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The impact of noise from open-cast mining on Atlantic forest biophony

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A B S T R A C T

The sound produced by human-made machinery (technophony) is known to exert negative effects on animal communication and well-being. Mining is an important economic activity in Brazil, which is often conducted close to forested areas and produces a diffuse noise. In this study, the impact of such noise on biophony (biological sounds) was investigated by characterizing and comparing the soundscapes of two different sites (close versus distant from an open-cast mine) in the same Atlantic forest fragment, matched for habitat type, in Southeast Brazil. Six automated recorders were installed at each site and were programmed to record continuously during seven consecutive days every two months between October 2012 and August 2013. Technophony and biophony values were derived from power spectra and the Acoustic Complexity Index (ACI). Mann–Whitney U tests demonstrated that the biophony exhibited a switch in daily dynamics, resulting in a statistically higher biophony during the day at the site close to the mine and a higher biophony during the night at the site far from the mine. Potential species richness was found to be higher at the site that was distant from the mine. The species composition and spectral characteristics of the calls were also found to differ between the two sites. These results provide the first investigation of potential disturbances caused by mining noise on biophony, demonstrating that it can cause alterations in the temporal dynamics and daily patterns of animal sounds, which are symptoms of altered behaviors or variations in community-species composition. These findings suggest remarkable insights that should be taken into consideration in the regulating of the use of natural areas for mining.

1. Introduction

Open-cast mining is known to produce high sound pressure levels through exploratory and production drilling, blasting, cutting, handling of materials, ventilation, crushing, conveying, ore processing and transportation (Donoghue, 2004). This massive noise pollution has the potential to negatively impact wildlife. Mining has been shown to impact breeding birds by reducing their density (Smith et al., 2005), their species diversity, and their population sizes (Saha and Padhy, 2011). Ant-species richness has also been found to decrease owing to mining activity (Queiroz, 2013). Despite the evidence that noise pollution negatively affects wildlife reproduction and longevity (Warren et al., 2006; Slabbekoorn and Ripmeester, 2008; Barber et al., 2009; Francis et al., 2011; Kight and Swaddle, 2011), sound pollution from mining activity is still poorly regulated around the world (Hessel and Sluis-Cremer, 1987; Frank et al., 2003).

Many animal species depend on acoustic signals for intraspecific communication (Catchpole and Slater, 2008). Several studies have demonstrated that high noise levels may reduce habitat quality for many species (Bayne et al., 2008) by masking sound signals and decreasing the efficiency of animal communication (Langemann et al., 1998; Lohr et al., 2003; Brumm, 2004; Bee and Swanson, 2007). Noise can also decrease reproductive success (Halfwerk et al., 2011), as well as altering mating systems (Swaddle and Page, 2007; Habib et al., 2007) and parental care in bird species (Schroeder et al., 2012). Nonetheless, some animal species are capable of adjusting their acoustic signals to communicate in noisy environments, for example, by increasing their amplitude (Brumm et al., 2004; Brumm et al., 2009), shifting frequencies

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(Slabbekoorn and Peet, 2003; Parks et al., 2007; Nemeth and Brumm, 2009), altering their calling rates (Sun and Narins, 2005), changing call duration (Brumm et al., 2004) or by shifting their time of calling (Fuller et al., 2007; Sousa-Lima and Clark, 2008). Other species exhibit behavioral changes including avoiding noisy areas during foraging (Miksis-Olds et al., 2007; Schaub et al., 2008) and other daily activities (Sousa-Lima and Clark, 2009; Duarte et al., 2011). Area avoidance and acoustic compensatory mechanisms to reduce or offset the effects of noise may alter the acoustic complexity of a community in a given location, resulting in a decrease in species' abundance (Bayne et al., 2008) and/or diversity (Proppe et al., 2013) at noise-polluted sites.

Technophony, which is the sound produced by human-made machinery, has become omnipresent in natural soundscapes (Barber et al., 2011) and, despite evidence demonstrating negative impacts on animals, there is still a lack of official regulation of the noise produced by industrial and exploratory activities in terrestrial natural areas. The Atlantic forest in Brazil is one of the richest and most endangered biomes of the world (Myers et al., 2000) where a high level of mining activity occurs. Despite this high level of mining activity, there are no laws regulating the sound-pollution levels permitted in this biome. In many countries of the world, noise monitoring from industrial activities is required only in respect to its impacts on human health. Consequently, the effects of noise on wildlife that are already known should drive efforts to develop environmental legislation to protect wildlife (Brown et al., 2013).

Passive acoustic monitoring (PAM) methods provide opportunities to evaluate the consequences of different land-use decisions (Blumstein et al., 2011; Joo et al., 2011; Mennitt and Fristrup, 2012; Brown et al., 2012, 2013), especially in environments such as mines, that are difficult to access or monitor using conventional methods (Mellinger and Barlow, 2003; Scott Brandes, 2008). PAM devices can record data during several days continuously and, consequently, a large amount of information can be collected from the acoustic environment. As a result, special software and indices to process audio files rapidly and efficiently are required (Kasten et al., 2012; Aide et al., 2013; Sueur et al., 2014; Villanueva-Rivera and Pijanowski, 2015). In this context, Pieretti et al. (2011) introduced the Acoustic Complexity Index (ACI), which facilitates an indirect and rapid measuring of the complexity of the soundscape. The ACI has been proven to be a useful tool in tracking the dynamics of the sounds produced by animal communities (Farina et al., 2013); this is achieved by describing the spectral complexity of the biophony of soundscapes through the intrinsic variability of biotic sounds. This index has already been applied in noisy environments (Pieretti et al., 2011; Pieretti and Farina, 2013) because it possesses the particular quality of helping to filter out most technophonies, such as trains, cars or airplane transit noise; additionally, Towsey et al. (2014) indicate ACI as one of the best indicators of bird biodiversity among 14 different acoustic indices.

There are no studies investigating how anthropogenic noise affects soundscapes and biophony in mining areas. Considering that, the aim of this study was to investigate noise effects on Atlantic forest soundscape dynamics by comparing the biophony and technophony at a site close to an active open-cast mine and at a habitat-matched site that was distant from the mine or other anthropogenic activities.

2. Methodology

2.1. Study area

Data were collected at the Environmental station of Peti in the municipalities of São Gonçalo do Rio Abaixo and Santa Bárbara, Minas Gerais state, Brazil (centered at 19°53′57″S and 43°22′07″W). The climate of southeastern Brazil can be divided into two macro-climatic seasons: a hot wet season, from October to March, and a cooler dry season from April to September (Minuzzi et al., 2007).

The reserve is an Atlantic forest fragment of approximately 605 ha located in the upper Rio Doce Basin (altitude range: 630–806 m). It is estimated that the area harbors approximately 29 species of anurans (Bertoluci et al., 2009), 231 species of birds (Faria et al., 2006) and 46 species of mammals (Paglia et al., 2005). A large part of the reserve is covered by secondary arboreal vegetation of continuous canopy and large trees (Nunes and Pedralli, 1995).

Peti is surrounded by small farms and is contiguous with the Brucutu Mine, which occupies an area of 8 km^2 and produces noise through road traffic, sirens and explosions during the day and night (Roberto, 2010). Brucutu's iron ore extraction began in 1992 and it is currently one of the largest mines of the world (Roberto, 2010).

2.2. Acoustic recordings and data analysis

Sensor arrays comprising six Song Meter Digital Field Recorders (SM2) (Wildlife Acoustics, Inc., Massachusetts), distributed in two triangles, were installed at two sites and were programmed to record continuously during seven days every two months from October 2012 to August 2013 (six recording sessions). Both sites were matched by habitat and were located in the same Atlantic forest fragment. The 6-SM2 array close to the active open-cast mine was installed at a distance of 500 m from the mine and 25 m from the closest mining road. The 6-SM2 array located at the site that was far from the mine was installed at a distance of approximately 2500 m from the mine and 25 m from a rarely used road in order to control for a potential border effect due to the physical structure of the road (Fig. 1).

In order to avoid overlap of the sounds recorded, each SM2 within each sensor triangle, was placed 80 m from each other. This distance between recorders was established during a pilot study conducted in the area. The distance between the two SM2 triangles was at least 100 m in order to have two independent recording samples at each site (close and far from the mine). The distance between the arrays (far and close sites) was approximately 2300 m (Fig. 1). The triangular array geometry was chosen to have one SM2 at the forest border and two located 80 m toward the interior of the forest.

Each SM2 was fixed on a tree at 1.5 m above the ground and was placed to have the two lateral microphones clear of any surface that could be an obstacle to incoming sound waves. They were configured to record in wave format at a sampling rate of 44.1 kHz, at 16 bits. No high-pass or low-pass filters were applied. One SM2 disappeared during the fifth session (at the site close to the mine), and the second session was not considered for one SM2 installed at the site distant from the mine because the noise produced by a flooded river masked all incoming sounds.

The collected data were subsampled by analyzing the first two minutes of recordings every hour. The resulting 23,520 min (392 h) were further processed using Wavesurfer software (Sjölander and Beskow, 2000) powered by the SoundscapeMeter plug-in (Farina et al., 2012). A Fast Fourier Transform (FFT) of 512 points was applied to obtain, from every two-minute file, a matrix made by 256 frequency bins of 86.13 Hz and 10,335 time intervals of 0.012 s. The resulting database of power spectra (i.e., the sound energy values along a frequency axis in each temporal interval) was used to analyze and describe two sonic components of the soundscape in each site: technophony and biophony.

All the files were separated into two frequency bands: 1) 0–1.5 kHz (predominantly occupied by noise or technophony) and 2) 1.5–22.05 kHz (mainly occupied by biophony). The lower frequency band was used to characterize the noise by analyzing the power spectrum and the second band was further processed to extract values for the ACI (Farina et al., 2011; Pieretti et al., 2011). The threshold of 1.5 kHz was chosen because most of the energy from anthropogenic noise is primarily concentrated under 2 kHz (Warren et al., 2006); this threshold was lowered 500 Hz to prevent the exclusion of some important biophonies that were just above 1.5 kHz from the ACI calculations (Pieretti and Farina, 2013). This was possible owing to the ACI being able to filter the noise over this threshold. Nonetheless, at the site closest to the mine, the noise produced by truck transit often covered

Fig. 1. Position of the passive acoustic monitoring devices close to and far from (2) the mine site at Peti Environmental station, Southeast Brazil.

frequencies up to 7–8 kHz, sometimes reaching upwards to 21 kHz. To avoid bias from these specific events in the ACI estimations of the biological sound expression, a specific routine was created in JustBasic v.1.01 to recognize and eliminate from the recordings every recorded truck passing. This was performed by cutting the portions of the files where the lower frequency bands presented amplitude levels higher than an established threshold, which was appositely verified to be always higher than any eventual biophony recorded in those frequency bands. Sound recording files dominated by rain or wind, which can also influence ACI estimations, were eliminated from the analysis.

Noise levels at the sites close to and far from the mine were compared by conducting two 20-minute measurements of the background sound pressure levels at each SM2 recording point using a Z-weighted B&K2270 sound level meter. All the animal sounds close to the microphone were excluded from the recordings using BZ5503 software (Bruel & Kjaer, Denmark). The standard sound-pollution measurement equivalent sound levels (Leq) were then extracted from the recordings (Rossing, 2007). The number of passings of the mining trucks per day was determined by listening to the recordings made at the site close to mine during 24 h over two days in each recording session using Raven Pro 1.5 software. Recurrent sounds produced by the mine were classified and characterized. Different types of anthropogenic sounds were selected from two days of recordings (48 h) from one SM2 at the site close to the mine for each recording session. The two most frequent types of noise were truck passing noise and the reverse warning sound of trucks. Twenty noise events were randomly selected per day, totaling 240 truck traffic events and 240 reversing truck sound events. For the less frequent noises, such as explosions, horns, and sirens, all events heard during two days were selected. These noise events were described using Raven Pro 1.5 by measuring their minimum, maximum and peak frequency, and duration.

Along with noise, variables including species richness, species composition and abundance could have influenced the acoustic dynamics of the two sites. To account for such differences between the sites close and far from the mine, species richness was calculated for each site using the aural identification of animals' sounds using Raven Pro 1.5 software. A single day of recording per session was randomly selected at four locations (two in the close and two in the far site) for species identification surveys. Sounds emitted by amphibians, birds, mammals, and insects were identified by specialists in the two-minute files between 0500 to 0700 h, 1000 to 1200 h, and from 1800 to 2200 h, totaling 528 analyzed minutes. The above time slots were chosen so that the following were included: the dawn and dusk choruses of birds and the midday and night activity of insects. It was not possible to determine species abundance aurally owing to the huge number of calls recorded. Insect sounds and bat social calls were classified as soundmorphs (different sound emissions or codas). This procedure was essential in order to identify potential species because the biodiversity in the Atlantic forest is so high that it is impossible to identify every species by aural census; additionally, there is a chance that some species recorded are not yet taxonomically classified.

From the recordings, the bandwidth, minimum and maximum frequencies of bird vocalizations and insect stridulations (most representative groups) that were identified only at one of the two sites (close or far from the mine) were extracted to compare the acoustic niche occupation of the singing community between the two sites.

2.3. Statistical analysis

Data analyses were separated into wet and dry seasons, and into day (5 am to 5 pm) and night (6 pm to 4 am) periods. Two analyses were conducted considering the time of day: (1) comparison of ACI day × ACI night in each site separately; and (2) comparison between sites of ACI day and ACI night. Preliminary analyses demonstrated that sample points on the border (closer to the roads), at both sites, were noisier than the other points; consequently, data analyses also included the groups: border and forest points.

All the statistical tests were performed using Statistica v.8.0. A non-parametric approach was employed because the variables were not normally distributed, even after attempted transformation of the data values. Mann–Whitney U tests were performed to test for differences in ACI and noise values between the following parameters: sites (close and far from the mine), seasons (wet and dry), and time period (day and night).

3. Results

3.1. Mining noise characterization

Sites close to and far from the mine differed significantly in terms of background noise. The site close to the mine exhibited levels 1–22

Table 1
Mean noise-level measurements at sites close to and far from an open-cast mine at Peti environmental station, Minas Gerais, Brazil.

Site	L_{eq} dB(Z)	L_{eq} max dB(Z)	L_{eq} min dB(Z)
Close (border)	62.3	67.9	56.8
Close (forest)	58.4	61.4	54.6
Far (border)	54.2	59.7	48.5
Far (forest)	53.7	60.2	45.2

dB(Z) higher in comparison with the site far from the mine. The mean L_{eq}, L_{eq}max and L_{eq}min of each type of soundscape are presented in Table 1. Noise levels in 1/3 octave bands are shown in Table 1 of the Supplementary Materials. The noise measured using the power spectral density confirmed the results of the noise-level measurements. These demonstrated that the noise was significantly higher at the site close to the mine both in the border and in the interior of the forest (Border: $U = 118$, $Z = 20.70$, $p < 0.01$, $N_{close} = 288$, $N_{far} = 288$; Forest: $U = 3556$, $Z = 28.4$, $p < 0.01$, $N_{close} = 552$, $N_{far} = 575$).

The five major mining noise sources identified at the site close to the mine were trucks passing, reversing alarm of trucks, work sirens, horns, and explosions (Fig. 2). The most frequent noise was truck transiting. A mean of 700 ± 43.8 (mean ± SD) trucks passed daily (29.91 ± 1.82 trucks/h) during the wet season and 244.6 ± 57 (10.91 ± 2.37 trucks/h) in the dry season. The descriptive statistics of the acoustic parameters of each noise event type are presented in Table 2.

Considering that a mean of 700 trucks passed per day in the wet season, with a mean duration of 20.2 s, this means that 16.2% of time during the day was occupied by truck transiting noise. The mean maximum frequency of this type of noise event was 15.2 kHz, meaning that the noise occupied 68% of the full spectrogram bandwidth (22.05 kHz).

3.2. Soundscape dynamics

3.2.1. Wet versus dry season

The ACI was significantly higher during the wet season than in the dry season at both sites. The noise exhibited a similar trend except for the interior of the forest at the site close the mine (Table 3).

3.2.2. Day versus night

In the wet season, at the site far from the mine, the ACI values were significantly higher during the night. By contrast, there was no difference between the ACI values of day and night at the site close to the mine. Noise values were significantly higher during the night at the site close to the mine. In the dry season, the ACI values were significantly higher during the night at both sites, except on the border points at the site close to the mine. At the site close to the mine, noise values were also significantly higher during the night, but only for the forest points (Table 3).

3.2.3. Close versus far site

In the wet season, during the night the ACI was significantly higher at the site far from the mine while it was found to be significantly higher during the day at the site close to the mine. During the dry season, there was no significant difference in the ACI values at night between the two sites, while during the day, the ACI values were significantly higher at the close site, except at the border points (Table 3; Figs. 3 and 4).

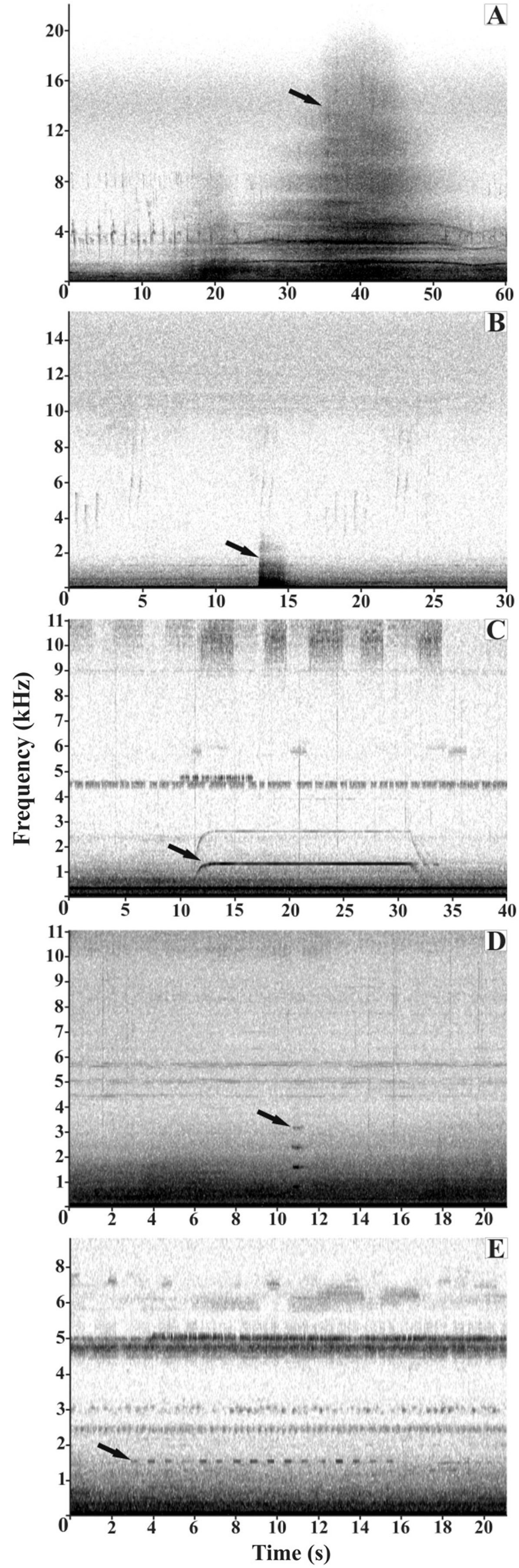

Fig. 2. Spectrograms of the noise produced by: A– transit of trucks, B — explosions, C — work sirens, D — horns, E — reversing alarms of trucks on a mining road at Peti environmental station, Southeast Brazil. In the background of the spectrograms there is also biophony.

Table 2
Acoustic variables of most frequent noise sources from mining activity at Peti environmental station, Minas Gerais, Brazil.

Noise source	Duration (s) mean ± SD	Peak freq.(Hz) mean ± SD	Max freq.(Hz) mean ± SD	Min freq.(Hz) mean ± SD
Truck N = 240	20.2 ± 8.9	553.9 ± 38.6	15,291.0 ± 43.8	0.0 ± 0.0
Reversing N = 240	10.56 ± 2.54	1314.6 ± 91.4	1373.9 ± 90.6	1255.1 ± 91.4
Siren N = 75	17.9 ± 4.6	1229.4 ± 136.1	1393.6 ± 101.4	872.3 ± 144.9
Horn N = 19	6.7 ± 14.5	1219.0 ± 98.5	4747.0 ± 55.4	781.0 ± 75.9
Explosion N = 19	5.9 ± 3.2	197.2 ± 117.8	4353.0 ± 206.0	90.4 ± 30.7

3.3. Characterization of fauna

Species richness results from the aural survey are shown in Table 4 (see also Table S2 in supplementary materials for a complete check list of the species). A total of 91 bird species (16 were classified as "not identified" owing to the short duration of the song or long distance from the microphone, which prevented identification), 84 different soundmorphs of insects, 9 soundmorphs of bats, 3 species of frogs and 2 species of primates were identified. At both sites, the insect community was particularly acoustically active during the night, although cicadas were highly active during the day (observed following an aural check).

Table 3
Mann–Whitney U tests performed to test for differences in ACI and noise values between: seasons (wet vs dry); time period (day vs night); and sites (close to vs far from the mine). Statistics on noise values refer to the site close to the mine.

	U	Z	p	N_{wet}	N_{dry}	Higher value
Wet vs dry season						
ACI close border	4824	7.84	<**0.01**	144	144	Wet
ACI close forest	20,759	8.04	<**0.01**	264	264	Wet
ACI far border	5915	6.3	<**0.01**	144	144	Wet
ACI far forest	23,689	7.65	<**0.01**	288	264	Wet
Noise border	6531	5.42	<**0.01**	144	144	Wet
Noise forest	37,359	−0.35	0.72	288	264	–
	U	Z	p	N_{day}	N_{night}	Higher value
Day vs night — Wet season						
ACI close border	2481	0.37	0.7	78	66	–
ACI close forest	8498	−0.24	0.8	143	121	–
ACI far border	1220	5.42	<**0.01**	78	66	Night
ACI far forest	3386	8.51	<**0.01**	146	121	Night
Noise border	1884	2.76	<**0.01**	78	66	Night
Noise forest	7304	4.24	<**0.01**	156	132	Night
Day vs night — Dry season						
ACI close border	2279	1.18	0.23	78	66	–
ACI close forest	5595	4.94	<**0.01**	143	121	Night
ACI far border	1987	2.35	<**0.01**	78	66	Night
ACI far forest	6840	4.9	<**0.01**	156	132	Night
Noise border	2276	1.19	0.23	78	66	–
Noise forest	6764	3.05	<**0.01**	143	121	Night
	U	Z	p	N_{close}	N_{far}	Higher value
Close vs far sites from the mine — Wet season						
ACI border night	1510	−3.04	<**0.01**	66	66	Far
ACI forest night	5145	−3.99	<**0.01**	121	121	Far
ACI border day	2032	3.57	<**0.01**	78	78	Close
ACI forest day	6191	5.76	<**0.01**	143	143	Close
Close vs far sites from the mine — Dry season						
ACI border night	2070	−0.49	0.62	66	66	–
ACI forest night	7156	−1.42	0.15	121	132	–
ACI border day	2633	−1.44	0.14	78	78	–
ACI forest day	8989	−2.89	<**0.01**	143	156	Close

The significant results are bolded.

The bird community demonstrated greater acoustic activity during the day, mainly during the dawn chorus, with few species singing during the night. Primates were especially vocal early in the morning. Insect species were estimated to be higher in the wet season and, in particular, during the night. Bat calls were detected only at night. The richness of species was found to be higher: (1) during the wet season on both sites; (2) during the day in both seasons and sites; and (3) on the site far from the mine, especially during the wet season.

Insect species that were detected only at the site far from the mine presented stridulations with significantly larger bandwidth, and higher maximum and minimum frequencies than species that occurred only at the site close to the mine. The opposite occurred with bird species. Species recorded close to the mine presented significantly larger bandwidth, and higher maximum and minimum frequencies than species recorded at the site far from the mine (Table 5).

4. Discussion

Large-scale human activities can have a considerable impact on the daily ecological functions within a community (Francis et al., 2011); in particular, on acoustic communication processes (Rabin et al., 2003; Slabbekoorn and Ripmeester, 2008). Noise is one of the most common threats to environments around the world owing to its, well-established, negative impact on fauna (Brown et al., 2013; Pieretti and Farina, 2013). Although mining is an important economic activity in many parts of the world, its subtle effects on animal ecosystems are still poorly understood. The approach taken in this study of investigating acoustic dynamics has recently been considered as a proxy for biodiversity measurement (Krause, 1987; Sueur et al., 2008) and can also provide additional information related to species' adaptation and reactions to changes in the environment (Farina et al., 2011).

4.1. Mining noise

The results of this study demonstrated that there was a conspicuous difference between the sites close to and far from the mine in terms of noise levels. Considering that the mining activity has been ongoing in the study area for decades, changes in the behavior of the animal community could be interpreted as long-term responses to the impact of mining. Noise sources in our study area were diverse, continuous and occupied a wide frequency bandwidth, potentially masking many animal sounds and affecting their behavior and distribution. As a confirmation of this hypothesis, some birds with low frequency vocalizations were only recorded far from the mine, such as *Patagioenas plumbea*, *Leptotila* sp., *Leptotila verreauxi*, and *Ramphastos toco* (see Table S2 in Supplementary Materials). During the wet season, almost 70% of the frequency bandwidth (0–22 kHz) was completely occupied by the truck-transit noise for 16% of the day time, interfering with the acoustic space used by the animal community.

4.2. Soundscape dynamics

4.2.1. Wet versus dry season

As expected, the acoustic complexity registered during the wet season was much higher than in the dry season at both sites. The wet season in Brazil coincides with breeding season of insects, amphibians and birds; consequently, animals are more acoustically active (Aichinger, 1987; Haddad et al., 1992; Rodrigues et al., 2005). This result was confirmed by the species count, with a greater number of species from all of the animal groups being detected during the wet season.

4.2.2. Day versus night

During the wet season, the site close to the mine lost the diel pattern of having significantly higher acoustic activity at night that was found at the site far from the mine (Table 3), presenting a tendency of a comparatively higher acoustic complexity during the day and lower acoustic

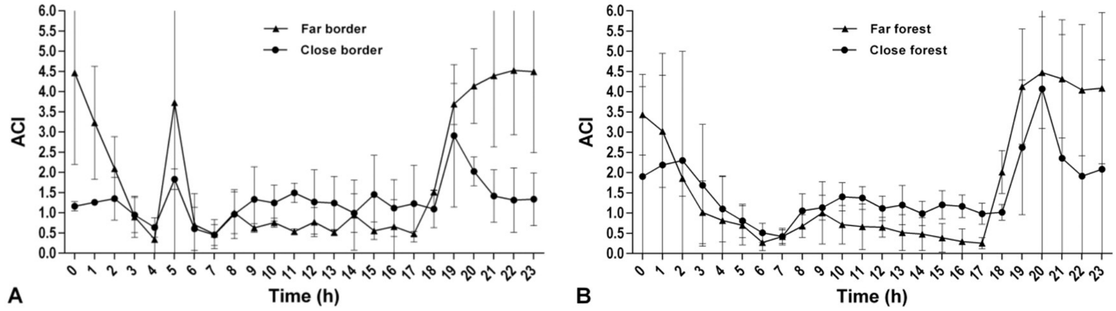

Fig. 3. Temporal distribution of the ACI values at border (A) and forest (B) points at sites close to and far from an open-cast mine during the wet season at Peti Environmental Station, Brazil.

complexity throughout the night (Fig. 3). Here, two possible explanations for this phenomenon are hypothesized: (1) noise levels are higher during the nighttime and, consequently, the acoustic community established in the site close to the mine can be more acoustically active during the day, when there is more available acoustic space and less competition with anthropogenic noise; (2) there is a similar number of species singing during day and night at the site close to the mine, and a great difference in species richness at the site far from the mine. The second explanation was proven false by the aural identification, with a higher number of species detected during the day at both sites (67 versus 41 at the site close to mine; 71 versus 49 at the site far from the mine). Nevertheless, the ACI was higher during the night at the site far from the mine. Greater acoustic activity during the night was expected at both sites because the majority of biophony was produced by insects. This animal group is mostly active during the night and produces long modulated songs often with high amplitude, resulting in high ACI values (Farina et al., 2011). During the dry season, both noise and ACI were always found to be higher at night, even if the border points of the site close to the mine did not produce results that were statistically significant. It is likely that the reduced number of truck transits and noise levels recorded in this season exerted less influence on the animal community. Nevertheless, a slight tendency of changing the daily patterns appeared to be present, even considering the low acoustic activity during this season (Fig. 4).

4.2.3. Close versus far site

In the wet season, the higher ACI values at night at the site far from the mine in comparison with the values from the same period at the site close to the mine, may be a direct effect of a higher number of species vocalizing, especially insects. Noise has already been proven to affect species diversity and the population density of birds in areas close to mining activity (Saha and Padhy, 2011). The results of this study demonstrate that the number of species detected was lower at the site close to the mine and that the species composition was different between the two sites. Many studies concerning the effects of road noise on animals have revealed that there is a strong negative relationship between traffic intensity and species richness, with changes occurring in composition and density of individuals (Forman et al., 2002; Rheindt, 2003). Bayne et al. (2008) recorded that, near noiseless energy facilities, passerine density was 1.5 times higher than in areas near noise-producing energy sites.

Other factors than noise can contribute to a low species richness, abundance and diversity in noisy environments; for example, quality of habitat, vegetation characteristics, air and chemical pollution, and soil vibration among others (Summers et al., 2011). Nevertheless, owing to the importance of acoustic communication, which animals use to locate food (Elowson et al., 1991; Slabbekoorn and Ripmeester, 2008) and reproductive partners (Patricelli et al., 2002), to escape from predators (Greig-Smith, 1980; Chan et al., 2010), and to defend resources (Zuberbuehler et al., 1997), just to name some major functions, it is expected that noise will affect species richness, abundance and community composition (Tucker et al., 2014).

Higher acoustic activity at the site close to the mine during the day could also be explained by anthropogenic noise. During the day, the number of species recorded was higher at the site far from the mine. A higher ACI value was also expected as well; however, the opposite was observed. It is suggested that this result might be related to compensatory mechanisms of individuals trying to propagate their signals with greater emphasis (higher amplitude or repetition of the strophes or syllables) in order to override the masking effect of anthropogenic noise. The number of individuals singing might have an effect on ACI values but unfortunately, species abundance was impossible to assess. Other studies have found similar results in different environments. Pieretti and Farina (2013) found that both ACI values resulting from birds and noise were significantly higher with greater proximity to a road, indicating a more active singing community where noise is more intense. The animal community in an urban forest in Brazil also presented higher activity at noisy sites (Santos, 2013). Birds and mammals can present a behavior known as the Lombard effect, in which animals increase the amplitude of their calls in the presence of high levels of competing environmental noise (Cynx et al., 1998; Brumm et al., 2004; Brumm and Slater, 2006). Additionally, many species are capable of increasing the rate and duration of their vocalizations to ensure the efficiency of their communication (Brumm et al., 2004; Sun and Narins, 2005). Greater amplitudes result in more defined and less degraded

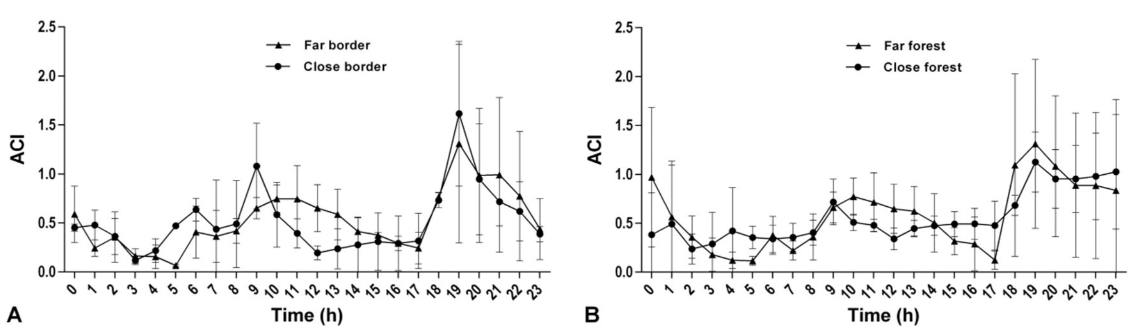

Fig. 4. Temporal distribution of the ACI values at border (A) and forest (B) points at sites close to and far from an open-cast mine during the dry season at Peti Environmental Station, Brazil.

Table 4
Potential number of species at close and far sites from an open-cast mine at the Peti Environmental Station, Brazil by season (wet versus dry) and time of day (day versus night).

Taxonomic group	Close						Far						Species in common	Species detected only in close	Species detected only in far
	Wet			Dry			Wet			Dry					
	Day	Night	Total	Day	Night	Total	Day	Night	Total	Day	Night	Total			
Insects	25	36	**49**	15	23	**33**	26	42	**54**	12	27	**36**	43	16	25
Amphibians	–	1	**1**	–	–	–	–	2	**2**	–	1	**1**	1	–	1
Birds	40	–	**40**	34	–	**34**	43	–	**43**	34	1	**35**	25	32	34
Bats	–	4	**4**	–	7	**7**	–	5	**5**	–	2	**2**	6	2	1
Primates	2	–	**2**	2	–	**2**	2	–	**2**	2	–	**2**	2	–	–
Total	67	41	**96**	51	30	**76**	71	49	**106**	48	31	**76**	77	50	62

recorded signals, leading the ACI to perceive greater variations of intensities. Higher emission rates and longer call duration could all lead to an increase in ACI values and would explain the results encountered.

Another alternative or complementary explanation for a higher acoustic complexity could be linked to the acoustic properties of the sounds emitted by the species detected in just one of the two sites, which could comparatively tend toward behavior to sing more or have a more complex song (such as longer strophes or greater heterogeneity of the song). This would result in higher ACI values being found.

4.2.4. Characterization of fauna

The acoustic measurements of the insect stridulations and bird vocalizations revealed other possible effects of anthropogenic noise on animal communication. The greater bandwidth of the insect stridulations at the site far from the mine could be interpreted as a natural pattern that evolved in the absence of anthropogenic noise. By contrast, the noise present at the site close to the mine could be selecting for species with narrowband stridulations, since a considerable part of the local acoustic space is occupied by anthropogenic noise. Species that produce sounds occupying less acoustic space can better cope with the competition from noise given that the probability of overlap would be reduced, especially if the spectral occupancy pattern of these animals' sounds overlaps with less intense bands of noise.

The bird vocalization analysis produced different results. Species producing sounds with larger bandwidths were recorded at the site close to the mine. This probably arises owing to the different features of bird acoustic emissions, which tend to be consistently shorter and less repetitive in time than insects stridulations. Consequently, in the case of birds' vocalizations, it is likely that a smaller bandwidth can suffer more the noise masking effects. Additionally, bird calls at the site close to the mine presented higher maximum and minimum frequencies in comparison with species from the site far from the mine. Consequently, it could be speculated that the pervasive noise at the site close to the mine could be selecting species that vocalize at higher frequencies and are less masked by the noise. This can be confirmed by the absence of species that vocalize at very low frequencies in that site. Rheindt (2003) has previously demonstrated that there is a significant relationship between the dominant frequency of bird vocalizations and a decline in abundance toward a motorway, indicating that having a higher pitched song, with frequencies above those of traffic noise, makes birds less susceptive to anthropogenic noise. Hence, the results in this study support the hypothesis that noise can affect the animal community by changing singing dynamics.

4.3. Considerations about the methodology

Although several automated indexes have been proposed for soundscape and biodiversity analyses, the application of a single index can hardly account for all the biological components (Sueur et al., 2014). Therefore, the simultaneous use of acoustic indices could provide additional insights on biophony reactions to mining noise, and may help to improve understanding of species reactions. Nevertheless, the separation of the two different soundscape components (technophony and biophony) still represents a difficult task because they overlap, particularly in the lower frequency bands. Consequently, when automatic processing procedures are applied in noise-polluted environments, technophony might be read as biophony and vice versa. In this study, one algorithm was selected for the processing phase, the Acoustic Complexity Index (ACI), because it has been previously proven to be effective for filtering out constant sounds (Pieretti et al., 2011) such as trucks' transits or background buzz from mining activity, while enhancing the variability of biological sonic productions. Therefore, ACI is regarded here as a proxy of biophonies that are compared across two different soundscapes, noisy and natural.

Future research might consider the application of several indices in recordings characterized by different kinds of noise, in order to analyze their pros and cons together with the emergent properties of their combined use. Indeed, studies describing the use of acoustic indices to investigate animal communities in noise-polluted environments are needed. Additionally, it is important to note that soundscape measurements are, currently, not able to provide precise and detailed information at a species-specific level. There is still the need for a comparison with classical fieldwork data, e.g. species aural census, in order to interpret the automatic procedure results correctly. When dealing with noise-polluted habitats, analytic compromises must be defined, such as to split the analyses into specific frequency bands (for example here 0–1.5 kHz and 1.5–22 kHz). Nevertheless, the exploration of acoustic communities and soundscapes offers an efficient way to analyze large-scale phenomena (Sueur et al., 2014). The assessment of acoustic temporal and spectral changes can provide a general overview of circadian

Table 5
Spectral characteristics of insect stridulations and bird calls in the sites close to and far to the mine at Peti Environmental Station, Brazil.

Animal group	Site	Bandwidth (Hz) (mean ± SD)	U	Z	p	Maximum frequency (mean ± SD)	U	Z	p	Minimum frequency (mean ± SD)	U	Z	p
Insect	Far	3233 ± 517	3391.5	−3.88	<**0.01**	8560 ± 615	3893	−2.67	<**0.01**	5326 ± 262	3877	−2.71	<**0.01**
Insect	Close	1777 ± 378				6117 ± 360				4340 ± 213			
Bird	Far	2088 ± 212	11,723	2.16	<**0.05**	3425 ± 249	6039	8.72	**0.01**	3425 ± 249	11,110	2.87	<**0.01**
Bird	Close	2189 ± 164				5832 ± 243				3643 ± 172			

rhythms and dynamics of entire animal communities, representing an effective tool in identifying significant variations and, eventually, to help promote conservation and preservation actions.

5. Conclusion

Many studies have demonstrated the negative impact of noise pollution on animal acoustic communication, as well as revealing the negative impact on species diversity, richness and abundance. Nevertheless, studies into the impact of technophony on the biophony in terrestrial soundscapes in tropical environments are still lacking. Here, it has been shown that sound pollution from open-cast mining activities has a significant impact on the biophonical soundscape of a neighboring tropical forest. Differences found in soundscape complexity were probably related to lower species richness at the site close to the mine, changes in animal community composition, spectral characteristics of calls between the two sites, and possible animal adaptive responses to noise. Given that open-cast mining is a major global economic activity, which frequently occurs in natural areas, these results demonstrate the need for its noise impact to be taken into consideration during the evaluation of conservation and management strategies of natural areas close to mining activity. Alongside this, data are provided to highlight the importance of establishing laws and regulations to monitor and control noise close to natural areas.

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Appendix A. Supplementary data

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