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Connecting soundscape to landscape: Which acoustic index best describes landscape configuration?

Susan Fuller[a,*], Anne C. Axel[b], David Tucker[a], Stuart H. Gage[c]

[a] Queensland University of Technology, Science and Engineering Faculty, GPO Box 2434, Brisbane, Queensland 4001, Australia
[b] Marshall University, Department of Biological Sciences, Science 260, One John Marshall Drive, Huntington, WV 25755, USA
[c] Michigan State University, Global Observatory for Ecosystem Services, 101 Manly Miles Building, 1405 South Harrison Road, East Lansing, MI 48824, USA

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ABSTRACT

Soundscape assessment has been proposed as a remote ecological monitoring tool for measuring biodiversity, but few studies have examined how soundscape patterns vary with landscape configuration and condition. The goal of our study was to examine a suite of published acoustic indices to determine whether they provide comparable results relative to varying levels of landscape fragmentation and ecological condition in nineteen forest sites in eastern Australia. Our comparison of six acoustic indices according to time of day revealed that two indices, the acoustic complexity and the bioacoustic index, presented a similar pattern that was linked to avian song intensity, but was not related to landscape and biodiversity attributes. The diversity indices, acoustic entropy and acoustic diversity, and the normalized difference soundscape index revealed high nighttime sound, as well as a dawn and dusk chorus. These indices appear to be sensitive to nocturnal biodiversity which is abundant at night in warm, subtropical environments. We argue that there is need to better understand temporal partitioning of the soundscape by specific taxonomic groups, and this should involve integrated research on amphibians, insects and birds during a 24 h cycle. The three indices that best connected the soundscape with landscape characteristics, ecological condition and bird species richness were acoustic entropy, acoustic evenness and the normalized difference soundscape index. This study has demonstrated that remote soundscape assessment can be implemented as an ecological monitoring tool in fragmented Australian forest landscapes. However, further investigation should be dedicated to refining and/or combining existing acoustic indices and also to determine if these indices are appropriate in other landscapes and for other survey purposes.

1. Introduction

Soundscape ecology is the study of sounds in the landscape ('soundscape') and is based on how sounds from biological, geophysical and anthropogenic sources can be used to understand natural and human systems at multiple temporal and spatial scales (Pijanowski et al., 2011a). Biophony, geophony and anthrophony are terms used to characterize sounds that occur in the landscape (Pijanowski et al., 2011a). Biophony refers to the sounds produced by living organisms, usually sounds that are used by animals as a means of communication. This may include birds, amphibians, insects, mammals, fish, amphipods, and crustaceans in both terrestrial and aquatic systems. Geophony is the collection of sounds caused by physical processes such as wind, water flow, thunder, rainfall, and earth movement. The sound created when humans use mechanical devices is referred to as anthrophony (or technophony). This includes the sounds that come from stationary machines such as fans and air conditioners, and mobile machines used for transportation and construction such as aircraft, cars, trucks, boats, building cranes, bulldozers etc.

There has been considerable interest and research to develop and compute acoustic indices that represent the characteristics of the soundscape. Early research in this field led to the application of landscape metrics (reviewed in Turner, 1989) to the soundscape using acoustic diversity indices (Gage et al., 2001; Napoletano, 2004). These indices were based on the quantification of spectrogram images, calculated by dividing the spectrum into frequency bins and using automated processing of multiple spectrograms (Gage and Napoletano, 2004). A computation approach using the power density spectrum (Welch, 1967) was then developed and used to characterize temporal changes in the soundscape in Sequoia National Park (Krause et al., 2011). The computation of

* Corresponding author. Tel.: +61 7 3138 2497.
E-mail address: s.fuller@qut.edu.au (S. Fuller).

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acoustic metrics from multiple recordings was further developed to compute soundscape power (Matlab code can be obtained from the authors). Subsequently, the normalized difference soundscape index (Joo, 2009; Kasten et al., 2012) was created to estimate the relative amount of biophony and anthrophony in the soundscape by computing the ratio of anthrophony to biophony found in field-collected acoustic recordings.

Farina et al. (2005) examined landscape ecology from a cognitive perspective and described new thinking about how organisms perceive landscapes according to signals and signs in the context of energy flows within the landscape. The acoustic complexity index was developed based on the observation that many biotic sounds, such as bird songs, are characterized by an intrinsic variability of intensities, while human-generated noise is often constant in intensity (Pieretti et al., 2011). Pieretti et al. (2011) found that this index correlates with the number of bird vocalizations, while efficiently filtering airplane noise. The acoustic complexity index has been used to describe avian soundscapes (Farina et al., 2011), relate avian soundscapes to vegetation complexity (Farina and Pieretti, 2014) and describe the influence of traffic noise (Pieretti and Farina, 2013). It is calculated as the average absolute fractional change in spectral amplitude, averaged over all frequency bins for the entire recording. Similarly, Boelman et al. (2007) developed a bioacoustic index which was a function of both the spectral amplitude and the number of frequency bands in a sound recording. This index was shown to be strongly correlated with avian abundance in Hawaiin forests experiencing weed invasion.

Acoustic diversity indices have also been developed to facilitate automated surveying of ecosystems for rapid biodiversity appraisal (Sueur et al., 2008b, 2012). The acoustic entropy index is one such index and is computed as the product of both the temporal (acoustic energy dispersal within a recording) and spectral entropies (acoustic energy dispersal through the spectrum) following application of the Shannon index (Sueur et al., 2008b). Simulations revealed a correlation between the acoustic entropy index and species diversity and in field studies this index was found to be sensitive to disturbance in Tanzanian forests (Sueur et al., 2008b). The acoustic diversity index (Villanueva-Rivera et al., 2011) is a modification of spectral entropy and is also calculated using the Shannon index, while the acoustic evenness index uses the Gini coefficient as a measure of evenness (Villanueva-Rivera et al., 2011).

The theoretical underpinning of the application of acoustic indices is that communities with more audible species have a greater acoustic diversity and that biodiversity will correlate positively with acoustic diversity (Gage et al., 2001; Qi et al., 2008). Despite the existence of a suite of acoustic indices, few comparative studies have been undertaken. Towsey et al. (2014) provided a thorough investigation of multiple indices relative to a comprehensive avifauna census dataset. However, the focus of their study was to develop a computer assisted sampling methodology to obtain a more efficient estimate of species richness than random sampling alone, rather than to evaluate acoustic indices relative to landscape condition or configuration.

While it has been proposed that there is an intrinsic relationship between the soundscape and the landscape (Pijanowski et al., 2011b), there have been few studies that have tested this explicitly (see Bormpoudakis et al., 2013; Tucker et al., 2014). Furthermore, recent studies in urban environments have highlighted the importance of land use planning regarding the evaluation of the soundscape using a landscape perspective (Kuehne et al., 2013; Votsi et al., 2012). However, while a range of studies have recorded and analyzed acoustic signals produced by birds, insects and other audible organisms to assess the effects of disturbance on biodiversity (Blumstein et al., 2011; Depraetere et al., 2012; Laiolo, 2010; Proppe et al., 2013; Sueur et al., 2008b), a lack of standardized methods to evaluate landscape characteristics has probably inhibited research on linking soundscape with landscape configuration. Recently, an ecological condition framework that assesses landscape characteristics has been developed to meet biodiversity offset policy demands (Eyre et al., 2011). Tucker et al. (2014) conducted an evaluation of fragmented spotted gum forests in eastern Queensland, Australia using this framework and found that there was a significant relationship between the soundscape and the size and connectedness of forest patches, but other landscape features such as road fragmentation and land use were not studied. Consequently, our study aims to investigate the patterns of six acoustic indices and relate these patterns to an array of landscape features and ecological condition in nineteen fragmented forest sites in south-eastern Australia.

2. Methods

2.1. Study sites

The study area was situated in South-east Queensland, Australia; a region characterized by a subtropical climate, fast growing population and increasing urban and peri-urban pressures including reduced native forest cover and habitat fragmentation. Nineteen sites were selected in forest patches ranging in size from 3 ha to 44,110 ha (see Supplementary Material 1 for site location details). Ten sites were located in patches of remnant spotted gum (*Corymbia citriodora* ssp. *variegata*) open forest and nine sites were in scribbly gum (*Eucalyptus racemosa*) woodland.

2.2. Ecological condition survey

In a terrestrial context, ecological condition relates to the viability or health of an ecosystem (Gibbons and Freudenberger, 2006) and is commonly measured by the structural and compositional integrity of native vegetation (Yapp et al., 2010). Ecological condition surveys were conducted according to biocondition V2.1 guidelines outlined by Eyre et al. (2011). A reference or benchmark site for each forest type was selected based on the knowledge of a professional botanist with extensive local experience. A range of site-based vegetation attributes, including number of large trees, recruitment of canopy species, tree canopy height, native grass, forb, shrub and tree species richness, native grass, shrub and tree canopy cover, non-native plant cover, leaf litter and course woody debris, were measured. Each vegetation attribute was scored as a comparison to those values associated with the reference site. Total vegetation attributes were scored out of 80. Patch size, patch connectivity and patch context variables were derived using a GIS based tool developed by the Queensland Herbarium (Kelley and Kelly, 2012) and scored as a comparison to those values associated with the reference site. A total landscape score (with a maximum possible value of 20) was calculated. An ecological condition score between 0 and 1 was computed for each site based on the addition of vegetation and landscape scores divided by one hundred. A score of 1 indicates very high ecological condition.

2.3. Soundscape recordings

Song Meter SM2 (Wildlife Acoustics 2013) recording devices were deployed at each site for approximately one month during September 2012 (spotted gum sites, 28 days) and September 2013 (scribbly gum sites, 36 days). Recording devices were placed in vegetation away from the patch edge and any walking tracks or disturbance and attached to trees at eye height. Song Meters were configured to record for 1 min every 30 min and monaural 16 bit recordings were made at a frequency of 22,050 Hz and stored in WAV file format.