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Dominant frequency of songs in tropical bird species is higher in sites with high noise pollution☆

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ABSTRACT

The structure and organization of acoustic signals arise through evolutionary processes and adaptive pressures on each species. During learning, natural or anthropogenic factors, such as high noise levels in urban areas, pose challenges to acoustic communication in birds. Many species adjust their acoustic signals to higher noise levels by increasing the frequency of vocalizations. The objectives of this study were to compare the dominant frequency of songs among birds dwelling in forest fragments distant from and near to urban areas, establish correlations between the dominant frequency of song and noise levels in these environments and verified the difference of response between oscines, suboscines and non-passerines. We recorded vocalizations of birds between July/2013 and November/2014 in four forest fragments, two of them near and two distant from urban areas. We used Audacity software to measure the dominant frequency. We measured the ambient noise by a calibrated sound pressure level meter in decibels (dBA) in each of the forest fragments. We analyzed 3740 vocalizations of nine tropical bird species. Forest fragments near to urban areas have higher noise levels than more distant forest fragments. Eight of nine studied species presented higher dominant frequencies of songs in forest fragments near to urban areas. Only one species, *Myiothlypis flaveola*, did not change the dominant frequency of song between the four analyzed forest fragments. The difference in dominant frequency between the forest fragments distant and closer to the urban areas did not vary between oscines, suboscines and non-passerines. Eight tropical birds exhibited higher dominant frequencies of song in forest fragments near urban areas with high level of ambient noise. Oscine, suboscine and non-passerine showed song variations. Bird species that have differences in the vocalization dominant frequency can be used in environmental monitoring and in ethological studies, as they are sensitive to high noise levels.

Noise pollution caused by the vehicular traffic and urbanization are correlates with changes in the vocalization of tropical birds in forest fragments.

1. Introduction

Sound communication is the act of conveying signals between a sender and a receiver (Vielliard and Silva, 2010). In forest environments, acoustic signals are an efficient means of communicating, because they can propagate in all directions (Silva, 2001). In birds, acoustic signals have a primary biological function for species-specific recognition (Vielliard, 1987) and can be classified according to their characteristics and roles in calls and songs. The song is used for communication over longer distances and is the prime target of studies. Songs may be emitted by the male to attract the female, defend territory and compete for resources with other males (Sick, 2001; Gill, 2007; Catchpole and Slater, 2008; Silva and Vielliard, 2011).

Evolutionary processes and adaptive pressures imposed on species by the environment determine the structure and organization of acoustic signals (Vielliard, 2004). Birds are under the influence of natural and anthropogenic factors that cause variations in their acoustic signals (Sick, 2001; Kroodsma, 2004; Tubaro and Lijtmaer, 2006; Catchpole and Slater, 2008). The high noise levels generated by cities have been related to changes in sound

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communication of birds (Brumm, 2004; Slabbekoorn and Den Boer-Visser, 2006; Ríos-Chelén et al., 2012a) and pose challenges to the species that depend on acoustic communication, especially to males, which use the song for mating opportunities and in defense of their territory (Slabbekoorn and Peet, 2003; Katti and Warren, 2004).

Several studies have demonstrated that birds (mostly oscines) adjust the amplitude of signals (Brumm, 2004; Halfwerk and Slabbekoorn, 2009). Many birds increase the minimum frequency (Slabbekoorn and Peet, 2003; Fernández-Juricic et al., 2005; Slabbekoorn and Den Boer-Visser, 2006; Nemeth and Brumm, 2009; Hu and Cardoso, 2010; Mendes et al., 2011; Ríos-Chelén et al., 2012b), maximum frequency (Mendes et al., 2011) and dominant frequency (Nemeth and Brumm, 2009; Parris and Schneider, 2009; Hu and Cardoso, 2010; Proppe et al., 2011, 2012; Luther and Derryberry, 2012; Lazerte et al., 2016, 2017). These changes in amplitude and frequency of signals lead to changes in the sound power distribution levels (Halfwerk and Slabbekoorn, 2009). In addition, birds also decrease the length of the acoustic sounds (Slabbekoorn and Den Boer-Visser, 2006; Nemeth and Brumm, 2009) and duration of notes and/or song elements (Slabbekoorn and Den Boer-Visser, 2006) and reduce the number of song notes (Fernández-Juricic et al., 2005; Nemeth and Brumm, 2009; Ríos-Chelén et al. 2012a). Studies have tested the song adjustment in response to high noise levels by birds in temperate regions (Mathevon et al., 2008) and little is known in tropical regions (Ríos-Chelén et al., 2012b; Redondo et al., 2013). Tropical regions are developing and urbanizing rapidly in recent years and studies shown association between urban population growth, urbanization and agricultural trade with tropical deforestation (Browder, 2002; DeFries et al., 2010; Angel et al., 2011).

Informations about the changes caused by noise in dominant frequency of songs in bird species (oscines, suboscines and non-passerines) from tropical regions are also scarce, hence the need to conduct studies in the tropics. Dominant frequency can be measured using an automatic parameter measurement tool in many programs, without having to be determined by the cursor, thus avoiding errors of measurement and making more precise and fast analyzes.

Oscines differ from suboscine species in song ontogeny. The former have a great capacity to learn and adjust their song to environmental changes. Instead the latter appear to have a lower capacity to change their song and vocal imitation does not appear to occur (Kroodsma, 1984, 2004; Catchpole and Slater, 2008). Studies have shown that oscine species have greater capacity to change their song frequency in response to high noise level than suboscines (Ríos-Chelén et al., 2012b). However, some studies have shown that suboscines (Francis et al., 2010) and non-passerines (Hu and Cardoso, 2010; Schuster et al., 2012) are also able to change the song frequency in response to high noise levels. Suboscines comprise approximately 20% of Passeriformes and occur mostly in tropical regions (Sibley and Monroe, 1990; Ericson et al., 2003; Barker et al., 2004; Moyle et al., 2006).

The current study aimed to investigate the occurrence of differences in the dominant frequency of songs between tropical bird species dwelling in forest fragments distant from and near to urban areas, testing the hypothesis that forest fragments near to urban areas present higher noise levels and birds in these sites present higher dominant frequency of songs. It was also tested if there was any adjustment in dominant frequency of songs between oscine and suboscine species, testing the hypothesis that oscines would show higher adjustment in dominant frequency to urban noise than suboscines. The variation in adjustment of dominant frequency between passerines and non-passerines was also verified.

2. Material and methods

2.1. Study sites

We conducted the study in four forest fragments in three municipalities in the state of Minas Gerais, Brazil: Uberlândia, Araguari, and Perdizes. All forest fragments are inserted in a highly impacted area of the Cerrado Domain, with over 70% of the land area occupied by agriculture and livestock (Brito and Prudente, 2005). The climate is *Aw* according to the Köppen climate classification, with hot and rainy summers between October and March, and dry and cold winter between April and September. The average annual rainfall is 1500 mm, and the average temperature is 22 °C (Rosa et al., 1991).

Two forest fragments (Glória and São José), are less than 0.5 km away from highways and urban areas. Both are situated near to the Uberlândia airport. The other two forest fragments (Galheiro and Água Fria) are more than 5 km away from highways and 20 km from urban areas (Fig. 1).

2.2. Field recordings

Bird vocalization was recorded with a digital Sony ICD-PX312 recorder using a sampling rate of 44,100 Hz, with 32-bit depth and a Yoga HT-81 directional microphone. To avoid recording the same individual twice, only one linear transect (2–3 km) in each forest fragment were selected to the recordings. Transect surveys occurred during the morning (6:00–11:00 h) and afternoon (14:00–18:00 h). Each forest fragment was sampled four times between July 2013 and November 2014.

Individuals were recorded along transects at a distance of between 5 and 10 m to obtain good-quality recordings. Birds of the same species were only considered to be different individuals when recorded at a minimum distance of 100 m. The identification of the individuals at species level occurred with the aid of binoculars (Nikon 12 × 50 mm) and identification guides (Gwynne et al., 2010; Sigrist, 2013), or through the recognition of their vocalization. Playback techniques were not employed to encourage vocalization or to attract them.

2.3. Noise measurements

The ambient noise level of each forest fragment were measured with a calibrated sound pressure level (SPL) meter (Instrutherm, DEC-490) (settings: A-weight and fast response; range: 30–80 dB). Ambient noise was measured, in decibels (dB), during approximately 1 min time lengths at 1 h intervals in the same period of the day in which the bird vocalization recordings were made. The SPL meter was pointing upward at a height of 1.5 m above the ground in the same transects of the vocalization recordings in all forest fragments.

2.4. Dominant frequency measurements

The songs were extracted from the recordings using Audacity 2.0.3 Beta (Mazzoni, 2011). Audacity (Hanning window length of 512) was also used to measure the dominant frequency of each song. The dominant frequency was presented in kilohertz (kHz) and is the frequency of maximum amplitude in the power spectrum. Only bird songs were used to develop our analyses; calls and other acoustic signals were not used. We used only complete songs where there was no overlap with other acoustic signals to avoid measurement errors. Only the species recorded in all forest fragments and with at least 10 recorded individuals were selected.

All recordings and metadata (species, name and city of the forest

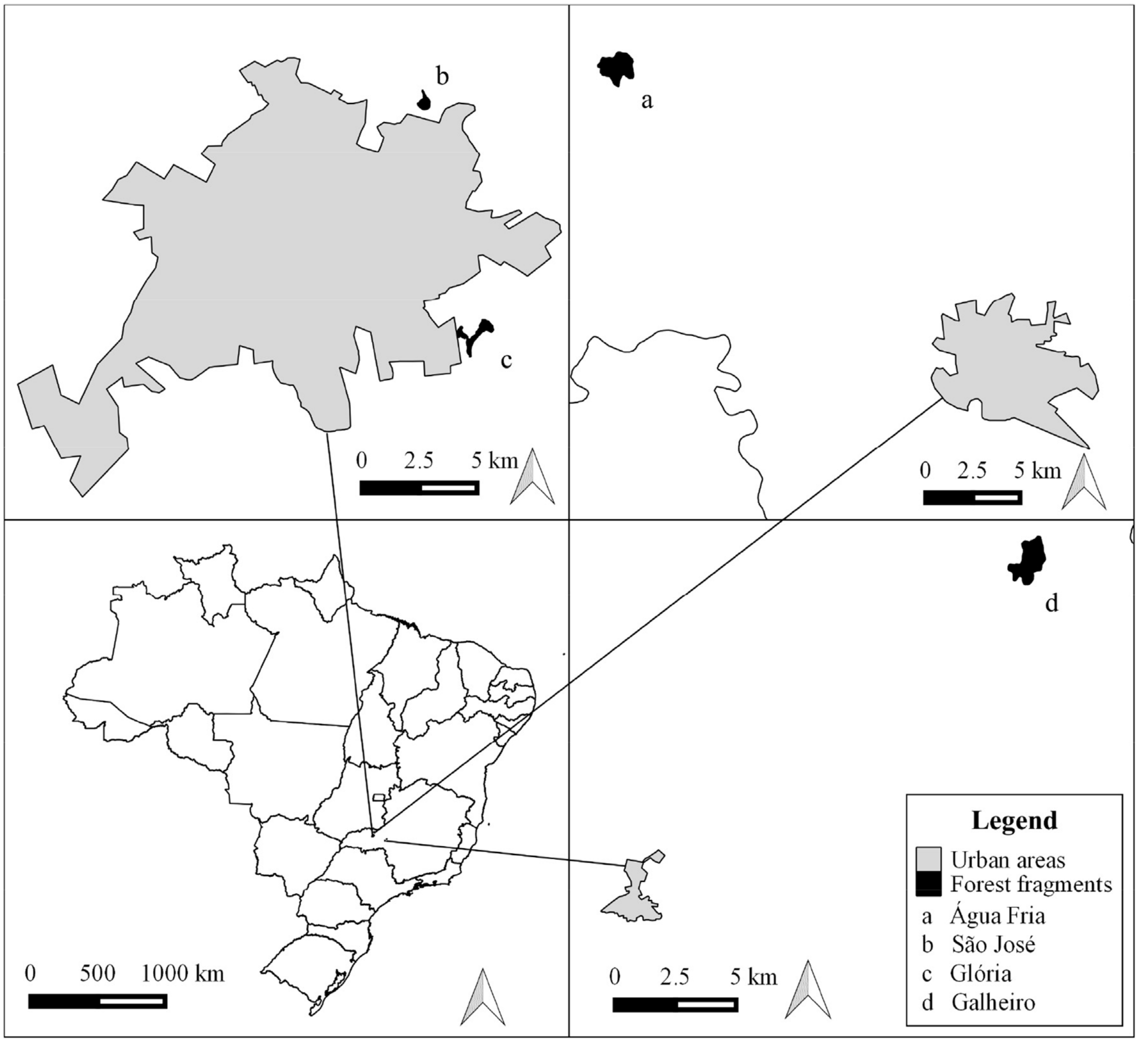

Fig. 1. Map of studied forest fragments showing its size and distance to urban areas.

fragments, vegetation type, date and time of day and type of vocalization) were deposited with the data files in the Laboratory of Ornithology and Bioacoustics (LORB) of the Federal University of Uberlândia.

2.5. Statistical analysis

To compare the ambient noise values amongst the four studied forest fragments we ran an ANOVA and a Tukey's test, *a posteriori*, to determine which forest fragments showed higher and lower values. To investigate the difference in the dominant frequency of bird songs between forest fragments distant from and close to the urban areas we performed an independent linear mixed model for each species. We used the average dominant frequency of each individual as the response variable, site type (near and distant do cities) as fixed factor and sites (Água Fria, Galheiro, Glória and São José) as the random factor. The significance of the model was tested with likelihood-ratio tests, comparing the complete model to null model that did not include site type as predictor. We calculated the mean values of dominant frequency for each individual from forest fragments distant from and near to the cities and after we calculated the average in each forest fragment in all species. The differences in dominant frequency were obtained by the difference between the mean dominant frequency of song for a specie in forest fragments near to cities and the mean dominant frequency of song in forest fragments distant from the cities. We used Student's T-tests for independent samples to verify if this difference varied between oscine and suboscine species and between passerine and non-passerine species. Figures were created with R package ggplot2 v. 2.1.0 (Wickham, 2009) and the spectrograms with R package seewave v. 1.6 (Sueur et al., 2008). All statistics were performed using R statistical software v. 3.4.1 (R Development Core Team, 2017), with $\alpha = 0.05$.

3. Results

The forest fragments closer to the urban areas (mean ± standard deviation: Glória = 41.49 ± 6.87 dB and São José = 46.69 ± 4.04 dB) showed the highest average of ambient noise level, while the fragments farther away from the urban areas (Galheiro = 39.97 ± 5.51 dB and Água Fria = 39.08 ± 4.22 dB) exhibited the lowest ambient noise level values ($F_{3,796} = 82.98$, $p < .01$ – Fig. 2).

Only nine species met the criteria of 10 or more individuals recorded. Two non-passerines: White-wedged Piculet (*Picumnus albosquamatus*) and Little Woodpecker (*Venilliornis passerines*); four oscines: Golden-crowned Warbler (*Basileuterus culicivorus*), Flavescent Warbler (*Myiothlypis flaveola*), Buff-breasted Wren

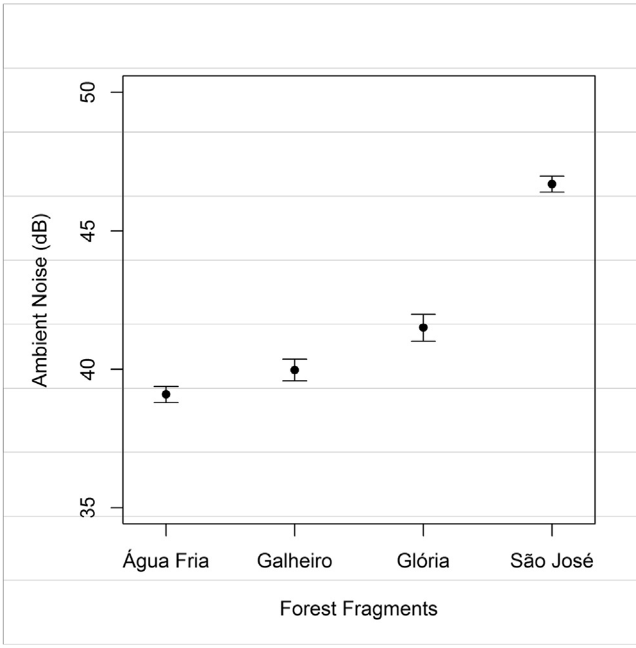

Fig. 2. Ambient noise levels (Mean values, error bars represent standard deviation) in the four forest fragments, with higher values for the areas closer to the city (São José and Glória).

(*Cantorchilus leucotis*) and Rufous-browed Peppershrike (*Cyclarhis gujanensis*) and three suboscines: Helmeted Manakin (*Antilophia galeata*), Sepia-capped Flycatcher (*Leptopogon amaurocephalus*) and Yellow-olive Flycatcher (*Tolmomyias sulphurescens*).

A total of 3740 songs of the nine tropical bird species in the four forest fragments was analyzed (Table 1). Among the studied species, eight species (*A. galeata, B. culicivorus, C. leucotis, C. gujanensis, L amaurocephalus, P. albosquamatus, T. sulphurescens* and *V. passerinus*) presented vocalizations at higher dominant frequency in the forest fragments closer to the city ($p \leq .05$ – Table 1 and Figs. 3–6), with higher noise level. Only *M. flaveola* did not show significant difference in the dominant frequency ($p = .373$ – Table 1 and Figs. 3 and 4).

The difference in dominant frequency between forest fragments distant and closer to the urban areas did not vary between oscines and suboscines ($t = -1.274$; $df = 5$; $p = .217$) and passerine and non-passerines ($t = -0.321$; $df = 7$; $p = .757$). Oscines were the group that presented the smallest difference in the dominant frequency of the songs (0.20 ± 0.21 kHz) and suboscines presented the biggest difference (0.43 ± 0.25 kHz). Non-passerines presented a mean difference of 0.24 ± 0.19 kHz (Fig. 7).

4. Discussion

All studied species commonly live in forest fragments of Cerrado from the Triângulo Mineiro region, Minas Gerais State, Brazil (Marçal Júnior et al., 2009; Malacco et al., 2013). They are found in both larger and well-conserved fragments, such as Galheiro and Água Fria, and smaller areas impacted by urbanization processes, such as the Glória and São José forest fragments. Thus, it is possible to compare the song parameters of these species between forest patches with different characteristics.

The forest fragments situated near urban areas presented higher noise levels, mainly due to vehicle traffic and proximity to the airport. Forest fragments distant from urban areas are not affected by these anthropogenic pressures, thus presenting lower noise levels. The effects of noise on bird vocalizations and acoustic parameters have been evaluated in recent years. Studies have shown

Table 1
Dominant frequency of nine species in forest fragments distant (Água Fria and Galheiro) and near (Glória and São José) from urban areas and respective significance of differences [x^2 (P)], using linear mixed models.

Species	Group	Dominant frequency (kHz)		x^2 (P)
		Distant fragments Mean ± SD (range)	Near fragments Mean ± SD (range)	
Venilliornis passerinus	non-passerine	3.72 ± 0.32 (3.26–4.68) n = 5	4.10 ± 0.74 (3.23–5.83) n = 7	6.68 (=0.009)
Picumnus albosquamatus	non-passerine	6.56 ± 0.35 (5.13–7.47) n = 18	6.66 ± 0.21 (6.07–7.45) n = 24	5.613 (=0.017)
Cantorchilus leucotis	oscine	2.53 ± 0.24 (1.80–3.64) n = 24	2.83 ± 0.36 (2.16–3.89) n = 25	10.006 (=0.001)
Cyclarhis gujanensis	oscine	2.40 ± 0.30 (1.69–3.14) n = 32	2.44 ± 0.19 (1.71–3.23) n = 35	4.797 (=0.028)
Basileuterus culicivorus	oscine	4.89 ± 0.44 (3.71–6.12) n = 36	5.34 ± 0.35 (4.35–7.05) n = 41	15.608 (<0.001)
Myiothlypis flaveola	oscine	5.02 ± 0.36 (3.49–6.11) n = 38	5.04 ± 0.25 (4.53–5.64) n = 27	0.793 (=0.373)
Antilophia galeata	suboscine	2.71 ± 0.33 (2.32–4.02) n = 28	2.95 ± 0.40 (2.29–3.96) n = 28	9.222 (=0.002)
Leptopogon amaurocephalus	suboscine	7.21 ± 1.09 (3.31–8.19) n = 9	7.92 ± 0.38 (7.21–8.60) n = 11	6.124 (=0.013)
Tolmomyias sulphurescens	suboscine	5.15 ± 0.40 (3.96–6.88) n = 36	5.49 ± 0.43 (4.38–6.94) n = 73	11.552 (<0.001)

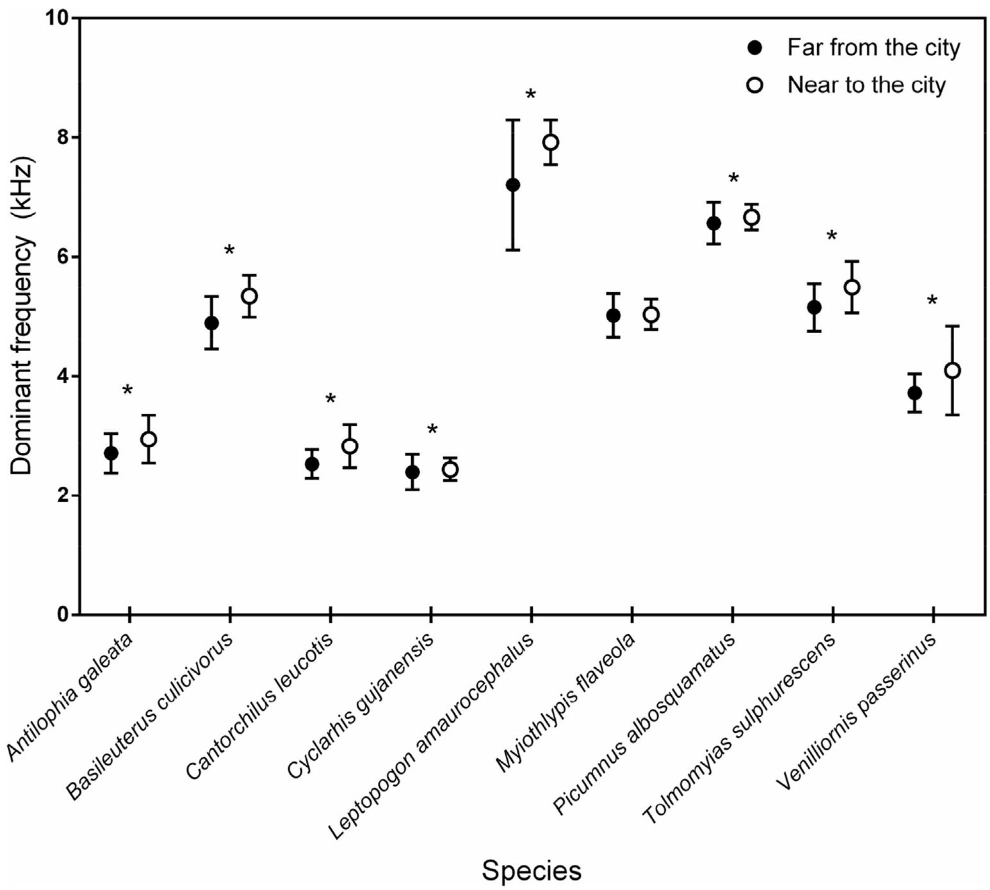

Fig. 3. Dominant frequency (Mean values, error bars represent standard deviation) of species song between forest fragments near (São José and Glória) and distant (Água Fria and Galheiro) from the city. * Significant differences (p ≤ .05).

that in environments with high noise levels birds sing songs with higher frequency and amplitude, shorter songs, shorter notes/elements and fewer song notes/elements (Brumm, 2004; Mockford and Marshall, 2009; Nemeth and Brumm, 2009; Parris and Schneider, 2009; Hu and Cardoso, 2010; Salaberria and Gil, 2010; Mendes et al., 2011; Proppe et al., 2011, 2012; Luther and Derryberry, 2012; Ríos-Chelén et al., 2012b; Schuster et al., 2012; Huffeldt and Dabelsteen, 2013; Nemeth et al., 2013; Redondo et al., 2013; Lazerte et al., 2016, 2017). These studies aim to understand how bird species respond to high noise levels in rural and urban areas, either changing or not changing their vocalization. And have revealed that high noise levels, such as those originating from vehicle traffic on roads and highways and the presence of airports near the areas studied affect the vocalization of many bird species (Slabbekoorn and Peet, 2003; Brumm, 2004; Roca et al., 2016).

Eight of the nine studied species showed vocalizations with higher dominant frequencies in the forest fragments closer to urban areas, with higher noise levels. The dominant frequency of vocalization can be considered the main acoustic communication channel (Hu and Cardoso, 2010). Other studies showed that some bird species [*Turdus merula* (Nemeth and Brumm, 2009), *Colluricincla harmonica* (Parris and Schneider, 2009), *Cracticus torquatus* and *Manorina melanophrys* (Hu and Cardoso, 2010), *Zonotrichia leucophrys* (Luther and Derryberry, 2012), *Poecile atricapillus* (Proppe et al., 2011, 2012; Lazerte et al., 2016) and *Poecile gambeli* (Lazerte et al., 2017)] have higher dominant frequencies of vocalization in urban or high noise level sites. Nevertheless, not all bird species are affected in a similar way, and some appear to not be sensitive to high traffic noise levels (Fernández-Juricic, 2001; Rheindt, 2003; Parris and Schneider, 2009), like *Myiothlypis flaveola*.

Even species less sensitive to environmental perturbation dwelling in areas with high noise levels can be affected (Brumm, 2004). The species analyzed in this study are examples of this. Some species alter the frequency range of their vocalizations when confronted by anthropogenic noise, producing typical song frequencies that do not overlap with the low-frequency environmental noise pollution (Mendes et al., 2011) produced by the traffic of vehicles (Skiba, 2000). Thus, bird species that vocalize at lower frequencies can be more affected by environmental noise (Slabbekoorn and Ripmeester, 2008) and would need to vocalize at higher frequencies and amplitude to avoid masking (Catchpole and Slater, 2008). These increase the intensity of bird acoustic signals and generates greater oxygen consumption (Eberhardt, 1994; Oberweger and Goller, 2001; Ward et al., 2003), as well as greater contraction of the syringeal muscles (Suthers et al., 1999) and can lead to increased energy expenditure (Brumm, 2004).

Most of the studies involving the effect of anthropogenic noise on bird vocalization show that the increase in minimum frequency is the primary change in the vocalization of birds in areas with high noise levels (Slabbekoorn and Peet, 2003; Fernández-Juricic et al., 2005; Slabbekoorn and Den Boer-Visser, 2006; Nemeth and Brumm, 2009; Hu and Cardoso, 2010; Mendes et al., 2011). However, in the last years, studies had shown changes in dominant frequency of vocalization by birds (Nemeth and Brumm, 2009; Parris and Schneider, 2009; Hu and Cardoso, 2010; Luther and Derryberry, 2012; Proppe et al., 2011, 2012; Lazerte et al., 2016,

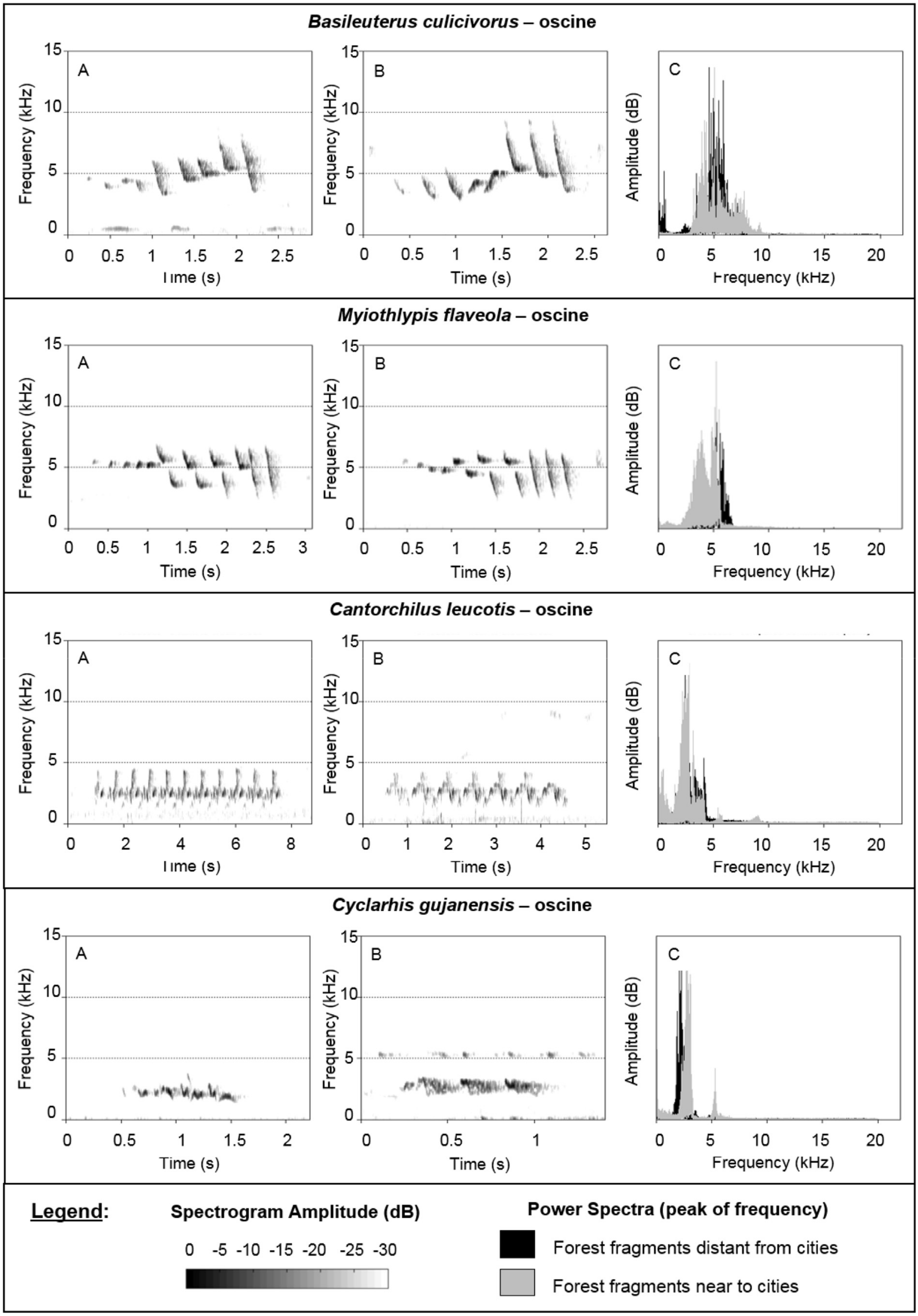

Fig. 4. A = Spectrograms of oscine bird songs in forest fragments distant from the city. B = Spectrograms of oscine bird songs in forest fragments near to the city. C = Power Spectra comparing the dominant frequency (peak of frequency) of two song examples of birds in forest fragments near and distant from the city.

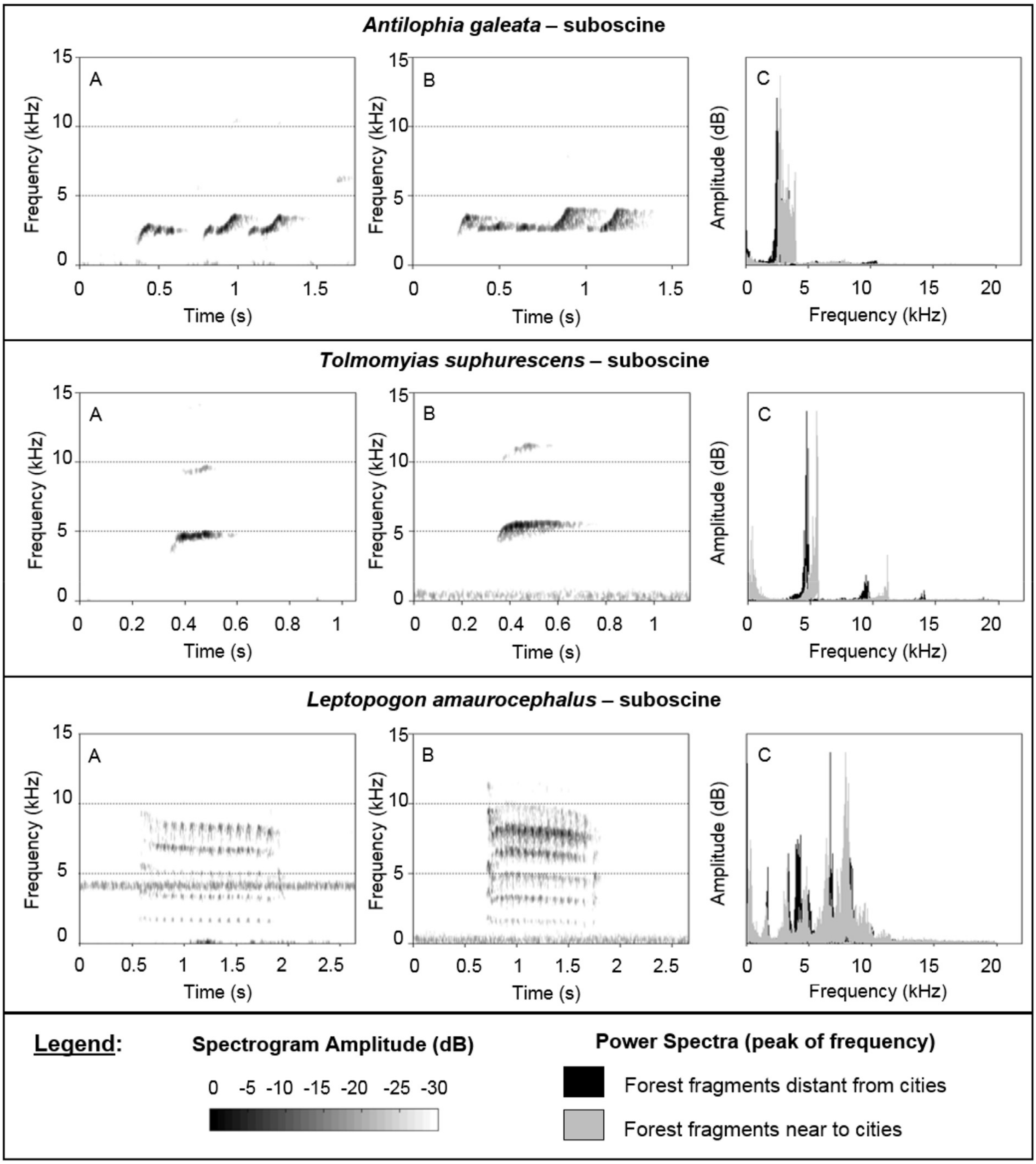

Fig. 5. A = Spectrograms of suboscine bird songs in forest fragments distant from the city. B = Spectrograms of suboscine bird songs in forest fragments near to the city. C = Power Spectra comparing the dominant frequency (peak of frequency) of two song examples of birds in forest fragments near and distant from the city.

2017). These studies revealed that the dominant frequency can be altered and may become an important study object for understanding the changes caused by noise in bird vocalization.

Variations in the acoustic parameters of vocalization in response to high noise levels caused by the noise produced by urbanization processes can be a result of phenotypic plasticity in the case of oscines (Patricelli and Blickley, 2006; Mendes et al., 2011). According to Price et al. (2003), the phenotypic plasticity can be genetically assimilated over time and lead the species to distinct evolutionary paths. This study showed variations in the dominant frequency of passerine (oscines and suboscines) and non-passerine vocalizations, suggesting that this plasticity may not be restricted to oscines.

However, other factors and selection pressures may cause changes in bird songs, beyond plasticity or adaptive response (Nemeth et al., 2013). The vegetation structure influences the transmission of sound signals (Mockford et al., 2011). In closed habitats low-frequency acoustic signals are better transmitted (Morton, 1975; Dabelsteen et al., 1993). In smaller areas and with higher population densities the individuals are closer, reducing the attenuation and degradation of the acoustic signals emitted (Nemeth and Brumm, 2009). Urban areas may present higher

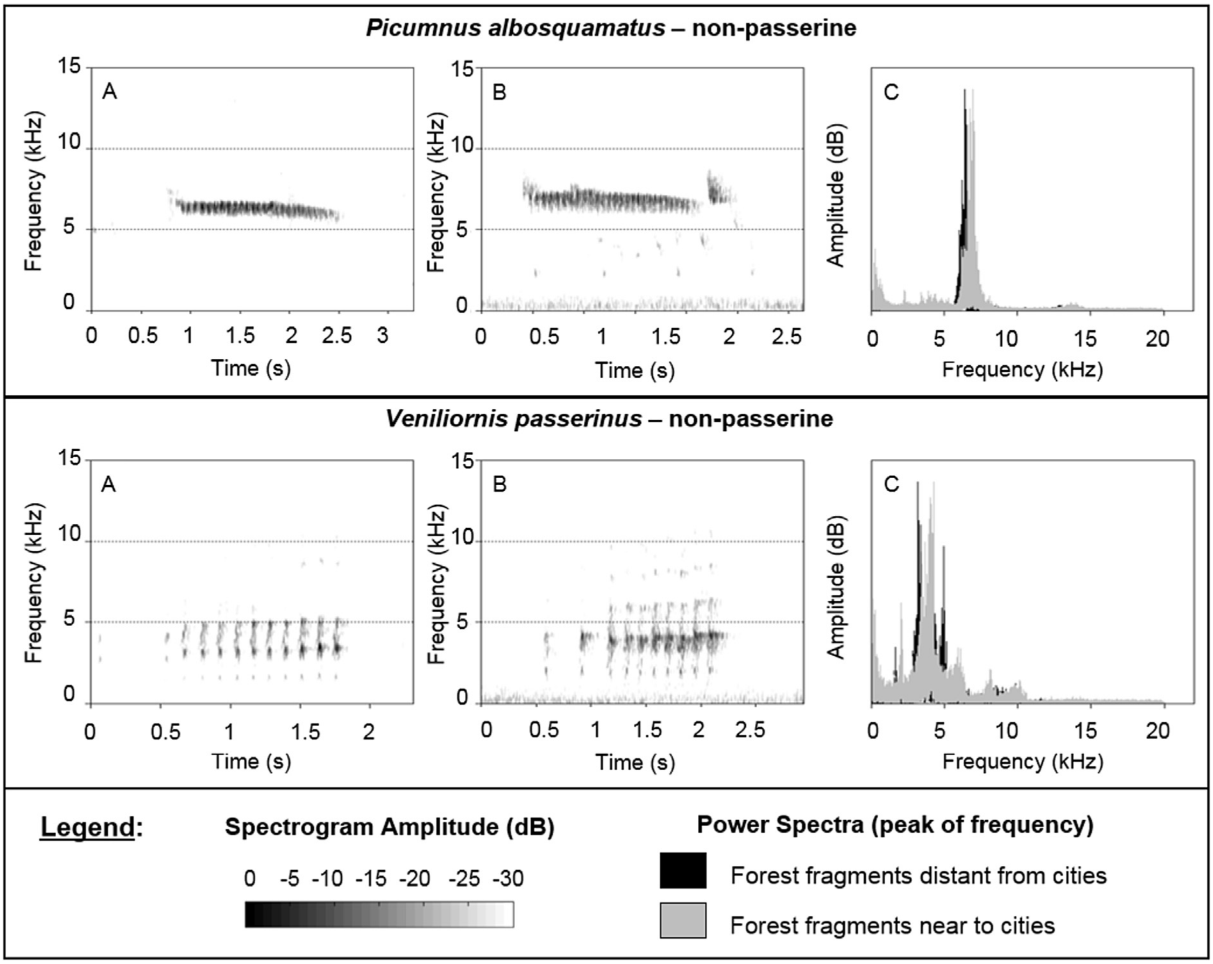

Fig. 6. A = Spectrograms of non-passerine bird songs in forest fragments distant from the city. B = Spectrograms of non-passerine bird songs in forest fragments near to the city. C = Power Spectra comparing the dominant frequency (peak of frequency) of two song examples of birds in forest fragments near and distant from the city.

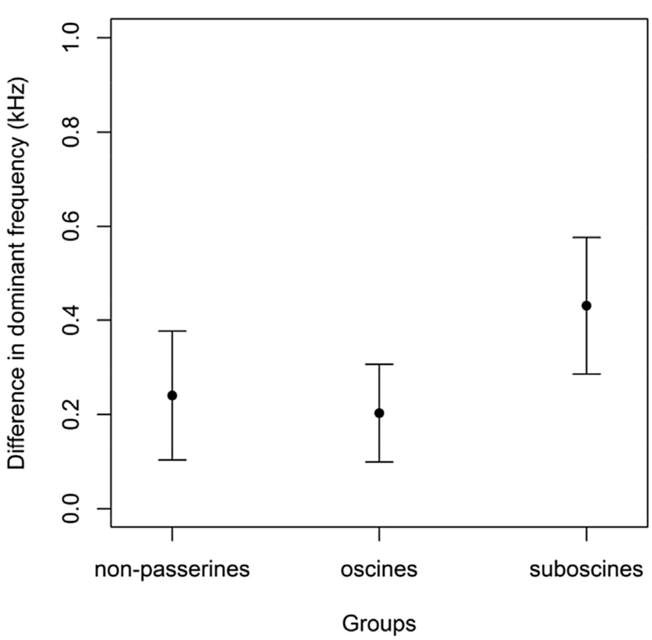

Fig. 7. Difference in dominant frequency (Mean values, error bars represent standard deviation) of species in each group: non-passerines, oscines and suboscines.

population densities and higher arousal of some species (Nemeth and Brumm, 2009). High population densities generate more intense social and territorial interactions, especially during reproduction (Snow, 1958; Goretskaia, 2004; Nemeth and Brumm, 2009). In areas with high arousal some bird species can sing with higher frequency and shorter interval between songs (Dabelsteen, 1984, 1985; Dabelsteen and Pedersen, 1985) and the grown of male-male interactions can change singing activity and song features (Goretskaia, 2004). The proximity to urban areas can lead to conditions of physiological stress in some bird species (Partecke et al., 2006). Studies show that testosterone levels in birds may be higher in areas far from cities and that these birds sing songs at lower frequencies (Cynx et al., 2005; Partecke et al., 2005).

The present study showed that tropical birds are also good objects of study in bioacoustics since eight of the nine studied species showed an increase in the dominant frequency of songs in areas with higher noise levels. Tropical regions are still not widely studied (Ríos-Chelén et al., 2012b; Redondo et al., 2013), despite the grown in urbanization and consequent high noise levels. Studies in tropical regions are encouraged to show how tropical birds adjust the vocalization in response to high noise. Knowing how tropical birds respond to increases in noise levels becomes important in order to support species conservation policies. This study may also encourage other researchers to expand the idea within tropical environments.

5. Conclusions

Forest fragments closer to urban areas present higher noise levels than forest fragments distant to cities. Eight tropical species exhibited songs with higher dominant frequencies in forest fragments near urban areas, suggesting that these species may be sensitive to high level of environmental noise. Oscine and suboscine passerine birds, as well as non-passerine, showed song variations. Dominant frequency of songs presented changes in response to high noise levels. The data obtained from these studies can be used in bioacoustics focusing on environmental monitoring and investigation of the ethological adjustment of species.

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