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Automatic identification of rainfall in acoustic recordings

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ABSTRACT

The rainfall regime is one of the main abiotic components that can cause modifications in the breeding activity of animal species. It has a direct effect on the environmental conditions, and acts as a modifier of the landscape and soundscape. Variations in water quality and acidity, flooding, erosion, and sound distortion are usually related with the presence of rain. Thereby, ecological studies in populations and communities would benefit from improvements in the estimation of rainfall patterns throughout space and time.

In this paper, a method for automatic detection of rainfall in forests by using acoustic recordings is proposed. This approach is based on the estimation of the mean value and signal to noise ratio of the power spectral density in the frequency band in which the sound of the raindrops falling over the vegetation layers of the forest is more prominent (i.e. 600–1200 Hz). The results of this method were compared with human auditory identification and data provided by a pluviometer. We achieved a correlation of 95.23% between the data provided by the pluviometer and the predictions of a regression model. Furthermore, we attained a general accuracy between 92.90% and 99.98% when identifying different intensity levels of rainfall on recordings.

Nowadays, passive monitoring recorders have been extensively used to study of acoustic-based breeding processes of several animal species. Our method uses the signals acquired by these recorders in order to identify and quantify rainfall events in short and long time spans. The proposed approach will automatically provide information about the rainfall patterns experienced by target species based on audio recordings.

1. Introduction

Among climatic processes, the rainfall is one of the main abiotic factors influencing the temporal patterns of reproductive activity in tropical and temperate animal species (Birkett et al., 2012; Gottsberger and Gruber, 2004; Keast and Marshall, 1954). The rain modifies the physical properties of the breeding sites, by adding water, and increases the relative humidity of the environment (Busby and Brecheisen, 1997; Ladányi et al., 2015). As a result, it stimulates or discourages reproductive behavior, which could produce modifications in the animal communication (Amézquita and Hödl, 2004; Lack, 1950; Zina and Haddad, 2005), changes in population dynamics (Georgiadis et al., 2003; Mondet et al., 2005; Ogutu and Owen-Smith, 2003), and shifts in phenology (Primack et al., 2009; Saenz et al., 2006; Yoo and Jang, 2012; van der Kolk et al., 2016).

Developing studies to estimate instant rainfall effects in animal sound production is a burdensome task. In general, weather stations are not necessarily located near the study area (Carey and Alexander, 2003; Mendelsohn et al., 2007), i.e., they are far from the site to be representative of the local weather conditions experienced by the community (Carey and Alexander, 2003). This implies that the correlation of rainfall data with the sounds produced by populations with narrow distribution is not always accurate. Additionally, the rainfall is normally measured in daily and hourly rates by weather stations (Ban and Schmidli, 2015; Hidalgo et al., 2014; Meek and Hatfield, 1994; Du et al., 2016), despite rain can disrupt or encourage animal auditory communication in shorter temporal spans (Lack, 1950; Zina and Haddad, 2005).

Automatic acoustic recorders have been extensively used in passive monitoring of animal species (Bedoya et al., 2014; Busby and Brecheisen, 1997; Depraetere et al., 2012; Farina, 2014; Gregory

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and van Strien, 2010; Kalan et al., 2015; Laiolo, 2010; Pace et al., 2010; Pieretti et al., 2011; Towsey et al., 2014; Sueur et al., 2008). These devices acquire the sounds of the landscape regardless the nature of their source; therefore, the collected recordings could be used to identify sounds of abiotic sources (e.g. rainfall) in terrestrial and aquatic ecosystems. The rainfall produces one of the most recognizable, and variable, sounds in nature; however, the detection of rainfall events in ecoacoustic studies (Sueur and Farina, 2015) has been barely studied.

Most of the current acoustic methods for rainfall identification have been proposed for signals collected with hydrophones in marine ecosystems (Amitai and Nystuen, 2008; Ma and Nystuen, 2005; Medwin et al., 1992). Although the sound of rainfall in aquatic and terrestrial ecosystems presents several similarities, they are generated under different circumstances. The underwater ambient sound generated by rainfall is a consequence of raindrops colliding with the water surface and trapping bubbles (Amitai and Nystuen, 2008). In a forest, or other landscapes, the sound of the rainfall is produced by the impact of raindrops on the vegetation layers (mainly in the canopy). In aquatic and terrestrial environments the rainfall sound is present throughout the audible spectrum with heterogeneous power in specific frequency bands. Nonetheless, sensors, soundscapes, and power distribution of the rainfall sound across the spectrum differ from both environments. For these reasons, methodologies developed for analyzing underwater rain sound cannot be directly extrapolated to the terrestrial case.

Few studies have been focused on rainfall identification in acoustic recordings of terrestrial ecosystems. To the best of our knowledge, the method proposed by Ferroudj et al. (2014) was the first and only known approach to solve this issue. They proposed a pattern recognition approach with the use of 5 features (temporal entropy, spectral entropy, acoustic complexity index, background noise, and spectral cover) and a decision tree for a bi-class classification problem (heavy rain or non-rain), obtaining an overall accuracy of 93%.

The aim of our study is to provide a tool for detecting, quantifying, and analyzing rainfall events in acoustic recordings obtained from evergreen forests. Thereby, short- and long-term effects of rainfalls in the animal sound production can be analyzed. This approach illustrates the potential for studies related with changes in phenology, auditory communication, or population dynamics as a result of changing rainfall conditions, by solely using acoustic signals provided by automatic recorders.

2. Materials and methods

2.1. Rainfall detection

The rainfall produces spectral components throughout the audible spectrum (the sound produced by the impact of each raindrop depends on its size and the material of the receptor). For this reason, the rainfall can be seen in the spectrogram as a background sound (similar to the static television noise). However, the power of this sound is not uniformly distributed across the spectrum. This effect is less visible in the spectrogram, but it is evident in the power spectral density (PSD).

Fig. 1 shows the PSD estimated in six recordings with different rainfall intensities (No rain, Drizzle, Light, Moderate, Heavy, and Violent). In general, the magnitude of the PSD increases with the intensity of the rainfall. However, this increment is more prominent in two specific frequency bands: a peak around 600–1200 Hz (see red ellipse in Fig. 1) and a peak around 4400–5600 Hz. These frequency bands are the sections of the audible spectrum in which the sound of the raindrops falling over the

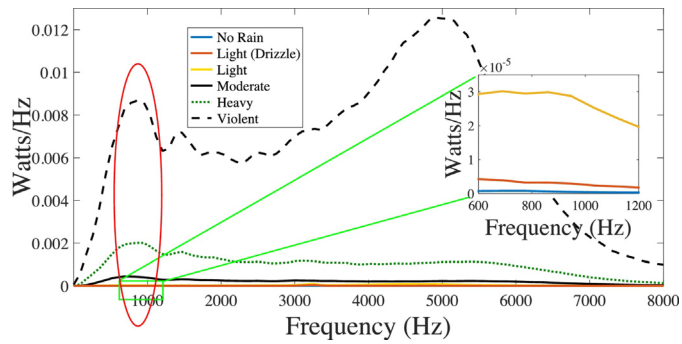

Fig. 1. Estimation of the power spectral density (PSD) of six acoustic recordings with different rainfall intensities (No rain, Drizzle, Light rain, Moderate rain, Heavy rain, and Violent rain). The black frame is a zoom of the PSDs for No rain, Drizzle, and Light rain in the frequency band that most differentiates among rainfall levels (i.e. 600–1200 Hz approx.). The red ellipse highlights the best peak for rainfall detection. This peak tends to be leptokurtic as the rainfall intensity increases. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

vegetation layers is discernible. These peaks are in general proportional in magnitude and kurtosis to the level of intensity of the rainfall.

The amplitudes of the peaks in the PSD are directly proportional to the intensity of the rainfall, allowing detection and quantification. Particularly, the impact sound of raindrops from rainfalls of light intensity is more discernible in the 600–1200 Hz frequency band than in the 4400–5600 Hz frequency band (see Fig. 1), which makes 600–1200 Hz a better frequency range for analysis. Additionally, the former (600–1200 Hz) is expected to have less biophonies than the latter (4400–5600 Hz), as argued by Pijanowski et al. (2011), which reduces the probability of false positives. Nonetheless, the PSD is not enough for detecting and estimating rainfall levels. Several vocalizations of specific animal species and anthropogenic noises such as planes, boats, and water pumps may have spectral content in this frequency band (Rossing et al., 2001). Therefore, an additional criterion able to discern between rainfall and other biotic or abiotic sounds is needed.

The signal-to-noise ratio (SNR) of the PSD in the selected frequency band (600–1200 Hz) is used in this paper to discern if an increment in the magnitude of the PSD could be a consequence of either the rainfall or specific sounds that concur in the same frequency band. The SNR establishes a comparison between the level of a desired signal (i.e. rainfall sound) and the level of background noise (Stremler, 1990). The ratio of mean to standard deviation (reciprocal of the coefficient of variation) was used as SNR (Bushberg, 2002).

The proposed procedure (see Algorithm 2.1) consists on calculating the PSD of the audio recording $\vec{\mathbf{x}} \in \mathbb{R}^{N_x}$, where N_x is the original length of the signal in number of samples. In this study, the Welch's method was selected as estimator of the power spectral density (Welch, 1967). In general terms, this is a fast method with noise reduction properties based on the averaging of individual periodograms obtained from overlapped segments of the original data. For this study, the PSD estimate was obtained by using the pwelch built-in function of Matlab.

After obtaining the power spectral density $\vec{\mathbf{p}} \in \mathbb{R}^{N_p}$, a section $\vec{\mathbf{a}} \in \mathbb{R}^{N_a}$ (of N_a data samples) corresponding to the frequency band in which the sound of the rain is manifested (600–1200 Hz) is extracted from $\vec{\mathbf{p}}$. Here, $N_p = (N_w/2) + 1$, and $N_w = 512$ is the size of the rectangular window (no overlap) used to calculate the Welch's PSD estimate, $N_a = N_p \cdot (\frac{l_2 - l_1}{F_{qs}})$, $l_1 = 600$ and $l_2 = 1200$ are the minimum and maximum frequencies of the rainfall frequency band,