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Original Articles

Sounding out ecoacoustic metrics: Avian species richness is predicted by acoustic indices in temperate but not tropical habitats

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ABSTRACT

Affordable, autonomous recording devices facilitate large scale acoustic monitoring and Rapid Acoustic Survey is emerging as a cost-effective approach to ecological monitoring; the success of the approach rests on the development of computational methods by which biodiversity metrics can be automatically derived from remotely collected audio data. Dozens of indices have been proposed to date, but systematic validation against classical, in situ diversity measures are lacking. This study conducted the most comprehensive comparative evaluation to date of the relationship between avian species diversity and a suite of acoustic indices. Acoustic surveys were carried out across habitat gradients in temperate and tropical biomes. Baseline avian species richness and subjective multi-taxa biophonic density estimates were established through aural counting by expert ornithologists. 26 acoustic indices were calculated and compared to observed variations in species diversity. Five acoustic diversity indices (Bioacoustic Index, Acoustic Diversity Index, Acoustic Evenness Index, Acoustic Entropy, and the Normalised Difference Sound Index) were assessed as well as three simple acoustic descriptors (Root-mean-square, Spectral centroid and Zero-crossing rate). Highly significant correlations, of up to 65%, between acoustic indices and avian species richness were observed across temperate habitats, supporting the use of automated acoustic indices in biodiversity monitoring where a single vocal taxon dominates. Significant, weaker correlations were observed in neotropical habitats which host multiple non-avian vocalizing species. Multivariate classification analyses demonstrated that each habitat has a very distinct soundscape and that AIs track observed differences in habitat-dependent community composition. Multivariate analyses of the relative predictive power of AIs show that compound indices are more powerful predictors of avian species richness than any single index and simple descriptors are significant contributors to avian diversity prediction in multi-taxa tropical environments. Our results support the use of community level acoustic indices as a proxy for species richness and point to the potential for tracking subtler habitat-dependent changes in community composition. Recommendations for the design of compound indices for multi-taxa community composition appraisal are put forward, with consideration for the requirements of next generation, low power remote monitoring networks.

1. Introduction

Numerous global initiatives aim to conserve biodiversity (e.g. United Nations Sustainable Development Goals, Convention on Biological Diversity AICHI biodiversity targets, REDD + +), but action can only be effectively taken if biodiversity can be measured and its rate of change quantified (Buckland et al., 2005). Coupled with rapid changes in landscape use (Betts et al., 2017; Newbold et al., 2015) the impact of climate change (Stocker et al., 2013) and growing fragmentation of natural landscapes globally (Crooks et al., 2017), the development of cost effective methods for biodiversity monitoring at scale is an urgent global imperative (Newbold et al., 2015).

1.1. Ecoacoustics and rapid acoustic survey

Operating within the conceptual and methodological framework of

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ecoacoustics (Sueur and Farina, 2015) Rapid Acoustic Survey (RAS) (Sueur et al., 2008) has been proposed as a non-invasive, cost-effective approach to Rapid Biodiversity Assessment (Mittermeier and Forsyth, 1993) and is gaining interest from researchers, decision-makers and conservation managers alike. Whereas bioacoustics infers behavioural information from intra- and interspecific signals, ecoacoustics investigates the ecological role of sound at higher organisational units – from population and community up to landscape scales. Sound is understood as a core ecological component (resource) and therefore indicator of ecological status (source of information). Rather than attempting to identify specific species calls, RAS aims to infer biodiversity at these higher levels of organization, through the collection and computational analysis of large scale acoustic recordings. RAS is a highly attractive solution for large scale monitoring, because it is non-invasive, obviates the need for expert aural identification of individual recordings, scales cost-effectively and is potentially sensitive to multiple taxa. This approach has potential to dramatically improve remote biodiversity monitoring, enabling data collection and analysis over previously inaccessible spatio-temporal scales, including in remote, hostile, delicate regions in both terrestrial and marine environments. The success of the approach rests on the development and validation of computational metrics, or acoustic indices, which demonstrably predict some facet of biodiversity.

1.2. Acoustic indices for biodiversity monitoring

Whereas classical biodiversity indices are designed to enumerate some facet of biotic community diversity at a particular time and place – richness, evenness, regularity, divergence or rarity in species abundance, traits or phylogeny (Magurran, 2013; Magurran and McGill, 2011; Pavoine and Bonsall, 2011) – acoustic indices are designed to capture the distribution of *acoustic energy* across time and/or frequency in a digital audio file of fixed length. As illustrated in Fig. 1, the use of acoustic indices (AIs) as ecological indicators is predicated firstly on the assumption that the *acoustic community* (Gasc et al., 2013) is representative of the wider ecological community at the place and time of interest; and secondly that computationally measurable changes in the acoustic environment are ecologically relevant. An effective index will reflect ecologically meaningful changes in the acoustic community, whilst being *insensitive* to potentially confounding variations in the

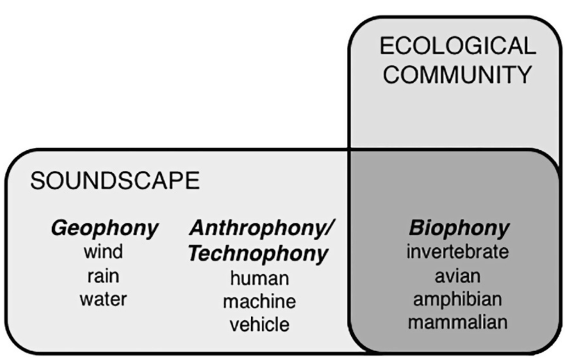

Fig. 1. The acoustic environment, or soundscape, is comprised of sounds made by noisy biotic and abiotic processes, including biological organisms (biophony), geological forces (geophony) and humans and machines (anthrophony/technophony). Acoustic indices provide terse numerical descriptions of the overall soundscape. The use of acoustic indices as a proxy for biodiversity is predicated on the assumption firstly that the acoustic community of vocalising creatures is representative of the wider ecological community and secondly that the facets of soundscape dynamics captured by acoustic indices are ecologically-meaningful. The current working hypothesis is that higher species richness will generate greater acoustic diversity; a suite of indices aimed at capturing spread and evenness of acoustic energy have been proposed but have yet to be conclusively validated against traditional, in situ biodiversity metrics.

wider acoustic environment – or *soundscape* (Pijanowski et al., 2011). Whilst there is an established tradition of aural survey of individual species (as in point counts), ecoacoustics aims to develop the study and theory of population, community or landscape level bioacoustics. The prevailing predicate of RAS is that higher species richness in a given community will produce a greater 'range' of signals, resulting in a greater *acoustic diversity* (Gasc et al., 2013; Sueur et al., 2014; Sueur et al., 2008).

Based on this premise, indices to measure within-group (alpha) and between-group (beta) indices have been proposed (Sueur et al., 2014). The current concern is validation against traditional metrics derived from species counts, therefore we focus on alpha indices. These are designed to estimate amplitude (intensity), evenness (relative abundance), richness (number of entities) and heterogeneity of the acoustic community. A suite of indices was made available via R packages *seewave* [1] (Sueur et al., 2008) [1] and *soundecology* [2] (Villanueva-Rivera et al., 2011) and has been rapidly taken up in ecological research – the libraries exceeding 61,000 downloads since 2012. However, experimental investigation of the relationship between these, and other acoustics metrics, with traditional, *in situ* biodiversity measures reveals mixed, and at times contradictory results (Boelman et al., 2007; Fuller et al., 2015; Mammides et al., 2017). Furthermore, simulation studies (Gasc et al., 2013) demonstrate that acoustic diversity can be influenced by sources of acoustic heterogeneity other than species richness, including variation in distance of animals to the sensors, and inter- and intra-specific differences in calling patterns and characteristics (e.g. duration, intensity, complexity of song, mimicry). The premise that biodiversity can be inferred from acoustic diversity is percipient but not fully substantiated: before these proposed indices can be confidently adopted for monitoring purposes, it is critical to understand i) how well AIs capture ecologically meaningful changes in community composition and ii) how robust they are to diverse ecological, environmental, and acoustic conditions. To this end, this study carried out the largest systematic, comparative study of the relationship between acoustic indices and observed avian diversity to date.

1.3. Acoustic indices

1.3.1. Ecologically inspired diversity indices

Early research led to the development of indices derived from landscape metrics (Turner, 1989) to measure changes at the level of soundscape (Gage et al., 2001; Napoletano, 2004). The *Normalised Difference Sound Index* (NDSI) (Kasten et al., 2012) seeks to describe the level of anthropogenic disturbance by calculating the ratio of mid-frequency biophony to lower frequency technophony in field recordings, the values for each being computed from an estimate of power density spectrum (Welch, 1967). In long term studies, the NDSI has been shown to reflect assumed seasonal and diurnal variation across landscapes (Kasten et al., 2012). It has subsequently been shown to be sensitive to biophony and anthrophony levels in urban areas (Fairbrass et al., 2017) and to be an indicator of anthropogenic presence in the Brazilian Cerrado (Alquezar and Machado, 2015). NDSI has also been evaluated as a proxy for species diversity with mixed results: significant relationships with bird species richness have reported across mixed habitats in China (Mammides et al., 2017); in Brazilian savanna habitats no relationships were observed (Alquezar and Machado, 2015).

Based on the foundational premise that biodiversity can be inferred from acoustic diversity, several indices draw an analogy between species distribution and distribution of energy in a spectrum, where each frequency band is seen to represent a specific 'species'. The entropy indices Hf and Ht (Sueur et al., 2008) are calculated as the Shannon entropy of a probability mass function (PMF) and designed to increase

[1] https://cran.r-project.org/web/packages/seewave/.
[2] https://cran.r-project.org/web/packages/soundecology/.

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