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Essays and Perspectives

Airport noise and wildlife conservation: What are we missing?

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ABSTRACT

Noise produced by aircraft is a concern for human populations and its production is controlled by specific laws around the world. Here, we address the conflicting existence of Natural Protected Areas (PAs) of high priority conservation located within noise-impacted areas of Brazilian airports and discuss how noise can generate physiological stress and jeopardize wildlife breeding. Further, we review how this subject has been handled around the world, and highlight the need to initiate a discussion focused on Brazilian legislation, setting in motion an evidence-oriented policy that considers the needs of wildlife for an environmental protection area and for the control of human produced-noise pollution.

Introduction

Noise produced by aircrafts represents a public human health concern (Jarup et al., 2008) and is considered to be a complex and difficult problem to mitigate (INFRAERO, 2004). The air transportation of passengers and cargo is globally widespread and ubiquitous in modern life, constituting a continuously growing industry. In Brazil, between 2003 and 2014, aviation activity increased 10% each year and worldwide is projected to continue increasing until 2050 (Yosimoto et al., 2016). Airline activity results in three major ecological impacts: wildlife–aircraft collisions, atmospheric pollution, and acoustic pollution (Kelly and Allan, 2006). This last impact is one of the major constraints for aviation growth (Antoine and Kroo, 2004).

In addition to generating a devaluation in property values around airports (Feitelson et al., 1996), human populations subjected to airport noise are also susceptible to various health problems. Airport noise leads to sleep disturbance in adults (Finegold, 2010; Jones, 2009), higher risks of hypertension (Babisch et al., 2013), and cardiovascular problems such as heart disease and stroke (Floud et al., 2013). In school-age children, airport noise causes high levels of annoyance (Nunes and Sattler, 2006), resulting in motivational deficit (Bullinger et al., 1999), impaired reading comprehension and impaired recognition memory (Haines et al., 2001; Stansfeld et al., 2005), although no relationship to cortisol levels or mental health problems have been found (Haines et al., 2001). Based on these findings, many laws and regulations focus on controlling the impacts of airport noise on human life, such as the Regulation of Civil Aviation, discussed below (ANAC, 2013).

In addition to the impacts on human well-being, airport noise is also reported to have negative impacts on wildlife (Pepper et al., 2003). The most obvious effect is animal fleeing in response to panic (Frid, 2003; Linley et al., 2018), caused by sudden peaks of noise, inducing escape behavior. But studies have also reported increases in alert behavior (Goudie, 2006; Klett-Mingo et al., 2016), changes in vocal behavior (Dominoni et al., 2016; Gil et al., 2014; Kruger and Du Preez, 2016; Sierro et al., 2017), and jeopardized reproductive success (Awbrey and Hunsaker, 1997; DeRose-Wilson et al., 2015).

Here, we provide information about Brazilian legislation focusing on airport acoustic impacts and protection of wildlife in the context of airport activities. We address existing legislation about

Abbreviations: ANAC, Agência Nacional de Aviação Civil/Brazilian National Agency of Civil Aviation; APA, Área de Proteção Ambiental/Area of Environmental Protection; ARIE, Área de Relevante Interesse Ecológico/Areas of Relevant Ecological Interest; ESEC, Estação Ecológica/Ecological Station; IBGE, Instituto Brasileiro de Geografia e Estatística/Brazilian Institute of Geography and Statistics; IUCN, International Union for Conservation of Nature; L_{AeqD}, Diurnal Levels of Acoustic Pressure; L_{AeqN}, Nocturnal Levels of Acoustic Pressure; L_{DN}, Day-Night Levels of Acoustic Pressure; MI, Ministério de Infraestrutura/Brazilian Infrastructure Ministry; MMA, Ministério do Meio Ambiente/Brazilian Environmental Ministry; PA, Unidades de Conservação/Natural Protected Areas; PZR, Plano de Zoneamento de Ruído/Noise-zoning Plan; RBAC, Regulamento Brasileiro de Aviação Civil/Brazilian Regulation of Civil Aviation; SNUC, Sistema Nacional de Unidades de Conservação/Brazilian National System of Protected Areas; UNESCO, United Nations Educational, Scientific and Cultural Organization; WHO, World Health Organization.

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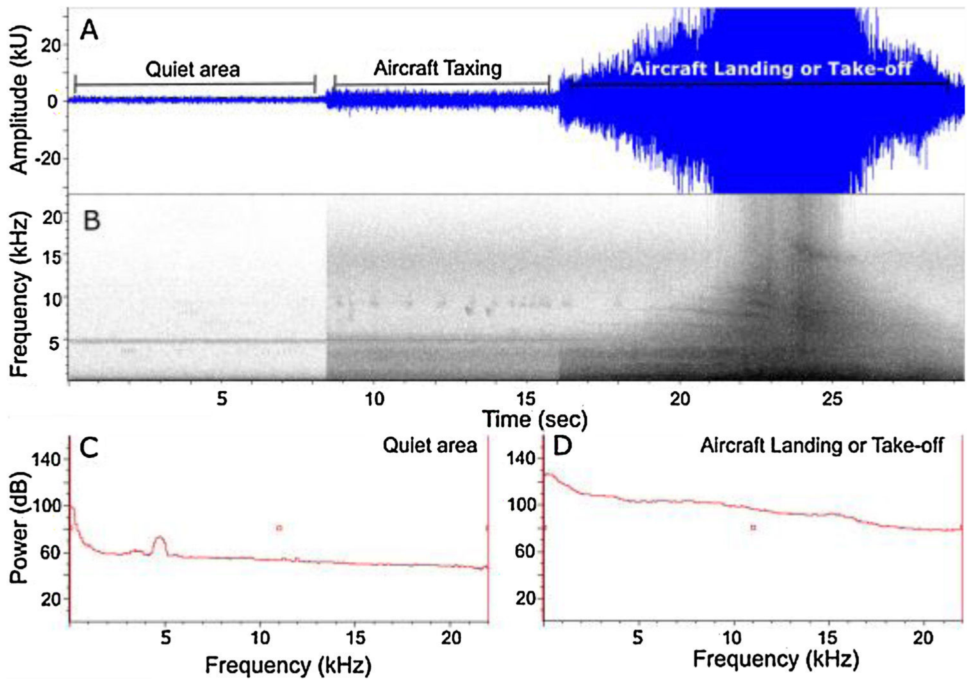

Fig. 1. Airport noise profile in a 30-s audio containing a quiet place soundscape and two airport soundscapes (aircraft taxing and aircraft landing or take off). (A) Waveform audio representation; (B) spectrogram audio representation; (C) power spectrum of the quiet area; and (D) power spectrum of the aircraft landing or take-off. All audio segments were recorded using Automated Recording Units (ARUs) in São Paulo state, on 08 December 2014.

the types of areas specified for wildlife protection according to the Brazilian National System of Protected Areas (SNUC: Sistema Nacional de Unidades de Conservação), present an overview of the 12 busiest Brazilian airports and their proximity to Protected Areas, focusing on a study case of airport activity and conservation area conflict, and provide information for understanding the impacts of noise and stress on wildlife breeding. Further, we present an overview on how this subject has been handled in other countries and point toward measures that could be implemented in Protected Areas and in airport policies, to address the airport–wildlife conflict in Brazil. Our objective is to provide scientific information to support policy-makers who are developing evidence-based conservation policy in Brazil (Karam-Gemael et al., 2018).

Noise regulation around airports

The Brazilian Regulation of Civil Aviation (RBAC – Regulamento Brasileiro de Aviação Civil) defines aviation noise as "noise originated from activities of aircraft circulation, approximation, take-off, landing, rolling and engine testing". Most of this noise is produced by engine activity and engineering aerodynamics (Rainho, 2016). Typical airport noise patterns are characterized by constant high amplitude noise in the low-frequency ranges and strong, sudden peaks of high amplitude noise in a broad range of frequencies (Sierro et al., 2017; Smith, 1989) (e.g., aircraft landing and take-off; Fig. 1).

Noise intensity in airport environments is internationally measured by a "Day-Night level of acoustic pressure" called the L_{DN} index. This is calculated as the mean levels of noise produced diurnally (L_{AeqD}) and nocturnally (L_{AeqN}), to which 10 dB are added (Falzone, 1999). These metrics are controlled by the A-weighting, which simulates human hearing, attenuating loudness of lower (below 500 Hz) and higher frequencies (above 4 kHz) (Berger, 2003).

The RBAC no. 161 establishes instructions for developing Noise Zoning Plans (PZR) for each Brazilian aerodrome, by setting parallel curves of equal noise intensities (isophones) produced by aviation activity at L_{DN} equivalents to 85, 80, 75, 70 and 65 dB (ANAC, 2013). Land use categories acceptable in airport neighborhoods are also regulated by RBAC no. 161, which determines noise levels that are allowed in residential (65 dB L_{DN}), commercial, industrial/animal production, recreational (65–75 dB L_{DN}), and public areas (schools, hospitals, churches: 65–75 dB L_{DN}) (ANAC, 2013). In contrast, the Brazilian Association of Technical Norms states, in its regulation NBR no. 10151 (ABNT, 2000), that the acceptable diurnal noise levels in human communities must not exceed a maximum of 70 dB (L_{AeqD}) for industrial areas, 60 dB (L_{AeqD}) for commercial areas, 50 dB (L_{AeqD}) for residential, hospital and school areas, and 40 dB (L_{AeqD}) for rural areas.

According to the World Health Organization (Berglund et al., 1999), constant exposure to noise levels above L_{Aeq} 65 dB can be detrimental to human health, levels between L_{Aeq} 60–65 dB can cause moderate annoyance, and levels between L_{Aeq} 55–60 dB can cause annoyance. However, RBAC no. 161 allows human occupation of areas with L_{DN} above the 65 dB limit, a range of noise known to be hazardous to humans.

Wildlife protection and airports

Although noticeably widespread in landscapes around the world (Barber et al., 2009), noise produced by human transportation has not received appropriate attention in terms of wildlife impacts (Francis and Barber, 2013). As pointed out before, the impacts of noise on wildlife include many behavioral changes, such as increased alert behavior (Goudie, 2006; Klett-Mingo et al., 2016), modifications in vocal behavior (Dominoni et al., 2016; Gil et al., 2014; Kruger and Du Preez, 2016; Sierro et al., 2017), and lower reproductive success (Awbrey and Hunsaker, 1997; DeRose-Wilson et al., 2015).

Airport laws concerning wildlife in Brazil only address the risk of wildlife–aircraft collision and do not consider the impact of airport noise on wildlife welfare in Protected Areas. The focus on wildlife–aircraft collision is understandable, due to the high expenses to airport administration generated by this type of accident (Allan, 2000). However, this does not justify the lack of initiatives for mitigation of noise impacts. Additionally, regulations for the purpose of noise assessment or to prevent aircraft noise within Protected Areas are also lacking in Brazilian environmental legislation.

Protected Areas in Brazil

Protected Areas (PA) in Brazil are defined by the Brazilian National System of Protected Areas (SNUC), established by law no. 9.985 (BRASIL, 2000). SNUC defines Protected Areas as "areas and their environmental resources (including water), with relevant natural characteristics, legally instituted by Public Law, with conservation objectives and defined limits, under special administration, to which are granted suitable protection". This law establishes two PA categories. The first comprises "Areas of Integral Protection", which includes Ecological Stations (ESEC), Biological Reserves, National Parks, Natural Monuments, and Wildlife Refuges. These areas have restrictive use and grant a higher level of protection of natural resources, allowing only indirect use without consumption of resources, harvesting or destruction. The second PA category includes "Areas of Sustainable Use", which incorporates Areas of Environmental Protection (APA), Areas of Relevant Ecological Interest (ARIE), National Forests, Extractive Reserves, Faunal Reserves, Sustainable Development Reserves, and Natural Heritage Private Reserves. These PA combine conservation with sustainable use of a portion of the area's natural resources, including commercial exploration.

As different activities are allowed inside each PA type, several of them are compatible with airport noise. However, the most restrictive areas, such as Areas of Integral Protection, should take airport noise influence into consideration, determining the acceptable levels of noise interference that can adequately allow maintenance of its objectives as an area of high conservation priority.

Airports and Protected Areas overlap in Brazil

Brazil has 588 public civil aerodromes registered in the National Agency of Civil Aviation (ANAC, 2018a), and 1911 smaller sized private aerodromes (MI, 2019). We were conservative when assessing the overlap of airports and PA in the country, selecting airports that process over five million passengers per year (Class IV according to RBAC 153, ANAC, 2018b) and observing a 10 km radius around each airport centroid position. We also included 115 real aircraft routes, collected from aircraft real-time positions. Information on PA and airport locations were acquired from the Brazilian Environmental Ministry (MMA, 2019) and the Brazilian Infrastructure Ministry (MI, 2019) websites, respectively. Information on aircraft real-time positions was acquired from Flight Aware website (Flight Aware, 2019). The latter data refer to flights among the selected airports and among some Class III airports, which are those with over one million passengers per year (RBAC 153; data acquired on 12 June 2019, ±1 day). See Supplementary Material I for further information on selected flights.

This selection resulted in a total of 12 airports in Class IV and included the busiest airports in Brazil. Here we present the airports and the PA included in their 10 km radius surroundings (Table 1 and Fig. 2). Based on this information we note that six airports raise major concerns due to their proximity to PA: Fortaleza International Airport – Pinto Martins (Fig. 2A), Brasília International Airport – Presidente Juscelino Kubitschek (Fig. 2D), Confins International Airport – Tancredo Neves (Fig. 2E), Rio de Janeiro International Airport – Santos Dumont (Fig. 2G), São Paulo International Airport – Guarulhos (Fig. 2H), and Porto Alegre International Airport – Salgado Filho (Fig. 2L).

Study case: Brasília International Airport – Presidente Juscelino Kubitschek

Brasília International Airport is located in Brasília (Federal District), capital of Brazil. This is the country's third major airport in terms of passenger movement, and first in terms of runway capacity, due to its recent expansion. This airport averages 412 daily flights, transporting approximately 46,000 passengers daily (INFRAMÉRICA, 2018).

The airport is located within a Sustainable Use PA, in the subtype Area of Environmental Protection (APA das Bacias Gama e Cabeça-de-Veado). The airport is also surrounded by several other PA, such as three Areas of Relevant Ecological Interest (ARIEs Capetinga-Taquara, Granja do Ipê, and Riacho Fundo), and one Ecological Station (ESEC Botanical Garden). In addition to these areas described in the SNUC classification, there are other areas inside the APA with a lower protection designation, such as IBGE Ecological Reserve and two Areas of Special Protection (Brasilia's Botanical Garden and Brasilia's Zoological Garden) (Fig. 3; based on IBRAM, 2014). All of the areas included in the Botanical Garden Ecological Station and the IBGE Ecological Reserve also belong to the Cerrado's Biosphere Reserve Core area, as designated in 2019 by the United Nations Educational, Scientific and Cultural Organization – UNESCO (UNESCO, 2019).

In the Brazilian Conservation System, Areas of Environmental Protection (APA) usually are large areas that include both public and private lands, created because of the presence of biotic, abiotic and cultural resources that are important for human welfare, and which present few restrictions in terms of use (BRASIL, 2000). Areas of Relevant Ecological Interest (ARIE), on the other hand, comprise small areas, including public and private lands, with little or no human occupation, created because of the presence of important ecological features, such as rare biotas (BRASIL, 2000). Ecological Stations – ESEC are the most restrictive PA type in the Brazilian system, including only public lands, and allowing no human visitation or disruption. This PA type is primarily intended for preservation of intact nature and scientific research activity (BRASIL, 2000). Finally, UNESCO's Biosphere Reserve, although not included in the SNUC system, represents an area of international concern for conservation issues. These areas were defined by the "Man and Biosphere Program" organized by UNESCO, and include areas of critical importance for the maintenance of global biodiversity. The Biosphere Reserve system comprises three complementary zones (Core, Buffer and Transition), with the "Core area" considered the most important for biodiversity maintenance, since it includes strictly protected ecosystems, species and genetic variations (UNESCO, 2019).

Brasília International Airport includes landing and take-off routes that fly over all the PA described above, generating noise disruption that has yet to be evaluated. According to the Brasilia airport's Specific Noise-Zoning Plan, the 65–70 dB7(A) isophones do not extend beyond airport limits. However, it is common knowledge that residential areas around the airport suffer from excessive aircraft noise (Júnior et al., 2012), which has even become an issue for public petitions and official notifications. A report provided by the National Agency of Civil Aviation (ANAC) evaluated the simultaneous operation of the two parallel runways in this airport (ANAC, 2016), and concluded that the 55 dB L_{DN} isophones reach the Ecological Station – ESEC area, since many flight routes include low altitude curves above the reserve. We evaluated this impact plotting real-time aircraft routes and their real-time altitude – decreased by 1000 m because of Brasilia's terrain elevation (Fig. 3). We observe that many curves are executed over the PA, in altitudes lower than 1000 m.

The noise produced by the airport is also perceived by visitors to the Botanical Garden and by governmental environment agents

Table 1
Busiest airports in Brazil (Class IV – RBAC 153), millions of passengers registered in 2018 (pass/year), and Protected Areas found within a 10 km radius around each airport centroid point.

Airport name	Pass/year	State	Areas of Integral Protection	Areas of Sustainable Use
São Paulo International Airport – Guarulhos	41.1 mi	SP	PEs (a) da Cantareira, (b) de Itaberaba	APA (a) Várzea do Rio Tietê
São Paulo Airport – Congonhas	21.6 mi	SP	PE das Fontes do Ipiranga	
Brasília International Airport – Presidente Juscelino Kubitschek	17.5 mi	DF	ESEC Jardim Botânico	APAs (a) do Planalto Central, (b) das Bacias do Gama e Cabeça de Veado, (c) do Lago Paranoá ARIEs (a) Capetinga-Taquara, (b) Riacho Fundo, (c) do Bosque
Galeão International Airport – Tom Jobim	14.7 mi	RJ		APA São Bento
Confins International Airport – Tancredo Neves	10.2 mi	MG	PE (a) Sumidouro, (b) Serra do Sobrado	APA Carste de Lagoa Santa
Rio de Janeiro Airport – Santos Dumont	9.0 mi	RJ	PN da Tijuca PE da Chacrinha PNMs (a) da Cidade, (b) Penhasco Dois Irmãos, (c) da Catacumba, (d) José Guilherme Merquior, (e) Fonte da Saúde, (f) Paisagem Carioca MN (a) dos Morros Pão de Açúcar e Urca	RESEX (a) Marinha de Itaipu APAs (a) do Sacopã, (b) dos morros da Babilônia e São João, (c) de São José, (d) do Morro do Leme, (e) da Orla Marinha
Campinas International Airport – Viracopos	8.7 mi	SP	PE da Ara PNMs (a) dos Jatobás, (b) do Campo Grande	
Recife International Airport – Guararapes Gilberto Freyre	8.2 mi	PE	RVSs (a) Mata do Engenho Uchôa, (b) Mata do Curado, (c) Mata de Mussaíba, (d) Mata São João da Várzea	
Porto Alegre International Airport – Salgado Filho	8.1 mi	RS	PE do Delta do Jacuí	APA do Delta do Jacuí
Salvador International Airport – Deputado Luís Eduardo Magalhães	7.7 mi	BA		APAs (a) Joanes Ipitanga, (b) Lagoas e Dunas do Abaeté, (c) Plataforma Continental do Litoral
Fortaleza International Airport – Pinto Martins	6.5 mi	CE	PE Rio Cocó	APAs (a) do Estuário do Rio Ceará – Rio Maranguapinho, (b) da Lagoa da Maraponga ARIEs (a) do Cambeba, (b) do Sítio Curió
Curitiba International Airport – Afonso Pena	6.1 mi	PR		APAs (a) do Rio Pequeno, (b) do Rio Piraquara, (c) do Iguaçu

Areas of Integral Protection: ESEC, Estação Ecológica/Ecological Station; PN, Parque Nacional/National Park; PE, Parque Estadual/State Park; PNM, Parque Natural Municipal/Municipality Natural Park; MN, Monumento Natural/Natural Monument; RSV, Refúgio da Vida Silvestre/Wildlife Refuge.
Areas of Sustainable Use: APA, Área de Proteção Ambiental/Areas of Environmental Protection; ARIE, Área de Relevante Interesse Ecológico/Areas of Relevant Ecological Interest; RESEX, Reserva Extrativista/Extractive Reserve.

allocated inside the Ecological Station of the Botanical Garden and the IBGE Ecological Reserve. Such noise is incompatible with the proposed objectives of an Ecological Station. The areas occupied by the Ecological Station of the Botanical Garden and the Cerrado's Biosphere Reserve comprise a continuum of preserved Cerrado biome, promoting the survival and reproduction of medium and large size wildlife, that are unable to maintain populations in smaller sized areas. Among such larger animals, species that have been recorded in these areas include: pumas (*Puma concolor*), ocelots (*Leopardus pardalis*), lowland tapirs (*Tapirus terrestris*), maned wolves (*Chrysocyon brachyurus*), crab-eating foxes (*Cerdocyon thous*), giant armadillos (*Priodontes maximus*), giant anteaters (*Myrmecophaga tridactila*), black-and-gold howler monkeys (*Alouatta caraya*), and gray brockets (*Mazama gouazoupira*) (Cardoso and Sant'Anna, 2017; Juarez, 2008; Lima and Saracura, 2008), some of them classified as Near-Threatened and Vulnerable to Extinction in the IUCN Red List (IUCN, 2016). Several conservation projects are also being developed within these PA.

Understanding how noise and stress impact wildlife reproduction

Several types of noise are known to affect animal welfare, including noise generated by aircrafts, helicopters, gas compressor stations, mines, industries, ships, sonars and road traffic (Bayne et al., 2008; Duarte et al., 2015; Gil et al., 2014; Habib et al., 2007; Kruger and Du Preez, 2016; Lampe et al., 2014; Sousa-Lima et al., 2002; Wright et al., 2011). Noise primarily causes sound masking, jeopardizing animal communication and eliciting costly changes in sound production, affecting birds (Gil et al., 2014), cetaceans (Sousa-Lima et al., 2002), insects (Lampe et al., 2014), frogs (Kruger and Du Preez, 2016), and other taxonomic groups. Because birds depend upon communication for reproductive purposes, exposure to continuous noise has been reported to cause decreases in nest success, brood size, nestling growth rates, and egg success (Fairhurst et al., 2013; Halfwerk et al., 2011; Hayward et al., 2011; Kleist et al., 2018; Strasser and Heath, 2013). This reduced reproductive success brings in turn reductions in population sizes and decreased species richness and diversity in areas impacted by noise (Francis et al., 2009; Reijnen et al., 1995), which even results in changes in patterns of seed dispersion and pollination (Francis et al., 2012). Another consequence of noise masking is the change in alertness, increasing vigilance behavior in detriment of other daily activities (Klett-Mingo et al., 2016). This constant state of alertness associated with stress can bring negative physiological consequences (Anderson et al., 2011).

Noise-elicited stress is the key factor that strengthens the argument that wildlife exposure to chronic noise can jeopardize

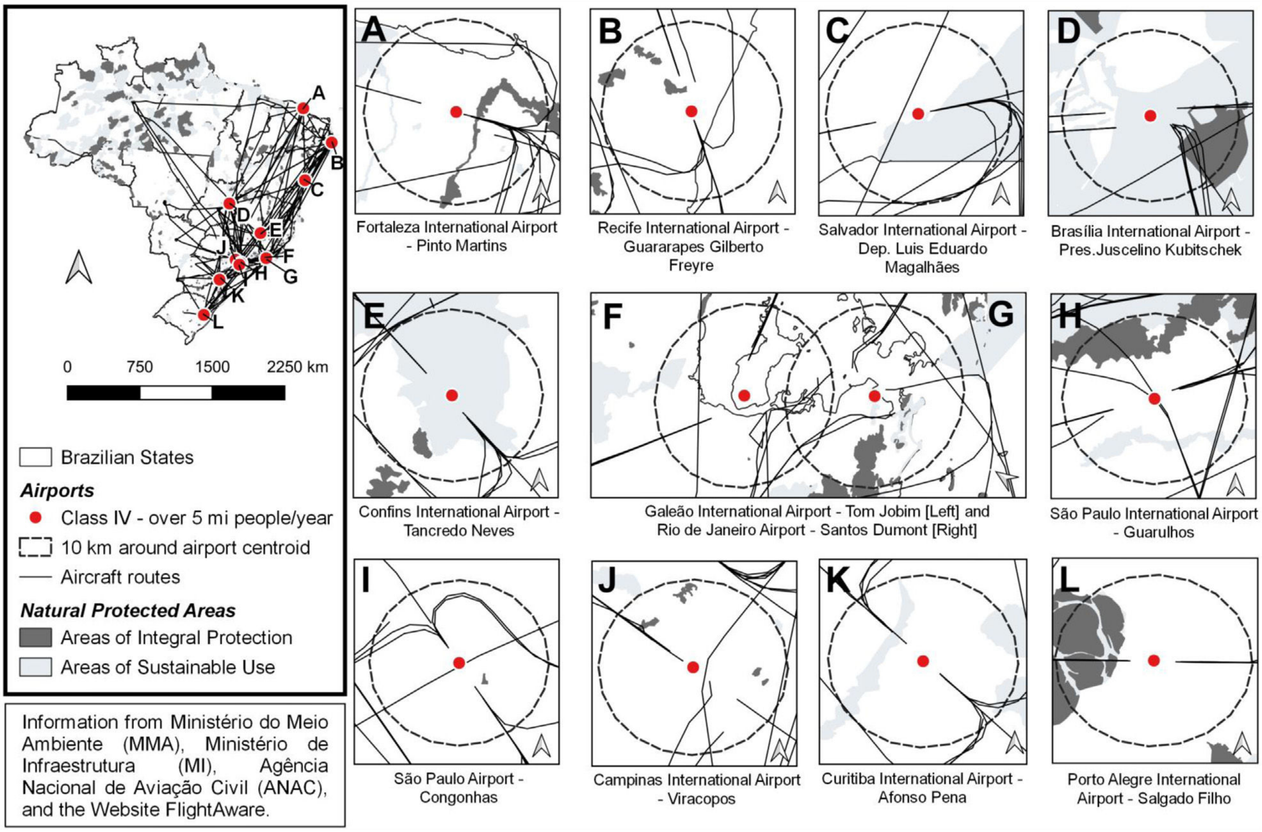

Fig. 2. Busiest airports in Brazil (Class IV – RBAC 153), Protected Areas found within 10 km radius around each airport centroid point, and real-time aircraft routes. Dark gray: Areas of Integral Protection, light gray: Areas of Sustainable Use.

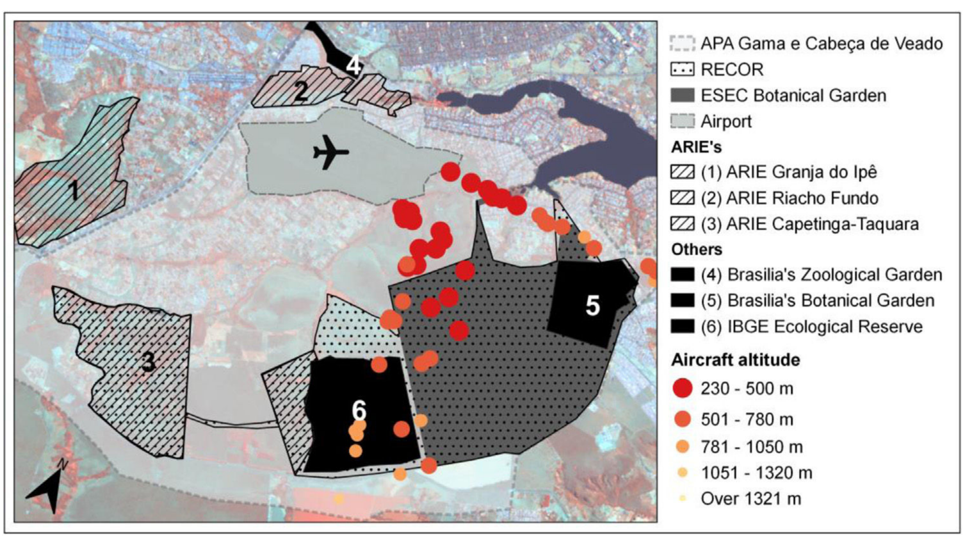

Fig. 3. Estimated areas occupied by Natural Protected Areas around Brasília International Airport, real-time aircraft routes over the PA, and real-time altitude information (decreased by 1000 m due to Brasilia's terrain elevation).

medium and large sized mammal reproduction in conservation areas affected by noise. Sporadic stressful situations (e.g. noise, predation attempts, food shortage) can cause the release of glucocorticoids, which help individuals to deal with novel situations, and even enhance the immune system (Wingfield and Kitaysky, 2002). However, exposure to constant stressful situations can generate a range of physiological responses, including a decline in immune condition (Martin, 2009; Sobrian et al., 1997). In vertebrates, glucocorticoid production and release occur in the hypothalamic–pituitary–adrenal (HPA) axis, and reproduction control occurs in the hypothalamic–pituitary–gonadal (HPG) axis. High levels of glucocorticoid are associated with a suppressed secretion of gonadotrophin releasing hormone (GnRH), luteinizing hormone (LH), and follicle stimulating hormone (FSH) (Breen et al., 2005), all of them critical for mammalian reproduction.

Sexually mature adults, pregnant females and offspring that are chronically exposed to stressful events can suffer severe consequences. Few studies have evaluated the effect of noise stress on mammalian reproduction (see Owen et al., 2004; Sobrian et al., 1997). There are, however, studies that explore how other types of stress affect mammalian reproduction, including the effects of captivity (Owen et al., 2004), laboratory protocols (Smith et al., 2004), farm management (von Borell et al., 2007), habitat fragmentation (Rangel-Negrín et al., 2009), human disturbance and climatic changes (Love et al., 2013).

Stress-related effects prior to copulation include reduced fertility (von Borell et al., 2007), reduction of gonad size (hypogonadism), decreased production of sperm which may be of lower quality, and in females, compromised maturation and reduced fertility of oocytes (Breen et al., 2005; Whirledge and Cidlowski, 2010). If copulation, fertilization and embryo implantation occur successfully, pregnant females exposed to high glucocorticoid levels can experience gestational stress, which will negatively affect offspring development (Smith et al., 2004). Gestational stress can jeopardize the development of fetal brain structures and function, affecting future offspring behavior and ability to deal with novel situations (Love et al., 2013; Smith et al., 2004; Whirledge and Cidlowski, 2010). Studies investigating prenatal stress resulting from noise have shown that offspring may develop less reactive immune systems (Sobrian et al., 1997).

After birth, mammalian offspring are highly dependent on maternal care. The implications of maternal stress in this phase involve a reduced rate of maternal effort in cleaning and protection (Smith et al., 2004), and even the rejection or accidental crushing of newborns (Owen et al., 2004). The exposure of the newborn mammals to stressful conditions can also produce disturbances (Moles et al., 2004), impairing HPA axis functioning, which persists during adult life. Both prenatal and postnatal stress can negatively affect population dynamics by influencing offspring survival, susceptibility to predation and dispersal capacity, which in turn result in consequences across all community interactions (Blas et al., 2007; Love et al., 2013).

What has been done around the world?

In the USA, noise production in airports is regulated by the Federal Aviation Administration according to the "Noise Compatibility Planning (14 CRF Part 150)", dated from 1985, with subsequent updates. The program is voluntary for each airport, and focuses on human welfare (FAA, 2019). The USA also counts with a Public Law (100-91) that requires an "acceptable level" of aircraft flight altitude over National Parks, and defines appropriate minimum altitude overflights (USA Government, 2000).

The concern over aircraft noise impacts on National Park wildlife dates back to 1984 in Wyoming state (USA), because the Grand Teton National Park includes the only commercial airstrip located within a National Park (Jackson Hole Airport). An agreement between government and airport in April, 1983, defined noise sensitive zones inside the park. The airport Board of Directors had to generate a 55 dB L_{DN} isophone curve to ensure protection of more sensitive areas, where noise could not exceed 45 dB L_{DN} (Bowlby et al., 1990). Nowadays, according to the local news, the airport Board of Directors enforces the agreement, studies changes in aircraft routes (Jackson Hole Daily, 2016), recognizes pilots that avoid producing noise over the National Park (Jackson Hole Daily, 2017), and suggests improved technologies to be applied in safe and more silent landings (FAA News, 2014). Concerns in other National Parks in the USA involve the huge problem of helicopter-based tourism using overflights, such as occurs in the Grand Canyon National Park, which annoys both visitors and wildlife alike (Mace et al., 2003; Stockwell et al., 1991). However, despite the increase in anthropogenic noise production in the USA, there is still a lack of policies as well as of monitoring and management services to control the negative impacts of aircraft noise in Protected Areas (Buxton et al., 2017).

In Europe, there is great concern about airport noise and its impact on human welfare, addressed by regulation no. 598/2014 (European Parliament and The Concil, 2014). However, studies conducted in continental Europe that address the effects of airports upon National Parks focus only on tourist perception and annoyance relative to aircraft noise (Iglesias-Merchan et al., 2015; Iglesias Merchan et al., 2014), without any consideration about adverse effects on wildlife.

Actions to be taken in Brazilian Protected Areas

Brazilian law contains no instructions relative to limitation of human-produced sounds within PA. Given that noise management can attenuate stress in wildlife, thus improving ecological resilience of populations within PAs (Barber et al., 2009; Buxton et al., 2017), here we propose some possible actions that can lead to a fruitful discussion and subsequent implementation.

A soundscape is composed by biotic (biophony), geophysical (geophony), and human-produced (anthrophony) sounds (Krause, 1987). In a PA it is expected that biophony and geophony should occupy the major soundscape space, and that anthrophony should play the smallest possible role. Soundscapes represent a valuable human and ecological natural resource, worthy of protection due to their value in human and wildlife welfare, and are currently the focus of a new body of studies called "Soundscape Conservation" (Dumyahn and Pijanowski, 2011).

In Miller's (2008) review concerning park soundscape management in the USA, he posed three core questions that have to be seriously addressed: (1) "How much human-produced sound is appropriate in a National Park setting?"; (2) "What logical chain of evidence is needed to support decisions about appropriate levels of human-produced sound?"; and (3) "How are National Park soundscapes to be quantified?".

Using this suggested outline for discussion, the first step to be implemented in Brazil would be to measure how much human-produced sound affects national PA, and to define how much sound is appropriate for each type of SNUC area. Possibly, more restrictive regulations would be appropriate for Areas of Integral Protection, and within such PA, it would be important to define even more sensitive areas. The definition of appropriate levels of noise is subjective, and must be determined based on how much noise occurs in the areas and what are their sources (aircrafts, road traffic, boats, industry). Based on such information, the next point would be to determine the feasibility of noise reduction.

The second step concerns the establishment of a logical chain of knowledge to support decisions about noise levels. This topic has been partly presented within the scope of this paper when we discuss how noise can jeopardize wildlife breeding, but there are remaining issues that have to be addressed. One of these would be to further explore PA visitors' perception and annoyance with human-produced noise. This could be easily accomplished with questionnaires.

The third step is to establish long-term methodologies to measure noise within PA. Currently, the measurement of airport noise for control purposes is the "day-night equivalent level of acoustic pressure in A-weighting" (L_{DN}). But how adequate is this metric when we consider non-human hearing thresholds? We have to remember that the "A-weighting" metric is based upon the human audible range, from 20 Hz to 20 kHz (Berglund and Hassmém, 1996), and that the audible range for non-human mammals is between 7 Hz and 160 kHz (Bowles, 1995; National Marine Fisheries Service, 2016). In other words, measurements currently used do not apply to possible impacts of human-produced noise on wildlife. Consequently, implementation of noise measurement that targets wildlife must consider a wider frequency range and should also include maximum values of noise intensity, since peaks of noise are also stressful (see Miller, 2008 for technical details).

Mitigating actions in airports

Air transportation provides important economic benefits and is an essential transportation modality in modern days. Thus, actions to mitigate its impacts must be taken cautiously, not only to optimize operation but also to improve well-being of humans and wildlife alike. Here we suggest some possibilities for cutbacks in noise impact.

(1) *Noise reduction in aircrafts*: Noise reduction is already a significant concern in aviation, with noise levels reduced in about 20 dB from 1960 to 2004 (Antoine and Kroo, 2004). New goals propose an additional 10 dB reduction by 2020 (European Commission, 2001), although an updated report has not been published yet. Much research is focused upon this topic, including projects such as the NASA "Quiet Aircraft Technology", the European Union "Silence" and the Brazilian "Silent Aircraft: An Aeroacoustics Investigation". Despite these intentions, it has become increasingly harder to reduce aircraft noise, which makes other actions even more important. One feasible reparation action, modeling initiatives by Japan, Australia and some European countries, is the payment of a "noise tax" by aviation companies, generating resources to be invested in research and environmental protection (Nero and Black, 2000).

(2) *Operational changes*: Landing and take-off procedures produce the most noise, with landings being noisier than take-offs. Operation strategies today avoid urbanized areas, and when such avoidance is impossible, there are regulations concerning minimum altitudes for the operation of air maneuvers (ANAC, 2016). We suggest that the same care that is taken over human-occupied areas should be applied over PA, including higher-angled landings and take-offs, and execution of maneuvers at higher altitudes. These changes may demand pilot training, but landings at a 4.5° inclination, instead of at 3° can reduce noise production in about 7.7 dB at ground level (Antoine and Kroo, 2004).

(3) *Updates in land use plans*: Current law (RBAC 161) concerning land use around airports (ANAC, 2013) mentions no PA type around airport influenced areas. We suggest that this law should define which PA types should or should not be allowed in airport surroundings.

Concluding remarks

Although Brazil is widely recognized as a biodiversity rich country, laws and their implementation relative to wildlife conservation are far from desirably developed. Current aviation laws are exclusively focused on issues of wildlife–aircraft collision and human perception of noise, excluding other ways in which aviation can jeopardize the welfare of both humans and animals. Protected Areas established in Brazil are essential for many aspects of human life, such as protection of water sources and maintenance of air quality, and their conservation and protection should be of the highest priority. Our intention in this essay was to provide scientific information to support policy-makers, emphasizing the need for establishment of regulatory laws that define the acceptable levels of noise incidence over Brazilian Natural Protected Areas. As we hope to have made clear in this publication, the mitigation of airport noise over Protected Areas is of utmost importance for wildlife conservation.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.pecon.2019.08.003.

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