Intersections of Soundscapes and Conservation: Ecologies of Sound in Naturecultures

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Abstract: An ecosystem is a reflection of coupled human and natural systems. A key, and less understood, interaction is with sound. Paralleling development in landscape ecology, soundscape ecology provides a diversity of measures of spatial and temporal variation in sound. Here we bridge disciplines to describe variation in soundscape measures across a gradient of novel to natural landscapes. Soundscape measures studied varied as a function of forest area but not matrix type, and season but not time. Results suggest future directions and allow practitioners to better identify management options that mitigate the impacts of noise on natural and human systems.

Résumé : Un écosystème est un reflet de l'appariement d'un système humain et d'un système naturel. L'une des interactions essentielles, et des moins bien comprises, se fait au moyen du son. Se développant parallèlement à l'écologie du paysage, l'écologie du paysage sonore procure une diversité de mesures de variations spatiales et temporelles du son. Ici nous établissons un pont entre les disciplines pour décrire la variation dans les mesures du paysage sonore le long d'une graduation allant des paysages nouveaux aux paysages naturels. Les mesures du paysage sonore étudiées variaient en fonction de la région forestière, mais non du type matriciel, et de la saison mais non du temps. Les résultats indiquent des orientations futures et permettent aux praticiens de mieux identifier les options de gestion qui atténuent les impacts du bruit sur les systèmes humains et naturels.

Most ecosystems are a reflection of interactions between human and natural systems (Liu et al. 2007; Ellis 2011). A key, albeit often less explored and thus less understood, interaction between systems is via sound. All environments are noisy, as sound is a perpetual, dynamic property of landscapes (Pijanowski et al. 2011). However, humans have altered much

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of the world's acoustic characteristics with anthropogenic sounds, even in our perceived remotest areas (Buxton et al. 2017). These are sounds that are different in pitch, amplitude, acoustic structure, and distribution, and are often more continuous than sounds produced in natural environments (Pijanowski et al. 2011; Slabbekoorn and Ripmeester 2008). These noise levels, particularly human-made noises from automobiles, industry, urban living, etc. (Blumstein et al. 2011), have been shown to be detrimental to the overall health and well-being of humans and wildlife (Goines and Hagler 2007; Quadros et al. 2014; Rodriguez et al. 2014; Ernstes and Quinn 2015; Oden et al. 2015; Roca et al. 2016; Shannon et al. 2016).

While the scope of research regarding ecological responses to variation in noise is expanding, these assessments have largely focused on a narrow definition of noise pollution: power, or the intensity of a sound often measured in decibels, and acoustic masking, or the overlap of sounds at a given frequency, where human noise overlapping natural sounds are most frequently of interest (Barber et al. 2011). However, paralleling the evolution of indices in landscape ecology, such as edge density, perimeter-area ratio, and total core area (McGarigal and Marks 1995), soundscape ecology has developed various measures of spatial and temporal variation in sound (Villanueva-Rivera et al. 2011; Fuller et al. 2015). Thus, similar to the value of considering multiple landscape indices in species management, studying a suite of soundscape measures will provide a better understanding of broader ecological processes and changes associated with sound. Extending from simple measurements of power, acoustic sound indices provide multiple ways to quantitatively measure the soundscape and more fully understand concurrent biophysical and human processes. Central to the soundscape is biophony, geophony, and anthrophony. The biophony, or non-human, biologically-generated sound, is created by birds, insects, and other ecological communities. These sounds vary by season, hour, and in the moment of species interaction. Geophony refers to environmental sounds not created by living creatures, such as thunder and wind. Anthrophony, or human-generated sound, is more consistent than biophony as an outcome of the sources of noise (e.g., vehicles, heavy machinery, or the general noise of a city), though there can be emergent patterns in anthrophony as well; for example, an increase in traffic noise during a city's morning rush hour traffic. A full assessment of the soundscape captures this complexity with different measures more fully described in the methods below. Across these measures, a change in the level of anthrophony, or a shift in the ratio between human and biological noises, can suggest a broader shift in the ecosystem as wildlife species lose the ability to communicate or interact in urban and rural spaces. In response, some species have apparently adapted to the increased noise by vocalizing louder and at higher frequencies (Roca et al. 2016), though a response is not consistent (Brumm and Zollinger 2013). Similarly in humans, the relational value of nature — that is to say, particular preferences, virtues, and principles implicated in particular relationships with natural soundscapes (Chan et al. 2016) — decreases as anthrophony replaces nature's complex acoustic space (Krause 2012). Consequently, soundscape measures can be used as indicators of ecosystem health.

Recently these acoustic indices have been used to look at local habitats (e.g., Lake Michigan [Gage and Axel 2014]), community diversity (Gasc et al. 2013), landscape configuration (Fuller et al. 2015), and avian phenology (Buxton et al. 2016), but more work is needed across ecosystem types with varied levels of human interaction and at different spatial and temporal scales (Fuller et al. 2015). While there is no objectively correct scale at which to study and manage ecosystems (Levin 1992), including the soundscape, consideration of multiple scales has proven valuable in research and practice (e.g., Quinn et al. 2014). The spatial and temporal scale of research in acoustic and soundscape ecology varies, including studies on small populations at local scales (e.g., Grace and Anderson 2015), snapshots at larger scales at a given time and place (e.g., Rodriguez et al. 2014; Oden et al. 2015; Buxton et al. 2017), and longer monitoring efforts (e.g., Frommolt and Tauchert 2014).

Given the increasing accessibility of sound data and deeper understanding of sound's ecological impacts, it is essential that we be able to connect soundscape data to scale-specific practitioner needs. For example, city and regional planners or conservation practitioners may be most interested in aggregated data over broad spatial scales with sampling targeted towards key times of day or year (e.g., breeding season, for avian conservation biologists). These data can also be used to understand broader ecological change including climate shifts or habitat loss. Though these data can provide a general measure of potential impact on a specific area, a more focused sampling effort would be of greater value to someone at a specific conservation easement or natural area with a small geographic extent. Similarly, the frequency of sampling within a timeframe may vary. For example, the morning is well known as the period of the avian dawn chorus but human noises may peak at different times of the day, resulting in different effects on disparate communities.

To better connect with and consider how soundscape measures can be of practical value to decision makers, we analyze and discuss two nested datasets, reflecting spatial management at different scales (a large county vs. a small zoo) and compare variation in soundscape measures between spatial and temporal scales. We discuss how these data may be useful for management efforts at each scale.

At the larger county scale, we bridge soundscape and landscape ecology (Villanueva-Rivera et al. 2011) to concurrently describe variation in multiple soundscape measures in natural, managed, and novel (i.e., an ecosystem that is different in structure when compared to natural conditions [Hobbs et al. 2006]) landscapes. We use two key measures of landscape structure: patch area and matrix type. Patch area refers to the total area of a contiguous type of habitat (e.g., forest patch) and matrix type refers to the dominant land use or land cover around a patch. These data enable a broader understanding of how future land use change could shape the soundscape, allowing researchers and practitioners to identify management options that mitigate the impacts of noise on natural and human systems. We also describe acoustic data collected within a small, urban zoo (our smaller scale context), specifically, how daily and seasonal changes affect the noises heard by zoo animals and visitors.

Methods

Study Sites

We sampled the soundscape at multiple spatial and temporal scales. At the broader scale, we sampled at 33 pine patches (Fig. 1) in Upstate South Carolina, USA. Study sites were widely spaced (≥ 400 metres apart) along an urban-rural gradient from protected forest patches in the north, through residential and urban development in the middle, and agricultural land in the southern portions of the county. At the smaller scale, we sampled within the Greenville Zoo in Greenville, South Carolina. The zoo is in a semi-urban area of the city adjacent to a large urban park and a commercial area with a major roadway (Fig. 2). We placed five recorders across the zoo: at an exhibit by the main entrance, in the middle of a walkway lined with various primate enclosures, at the entrance of the African savanna exhibit, in an exhibit that contained a mix of different species, and between a water feature and several bird enclosures (Fig. 2).

Data Collection

At both scales, we used SM2+ Automated Recording Units (ARUs; Wildlife Acoustics Inc., Maynard, MA, USA, 2013) to record the soundscape. Gain settings were set at 48 dB, a high pass filter was set at 3 Hz, and noise floor was -54dB on all ARUs. We hung the recorders between one and two metres off the ground, and files were processed in WAV file format. At the county scale, we gathered acoustic data from May through July of 2013. Each ARU was set to record at a sampling rate of 16000 Hz for 10 minutes on the hour for every hour between 0600 and 1000 EST, mimicking sampling protocols for avian ecology. Each ARU was left at the study site for a minimum of four days, but no longer than a week. To classify the landscape metrics of patch area and matrix type for the county-scale assessment, we used ArcGIS tools to conduct spatial analyses

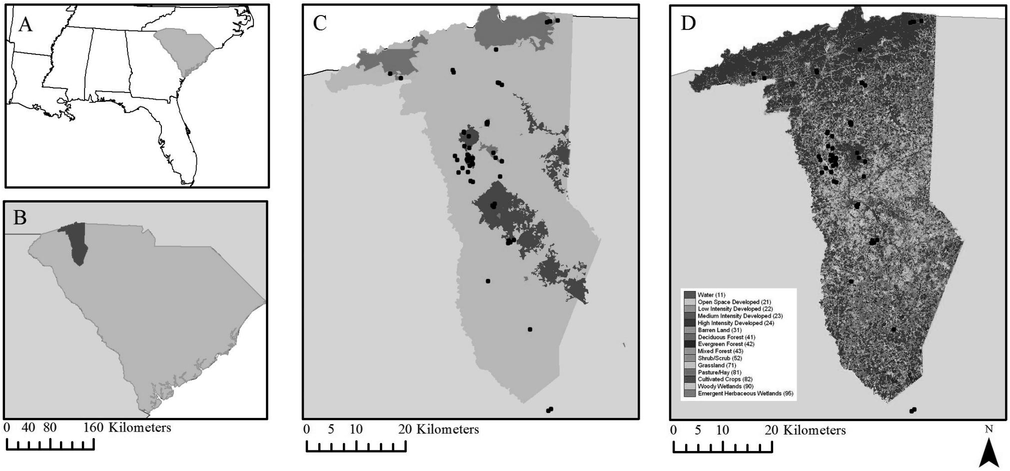


Fig. 1. Distribution of sampling sites in Greenville Co. SC (A, B) with placements of recorders within municipal and protected boundaries (C), and across county land use and land cover variation (D).

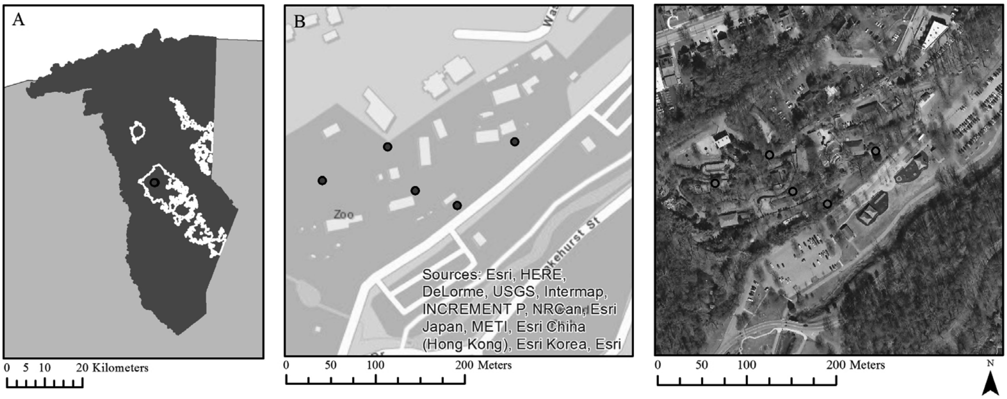


Fig. 2. Location of the Greenville Zoo within Greenville Co. SC and the city of Greenville (A) with placements of recorders within the zoo (B), and showing street and building layout in relation to land cover within and around the zoo (C).

of matrix type and patch area. We used the spatial analyst tool in ArcGIS to calculate the area of each pine patch. We followed Wood and Quinn's (2016) classification of matrix type as Forest, Cultivated, Urban Developed, or Urban Residence, following the SC GAP classifications (SC DNR).

For the local zoo scale, we recorded at all five sites for one week in winter (November-December 2016) and one week in summer (July 2017). During the winter sampling, we recorded 10-minute intervals between 6:00 to 16:00 and 20:00 to 0:00 for a total of 17 hours of the 24-hour day, coinciding with the operating hours of the zoo and possible nocturnal activities of species. During the summer, we recorded for 10 minutes on the hour for a full 24 hours. Our recordings captured the auditory stimuli caused by humans, infrastructure, and the animal species located in the zoo.

Data Analysis

The soundscape indices we focus on are Biophony, Anthrophony, Normalized Difference Soundscape Index, Acoustic Entropy, Acoustic Complexity Index, Acoustic Diversity Index, Acoustic Evenness Index, and Bioacoustic Index (reviewed fully in Fuller et al. 2015):

1. Biophony is non-human, biologically-generated sound;
2. Anthrophony is human-generated sound;
3. Normalized Difference Soundscape Index (NDSI) is the proportion of biophony to anthrophony in the soundscape, calculated as (biophony - anthrophony) / (biophony + anthrophony) (Kasten et al. 2012);
4. Acoustic Entropy (H) is a function of temporal energy dispersal and spectral energy dispersal (Sueur et al. 2008);
5. The Acoustic Complexity Index (ACI) is a function of the amount of variation in the intensity of sounds (Pieretti et al. 2011);
6. The Acoustic Diversity Index (ADI; Villanueva-Rivera et al. 2011) measures the diversity of sounds; it is the proportion of signals in each bin above a threshold, with the final value calculated with the Shannon diversity index;[1]
7. The Acoustic Evenness Index (AEI) measures the equality/inequality of distribution of sound power in different frequency ranges (Villanueva-Rivera et al. 2011) and is calculated in the same way as the Acoustic Diversity Index, but with the Gini index of evenness;[2] and

8. The Bioacoustic Index (BAI) is a function of both the power and frequency range of sound generated by wildlife; it is calculated as the area under each curve, including all frequency bands associated with the dB value that was greater than the minimum dB value for each curve (Boelman et al. 2007).

We used the tuneR package[3] (Ligges et al. 2017) for Program R (R Development Core Team 2008) to read the sound files. We then used the soundecology (Villanueva-Rivera and Pijanowski 2015) package to obtain values of Anthrophony and Biophony. For each sound file — and following Kasten et al. (2012), who used a large number of samples to determine Anthrophonic frequency — we defined Anthrophony as sound occurring in the 1-2 kHz range while we defined Biophony as sound occurring in the 2-8 kHz frequency range. We also used the soundecology package to obtain values of the Normalized Difference Soundscape Index, Acoustic Entropy, Acoustic Complexity Index, Acoustic Diversity Index, Acoustic Evenness Index, and Bioacoustic Index for each recording. To avoid pseudo-replication[4] in statistical analyses, we averaged all values for each index for each site (forest patch or point in the zoo). Thus, a point within a given forest patch or the zoo was the unit of study for subsequent statistical analyses. Data were tested for normality with the Shapiro test;[5] if non-normal, they were log-transformed.[6] We used linear models (used to understand and predict the behaviour of complex systems) estimated in Program R to test if each measure (Biophony, Anthrophony, H, BAI, ADI, NDSI, ACI, and AEI) varied as a function of landscape context (specifically patch area), the matrix within which the patch was embedded, or the time of year. All alpha values (aka significance values) were set *a priori* at 0.05.

Results

Landscape Scale: Greenville Co.

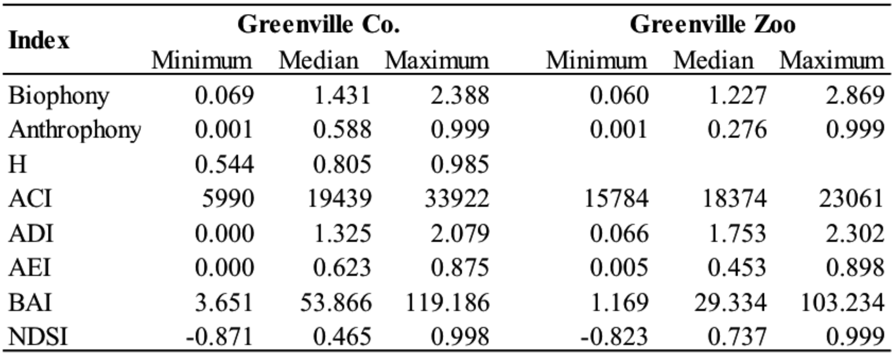
At the county scale, Biophony, Anthrophony, ACI, and NDSI were non-normal ($p<0.05$), and subsequently log-transformed for analyses. ADI decreased ($F_{1,31}$ F=6.58, p=0.015) and AEI increased ($F_{1,31}$ F=5.53, p=0.025) as a function of forest patch area (Fig. 3). Surprisingly, there was a negative trend between the size of the patch area and the Biophony (Fig. 3, top left) though the relationship was not significant ($F_{1,31}$ F=0.70, p=0.41). The relationship between the other soundscape indices and patch area were not significant ($p>0.10$). Similarly, there was no effect of matrix type on any soundscape index (Fig. 4, $p>0.10$). As with area, patterns are suggestive, but variability in sound over time may add sufficient quantitative noise to limit statistical inference of averaged values.

Local Scale: The Zoo

At the local zoo scale, Anthrophony ($F_{1,8}$ F=40.24, $p<0.000$) varied between seasons, but Biophony did not ($F_{1,8}$ F=3.39, $p=0.103$) (Fig. 5). Across a 24-hour period (Fig. 6), there was clear variation between indices and seasons, though the small sample size makes statistical inference less valuable. Biophony was less varied across the day during summer than winter, though it is interesting to note that Biophony increased for only one recording site during the winter. During the winter, Anthrophony was relatively constant. In contrast, during the summer Anthrophony peaked in the early afternoon (~1300), though there is a clear differentiation in the two groups. Lastly, during the winter, as Anthrophony increased, there was a clear decline in Biophony (Fig. 7). In the summer, there is a slight negative relationship between Biophony and Anthrophony.

Comparison Between Scales

The greatest Biophony was recorded at the Greenville Zoo (Fig. 3), but the range of Anthrophony did not differ between scales. The zoo had a narrower range of Acoustic Complexity, but the other indices were similar in range, though the median BAI and AEI are notability lower.



Index	**Greenville Co.**			**Greenville Zoo**		
	Minimum	Median	Maximum	Minimum	Median	Maximum
Biophony	0.069	1.431	2.388	0.060	1.227	2.869
Anthrophony	0.001	0.588	0.999	0.001	0.276	0.999
H	0.544	0.805	0.985			
ACI	5990	19439	33922	15784	18374	23061
ADI	0.000	1.325	2.079	0.066	1.753	2.302
AEI	0.000	0.623	0.875	0.005	0.453	0.898
BAI	3.651	53.866	119.186	1.169	29.334	103.234
NDSI	-0.871	0.465	0.998	-0.823	0.737	0.999

Table 1. Summary statistics from two scales of analysis, Greenville Co. and the Greenville Zoo.

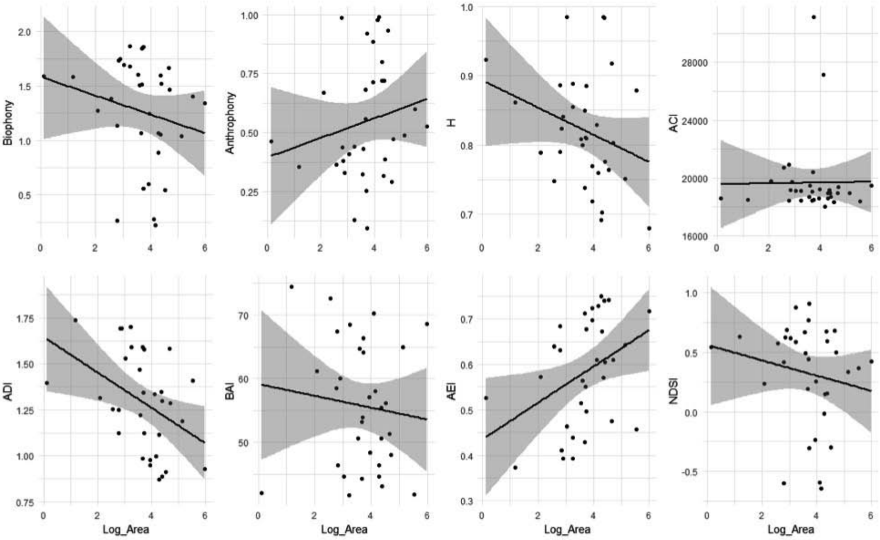


Fig. 3. Variation in soundscape index as a function of area (log-transformed) where AEI increased (p=0.025) and ADI decreased (p=0.015).

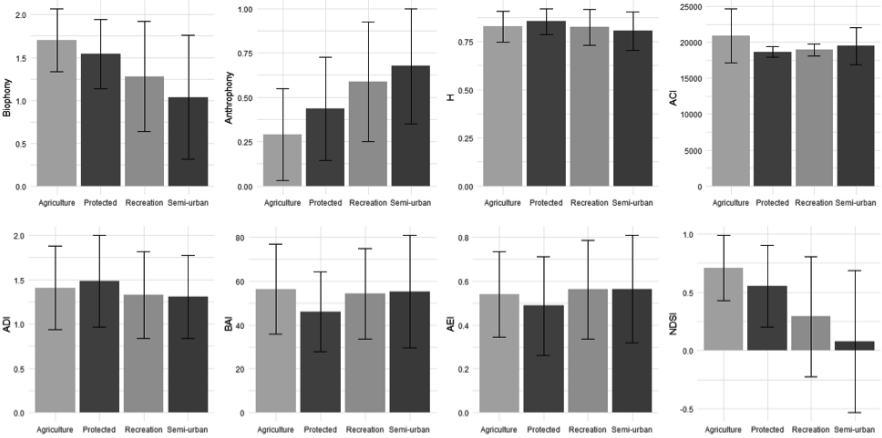


Fig. 4. Variation in soundscape index as a function of matrix type.

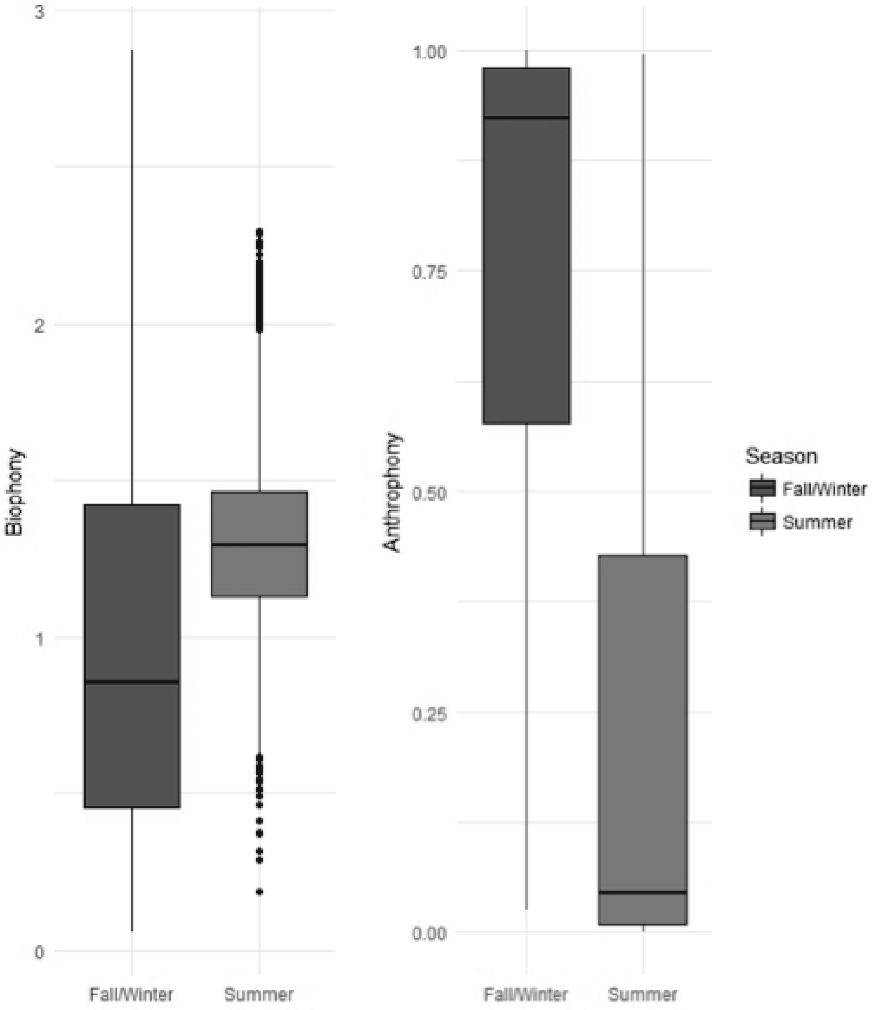


Fig. 5. Variation in in Biophony ($p>0.05$) and Anthrophony ($p<0.05$) between fall/winter and summer sampling periods.

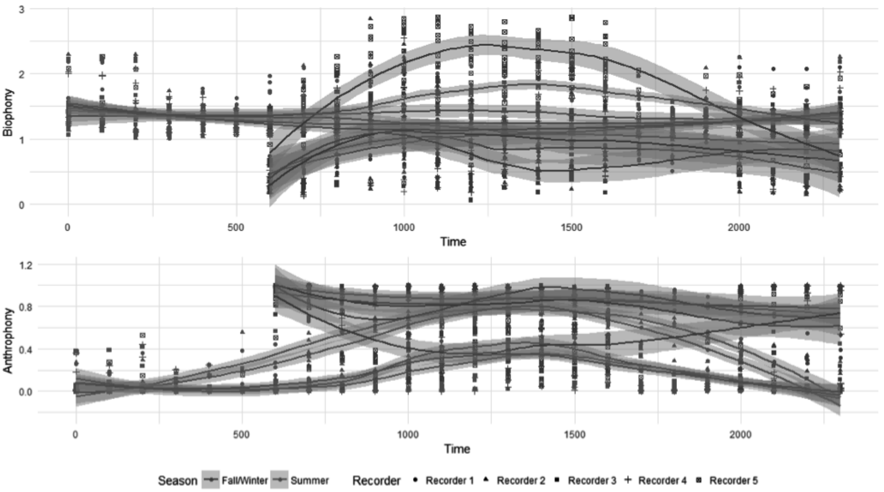


Fig. 6. Daily variation between sites and seasons. Best fit loess[7] lines plotted by recording site and season.

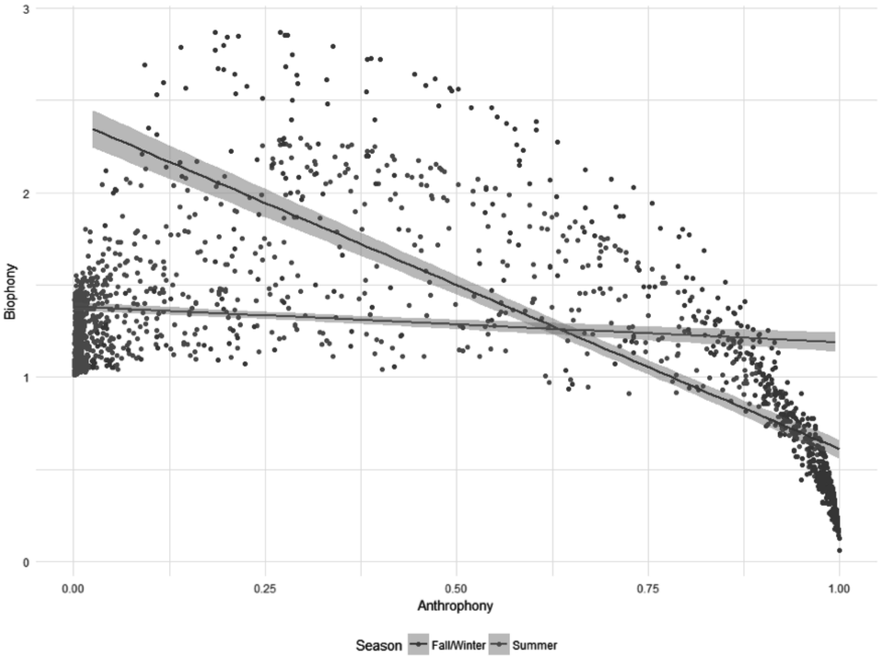


Fig. 7. Relationships between Anthrophony and Biophony across sites and season.

Discussion

Landscape ecology and soundscape ecology overlap in terms of their questions, tools, and consideration of scale (Villanueva-Rivera et al. 2011; Fuller et al. 2015). Moving between and applying concepts across disciplines stimulates novel insights (Ledford 2015) and can enhance the translation of science into policy (Haider et al. 2018). As the field of soundscape ecology evolves it should continue to engage not only other natural sciences, but also disciplines that use tools from economics, policy, and the study of values. Here we show how regional and local soundscapes, across a gradient of human land-use intensity (i.e., protected forest watersheds, residential developments, zoos) shaped by human and ecological actions, vary over space and time, as well as how the landscape and interactions of humans with the environment can affect these patterns — perhaps in unexpected ways. These data could in turn be used to determine the extent of the willingness to pay[8] for greater biophony along an urban-rural gradient or the preference for policy that prioritizes quiet spaces.

Larger patches are often identified as better for species conservation, given that they tend to host greater diversity and abundance of species (Shaffer 1981). Greater acoustic diversity does suggest that larger patches may have a larger variety of vocalizing species. We found greater acoustic evenness was suggestive of better habitat quality, specifically a larger forest patch, though Fuller et al. (2015), showed that acoustic evenness declined with improved biocondition. Though only suggestive, the decline in Biophony within larger patches was unexpected, implying perhaps reduced abundance in larger patches. There is also clear literature showing that the land use and land cover *around* patch (i.e., the matrix) affects diversity and abundance *within* a patch (Ricketts 2001). For example, Wood and Quinn (2016) demonstrated that the Brown-Headed Nuthatch was more abundant in the same pine forest patches when the patch was surrounded by urban residential landscapes compared to patches embedded in other forest types. Though not significant, the reduced values of Biophony in the more urban environments is consistent with our understanding of the effects of urbanization on noise. Future work at these scales should consider sampling on a 24-hour schedule to better understand how the soundscape varies throughout the day; this is a data set we did not collect because the focus of the study was to match the morning sampling efforts (within four hours of sunrise) typical of active field sampling for birds. Other variables more explicitly linked to sources of noise along the urban-rural gradient, including the proximity to roads (Riitters and Wickham 2003), would be valuable to include as research and practice work to limit the impact of noise on ecosystem (Pater, Grubb, and Delaney 2009) and human health (Goines and Hagler 2007). Likewise, yearround monitoring can add additional insight, for example on the differences between responses to noise in the summer and winter, as was seen at the local scale within the zoo (Oden et al. 2015).

The soundscape of the Greenville Zoo varied across seasons and time. By collecting data within the zoo, at a finer spatial and temporal scale than the countywide project, we were able to provide a richer dataset for zoo managers to consider. These data show that urban and suburban zoos may need to consider variation between seasons when attempting to mitigate the effects of noise from within and beyond the zoo, particularly in winter. This could improve the well-being of the zoo animals as well as the visitor experience during the winter. To date, the auditory stimuli present in zoos due to visitors, infrastructure, and other species has been under-acknowledged despite the evidence that loud levels of noise within the zoo can have negative impacts on the captive animals living there as well as on visitors looking for an immersive experience (Quadros et al. 2014; Robbins and Margulis 2016; Sherwen et al. 2015). Future research in such novel ecosystems like the zoo should consider how noise in general, and specific species vocalizations, vary as a function of human interactions, use of space, and engagement with the ecosystem. Likewise, beyond the boundaries of the area of interest, greater attention to noise from the external environment is warranted (Newberry 1995). Indeed, greater attention to noise across landscapes is necessary to mitigate anthropogenic noise and its subsequent impacts on ecosystem health (Barber et al. 2011).

We have been working for many years with local conservation groups. These data are now being used as part of the evaluation process for prioritizing land acquisition and mitigating impacts of future urban development. Though sound is only one measure considered, the novelty of the data and clear connection to the relational value to nature has made it a valuable addition. As an exploratory analysis, these results can help develop future *a priori* models to evaluate the relationship between soundscape and ecosystem function. We have shared the local data with the Greenville Zoo[9] and are currently working with zoo staff to design a sampling effort to understand and mitigate the impacts of an approaching construction project on the soundscape of the zoo (and consequently the animals in the zoo and human visitors).

Evaluating indices of soundscape change demonstrates multiple ways that these data can benefit stakeholder decisions. Regional data may be more useful to county governments and conservation groups working with broader spatial scales and seeking to identify the best lands to protect. Intensive sampling of forest and other habitat patches is time and resource intensive. Soundscape measures may provide a tool for rapid assessment of habitat quality. Local data, similar to the zoo, may be more valuable to those managing smaller properties

— for example, easements, parks, and neighbourhoods — and who therefore are more interested in a finer scale of change. However, researchers need to work on aligning research questions, study design, and sampling patterns with the needs of data users. Ultimately, linking monitoring efforts at both scales in hierarchical analyses and creating effective ways of sharing the data (e.g., an interactive web-based data visualization app built with Shiny[10]) will improve the application of soundscape data to local and regional conservation planning.

Notes

1. The Shannon diversity index is a commonly used measure in ecology. It is a mathematical measure of species diversity in a given area. Diversity indices provide information about the relative abundance of various species present, rather than just the number of species present. Such information is valuable for those scholars wanting to understand community structures (see http://www.tiem.utk.edu/~gross/bioed/bealsmodules/shannonDI.html).
2. The Gini index is used to measure the relative equality or inequality of distribution.
3. "Packages" refer to computer programs and software designed to conduct various types of analyses and calculate indices.
4. Pseudo-replication occurs when individual observations are heavily dependent on each other; in such a case, replicates are not statistically independent. Pseudo-replication is the artificial inflation of the number of samples or replicates, resulting in unreliable statistical analyses.
5. The Shapiro test is commonly used in statistics to ensure that a data-set is well modelled by a normal distribution. Non-normal data indicate that a test is inaccurate.
6. When data are determined to be non-normal, a transformation can be applied to help them conform to normality. The log-transformation is perhaps the most popular among different types of possible transformations.
7. Loess refers to "locally weighted smoothing," and is a popular tool used to create a smooth line through a timeplot or scatterplot to clarify relationships between variables and to predict trends.
8. Willingness to Pay is a tool from the field of economics used to estimate the value of a resource by asking an individual how much they are willing to give up, or pay, to see a change in that resource. In this application, it would be asking how much people would be willing to pay to for a more natural or quiet soundscape.
9. https://dakotahoward.shinyapps.io/shinyZoo/
10. https://dakotahoward.shinyapps.io/shinyZoo/

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