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Measuring sound detection spaces for acoustic animal sampling and monitoring

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A B S T R A C T

Sound recordings obtained from passive acoustic monitoring systems are increasingly used to sample animal biodiversity. However, sound recorders sample variable detection spaces, so that data may not be comparable between sampling sites and recording setups.

Focusing on terrestrial systems, we measured understory vegetation, tree structure, sound transmission, ambient sound pressure level, and derived sound detection spaces of 38 plots in lowland rainforest, jungle rubber, and oil palm and rubber plantations, using different combinations of sound frequency (0.05 to 40 kHz) and source height (0 to 5 m).

We show that simple vegetation structure measures poorly predict sound transmission, so that direct sound transmission measurements are indispensable. We depict highly variable sound detection spaces in different land-use types. Finally we estimated species richness of exemplary animal groups and found considerable differences between land-use types on the basis of variable detection space areas alone.

Sound detection spaces respond non-linearly to sound frequency and source height, and they need to be quantified in acoustic surveys to avoid substantial bias in biodiversity estimates between sampling sites. Detection spaces also determine species detection probabilities and allow comparing data between recording setups. We provide guidelines and computer scripts for measuring sound transmission and ambient sound level using consumer audio equipment, and for computing detection spaces. Appreciating the effective sampling area of acoustic recorders closes a gap between acoustic and traditional animal survey methods. Species richness estimates can now be reported for measured sampling areas, and animal population variables such as abundance, density, and activity can be compared at equal areas.

1. Introduction

Passive acoustic monitoring systems are increasingly prevalent for surveying a wide range of sound-emitting animals: ecologists use these systems to record birds (Celis-Murillo et al., 2009), bats (Bader et al., 2015), amphibians (Aide et al., 2013), insects (Lehmann et al., 2014), terrestrial (Mielke and Zuberbühler, 2013) and marine mammals (Wiggins and Hildebrand, 2007), to determine species richness (Wimmer et al., 2013), to record soundscapes, and to construct general biodiversity indices (Sueur et al., 2014). More complex systems using microphone arrays have been proposed for a wider audience of biologists to study a variety of other aspects such as anthropogenic noise, species interactions and social dynamics (reviewed in Blumstein et al., 2011). Conservationists recognize the potential of passive acoustic monitoring techniques (Brandes, 2008) and practitioners also increasingly embrace and implement acoustic monitoring programs on large scales (Fristrup, 2009). While challenges in automated signal recognition have been identified (e.g. Swiston and Mennill, 2009), there have been few attempts to standardize the sound recording methodology itself (but see Llusia et al., 2011; Merchant et al., 2015).

Basic biodiversity estimates – such as species richness, activity, abundance and density – are derived from sampling methods that apply to defined areas or volumes, but when sampling sound, it is challenging to measure that space. In essence, biodiversity estimates derived from sound recordings in different sites may not be directly comparable due to site-specific acoustic characteristics: sound travels

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variable distances depending on the frequency, its sound pressure level, the background noise, the location of the sound source and also due to varying topography, climatic conditions and vegetation.

The determinants of sound transmission (or sound attenuation, hereafter "transmission") are well known. They have been described early for audible sound (Wiley and Richards, 1978) and later also for higher frequencies reaching ultrasounds (Romer and Lewald, 1992). The effect of vegetation has also been specifically addressed (Marten et al., 1977; Marten and Marler, 1977; Aylor, 1972) and reviewed later (Forrest, 1994). In most sound transmission studies, the focus has been on animal communication and rarely on the implications for acoustic biodiversity sampling (though see Hobson et al. (2002) and Patriquin et al. (2003)), a field which has expanded only relatively recently.

The area sampled by acoustic monitoring systems needs to be measured to identify the scale of a particular biodiversity estimate, as basic biodiversity estimates invariably increase with sampled area. Furthermore, it has been recognized that acoustic detectors vary in detection efficacy and range for different bat species (Adams et al., 2012), for aquatic organisms (Huveneers et al., 2015), and also for birds (Rempel et al., 2013). Furthermore birds have different detection probabilities (Sliwinski et al., 2015), but the acoustic sampling area has not been considered yet to tackle these issues. The sampled area also depends on the ambient sound pressure level: distant sounds are more difficult to detect in noisy environments. Relatively early, Morton (1975) calculated distances from the sound source over which sounds would reach the ambient sound level. More recently, a comprehensive analysis of acoustic communication distance determinants was made by Ellinger and Hödl (2003) but it described only one study site and focused on implications for animal communication. We use the term "sound detection space" (hereafter "detection space"), which was introduced later by Llusia et al. (2011), to define the space – in terms of area or volume – sampled by acoustic monitoring systems. Fortunately, the source sound pressure level and frequency – and to a certain degree, the source position – of animal sounds and vocalizations are generally characteristic and measurable for different species, and we assume here that variation between species is higher than within them. Thus, it is possible to compute detection spaces for different species across habitats, but as of today this has not been achieved.

We propose a method to measure sound transmission in various habitat types using consumer audio recording and playback equipment. We challenge the usefulness of our measurements by investigating whether vegetation structure data can predict sound transmission. Then, combining sound transmission values with calibrated ambient sound pressure level measures, we derive detection space areas of different land-use types. Finally, using representative species, we illustrate the impact that variable detection spaces can have on biodiversity measures derived from sound recordings.

2. Materials and methods

2.1. Study region and vegetation structure measurements

The study region is situated in the Batanghari and Sarolangun regencies of the province of Jambi, Sumatra, Indonesia. We recorded sound in 38 plots split into 5 land-use types. Core plots comprised 8 lowland rainforest plots, 8 jungle rubber plots, 8 rubber plantation plots, and 8 mature oil palm plantation (older than 8 years) plots. Six additional young oil palm plantation plots (younger than 4 years) were established to determine sound detection spaces in plantations without closed canopy. Our forest plots are located in an area of disturbed primary lowland rainforest that has been selectively logged in the past. Jungle rubber is an agroforestry system that is minimally managed, consisting of forest and rubber trees. The rubber (*Hevea brasiliensis*, Müll. Arg.) and oil palm (*Elaeis guineensis*, Jacq.) plantations are intensively managed monocultures. For more detailed information about the study area and the core plot design, see Drescher et al. (2016).

In the 50 × 50 m core plots, all trees with a diameter at breast height (DBH) equal to or higher than 10 cm were counted to derive tree density per hectare, and their DBH was measured to derive total basal area per hectare (Kotowska et al., 2015). Oil palm DBH was measured including the remaining leaf bases which stay attached to the trunk for many years after the leaf is cut, inflating its measure. The trunks in young oil palm plots did not yet reach breast height, therefore their DBH was null; their density was determined by measuring the area of a block containing 49 oil palms (a 7 × 7 block). Tree and mature oil palm height and crown base height were measured using a Vertex measuring device (IV-GS, Haglöf, Långsele, Sweden), and young oil palm height was measured using a meter. Tree height was measured until the tip of the highest branch and oil palm height was measured until the meristem. The crown base height was defined as the height of the lowest branch, or in the case of oil palm the lowest uncut frond. All vascular understory plant individuals (>1 cm height) growing within five randomly placed 5 × 5 m subplots (3 subplots in young oil palm plots) were counted and their height measured. Understory plant density was expressed as the number of plants per hectare. In core plots, trees were counted and their DBH measured between August and September 2012 (Kotowska et al., 2015); all other plant measurements were carried out between February 2013 and August 2014. In young oil palm plantations, all vegetation structure measurements were done in September 2015.

2.2. Sound transmission measurement

The sound transmission measurements were carried out in March 2014 in the core plots and January 2015 in the young oil palm plots, in good weather (no rain) and windless conditions, when insect noise was not prominent. We ruled out daily micro-climate variation effects by varying measurement times in the focal land-use types (Fig. A1 in Appendix A), although time of day effects on sound transmission are known to be minor (Ellinger and Hödl, 2003). We created a website to help researchers measure sound detection spaces which will be updated with new developments (Darras, 2015).

In the middle of each plot, we attached autonomous sound recorders ("Song meters": SM2+ and SM2Bat+, default amplifier gain: 48 dB, Wildlife Acoustics Inc., Massachusetts, USA) to a pole at a height of 2 m. The SM2+ recorder was set to a sampling rate of 44.1 kilohertz (kHz) with two acoustic omni-directional microphones for audible sound (SMX-II with Panasonic WM-61 unit), and the SM2Bat+ was set to 192 kHz with two ultrasonic omni-directional microphones for ultrasound (SMX-US with Knowles SPM0404UD5 element). A rope with markings at 1, 2, 4, 8, 16, 32 and 64 m was stretched from the recorder front face to the plot border to position the sound emitters at logarithmically increasing distances. The sound emitters' polar axes were always at 90° from the microphones' polar axes, thus ruling out variation in recorded sound level due to the microphone's polar pattern.

At each marked distance step, we used portable loudspeakers (OnePe DZ-250, Dazumba, Indonesia) and an ultrasound emitter in "chirp" mode (US calibrator Wildlife Acoustics Inc., Massachusetts, USA), to emit audible and ultrasonic test sounds. The audible test sound consisted of a pure tone sequence at 0.5, 2, 4, 8, 12 and 16 kHz, 1 s long at each step, repeated 3 times (Appendix B). The ultrasound test sound was not adjustable and consisted of pure tones at 40 kHz, emitted approximately every 0.25 s for 10 s. The loudspeaker and calibrator were attached to a squeegee with rubber strips to minimize vibration. We emitted test sounds from ground level (10 cm) and then fitted the squeegee onto a telescopic cleaning pole to reach heights of 2 and 5 m. After recording all test sounds from 1 to 64 m (only until 32 m for ultrasound) at all heights, we stretched the rope from the back side of the recorder to the opposite direction and repeated the measurements.