius robustus*	Mammalia	Eschrichtiidae	marine	78	2018	Behavioral Ecology	xxxxx	Torres et al. 2018
82	*Eschrichtius robustus*	Mammalia	Eschrichtiidae	marine	92	2019	Animal Morphometrics and Individual Health	Establish methods for co	Burnett et al. 2019
82	*Eschrichtius robustus*	Mammalia	Eschrichtiidae	marine	123	2020	Behavioral Ecology	Monitor visual and acous	Frouin-Mouy et al. 2020
83	*Eudocimus albus*	Aves	Threskiornithidae	terrestrial	7	2006	Animal Population Assessments	Test the feasibility of usin	Jones IV et al. 2006
83	*Eudocimus albus*	Aves	Threskiornithidae	terrestrial	126	2020	Behavioral Ecology	Disturbance Analysis	Barr et al. 2020
83	*Eudocimus albus*	Aves	Threskiornithidae	terrestrial	128	2020	Animal Population Assessments	Identification/Detection	Francis et al. 2020
84	*Eudyptes chrysochome*	Aves	Spheniscidae	terrestrial	68	2018	Behavioral Ecology	Disturbance Analysis	Weimerskirch et al. 2018

85	*Eudyptes chrysolophus*	Aves	Spheniscidae	terrestrial	68	2018	Behavioral Ecology	Disturbance Analysis	Weimerskirch et al. 2018
86	*Eudyptes schlegeli*	Aves	Spheniscidae	terrestrial	13	2016	Animal Population Assessments	Compare between drone	Hodgson et al. 2016
87	*Eumetopias jubatus*	Mammalia	Otariidae	marine	63	2016	Animal Population Assessments	xxxxx	Sweeney et al. 2016
88	*Falco eleonorae*	Aves	Falconidae	terrestrial	140	2020	Animal Population Assessments	Reproductive Success Rat	Hadjikyriakou et al. 2020
89	*Falco naumanni*	Aves	Falconidae	terrestrial	16	2012	Animal Population Assessments	Habitat analysis	Rodríguez et al. 2012
90	*Falco peregrinus*	Aves	Falconidae	terrestrial	135	2020	Behavioral Ecology	Disturbance Analysis	Dwyer et al. 2020
91	*Falco sparverius*	Aves	Falconidae	terrestrial	111	2019	Animal Population Assessments	Identification/Detection	Kamm et al. 2019
92	*Fregata ariel*	Aves	Fregatidae	terrestrial	13	2016	Animal Population Assessments	Compare between drone	Hodgson et al. 2016
93	*Fulica atra*	Aves	Rallidae	terrestrial	124	2020	Behavioral Ecology	Disturbance Analysis	Weston et al. 2020
94	*Galeocerdo cuvier*	Chondrichthyes	Carcharhinidae	marine	65	2018	Behavioral Ecology	Eating behavior	Gallagher et al. 2018
95	*Gallinula tenebrosa*	Aves	Rallidae	terrestrial	124	2020	Behavioral Ecology	Disturbance Analysis	Weston et al. 2020
96	*Gavialis gangeticus*	Reptilia	Gavialidae	freshwater	60	2018	Animal Population Assessments	Identification/Detection	Thapa et al. 2018
97	*Ginglymostoma cirratum*	Chondrichthyes	Ginglymostomatidae	marine	76	2018	Animal Population Assessments	Identify and estimate shar	Hensel et al. 2018
98	*Giraffa camelopardalis*	Mammalia	Giraffidae	terrestrial	88	2019	Behavioral Ecology	Disturbance Analysis	Bennit et al. 2019
99	*Glossopsitta concinna*	Aves	Psittaculidae	terrestrial	124	2020	Behavioral Ecology	Disturbance Analysis	Weston et al. 2020
100	*Grallina cyanoleuca*	Aves	Monarchidae	terrestrial	124	2020	Behavioral Ecology	Disturbance Analysis	Weston et al. 2020
101	*Inia geoffrensis*	Mammalia	Iniidae	freshwater	102	2019	Animal Population Assessments	Identification/Detection	Oliveira-da-Costa et al. 2019
101	*Gull Larus pacificus*	Aves	Laridae	terrestrial	124	2020	Behavioral Ecology	Disturbance Analysis	Weston et al. 2020
102	*Haematopus longirostris*	Aves	Haematopodidae	terrestrial	124	2020	Behavioral Ecology	Disturbance Analysis	Weston et al. 2020
103	*Haliaeetus leucocephalus*	Aves	Accipitridae	terrestrial	113	2015	Animal Population Assessments	Identification/Detection	Junda et al. 2015
104	*Halichoerus grypus*	Mammalia	Phocidae	marine	11	2017	Animal Population Assessments	Automatic detection and	Seymour et al. 2017
104	*Halichoerus grypus*	Mammalia	Phocidae	marine	24	2015	Animal Population Assessments and Behaviora	xxxxx	Pomeroy et al. 2015
104	*Halichoerus grypus*	Mammalia	Phocidae	marine	45	2017	Animal Population Assessments	Comparison of methodol	Johnston et al. (2017)
104	*Halichoerus grypus*	Mammalia	Phocidae	marine	62	2018	Behavioral Ecology	Disturbance Analysis	Arona et al. 2018
105	*Hemiscyllium ocellatum*	Chondrichthyes	Hemiscylliidae	marine	70	2018	Behavioral Ecology	Movements and behavio	Raoult et al. 2018
106	*Himantura fai*	Chondrichthyes	Dasyatidae	marine	10	2016	Animal Population Assessments	Estimate density	Kiszka et al. 2016
107	*Hippopotamus amphibius*	Mammalia	Hippopotamidae	freshwater	74	2018	Animal Population Assessments	Population analyzes	Linchant et al. 2018
108	*Histriophoca fasciata*	Mammalia	Phocidae	marine	43	2015	Animal Population Assessments	Population analyzes	Moreland et al. 2015
109	*Hydrurga leptonyx*	Mammalia	Phocidae	marine	8	2015	Animal Morphometrics and Individual Health	Test the feasibility of usin	Goebel et al. 2015
109	*Hydrurga leptonyx*	Mammalia	Phocidae	marine	52	2017	Animal Morphometrics and Individual Health	Test the accuracy of pinni	Krause et al. 2017
111	*Ixobrychus exilis*	Aves	Ardeidae	terrestrial	20	2014	Animal Population Assessments	Habitat analysis	Chabot et al. 2014
112	*Kobus leche*	Mammalia	Bovidae	terrestrial	88	2019	Behavioral Ecology	Disturbance Analysis	Bennit et al. 2019
113	*Lama guanicoe*	Mammalia	Camelidae	terrestrial	122	2020	Animal Population Assessments and Behaviora	Evaluate the variation in	Schroeder et al. 2020
114	*Larus canus*	Aves	Laridae	terrestrial	17	2013	Animal Population Assessments	Automatic detection and	Grenzdorffer, 2013
114	*Larus canus*	Aves	Laridae	terrestrial	23	2015	Animal Population Assessments and Behaviora	xxxxx	Drever et al. 2015
115	*Larus fuscus*	Aves	Laridae	terrestrial	77	2018	Animal Population Assessments and Behaviora	xxxxx	Rush et al. 2018
116	*Larus glaucescens*	Aves	Laridae	terrestrial	23	2015	Animal Population Assessments and Behaviora	xxxxx	Drever et al. 2015
116	*Larus glaucescens*	Aves	Laridae	terrestrial	120	2019	Animal Population Assessments	Population analyzes	Blight et al. 2019
117	*Larus glaucoides*	Aves	Laridae	terrestrial	49	2017	Animal Population Assessments and Behaviora	Comparison of methodol	Brisson-Curadeau et al. 2017
118	*Larus hyperboreus*	Aves	Laridae	terrestrial	49	2017	Animal Population Assessments and Behaviora	Comparison of methodol	Brisson-Curadeau et al. 2017
119	*Lathamus discolor*	Aves	Psittaculidae	terrestrial	69	2018	Animal Population Assessments	Tracking small radio-tagg	Cliff et al. 2018
120	*Lepidochelys olivacea*	Reptilia	Cheloniidae	marine	40	2017	Animal Population Assessments	Population analyzes	Sykora-Bodie et al. 2017

121	*Leptonychotes weddellii*	Mammalia	Phocidae	marine	61	2018	Animal Population Assessments	Population analyzes	Korczak-Abshire et al. 2018
122	*Leptoptilos crumenifer*	Aves	Ciconiidae	terrestrial	128	2020	Animal Population Assessments	Identification/Detection	Francis et al. 2020
123	*Lepus europaeus*	Mammalia	Leporidae	terrestrial	127	2020	Animal Population Assessments	Identification/Detection	Karp, 2020
124	*Leucophaeus atricilla*	Aves	Laridae	terrestrial	126	2020	Behavioral Ecology	Disturbance Analysis	Barr et al. 2020
125	*Loxodonta africana*	Mammalia	Elephantidae	terrestrial	2	2013	Animal Population Assessments	Survey methodology	Vermeulen et al. 2013
125	*Loxodonta africana*	Mammalia	Elephantidae	terrestrial	35	2016	Animal Population Assessments	Actions for species conser	Hahn et al. 2017
125	*Loxodonta africana*	Mammalia	Elephantidae	terrestrial	88	2019	Behavioral Ecology	Disturbance Analysis	Bennit et al. 2019
126	*Macronectes giganteus*	Aves	Procellariidae	terrestrial	61	2018	Animal Population Assessments	Population analyzes	Korczak-Abshire et al. 2018
126	*Macronectes giganteus*	Aves	Procellariidae	terrestrial	68	2018	Behavioral Ecology	Disturbance Analysis	Weimerskirch et al. 2018
127	*Macronectes halli*	Aves	Procellariidae	terrestrial	68	2018	Behavioral Ecology	Disturbance Analysis	Weimerskirch et al. 2018
128	*Macropus giganteus*	Mammalia	Macropodidae	terrestrial	136	2020	Animal Population Assessments	Population analyzes	Brunton et al. 2020
128	*Macropus giganteus*	Mammalia	Macropodidae	terrestrial	143	2020	Behavioral Ecology	Disturbance Analysis	Brunton et al. 2019
129	*Manorina melanocephala*	Aves	Meliphagidae	terrestrial	15	2015	Animal Population Assessments	Radio localization	Cliff et al. 2015
129	*Manorina melanocephala*	Aves	Meliphagidae	terrestrial	124	2020	Behavioral Ecology	Disturbance Analysis	Weston et al. 2020
130	*Megaptera novaeangliae*	Mammalia	Balaenopteridae	marine	9	2017	Animal Population Assessments	Identification/Detection	Hodgson et al. 2017
130	*Megaptera novaeangliae*	Mammalia	Balaenopteridae	marine	33	2016	Animal Morphometrics and Individual Health	Test the feasibility of usin	Christiansen et al. 2016
130	*Megaptera novaeangliae*	Mammalia	Balaenopteridae	marine	41	2017	Animal Population Assessments	Comparison of methodolo	Hodgson et al. 2017
130	*Megaptera novaeangliae*	Mammalia	Balaenopteridae	marine	42	2010	Animal Morphometrics and Individual Health	Collection of exhaled brea	Acevedo-Whitehouse et al. 2010
130	*Megaptera novaeangliae*	Mammalia	Balaenopteridae	marine	50	2017	Animal Morphometrics and Individual Health	Development of a new m	Pirotta et al. 2017
130	*Megaptera novaeangliae*	Mammalia	Balaenopteridae	marine	54	2018	Animal Population Assessments	Analysis of environmental	Aniceto et al. 2018
130	*Megaptera novaeangliae*	Mammalia	Balaenopteridae	terrestrial	119	2019	Animal Morphometrics and Individual Health	Quantifying marine mam	Horton et al. 2019
131	*Mephitis mephitis*	Mammalia	Mephitidae	terrestrial	101	2019	Animal Population Assessments	Identification/Detection	Bushaw et al. 2019
132	*Mirounga leonina*	Mammalia	Phocidae	marine	61	2018	Animal Population Assessments	Population analyzes	Korczak-Abshire et al. 2018
133	*Mobulidae sp.*	Chondrichthyes	Mobulidae	marine	129	2020	Animal Population Assessments	Identification/Detection	Kelaher et al. 2020
134	*Mustela sp.*	Mammalia	Mustelidae	terrestrial	101	2019	Animal Population Assessments	Identification/Detection	Bushaw et al. 2019
135	*Mycteria ibis*	Aves	Ciconiidae	terrestrial	128	2020	Animal Population Assessments	Identification/Detection	Francis et al. 2020
136	*Myliobatis sp.*	Chondrichthyes	Myliobatidae	marine	129	2020	Animal Population Assessments	Identification/Detection	Kelaher et al. 2020
137	*Natator depressus*	Reptilia	Cheloniidae	marine	55	2018	Behavioral Ecology	Disturbance Analysis	Bevan et al. 2018
138	*Negaprion brevirostris*	Chondrichthyes	Carcharhinidae	marine	76	2018	Animal Population Assessments	Identify and estimate shar	Hensel et al. 2018
139	*Neovison vison*	Mammalia	Mustelidae	terrestrial	101	2019	Animal Population Assessments	Identification/Detection	Bushaw et al. 2019
140	*Nycticorax nycticorax*	Aves	Ardeidae	terrestrial	132	2020	Animal Population Assessments	Nest Identification/Detec	Schedl et al. 2020
141	*Ocyphaps lophotes*	Aves	Columbidae	terrestrial	124	2020	Behavioral Ecology	Disturbance Analysis	Weston et al. 2020
142	*Odocoileus virginianus*	Mammalia	Cervidae	terrestrial	39	2016	Animal Population Assessments	Identification/Detection	Chrétien et al. 2016
142	*Odocoileus virginianus*	Mammalia	Cervidae	terrestrial	133	2020	Animal Population Assessments	Population analyzes	Beaver et al. 2020
143	*Onychoprion aleuticus*	Aves	Laridae	terrestrial	101	2019	Animal Population Assessments	Identification/Detection	Bushaw et al. 2019
143	*Onychoprion aleuticus*	Aves	Laridae	terrestrial	104	2019	Animal Population Assessments	Population analyzes	Magness et al. 2019
144	*Orcinus orca*	Mammalia	Delphinidae	marine	31	2015	Animal Morphometrics and Individual Health	Test the feasibility of usin	Durban et al. 2015
144	*Orcinus orca*	Mammalia	Delphinidae	marine	54	2018	Animal Population Assessments	Analysis of environmental	Aniceto et al. 2018
145	*Pan troglodytes*	Mammalia	Hominidae	terrestrial	27	2015	Animal Population Assessments	Nest Identification/Detec	Van Andel et al. 2015
145	*Pan troglodytes*	Mammalia	Hominidae	terrestrial	56	2018	Animal Population Assessments	Evaluate performance for	Bonnin et al. 2018
146	*Pandion haliaetus*	Aves	Pandionidae	terrestrial	113	2015	Animal Population Assessments	Identification/Detection	Junda et al. 2015
147	*Pantholops hodgsonii*	Mammalia	Bovidae	terrestrial	103	2018	Animal Population Assessments	Population analyzes	Hu et al. 2018

148	*Passer domesticus*	Aves	Passeridae	terrestrial	124	2020	Behavioral Ecology	Disturbance Analysis	Weston et al. 2020
149	*Pelecanus conspicillatus*	Aves	Pelecanidae	terrestrial	124	2020	Behavioral Ecology	Disturbance Analysis	Weston et al. 2020
150	*Pelecanus rufescens*	Aves	Pelecanidae	terrestrial	128	2020	Animal Population Assessments	Identification/Detection	Francis et al. 2020
151	*Pelecanus thagus*	Aves	Pelecanidae	terrestrial	109	2019	Behavioral Ecology	Disturbance Analysis	Irigoin-Lovera et al. 2019
152	*Phalacrocorax atriceps bransfieldensis*	Aves	Phalacrocoracidae	terrestrial	61	2018	Animal Population Assessments	Population analyzes	Korczak-Abshire et al. 2018
152	*Phalacrocorax atriceps*	Aves	Phalacrocoracidae	terrestrial	68	2018	Behavioral Ecology	Disturbance Analysis	Weimerskirch et al. 2018
153	*Phalacrocorax auritus*	Aves	Phalacrocoracidae	terrestrial	14	2015	Animal Population Assessments	Investigate application of	Dulava et al. 2015
154	*Phalacrocorax bougainvilli*	Aves	Phalacrocoracidae	terrestrial	109	2019	Behavioral Ecology	Disturbance Analysis	Irigoin-Lovera et al. 2019
155	*Phalacrocorax sulcirostris*	Aves	Phalacrocoracidae	terrestrial	124	2020	Behavioral Ecology	Disturbance Analysis	Weston et al. 2020
156	*Phalacrocorax varius*	Aves	Phalacrocoracidae	terrestrial	124	2020	Behavioral Ecology	Disturbance Analysis	Weston et al. 2020
157	*Phaps chalcoptera*	Aves	Columbidae	terrestrial	124	2020	Behavioral Ecology	Disturbance Analysis	Weston et al. 2020
158	*Phascolarctos cinereus*	Mammalia	Phascolarctidae	terrestrial	4	2016	Animal Population Assessments	Identification/Detection	Gonzalez et al. 2016
158	*Phascolarctos cinereus*	Mammalia	Phascolarctidae	terrestrial	89	2019	Animal Population Assessments	Identification/Detection	Corcoran et al. 2019
159	*Phoca largha*	Mammalia	Phocidae	marine	43	2015	Animal Population Assessments	Population analyzes	Moreland et al. 2015
160	*Phoca vitulina*	Mammalia	Phocidae	marine	24	2015	Animal Population Assessments and Behaviora	xxxxx	Pomeroy et al. 2015
161	*Phocoena phocoena*	Mammalia	Phocoenidae	marine	54	2018	Animal Population Assessments	Analysis of environmental	Aniceto et al. 2018
162	*Phoebetria fusca*	Aves	Diomedeidae	terrestrial	68	2018	Behavioral Ecology	Disturbance Analysis	Weimerskirch et al. 2018
163	*Phoebetria palpebrata*	Aves	Diomedeidae	terrestrial	68	2018	Behavioral Ecology	Disturbance Analysis	Weimerskirch et al. 2018
164	*Phoenicopterus roseus*	Aves	Phoenicopteridae	terrestrial	30	2015	Behavioral Ecology	Test the impact of drones	Vas et al. 2015
165	*Physeter macrocephalus*	Mammalia	Physeteridae	marine	42	2010	Animal Morphometrics and Individual Health	Collection of exhaled brea	Acevedo-Whitehouse et al. 2010
166	*Platalea ajaja*	Aves	Threskiornithidae	terrestrial	126	2020	Behavioral Ecology	Disturbance Analysis	Barr et al. 2020
167	*Platalea minor*	Aves	Threskiornithidae	terrestrial	32	2015	Animal Population Assessments	Population analyzes	Liu et al. 2015
167	*Platalea minor*	Aves	Threskiornithidae	terrestrial	100	2019	Animal Population Assessments	Identification/Detection	Lee et al. 2019
168	*Platycerus elegans*	Aves	Psittaculidae	terrestrial	124	2020	Behavioral Ecology	Disturbance Analysis	Weston et al. 2020
169	*Platycerus eximius*	Aves	Psittaculidae	terrestrial	124	2020	Behavioral Ecology	Disturbance Analysis	Weston et al. 2020
170	*Plegadis falcinellus*	Aves	Threskiornithidae	terrestrial	75	2018	Animal Population Assessments	Perform aerial censuses o	Afán et al. 2018
170	*Plegadis falcinellus*	Aves	Threskiornithidae	terrestrial	84	2018	Behavioral Ecology	Disturbance Analysis	Reintsma et al. 2018
171	*Pluvialis squatarola*	Aves	Charadriidae	terrestrial	23	2015	Animal Population Assessments and Behaviora	xxxxx	Drever et al. 2015
172	*Pongo abelii*	Mammalia	Hominidae	terrestrial	36	2016	Animal Population Assessments	Nest Identification/Detect	Wich et al. 2016
172	*Pongo abelii*	Mammalia	Hominidae	terrestrial	44	2017	Animal Population Assessments	Habitat analysis	Szantoi et al. 2017
172	*Pongo abelii*	Mammalia	Hominidae	terrestrial	86	2012	Animal Population Assessments	Identification/Detection	Koh e Wich (2012)
173	*Pongo pygmaeus*	Mammalia	Hominidae	terrestrial	94	2019	Animal Population Assessments	Identification/Detection	Burke et al. 2019
173	*Pongo pygmaeus*	Mammalia	Hominidae	terrestrial	106	2019	Animal Population Assessments	Identification/Detection	Hasanah et al. 2019
174	*Porphyrio porphyrio*	Aves	Rallidae	terrestrial	124	2020	Behavioral Ecology	Disturbance Analysis	Weston et al. 2020
175	*Potos flavus*	Mammalia	Procyonidae	terrestrial	110	2019	Animal Population Assessments	Identification/Detection	Kays et al. 2019
176	*Procapra picticaudata*	Mammalia	Bovidae	terrestrial	80	2018	Animal Population Assessments	Population analyzes	Guo et al. 2018
177	*Procyon lotor*	Mammalia	Procyonidae	terrestrial	101	2019	Animal Population Assessments	Identification/Detection	Bushaw et al. 2019
178	*Propithecus tattersalli*	Mammalia	Indriidae	terrestrial	134	2020	Animal Population Assessments and Behaviora	photograph and quantify	Semel et al. 2020
179	*Pseudois nayaur*	Mammalia	Bovidae	terrestrial	80	2018	Animal Population Assessments	Population analyzes	Guo et al. 2018
180	*Pygoscelis adeliae*	Aves	Spheniscidae	terrestrial	37	2016	Behavioral Ecology	Disturbance Analysis	Rummler et al. 2016
180	*Pygoscelis adeliae*	Aves	Spheniscidae	terrestrial	61	2018	Animal Population Assessments	Population analyzes	Korczak-Abshire et al. 2018
180	*Pygoscelis adeliae*	Aves	Spheniscidae	terrestrial	64	2018	Animal Population Assessments	Population analyzes	Borowicz et al. 2018

180	*Pygoscelis adeliae*	Aves	Spheniscidae	terrestrial	79	2018	Behavioral Ecology	Disturbance Analysis	Rummler et al. 2018
181	*Pygoscelis antarcticus*	Aves	Spheniscidae	terrestrial	8	2015	Animal Morphometrics and Individual Health	Test the feasibility of usin	Goebel et al. 2015
181	*Pygoscelis antarcticus*	Aves	Spheniscidae	terrestrial	61	2018	Animal Population Assessments	Population analyzes	Korczak-Abshire et al. 2018
181	*Pygoscelis antarcticus*	Aves	Spheniscidae	terrestrial	67	2011	Animal Population Assessments	Identification/Detection	Gardner et al. 2011
182	*Pygoscelis papau*	Aves	Spheniscidae	terrestrial	8	2015	Animal Morphometrics and Individual Health	Test the feasibility of usin	Goebel et al. 2015
182	*Pygoscelis papau*	Aves	Spheniscidae	terrestrial	46	2015	Animal Population Assessments	Develop protocol for mon	Ratcliffe et al. 2015
182	*Pygoscelis papau*	Aves	Spheniscidae	terrestrial	67	2011	Animal Population Assessments	Identification/Detection	Gardner et al. 2011
182	*Pygoscelis papua*	Aves	Spheniscidae	terrestrial	68	2018	Behavioral Ecology	Disturbance Analysis	Weimerskirch et al. 2018
182	*Pygoscelis papua*	Aves	Spheniscidae	terrestrial	79	2018	Behavioral Ecology	Disturbance Analysis	Rummler et al. 2018
183	*Recurvirostra novaehollandiae*	Aves	Recurvirostridae	terrestrial	124	2020	Behavioral Ecology	Disturbance Analysis	Weston et al. 2020
184	*Rhinobatidae sp.*	Chondrichthyes	Rhinobatidae	marine	129	2020	Animal Population Assessments	Identification/Detection	Kelaher et al. 2020
185	*Rhinopithecus roxellana*	Mammalia	Cercopithecidae	terrestrial	98	2019	Animal Population Assessments	Identification/Detection	He et al. 2019
186	*Rhinoptera neglecta*	Chondrichthyes	Rhinopteridae	marine	91	2019	Animal Population Assessments	Identification/Detection	Colefax et al. 2020
186	*Rhinoptera neglecta*	Chondrichthyes	Rhinopteridae	marine	129	2020	Animal Population Assessments	Identification/Detection	Kelaher et al. 2020
187	*Rhipidura leucophrys*	Aves	Rhipiduridae	terrestrial	124	2020	Behavioral Ecology	Disturbance Analysis	Weston et al. 2020
188	*Rynchops niger*	Aves	Laridae	terrestrial	126	2020	Behavioral Ecology	Disturbance Analysis	Barr et al. 2020
189	*Saundersilarus saundersi*	Aves	Laridae	terrestrial	137	2020	Animal Population Assessments	Population analyzes	Choi et al. 2020
190	*Sotalia fluviatilis*	Mammalia	Delphinidae	freshwater	102	2019	Animal Population Assessments	Identification/Detection	Oliveira-da-Costa et al. 2019
191	*Sphyrna tiburo*	Chondrichthyes	Sphyrnidae	marine	76	2018	Animal Population Assessments	Identify and estimate shar	Hensel et al. 2018
192	*Spizella pusilla*	Aves	Passerellidae	terrestrial	90	2019	Animal Population Assessments	Compare methodologies f	Scholten et al. 2019
193	*Stercorarious antarcticus*	Aves	Stercorariidae	terrestrial	68	2018	Behavioral Ecology	Disturbance Analysis	Weimerskirch et al. 2018
194	*Sterna hirundo*	Aves	Laridae	terrestrial	25	2015	Animal Population Assessments	Determine the effectivene	Chabot et al. 2015
194	*Sterna hirundo*	Aves	Laridae	terrestrial	84	2018	Behavioral Ecology	Disturbance Analysis	Reintsma et al. 2018
195	*Streptopelia chinensis*	Aves	Columbidae	terrestrial	124	2020	Behavioral Ecology	Disturbance Analysis	Weston et al. 2020
196	*Sternula antillarum*	Aves	Laridae	terrestrial	130	2020	Animal Population Assessments and Behaviora	Strategies to minimize po	Mapes et al. 2020
197	*Streptoprocne zonaris*	Aves	Apodidae	terrestrial	139	2020	Behavioral Ecology	Disturbance Analysis	Mesquita et al. 2020
198	*Sturnus vulgaris*	Aves	Sturnidae	terrestrial	124	2020	Behavioral Ecology	Disturbance Analysis	Weston et al. 2020
199	*Sula variegata*	Aves	Sulidae	terrestrial	109	2019	Behavioral Ecology	Disturbance Analysis	Irigoin-Lovera et al. 2019
200	*Sus scrofa*	Mammalia	Suidae	terrestrial	5	2017	Animal Population Assessments	Identification/Detection	Witczuk et al. 2017
200	*Sus scrofa*	Mammalia	Suidae	terrestrial	85	2018	Animal Population Assessments	Describe and assess a new	Laguna et al. 2018
201	*Tadarida brasiliensis*	Mammalia	Molossidae	terrestrial	58	2018	Animal Morphometrics and Individual Health	Conduct acoustic recordin	Kloepper and Kinniry, 2018
202	*Taxidea taxus*	Mammalia	Mustelidae	terrestrial	101	2019	Animal Population Assessments	Identification/Detection	Bushaw et al. 2019
203	*Thalasseus bergii*	Aves	Laridae	terrestrial	13	2016	Animal Population Assessments	Compare between drone	Hodgson et al. 2016
203	*Thalasseus bergii*	Aves	Laridae	terrestrial	55	2018	Behavioral Ecology	Disturbance Analysis	Bevan et al. 2018
204	*Thalasseus maximus*	Aves	Laridae	terrestrial	126	2020	Behavioral Ecology	Disturbance Analysis	Barr et al. 2020
205	*Threskiomis Molucca*	Aves	Threskiornithidae	terrestrial	124	2020	Behavioral Ecology	Disturbance Analysis	Weston et al. 2020
206	*Threskiornis spinicollis*	Aves	Threskiornithidae	terrestrial	82	2018	Behavioral Ecology	Disturbance Analysis	Lyons et al. 2018
206	*Threskiornis spinicollis*	Aves	Threskiornithidae	terrestrial	97	2019	Animal Population Assessments	Population analyzes	Lyons et al. 2019
206	*Threskiomis spinicollis*	Aves	Threskiornithidae	terrestrial	124	2020	Behavioral Ecology	Disturbance Analysis	Weston et al. 2020
206	*Threskiornis spinicollis*	Aves	Threskiornithidae	terrestrial	128	2020	Animal Population Assessments	Identification/Detection	Francis et al. 2020
207	*Trichechus manatus*	Mammalia	Trichechidae	marine	7	2006	Animal Population Assessments	Test the feasibility of usin	Jones IV et al. 2006
207	*Trichechus manatus manatus*	Mammalia	Trichechidae	marine	73	2018	Behavioral Ecology	Disturbance Analysis	Ramos et al. 2018

207	*Trichechus manatus manatus*	Mammalia	Trichechidae	marine	125	2020	Animal Population Assessments	Identification/Detection	Landeo-Yauri et al. 2020
208	*Tringa nebularia*	Aves	Scolopacidae	terrestrial	30	2015	Behavioral Ecology	Test the impact of drones	Vas et al. 2015
209	*Tursiops truncatus*	Mammalia	Delphinidae	marine	42	2010	Animal Morphometrics and Individual Health	Collection of exhaled brea	Acevedo-Whitehouse et al. 2010
209	*Tursiops truncatus*	Mammalia	Delphinidae	marine	73	2018	Behavioral Ecology	Disturbance Analysis	Ramos et al. 2018
209	*Tursiops truncatus*	Mammalia	Delphinidae	marine	96	2019	Animal Population Assessments	Identification/Detection	Subhan et al. 2019
209	*Tursiops sp.*	Mammalia	Delphinidae	marine	129	2020	Animal Population Assessments	Identification/Detection	Kelaher et al. 2020
210	*Uria aalge*	Aves	Alcidae	terrestrial	49	2017	Animal Population Assessments and Behaviora	Comparison of methodolo	Brisson-Curadeau et al. 2017
210	*Uria aalge*	Aves	Alcidae	terrestrial	71	2018	Behavioral Ecology	Disturbance Analysis	Fuller et al. 2018
211	*Uria lomvia*	Aves	Alcidae	terrestrial	49	2017	Animal Population Assessments and Behaviora	Comparison of methodolo	Brisson-Curadeau et al. 2017
212	*Ursus americanus*	Mammalia	Ursidae	terrestrial	22	2015	Behavioral Ecology	Disturbance Analysis	Ditmer et al. 2015
212	*Ursus americanus*	Mammalia	Ursidae	terrestrial	87	2019	Behavioral Ecology	Disturbance Analysis	Ditmer et al. 2019
213	*Ursus maritimus*	Mammalia	Ursidae	terrestrial	53	2018	Animal Population Assessments	Identification/Detection	Barnas et al. 2018
213	*Ursus maritimus*	Mammalia	Ursidae	terrestrial	141	2019	Animal Population Assessments	Identification/Detection	Chabot et al. 2019
214	*Vanellus miles*	Aves	Charadriidae	terrestrial	124	2020	Behavioral Ecology	Disturbance Analysis	Weston et al. 2020
215	*Vanellus vanellus*	Aves	Charadriidae	terrestrial	51	2017	Animal Population Assessments	Nest Identification/Detect	Israel and Reinhard, 2017
215	*Vanellus vanellus*	Aves	Charadriidae	terrestrial	138	2020	Animal Population Assessments	Nest Identification/Detect	Santangeli et al. 2020
216	*Vombatus ursinus*	Mammalia	Vombatidae	terrestrial	117	2019	Animal Population Assessments	Population analyzes	Old et al. 2019
217	*Vulpes vulpes*	Mammalia	Canidae	terrestrial	101	2019	Animal Population Assessments	Identification/Detection	Bushaw et al. 2019
218	*Mobula birostris*	Chondrichthyes	Myliobatidae	marine	142	2020	Animal Population Assessments and Behaviora	Behavior and spatio-temp	Pate and Marshall, 2020

* https://www.worldwildlife.org/biomes