# Scale-free distribution of silences

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Soundscape studies help us understand ecological processes, biodiversity distribution, anthropic influences, and even urban quality, across a wide variety of places and time periods. In this work, instead of looking for differences, we ask if there are common characteristics shared by all soundscapes. Based on our results, we propose a universal distribution of quiet-time (background noise) and sound-time (acoustic energy bursts) in audio recordings. We analyzed one continuous hour during daylight and one at night, from ten randomly selected days in each environment: urban, dry forest, savanna, rupestrian field, Atlantic forest, marine, and freshwater. We found that the histograms of the quiet-time followed a power law for all scenarios analyzed, they present fractal events or scale-free distributions. This distribution covers up to four orders of magnitude, with an exponent of $1.6 \leqslant \alpha \leqslant 2.0$ for all soundscapes. By contrast, the sound-time distribution in all environments followed a log-normal or timescale dependence, with a typical time for the duration of sounds (0.06–0.12 s). Such time duration limitation can be related to the physiology of sound emission in animals.

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## I. INTRODUCTION

The soundscape is the arrangement of sounds produced in a place by multiple acoustic sources that can be classified into biophony, geophony, and technophony [1]. The complex structure of sounds arranged in space and time that characterize the soundscape interfaces with different areas of research from landscape ecology [2], animal behavior [3], eco- and bioacoustics [1,4] to cognitive behavior [5] and urban studies [6]. To study soundscapes, one can consider their temporal, spectral, and spatial patterns [7,8], and account for natural features as well as anthropic influences [9,10] on these environments. To that end, a plethora of acoustic indices are being developed to discriminate, characterize, and classify this enormous diversity of acoustic information and translate it into ecological inferences [11,12].

The search for adequate indices to characterize and discriminate soundscapes is indeed an important issue in the acoustics of natural and urban environments [13,14]. However, we may also focus our attention on the opposite direction: instead of searching for differences in the soundscapes, we can look for intrinsic aspects shared by soundscape records. And ask, are there physical, or statistical properties that are common to all, or at least, to most soundscapes? At a first glance, this seems to be very unlikely considering that particular landscape characteristics can affect both the composition and dynamics of soundscapes [15]. For instance, one can investigate an urban location, or a pristine environment, and see clear variations along the seasons, or even throughout different periods of the day and night. Yet, with the right focus, one may see other patterns in sound and silence durations.

To the best of our knowledge, there are no general rules that unite soundscapes into a single entity. Nonetheless, there may be common patterns for zoophony, i.e., animal sounds [16]. Animals are theoretically selected to produce sounds with characteristics better suited to propagate in the environment in which they have evolved (acoustic adaptation hypothesis [17–19]), exploring frequencies and moments with lower acoustic competition within the soundscape (acoustic niche hypothesis [20]). These hypotheses about animal signal evolution may result in general patterns of sound and silence in natural soundscapes. It is harder to find general rules for geophony and technophony considering the lack of evolutionary pressure on these sounds. Nevertheless, some studies have shown that similar patterns in urban and more natural soundscapes may indeed occur [6,21]. A $1/f$ spectrum pattern in the frequency domain and temporal autocorrelation have been found in many soundscapes [21].

In this work, we slice the acoustic record into bursts of acoustic events interspersed by silent (or quiet) backgrounds. Once slicing is achieved, it is possible to study the statistical

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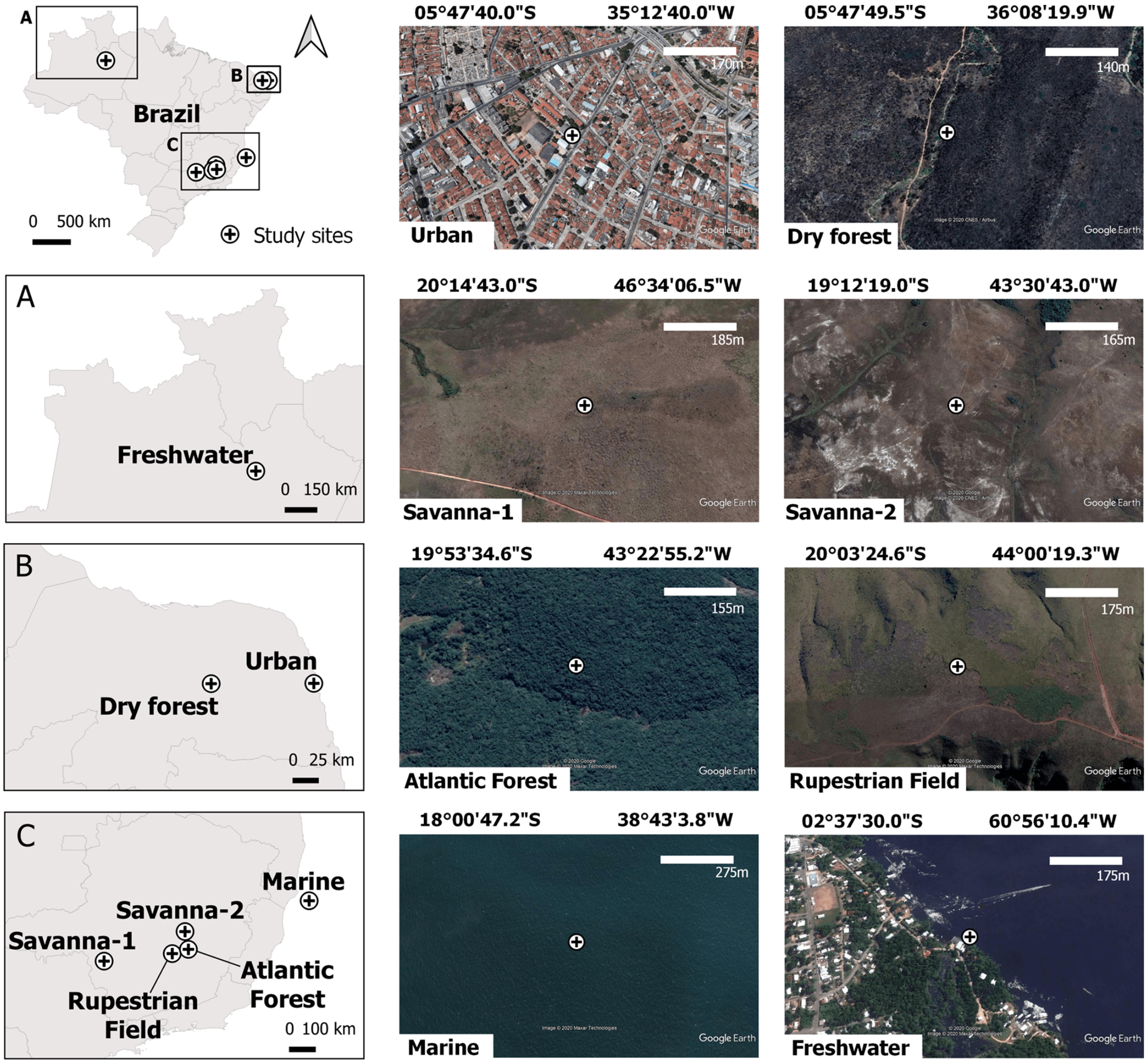


FIG. 1. Analyzed soundscapes from eight different environments. Satellite images highlight the differences among the urban, dry forest, savanna-1, savanna-2, Atlantic forest, rupestrian field, marine, and freshwater environments. The figure was generated with QGIS, V 3.14.1 [24]. Satellite images were taken from Google Earth V 7.3.3.7786 [25]. Google, CNES / Airbus, Maxar Technologies (2020).

properties of the quiet and sound portions of the acoustic record as distinct parts of the soundscapes [22,23]. Our study was performed with acoustic data from eight diverse environments: two subaquatic (marine and freshwater ecosystems) and six terrestrials (one urban and five natural ecosystems; see Fig. 1). These soundscapes are analyzed according to two periods: day and night. In all studied soundscapes we found the same universal pattern: the structure of the silences is scale-free while the sound emissions statistics are always characterized by a typical finite duration. Silence is the essential background of any sound, and we have found that the statistics of the duration of silences have no characteristic length in contrast to the sound duration. This manuscript poses an ambitious question: Is there a general behavior in the statistics' pattern of the duration of silences and sounds? Our results point to an affirmative answer. In the final section, we discuss the theoretical mechanisms which may explain our findings and, besides, we consider the extent and implications of our working hypothesis.

## II. MATERIALS AND METHODS

### A. Data set

The dataset was provided by different projects (different environments: urban, dry forest, savannas 1 and 2, rupestrian field, Atlantic forest, marine, and freshwater, therefore data format is highly variable (Table S1 of Supplemental Material [26]). Sampling rates varied from 2 000 to 48 000 Hz, coded in wav, aiff, or MP3 format. As we were only interested in the sound amplitudes and not in the frequencies, our results are not dependent on the sampling rate. Still, the typical sound emissions are in the order of 0.06 s which is much larger than the duration of the smaller recording rate of 2000 Hz, that is $1/2000 = 0.0005$ s. In addition, we tested if sampling rate had any influence on our results by resampling part of our data set (urban, savanna-2, and dryforest; results of this test are in Figs. S3 and S4 of the Supplemental Material [26]). All sound files had a length of one continuous hour. For each site we used 10 diurnal hours and 10 nocturnal hours (except for the freshwater dataset, limited to 4 h each), taking one recording hour for each randomly selected day. We used the same hours of the day in each environment (e.g., 3–4 h a.m. and 12–1 h p.m., Table 1 of the Supplemental Material [26]) and tried to select similar hours across environments, although some variation was inevitable. Here, we focus on the duration of silences and sounds, not in the frequency content within our sound records. Nevertheless, a brief description of the main sound sources of each soundscape sampled will be offered here for illustrative purposes. Also, a 5-min spectrogram of each environment can be found in Fig. S2 of the Supplemental Material [26].

#### *1. Urban soundscape*

The acoustic records of an urban environment were acquired in the city of Natal, Northeast Brazil (Fig. 1). The city is the capital of the state and has a population of about 800 000 inhabitants. The recording site is in a residential neighborhood composed of houses, trees, commercial establishments, residential buildings, and some busy roads. Recordings were done between the months of July and August 2018. At this (sampling rate) the zoophony of this environment includes mainly birds (mostly between 3 and 10 kHz), insects (many bands) and domestic animals (most energy below 4 kHz). However, the soundscape is dominated by technophony, especially traffic noise (broadband but most energy below 2 kHz) and sirens (many bands but generally below 12 kHz), and pedestrian talk (most energy below 4 kHz). More details about data collection can be found in Ref. [23].

#### *2. Dry forest soundscape*

Recordings of this soundscape were made in the Caatinga biome, a seasonally dry tropical forest (named here as “dry forest” for simplicity) which occupies about 11% of the Brazilian territory and 54% of the Northeast region [27]. This biome is composed of arid adapted vegetation, mainly small thorny trees, shrubs, and cacti. The climate is hot and semiarid, with a brief rainy season, although humid forest patches can occur [28]. The recording site was located in Lajes, also in the state of Rio Grande do Norte (Fig. 1). The sound samples were recorded between June and July 2017 (in the rainy season). The sampling rate used in this soundscape allows the inclusion of birds (mostly between 3 and 10 kHz), which are common during the day, and insects at many bands, common during the night [16]. Donkeys, at lower bands (4 kHz −), and bats, at higher bands (16 kHz +), are occasionally present. Cicadas produce very intense sounds and may dominate all spectrum, as does the wind when present [16].

#### *3. Savanna soundscape*

Recordings of this soundscape were made in the Cerrado biome. The Cerrado is the second-largest biome in South America, occupying about 22% of the Brazilian territory [29]. Vegetation types include forest, woody, and open savannas, and occasionally gallery forests [30]. It is considered the most biodiverse savanna in the world [30]. The recordings were made in two sampling points located at Serra da Canastra National Park, and Serra do Cipó National Park, state of Minas Gerais, Brazil. (Fig. 1). The savanna-1 (20°14′43.0″ S 46°34′06.5″ W) includes patches of woody and open savannas and the savanna-2 (19°12′19″ S and 43°30′43″ W) represents an area of Cerrado *sensu stricto*. Serra da Canastra National Park: The zoophony included in this recording consists mainly of insects and anurans (many bands), with also birds that vocalize at relative lower frequencies (up to 4 kHz) and rarely large mammals (2 kHz −), like the maned wolf. In addition, low bands (0.5 kHz −) are dominated by geophony, like wind and rain, that occasionally occupies the entire spectrum. More details about the data collection can be found in Ref. [31]. Serra do Cipó National Park: The zoophony included in this recording consists mainly of insects and birds. In addition, low bands (0.5 kHz −) are dominated by geophony, like wind, and rain during the months of September and November 2012 (rainy season).

#### *4. Atlantic forest soundscape*

Data were collected at the environmental station of Peti in the municipalities of São Gonçalo do Rio Abaixo and Santa Bárbara (19°53′34.61” S and 43°22′55.17″ W), Minas Gerais, Brazil (Fig. 1). The study area is approximately 605 hectares in size and is located in the upper Rio Doce Basin (altitude range: 630–806 m). The reserve is covered by secondary arboreal vegetation, with large trees and a continuous canopy. The zoophony included in this recording consists mainly of insects, birds, bats, and primates. In addition, low bands (0.5 kHz −) are dominated by geophony, like wind and rain, that occasionally occupies the entire spectrum.

#### *5. Rupestrian field soundscape*

Recordings were made in the Rupestrian fields at the State Park of Rola Moça, located in the northwest of “Quadrilátero Ferrífero,” Minas Gerais, Brazil (20°03′24.58” S, 44°00′19.25” W; Fig. 1) at a mean altitude of 1450 m. “Rupestrian ferruginous fields” are among the most endangered and least studied ecosystems of Brazil due to restricted geographical distribution and the presence of the country’s main iron ore deposits. The zoophony included in this recording consists mainly of insects and birds. In addition, low bands (0.5 kHz −) are dominated by geophony, like wind and rain, that occasionally occupies the entire spectrum.

#### *6. Marine soundscape*

The marine soundscape recordings were made in the Abrolhos bank, located in Bahia state (Fig. 1). Abrolhos is a sediment capped volcanic bank in the East coast of Brazil, consisting of an enlargement of the continental shelf [32]. Abrolhos covers the most extensive and richest area of coral reefs in Southwestern Atlantic [33] and one of the most important breeding sites of humpback whales in the world [34]. The recording site (18°00′47.24″ S 38°43′3.78″ W) was inside the Abrolhos Marine National Park, a protected area located in the northeast of the Abrolhos bank. Recordings were made from July to October 2005 (during humpback whale breeding season). Detailed information of the data collection can be found in Ref. [35]. The Abrolhos soundscape at this sampling rate includes mainly fish choruses (most energy below 300 Hz), humpback whale songs (most energy below 350 Hz)

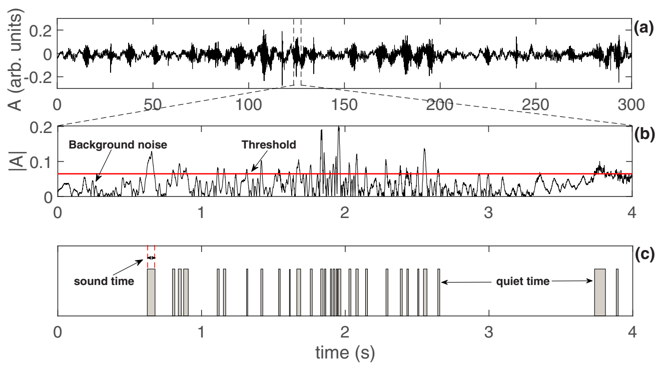


FIG. 2. Outline of the methodology used to determine the silence and sound durations. Panel (a) shows a 300-s acoustic record with arbitrary units. Panel (b) shows a 4-s zoom of the time series, with the threshold line and background noise indicated. And panel (c) indicates the sound-times (emissions above the threshold) and quiet-times intervals (emissions below the threshold).

and vessel noise from fisheries and tourism activity (most energy below 500 Hz) [36].

#### *7. Freshwater soundscape*

The soundscape of the freshwater environment was recorded at the limit of the Parque Nacional da Anavilhanas, a Federal Conservation Unit next to the city of Novo Airão, Amazonas State, Brazil (Fig. 1), in the lower portion of the Negro River Basin. The recordings were done between March 2018 and May 2020. The exact collection site for each recording seasonally oscillated around the coordinate 02°37′30.0″ S 60°56′10.4″ W because the hydrophones were fixed under a floating laboratory that accompanies the water level which falls and rises during the dry and rainy seasons, respectively. The water level difference between the peak of the dry and the rainy seasons is around 17 m in the sampling point. The soundscape in this location includes zoophony from fish, insect larvae and possibly river dolphins (*Inia geoffrensis and Sotalia fluviatilis*), geophony derived mainly from rain and storms, and technophony associated to several types and sizes of boat engines, varying from large commercial ships to small canoes with small outboard engines.

### B. Definition of quiet-time and sound-time intervals

To define the quiet-time and sound-time intervals, we divided the time series of acoustic recordings in two subsets: quiet and sound intervals. We defined quiet intervals as the intervals whose amplitude is under a given threshold. The sound intervals are the ones when the amplitude values are above this threshold. We define the threshold value using an adequate n in the expression $\mu + \mathrm{n}\sigma$, for $\mu$ the average of the absolute value of the signal and $\sigma$ the corresponding standard deviation. In this study, we chose the particular threshold $\mu + 2\sigma$; see (Fig. 2). We tested the statistical analysis for different n to assure that the choice of the threshold does not impact the main statistical results of the work. In fact, we varied the thresholds (from $\mu + \sigma$ to $3.5\sigma$) on a portion of the data set (savanna-1 and savanna-2) to test if any effect on our results would emerge.

### C. Statistical distributions for quiet time and sound time

The focus of this paper is about the characterization of the probability distribution function (PDF) that we call $P(T)$. In this context, it is important to study the power-law distribution $\mathrm{P(T)} \propto (T)^{-\alpha}$, for $\alpha$ a parameter. We performed the adjustment of all statistical distribution curves to the data using the Method of Maximal Likelihood (MML) [37–41]. In this approach, the Cumulative Distribution Function (CDF) $(T) = \Pr(T \geqslant t)$ is plotted, and the probability distribution is obtained by derivation of the CDF$(T)$. The case of the power-law distribution is depicted as follows:

$$P(T) \propto (T)^{-\alpha}, \tag{1}$$

where $P(T)$ is the distribution of probability associated to the quiet-times $T$. In Eq. (1) the exponent $\alpha$ of $P(T)$ is associated to $\mathrm{CDF}(T) \propto (T)^{-\alpha+1}$. We call attention that the power-law distribution does not show a typical characteristic timescale. In addition, we consider the log-normal distribution, which is constructed using the logarithmic transformation of the Normal distribution [42]. For a random variable, the log-normal probability density function is given by [43]

$$f(t) = \frac{1}{t\sigma_L\sqrt{(2\pi)}}\exp\left[\frac{-(\log(t) - \mu_L)^2}{2\sigma_L^2}\right], \tag{2}$$

where $\mu_L$ and $\sigma_L$ are the two parameters of the distribuiton. The median of the distribution is given by median $= \exp(\mu_L)$, the average of the log normal is given by average $= \exp(\mu_L + \sigma_L/2)$ and the mode of the distribution is done by the mode $= \exp(\mu - \sigma^2)$. In addition, the $S^2$ variance that evaluates the data dispersion is done by $S^2 = [\exp(\sigma_L^2) - 1]\exp(2\mu_L + \sigma_L^2)$. A good indicator of the error around the mean is given by the standard deviation $\sigma = \sqrt{S^2}$. We highlight that the log normal is constructed using the log transformation of the Normal distribution and, consequently, it has a characteristic timescale. Since the log normal is an asymmetric distribution, the mean is not the central reliable measure of the random data. In this way, the median and the model are also employed to characterize log-normal data centers.

## III. RESULTS

### A. Quiet-time distribution

The absence of typical temporal scales characterizes the statistics of the silences; in fact, the quiet-time distribution follows a power-law behavior. We plot the accumulated probability distribution of the silent time in Fig. 3, to illustrate we show one curve for each biome, day and night. In this figure we plot the power law and added an exponential and a log-normal fittings to compare with the power-law curve. Figure 4 shows the accumulated probability distributions for the quiet-times corresponding to the analyzed acoustic records for all sites. The curves are plotted using logarithmic axes to highlight power-law behavior. The silence interval scales span from 0.02 to 100 s. The results were divided into two periods: diurnal (Fig. 4, left panels) and nocturnal (Fig. 4, right panels). Each panel shows 20 1-h samples for each soundscape (with exception to the freshwater soundscape data, which was composed by 8 1-h samples).

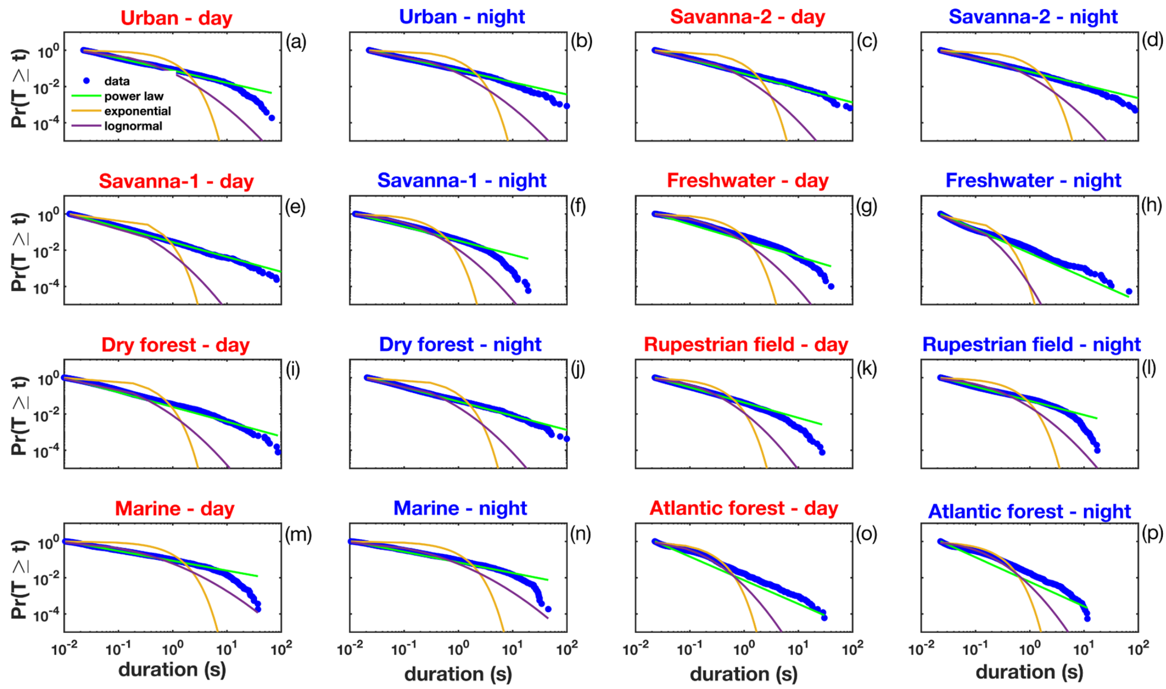


FIG. 3. The cumulative sum of quiet times is presented with logarithmic axes, all biomes, day and night are represented. We choose one particular curve of each biome to illustrate the power-law (green), exponential (yellow), and log-normal (magenta) fittings. The power law shows the best curve fitting among the functions. A table containing all statistical results corresponding to this figure is shown in the Supplemental Material [26].

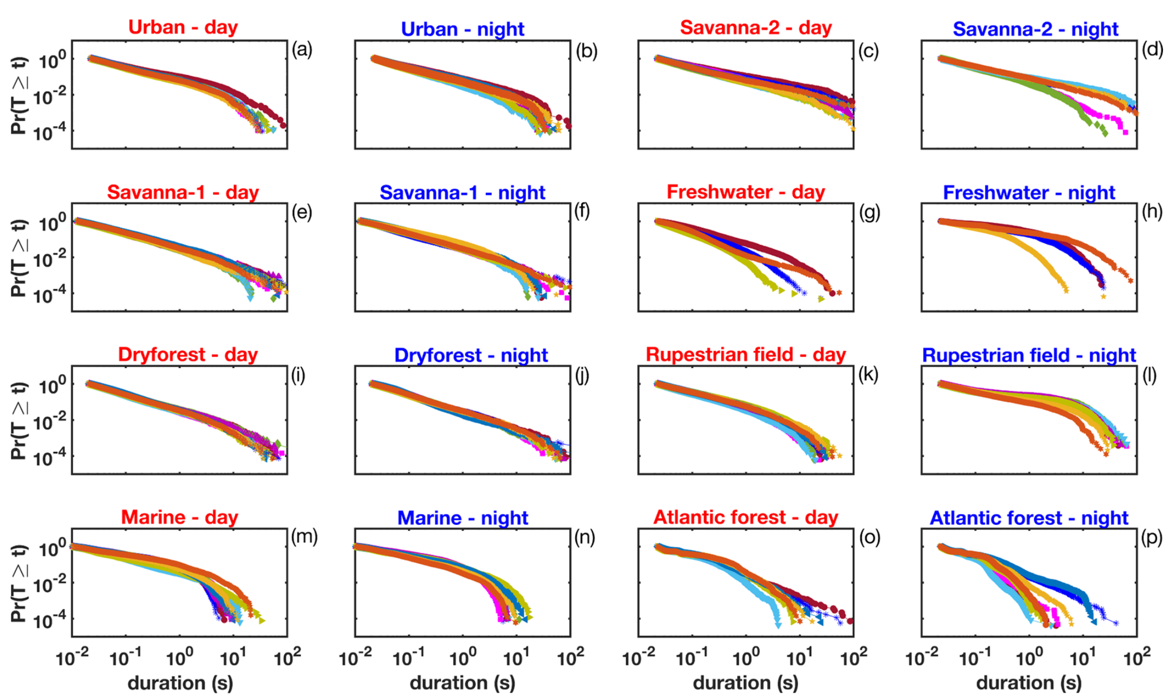


FIG. 4. Quiet-time cumulative distribution: scale-free scenario. The distribution of quiet-times presented with logarithmic axes for the studied soundscapes: Panels (a) and (b): Urban; (c) and (d): Dry forest; (e) and (f): Savanna-1, (g) and (h) Savanna-2, (i) and (j): Atlantic forest; (k) and (l): Rupestrian field; (m) and (n): Marine; and (o) and (p): Freshwater. The graphics are separated according to diurnal (left) and nocturnal (right) records. For each biome we choose around 10 samples that come from measurements for different days at roughly same hour. These measures are represented by different colors. Despite the hour of the day and the distinct locations, all records show a power-law behavior.

TABLE I. Quiet time power-law $\alpha$ parameter values. The single parameter of the power-law probability distribution for the duration of quiet times in the studied soundscapes according to the time period.

| | | $\alpha(s^{-1})$ |
|---|---|---|
| Urban | Diurnal | $1.80 \pm 0.02$ |
| | Nocturnal | $1.85 \pm 0.09$ |
| Dry forest | Diurnal | $1.93 \pm 0.04$ |
| | Nocturnal | $2.00 \pm 0.07$ |
| Savanna-1 | Diurnal | $1.94 \pm 0.06$ |
| | Nocturnal | $1.95 \pm 0.05$ |
| Savanna-2 | Diurnal | $1.85 \pm 0.03$ |
| | Nocturnal | $1.87 \pm 0.05$ |
| Atlantic forest | Diurnal | $2.00 \pm 0.06$ |
| | Nocturnal | $1.98 \pm 0.07$ |
| Rupestrian field | Diurnal | $1.92 \pm 0.05$ |
| | Nocturnal | $1.91 \pm 0.07$ |
| Marine | Diurnal | $1.62 \pm 0.09$ |
| | Nocturnal | $1.64 \pm 0.09$ |
| Freshwater | Diurnal | $1.85 \pm 0.05$ |
| | Nocturnal | $1.69 \pm 0.04$ |

TABLE II. Sound time parameter values of central tendencies. The central statistics (mean, mode, and median) and the standard deviation for each of the log-normal distributions of the duration of sounds from each soundscape sampled are shown. The central tendency parameters are separated into diurnal and nocturnal periods.

| | | Mean | Mode | Median | SD |
|---|---|---|---|---|---|
| Urban | Diurnal | 0.07 s | 0.05 s | 0.06 s | 0.03 s |
| | Nocturnal | 0.10 s | 0.06 s | 0.08 s | 0.05 s |
| Dry forest | Diurnal | 0.06 s | 0.05 s | 0.06 s | 0.03 s |
| | Nocturnal | 0.06 s | 0.05 s | 0.06 s | 0.03 s |
| Savanna-1 | Diurnal | 0.07 s | 0.06 s | 0.06 s | 0.02 s |
| | Nocturnal | 0.06 s | 0.05 s | 0.06 s | 0.01 s |
| Savanna-2 | Diurnal | 0.07 s | 0.06 s | 0.06 s | 0.02 s |
| | Nocturnal | 0.06 s | 0.06 s | 0.06 s | 0.01 s |
| Atlantic forest | Diurnal | 0.07 s | 0.06 s | 0.07 s | 0.03 s |
| | Nocturnal | 0.08 s | 0.06 s | 0.07 s | 0.03 s |
| Rupestrian field | Diurnal | 0.10 s | 0.08 s | 0.09 s | 0.04 s |
| | Nocturnal | 0.09 s | 0.08 s | 0.09 s | 0.03 s |
| Marine | Diurnal | 0.12 s | 0.09 s | 0.11 s | 0.04 s |
| | Nocturnal | 0.11 s | 0.09 s | 0.10 s | 0.04 s |
| Freshwater | Diurnal | 0.10 s | 0.08 s | 0.09 s | 0.04 s |
| | Nocturnal | 0.10 s | 0.08 s | 0.10 s | 0.04 s |

The interval of silence duration is diverse among the soundscapes. The wider range of quiet-times belong to the savannas that span from 0.02 to 100 s, encompassing almost four orders of magnitude. However, the Atlantic forest is the soundscape with the smallest range of quiet-times, i.e., there are no extremely short nor extremely long silences. The downward bending of the straight line in the log-log curves of Fig. 4 are more pronounced in the Atlantic forest, marine, and fresh water records. Although larger records could, in principle, capture larger silence intervals, our records are one-hour long, therefore the maximum value of the quiet-time in our records is limited. However, we notice that the long duration cutoff depends on the biome and it is much smaller than this maximum experimental cutoff. In the Discussion section we return to this point.

The overall view of Fig. 4 points out the universality of the power-law distribution to the quiet-time statistics of soundscapes. The best fitting of the parameters is shown in Table I. A comparison between diurnal and nocturnal results for all the soundscapes show no conspicuous difference related to the $\alpha$ parameter, even though our samples were taken at slightly different times within each period for different soundscapes (see Table S1 of the Supplemental Material [26]). In fact, the standard deviation depicted in the table is large enough for the exponents of day and night to overlap. The only exception is the Freshwater soundscape, which shows different $\alpha$ values between time periods (diurnal = 1.85 and nocturnal = 1.69). Another result concerns differences among the Freshwater $\alpha$ values and the other soundscapes. During the day, the Freshwater soundscape $\alpha$ is similar to those from terrestrial soundscapes (1.8-2.0) while at night it is similar to the alpha value of the Marine soundscape (1.6-1.7).

We found that the sampling rate (Fig. S3 of the Supplemental Material [26]) and the value of the thresholds (Fig. S4) did not change the statistical distribution of quiet-times. In Fig. S3 we show the quiet-time distribution of urban, savanna-2, and dry forest biomes resampled at different rates (colors) to test the invariance of the curves for distinct sampling rates. In fact, we used the audio record with the largest acquisition rate, 44 kHz, and resampled it to smaller sampling rates as indicated in the figure. In (Fig. S4, also of the Supplemental Material [26]) we depict the power-law distributions of the quiet-times for two biomes: savanna-1 and savanna-2. In this figure we used several thresholds: from ($\mu + \sigma$ to $3.5\sigma$). Therefore, the pattern found here is independent of sampling rate or of the choice of the intensity threshold value defining the cutoff between quiet and sound durations.

### B. Sound-time distribution

The analysis of the sound durations follows a methodology similar to the analysis of the quiet-time durations. However, the results from these two intervals are quite different. Unlike the power law found in the silent durations, the distribution of sounds shows a characteristic timescale for all analyzed environments. In other words, the sound duration distribution shows a well-defined peak which characterizes a typical time. The distribution of the sound emissions for the eight studied soundscapes is shown in (Fig. 5) and some parameters of the distribution are shown in Table II. We interpret these peaks in the statistical distribution as the typical average duration of an acoustic source that produces sounds in both the terrestrial and underwater environments.

For comparison, the histograms of the sound-time events have been normalized and shown in (Fig. 5). The diurnal data are represented in the left panels, while the nocturnal data are represented in the right panels. In both cases, we fitted the data with a log-normal distribution. The adjusted parameters for the log normal of the data are shown in Table II. The log-normal distribution is quite asymmetric, so the mean, median, and mode are not the same. A comparative analysis of Fig. 5

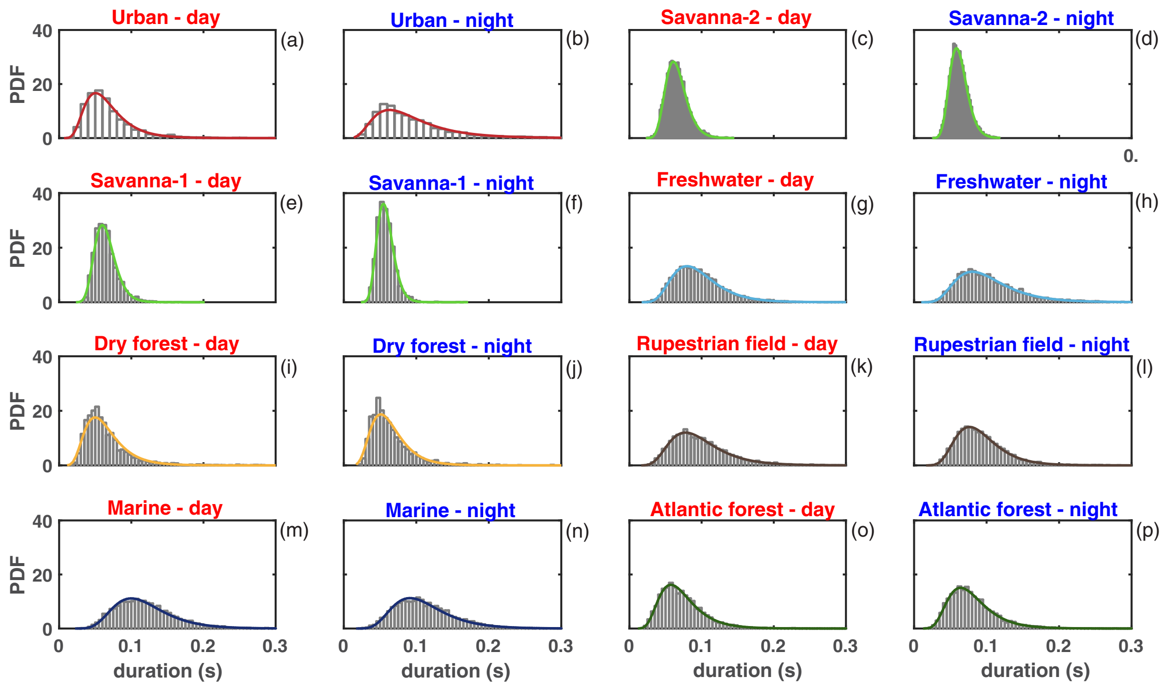


FIG. 5. Sound-time statistic distribution: a characteristic timescale. The log-normal distribution for the studied soundscapes: (a, b) urban; (c, d) dry forest; (e, f) savanna-1; (g, h) savanna-2; (i, j) Atlantic forest; (k, l) rupestrian field; (m, n) marine; (o, p) freshwater. The graphics are separated according to diurnal (left) and nocturnal (right) records. Despite the hour of the day and the distinct locations, all records show a log-normal distribution behavior.

and Table II reveals the following quantitative characteristics of the distributions: the highest means and modes are shown in the underwater soundscapes; the values are least dispersed in the distribution of the savannas; and the differences between day and night within soundscapes are not pronounced. The exception is the Urban soundscape, where the night period shows greater data deviation than during the day. Similarly to what was found for the duration of silences (quiet-times), the sampling rate (Fig. S5) and the value of intensity thresholds (Fig. S6) did not change the statistical distribution pattern of sound-times, figures in the Supplemental Material at [26]. In addition, to test the log-normal fitting we take the logarithm of the original data distribution and shift the data to the origin (Fig. S7). In the new format, the data assumes a perfectly symmetrical pattern. Moreover, we plot all curves into the same graphic and normalize the standard deviation such that all curves collapse into the same Gaussian pattern, see Fig. S8 and S9 of the Supplemental Material [26]. Finally, we show the sound-time distribution in a log-log axes plot to show the log-normal and the exponential fittings, Fig. S10. The set of figures S7–S10 of the Supplemental Material [26] confirms the adequate log-normal fitting of the quiet-time data.

## IV. DISCUSSION

Despite contradicting common sense, our study shows that urban soundscapes, terrestrial or aquatic, follow similar distribution patterns as natural acoustic habitats with little or no human influence. Our Freshwater site has considerable anthropic influence, especially during the day (vessel traffic), thus it could be considered an urban-like acoustic scenario [23]. The similarity among urban and natural soundscapes is observed both: in the sound emission statistics, with a typical timescale; and also in the parameter that determines the quiet-time distributions, $\alpha$, which is similar for all terrestrial cases and the diurnal Freshwater soundscape. In contrast, this parameter value is smaller in Marine and Freshwater (nocturnal period only) soundscapes. This suggests that idiosyncrasies can be influenced both by terrestrial vs underwater differences and urban vs natural acoustic scenarios. The quiet-time power-law distribution can be interpreted as a fractal property of silence durations [44–46]. Short intervals of silence are more abundant than long silences, but all quiet-time magnitudes are recorded in the soundscape. Yet, we highlight that a mathematical fractal is infinite in opposition to an empirical fractal that is bounded by cut-offs [47]. In our case, the minimal silence duration is limited by the noise background and the electronic noise of the recording system. However, the superior cut-off should, at least, be smaller than the sample record size. After all, this paper puts in evidence the fractality of silences in soundscapes as a general property.

There are several possible mechanisms behind a power-law behavior of a statistical distribution. The scaling of the power-law type in statistical physics may be associated with critical behavior, such as earthquake dynamics [48], solar flare dynamics [49], activity on animal tissue [50], Barkhausen noise [51] or in neuronal avalanche behavior [52]. It is usual to interpret the phenomena described by power laws in nature as being associated with some generating mechanism that provides a theory behind the natural phenomenon. However, there is also a long discussion in the literature around the excessive interpretation of the power law as produced by critical phenomena [53,54]. In fact, we could ask the following question: Is the power law found in the soundscape quiet-time statistics the signature of an underlying complex system? At this time, we do not have a conclusive answer following this point. It is also possible that the observed power law is related to a superposition of random effects like in a Markov mechanism [55] which describes the quiet-times in the studied soundscapes, or by the conjugate effect of several exponentials—like a distribution from independent acoustic sources [56–58].

The sound emission distribution is well-fitted by a log-normal distribution for all analyzed soundscapes. The savannas show a peaked distribution when compared with other environments. We suspect that those sites predominantly have isolated sound emissions, producing a peaked distribution. Other sites probably show more overlap of different sound sources, generating a fatter tail in the distribution. Some factors contributing to the overlap may be: more individuals competing in the acoustic space (Atlantic forest); reverberation in rocky surfaces (rupestrian field), wind particularities; and/or anthropic influence (all sites to some degree). We notice that the Atlantic forest, especially during the day, has the smallest power-law tail among the terrestrial environments. This phenomenon may be due to the proper acoustic characteristic of the forest, indeed, the forest compared with the rupestrian field, the savanna, the dry forest, or even the urban environment, is the site with more obstacles to sound propagation. These obstacles impose an acoustic dispersion that impacts the statistics of inter sound duration. In underwater environments, the longer sound times and shorter quiet times can be related to reverberation phenomena. Reverberation may happen in the areas since the depth varies between 15 and 30 m; in this way, sound waves remain in the medium for longer times due to multiple reflections between the floor and the top of the aquatic environment. Also, during the records, humpback whales were the main sound source in the marine environment, where multiple competing males sing continuously during night and day, sometimes overlapping each other [36]. Another hypothesis about aquatic environments concerns the character of the sound propagation in the water. Indeed, sound propagates better in the water than in the air, the wave energy damping is weaker allowing for longer sound propagation. In this way, the sound sources in the aquatic medium should be listened to longer distances, which will impact the long-time statistics.

About the characteristics of animal sound sources: the duration of sound vocalizations in animals is physiologically limited, an animal produces a sound during a limited time because of the breathing or other mechanical constraint [59,60]. We believe that the typical scale of sound emission distribution comes from such limitations in animal physiology. The acoustic organ is not a horn that can stay switched on for several minutes. Besides, our methodology is not impacted by constant sounds, as a steady wind. A steady sound will just change the background level and, as in consequence, only louder or closer sound sources will be registered. Moreover, the log-normal distribution can be interpreted as a competition of independent agents, see for instance, the wealth distribution in economics [61,62] or species competition and log-normal distribution of species abundance [63]. In this context, the log normal in the soundscape can be interpreted as competition for sound emission among individuals in a community. Therefore, the log-normal distribution could be associated with the acoustic niche hypothesis [20]. In this context, the shape of the log normal provides us insights into the occupation of the acoustic space. If the time during which an animal can produce sound is limited, then the more animals we have competing for the acoustic space, the fatter the tail of that distribution will be.

An acoustic record can be viewed as an interplay of sounds and silences, and the statistics of intervals of silence and sound emissions are the subject of this manuscript. Our results show that the quiet-time statistical distribution, for all studied soundscapes, follows a power law indicating an absence of temporal scale, which means a fractal scenario. In contrast, the durations of the sound emissions are related to a log-normal distribution, with a mean duration ranging from 0.06 to 0.12 s.

To conclude, a word of caution about excessive generalization. When we claim we have found a similar distribution for the statistics of sound emissions and silences, this pattern should be interpreted as a tendency or a benchmark. Our data bank is composed of eight spatial locations and only two temporal patterns; more terrestrial and aquatic biomes, as well as anthropic environments, should be tested to strengthen our hypothesis about the universality of silence and sound emission statistics. A good point is that a simple one-hour acoustic record is adequate to empirically test this hypothesis, as well as deviations of the studied distributions. We hope that future studies will improve, or establish limits, to our findings.

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