



The quantitative relation between ambient soundscapes and landscape development intensity in North Central Florida

Jenet M. Dooley · Mark T. Brown

Received: 17 December 2018 / Accepted: 13 November 2019 / Published online: 23 November 2019
© Springer Nature B.V. 2019

Abstract

Context It is widely accepted that wildlife is subjected to detrimental human noise within urban landscapes but little is known about how the intensity of land use changes soundscapes.

Objectives The objective of this research was to produce quantitative associations between characteristics of ambient soundscapes and land use intensity. These relations were used to examine the 2 kHz demarcation between anthrophony and biophony and compare the impact of different sized contributing areas on ambient soundscape characteristics.

Methods This study related the surrounding land use intensity of 67 sites in north central Florida (USA) to

several metrics describing their recorded soundscapes. Land use intensity was measured remotely at three scales using the landscape development intensity index (LDI).

Results The analysis revealed that the LDI index had a statistically significant effect on soundscape characteristics after controlling for important factors such as climate, season, and attenuation due to hard ground. The trends between LDI and soundscape confirmed that human generated sounds are loud, continuous, and occupy low frequencies. The evenness of the sound distribution decreased with landscape intensity and LDI correlated significantly with sound below 3 kHz. Land use intensity within a 100 and 500-m radius contributing area were most closely related to soundscape metrics.

Conclusions LDI is a tool with the potential to predict the extent and intensity of anthropogenic noise disturbance on wildlife from remote sensing data. The utility of this tool allows for widespread application to identify and mitigate conflicts in the acoustic realm between human noise and wildlife.

Electronic supplementary material The online version of this article (<https://doi.org/10.1007/s10980-019-00936-2>) contains supplementary material, which is available to authorized users.

J. M. Dooley (✉)
Engineering School of Sustainable Infrastructure and Environment, Howard T. Odum Center for Wetlands, University of Florida, Gainesville, FL 32611, USA
e-mail: dooley@ualebrta.ca

M. T. Brown
Center for Environmental Policy, Environmental Engineering Sciences, University of Florida, Gainesville, FL 32611, USA

J. M. Dooley
Alberta Biodiversity Monitoring Institute, University of Alberta, Edmonton, AB, Canada

Keywords Development intensity · Soundscape · Noise disturbance · Biophony · Anthrophony · Technophony · LDI index · Power spectral density · Remote sensing · Ambient sound

Introduction

The increasing quantity and intensity of human generated sound within landscapes has stimulated interest, in recent years, from the scientific community and the public. This has led to a significant expansion in the measurement and characterization of what has been termed the *soundscape*, or the composite of sounds of an environment (Pijanowski et al. 2011b). The analysis of soundscapes has been fast evolving, resulting in new perceptions of the interface between human and the natural soundscape and new tools for its study. Based primarily on findings of acoustic signal alteration in birds and amphibians (Brumm and Slabbekoorn 2005; Laiolo 2010) and evidence of altered reproductive behavior (Habib et al. 2007; Bayne et al. 2008; Ware et al. 2015), the anthropogenic portion of soundscapes is increasingly considered a disturbance. And while it may be intuitively obvious that human sourced sound intensity is related to land use intensity, few if any studies have documented the relation in a quantitative way.

Research documenting the relation between soundscape patterns and gradients of human footprint has been limited. Two recent studies used the percent cover of specific human dominated land uses to measure human influence and found negative correlations with soundscape complexity ($n = 7$) (Pijanowski et al. (2011a) and positive correlations with acoustic intensity below 2 kHz (Joo et al. 2011). Two earlier studies in western Greece found correlations between the human perception of the acoustic environment and quantitative descriptions of the surrounding human landscape (Matsinos et al. 2008; Mazaris et al. 2009). Tucker et al. (2014) found that the soundscape characteristics of forest patches in Queensland, Australia correlated with patch size and connectivity. In another study, Fuller et al. (2015) suggested that research linking the soundscape and landscape has been inhibited by the lack of landscape evaluation methods.

Soundscape areal dimensions

The physical area that contributes sound to a recorded soundscape is not easily defined and not standardized in the literature (Farina and Pieretti 2014). The physical area of influence for a soundscape is dynamic since it is dependent on many factors including the

location and loudness of transient sound signals and changing environmental conditions (ISO 1993, 1996; Qi et al. 2008). Previous soundscape ecology studies have assumed areas of influence as circular areas with radii of 100 m (Pijanowski et al. 2011a), 175 m (Mazaris et al. 2009), 300 m (Joo et al. 2011; Depraetere et al. 2012), and 500 m (Krause et al. 2011). In the above literature, the justification for size of the influence areas used were not discussed with the exception of Krause et al. (2011) and Joo et al. (2011) which based the area on microphone sensitivity distance.

Anthrophony versus biophony

Studies of the soundscape commonly identify sources of sound as either anthropogenic or biologic using a sound frequency cutoff of 2 kilohertz (kHz), where sounds below 2 kHz are classified as anthropogenic (anthrophony or technophony) and above as biologic (biophony) (Joo 2009; Joo et al. 2011; Krause et al. 2011). However, there is evidence that this boundary is somewhat arbitrary (Sueur et al. 2014). The 2 kHz boundary was based on observations of the frequency ranges of biological and anthropogenic sounds (Napolitano 2004; Joo et al. 2011; Kasten et al. 2012). However, human and biological sounds have been documented crossing the 2 kHz point in the frequency spectrum (Makarewicz and Sato 1996; Napolitano 2004; Bee and Swanson 2007; Can et al. 2010). It is important that we understand the limitations of this boundary, as it is used in studies to infer the relative contribution of biophony and anthrophony to soundscapes (Qi et al. 2008; Gage and Axel 2014; Fuller et al. 2015).

Landscape development intensity

This study uses a metric of land use intensity called LDI (Brown and Vivas 2005), to link the sound by-products of land uses to soundscapes. The LDI index is a quantitative measure of land use intensity based on non-renewable resource use per unit area per unit time. Further, it uses the concept of emergy (Odum 1996) to express all resource flows supporting land uses in common units of solar emergy. Expressed in this way, resource use per unit area per unit time (units = $\text{sej area}^{-1} \text{time}^{-1}$) becomes *aerial empower intensity* (where empower is emergy per time). The LDI of a

point or area takes into account the aerial empower intensity of surrounding land uses. The size of the analysis area depends on the application. The LDI has been used as a human disturbance gradient to develop bio-indicators of ecosystem, stream and lake condition (Fore 2004, 2005; Lane and Brown 2007; Reiss et al. 2010). The LDI correlated with wetland rapid assessment evaluation methods in Florida (Brown and Vivas 2005), South Dakota (Bouchard 2009), Ohio (Mack 2006), and Hawaii (Margruter et al. 2014). It also correlated with coral reef condition in St. Croix and wetland condition in Taiwan (Chen and Lin 2011; Oliver et al. 2011).

The characteristics of a soundscape are impacted by the attenuation of sound as it travels from the source (ISO 1993, 1996). Sound attenuation is impacted by climatic conditions (ISO 1993) and characteristics of the propagation path (ISO 1996). The effects of these factors are not consistent across the frequency spectrum; high frequency sounds are generally more susceptible to attenuation than low frequency sounds (ISO 1993, 1996). Attenuation is an important factor to consider in addition to sound sources when predicting soundscape characteristics.

Problem statement and plan of study

In this study, we evaluate several characteristics of ambient soundscapes generated by landscapes of varying degrees of development intensity to produce quantitative associations between sound and land use intensity and spatial area. In addition, we explore the 2 kHz demarcation between anthropony and biophony with statistical correlations between land use intensity and the distribution of sound across the frequency spectrum.

Methods

Description of study sites

This study collected data from 67 sites in north central Florida (Fig. 1) selected to capture a variety of land use/land cover (LU/LC) classes across a spectrum of anthropogenic influence. Six different LU/LC classes were targeted as follows, conservation (CON; $n = 10$), recreational park (RP; $n = 10$), single family residential (SFR; $n = 16$), industrial (IND; $n = 8$),

commercial shopping center (CSC; $n = 13$), central business districts (CBD; $n = 4$), and mixed uses (including roadsides and agriculture, MU; $n = 6$). These classifications coincided with the Florida Land Use, Cover and Forms Classification system (FLUCCS) as described in Table 1.

Data collection

The soundscapes of each site were sampled using a Fostex fr-2le field recorder and a Seinheisser ME 62 omni-directional microphone. The frequency response of the microphone was 20–20,000 Hz. The recordings were 30 min long and used a waveform format with a 24-bit depth and 48 kHz sampling rate. The recordings took place between 0900 and 1000 on week days over 2 years from April 2013 until March 2015. This time of day was selected for its ambient nature, avoiding known times of increased acoustic activity like dawn chorus (Stacier et al. 1996) or early morning rush hour traffic (Mennitt and Fristrup 2016). A tripod ensured that the recording equipment was consistently 1 m off the ground. Recordings were not taken if the wind in the area exceeded 10 mph or if it was raining. The location of the recording was documented with a handheld GPS unit.

At each site, climatic conditions were documented at the time of the recording. This information was taken from real time data available online from the closest weather station.

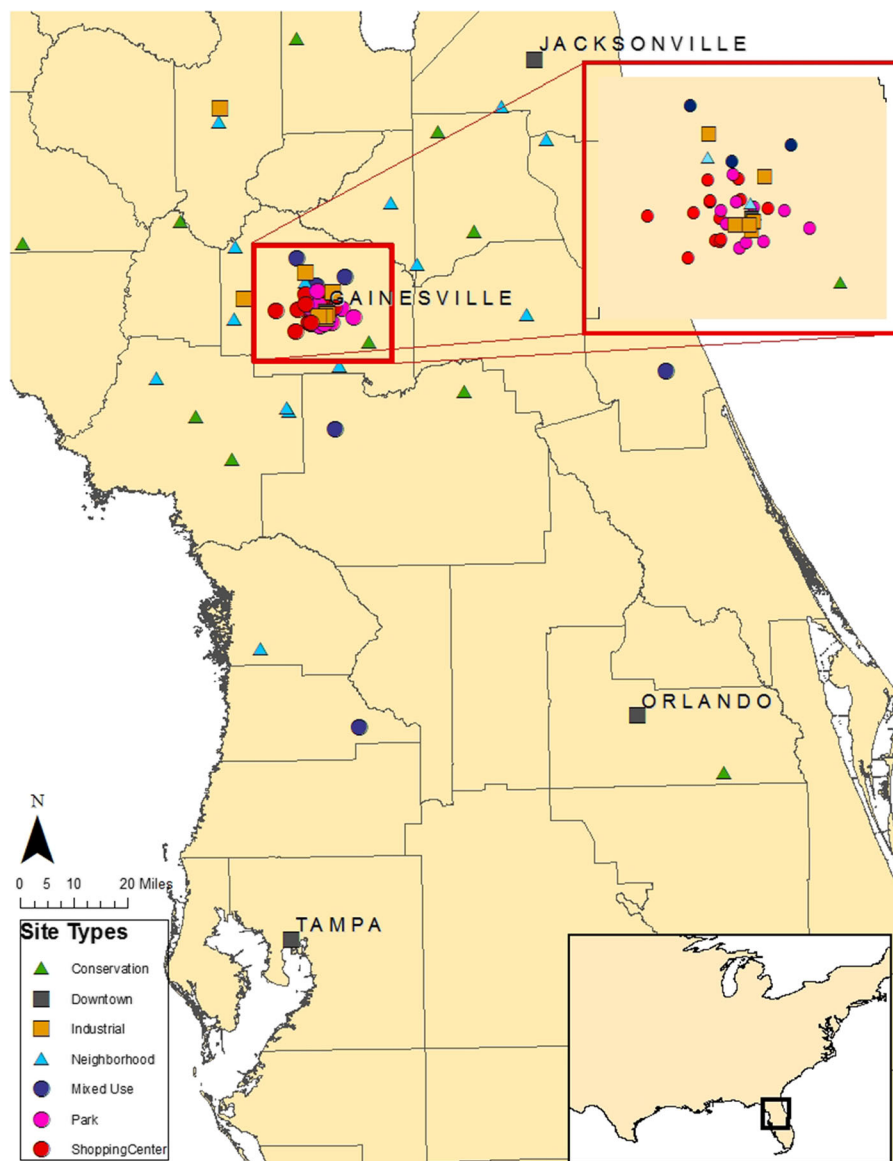
Acoustic analysis

The analysis of the acoustic data utilized two different divisions of the frequency spectrum to describe the soundscapes. First, the entire frequency spectrum (20–20,000 Hz) was analyzed as a whole. Second, each site's spectrogram was divided into twenty, 1 kHz wide frequency bands. All analysis was confined to above 20 Hz, the limit of the microphone's frequency response.

Acoustic metrics

The metrics used in this study to describe the soundscapes were calculated from spectrograms made with Raven Pro 1.4 (Bioacoustics Research Program 2011) software. The spectrograms used a Hann window with a discrete Fourier Transform size of

Fig. 1 Location of the 67 sites where data was collected for this study



256 samples and 188 Hz grid size that slightly favored spectral resolution over time resolution since this was the focus of the study. The metrics were based on the power spectral density (PSD), the amount of sound per unit frequency (dB/Hz), of the frequency-time bins in the spectrogram, which was calculated internally within Raven using Fourier Transforms. The decibel units are relative to an arbitrary reference of 1. Five different metrics were calculated using the PSD values from each recording: inband power, average PSD, delta power, aggregate entropy, and center frequency. The acoustic metrics were the dependent variables in

the statistical analysis. A brief description of each measure is given in Table 2. Aggregate Entropy was calculated within Raven according to the following formula (Charif et al. 2010):

$$H_{selection} = \sum_{f=f_1}^{f_2} \left(\frac{E_{bin}}{E_{selection}} \times \log_2 \left(\frac{E_{bin}}{E_{selection}} \right) \right) \quad (1)$$

where $H_{selection}$ is the aggregate entropy for the part of the frequency spectrum selected for analysis and f_1 and f_2 are the upper and lower limits of the selected frequency spectrum, respectively. E_{bin} is the energy

Table 1 Land use descriptions of study sites

LU/LC class	FLUCCS codes
Conservation (CON)	4000 (Upland Forest); 6300 (Wetland Forested Mixed); 6170 (Mixed Wetland Hardwood)
Recreational Park (RP)	1860 (Community Recreation Facilities); 1850 (Parks and Zoos); 2110 (Improved Pasture)
Single Family Residential (SFR)	1200 (Residential, Medium Density); 1100 (Residential, Low Density)
Industrial (IND)	1530 (Mineral Processing); 8300 (Utilities)
Commercial Shopping Center (CSC)	1400 (Commercial and Services)
Central Business District (CBD)	1400 (Commercial and Services)
Mixed Use (MU)	8100 (Transportation); 2100 (Cropland & Pastureland); 4410 (Pine Plantation); 6000 (Wetlands); 2600 (Other Open lands); 1300 (Residential, High Density); 4340 (Hardwood Conifer Mixed)

Table 2 Acoustic metrics used to describe the soundscapes Metric descriptions adapted from Charif et al. (2010) and Joo et al. (2011)

Measure	Definition
Average Power Spectral Density (dB/Hz)	The total PSD within the selection of spectrogram divided by the number of time–frequency bins
Average Inband Power (dB/Hz)	The PSD within the selection averaged over time, summed over frequency and then multiplied by the size (Hz) of the frequency bins to convert to total time-averaged spectral power. This value is then divided by the sampling rate of the recording
Aggregate Entropy	This measure quantifies sound disorder. The measure is high if sound is evenly spread throughout the frequency spectrum. Selection of spectrogram is broken up into frequency bands. The PSD value is summed over time for each frequency band. The diversity of the band power values is calculated
Delta Power (dB)	The difference in time-averaged PSD at the upper and lower frequency limits of the selection
Center Frequency (Hz)	The point in the frequency spectrum that splits the selection into two equaled energy parts

contained within a specific frequency bin and $E_{\text{selection}}$ is the total energy within the selection (summed over all bins). The frequency bin size is the grid size of the spectrogram (188 Hz).

Analysis of total frequency spectrum

The analysis of the total frequency spectrum (20–20,000 Hz) applied the inband power, aggregate entropy, delta power, and center frequency measures. These measures were selected because they were expected to indicate the presence of anthropogenic sound in the soundscape. Human sound is known to be powerful and concentrated in low bands (Warren et al. 2006; Slabbekoorn and Ripmeester 2008; Barber et al.

2010; Pieretti and Farina 2013). It was anticipated that relative to sites surrounded by natural landscape, the soundscapes of sites surrounded by high landscape development intensity would have more sound. This was expected to result in higher overall power spectral density, spectrums with sound concentrated in low frequencies, and increased disparity between high and low frequencies.

Analysis of 1 kHz frequency bands

The 1 kHz band analysis looked at the pattern of sound in each frequency band and the relation between the sound and the landscape development and other covariates. The average PSD measure was used over

inband power to avoid bias that could result from the first band having a slightly smaller frequency range. The aggregate entropy, delta power, and center frequency measures were not used because they did not inform the study when applied to the 1 kHz frequency bands.

Site condition characteristics

Landscape development intensity (LDI)

LDI measures human influence based on the amount of nonrenewable resource use in a determined area of influence surrounding the system (point) of interest. The surrounding areas of influence for this study were circular areas centered at the point where the microphone was placed during site recordings. Three different sized circular areas were used with 100, 500, and 1500-m radii to compute the LDI. Within each area of influence, the area of each unique LU/LC was calculated in ArcMap 10.3 (ESRI 2014), using the most recent land use and cover layers from the Florida Geographic Data Library (FGDL 2015). LU/LC classes were confirmed from observations on site and discrepancies were updated before analysis. Aerial empower intensities for the LU/LC classes (Table 3) were multiplied by the fraction of total area of each LU/LC class and summed to compute land use areal empower density ($emPD_{LU/LC}$). The LDI index for each area of influence was computed using the equation presented in Reiss et al. (2010) as follows:

$$LDI = 10 \log \left(\frac{emPD_{Total}}{emPD_{Ref}} \right) \quad (2)$$

where the total empower density ($emPD_{Total}$) was calculated as the sum of $emPD_{LU/LC}$ and the empower density of the background environment ($emPD_{Ref}$) as follows:

$$emPD_{Total} = emPD_{LU/LC} + emPD_{Ref}$$

$$emPD_{Ref} = 1.97E + 15sejha^{-1}y^{-1}$$

In addition, a distance weighted LDI was calculated for each landscape scale. For these index values, the aerial empower intensity of each LU/LC was area weighted and divided by the distance (meter) from the center to reflect attenuation due to geometric divergence (ISO 1996).

Supplemental landscape variables

Wetland habitats support a large abundance of wildlife (Mitsch and Gosselink 2007), many of which use acoustic communication. A wetland indicator variable was used to specify sites near wetlands where this influence may affect the soundscape. If there was a wetland system within 100 m of the sampling location, the wetland indicator variable was given a value of one, otherwise the variable was zero. This determination was done post-sampling in ArcMap 10.3 (ESRI 2014) using the latest National Wetland Inventory shapefile from US Fish and Wildlife, accessed through the Florida Geographic Data Library (FGDL 2015).

Roads contribute a lot of sound to soundscapes (Forman et al. 2003; Dooling and Popper 2007; Kociolek et al. 2011; Nega et al. 2013). Roads were included in LDI values but the physical area they cover is relatively small compared to the amount of sound emitted from this LU/LC. To capture a more realistic impact of roads, a separate variable that captured the proximity and intensity of roads was created to identify the exaggerated acoustic effect of roads. This measure was computed as the distance (meters) from each site to the nearest large-scale road (collector or arterial) and the annual average daily traffic (AADT) on the road. These values were calculated from the AADT shapefile accessed through the Florida Geographic Digital Library (FGDL 2015). The variable was calculated as the product of the AADT and the inverse distance (meter) of the closest road to each site.

$$RoadProx = \left(AADT * \left(\frac{1}{distance_{toroad}(m)} \right) \right) \quad (3)$$

Hard ground variable

Ground attenuation impacts sound propagation outdoors. This effect is a function of sound absorption from porous ground over the sound propagation path (ISO 1996). To control for this effect, a proportion hard ground variable was included in all regressions. This variable was estimated by calculating the proportion of impervious surface of each area of influence used for the LDI index (100 m, 500 m, and 1500 m). Impervious surface estimates for each LU/

Table 3 Non-renewable areal empower intensities for LU/LC classes used to calculate the LDI index values Adapted from Reiss et al. (2010)

Land use	Non-renewable areal empower intensity (E15 sej ha ⁻¹ year ⁻¹)
Natural land/open water	0.00
Pine plantation	0.51
Low intensity open space/recreational	0.52
Unimproved pasture (with livestock)	0.53
Low intensity pasture (with livestock)	3.38
High intensity pasture (with livestock)	5.93
Medium intensity open space/recreational	6.06
Citrus	7.76
General agriculture	15.10
Row crops	20.30
High Intensity agriculture (dairy farm)	50.40
Recreational/open space (high-intensity)	123.00
Single family residential (low-density)	197.50
Transportation—2 lane highway	308.00
Single family residential (med-density)	658.33
Single family residential (high-density)	921.67
Institutional	4042.20
Multi-family residential (low density)	4213.33
Transportation 4 lane highway—high intensity	5020.00
Low intensity commercial (comm strip)	5175.40
Industrial	5210.60
High intensity commercial (mall)	8372.40
Multi-family residential (high rise)	12771.67
Central business district (avg 2 stories)	16150.30

LC (SJRWMD 2012) were used to calculate area weighted approximations for the proportion of hard ground surrounding each recording site.

Seasonal Variables

Soundscapes have seasonal patterns (Schafer 1977; Truax 2001; Krause et al. 2011; Gage and Axel 2014). Temporal trends can affect component sounds such as the seasonality of dawn chorus characteristics (Stacier et al. 1996; Brunni et al. 2014) or the thermo-regulated sound power of cicada calls (Fonseca and Revez 2002; Suer and Sanborn 2003). Variables were included to

capture the temporal variation present in the soundscapes. The season indicator included four categories defined by the month the site was sampled during. Winter sites were defined as sites sampled in December, January, and February, spring as March through May, summer as June through August and fall as September through November.

Climate variables

Temperature and humidity are known to affect the attenuation of sound as it propagates outdoors (ISO 1993). Temperature and relative humidity were included in all regressions to control for this effect. The temperature variable was the observed temperature in Celsius rounded to the nearest integer at the beginning of the sample. Relative humidity was rounded to two decimal places normalized between 0 and 1.

Statistical analysis

The relations between the landscape and the soundscape variables were described with multiple ordinary least squares (OLS) linear regressions with robust standard errors using Stata SE13 software (StataCorp 2013). This analysis was applied to both divisions of the frequency spectrums (total spectrum and 1 kHz band analysis).

Variable selection and total spectrum analysis

The model selection procedure assessed the six versions of the LDI (3 scales, flat and distance weighted) and the potential inclusion of the supplemental landscape variables (road proximity and wetland indicator). The hard ground, seasonal and climate variables were included in all model variations. The acoustic metrics describing the total spectrum were used to select the explanatory variables. The regressions between each of the six LDI variables and each acoustic metric were compared and the best fit was selected using the Akaike's Information Criterion (AIC). Generally, lower AIC values represent better models. Each of the supplemental landscape variables was added to each model to determine if they increased the explanatory power using Partial R-Squared and AIC. If the addition of each variable

had a positive Partial R-Squared and decreased the model AIC, the variable was included.

1 kHz band analysis

The 1 kHz band analysis described the relation between the average PSD and the LDI index and covariates in separate regression analysis for each band. Significant relations between LDI and average PSD were compared across bands with a Wald test using Stata SE13 software (Stata Corp, College Station, Texas).

Data availability

The datasets analyzed for this study are available in the Mendeley repository at the following link: <https://data.mendeley.com/datasets/wpb5fx6x6g/1>.

Results

Variable selection

Results from the total spectrum analysis show that the flat weighted LDI_{100} was the best performing LDI score for the inband power predictions and the flat weighted LDI_{500} was the best performing LDI score for the delta power, aggregate entropy, and center frequency measures. The road proximity and wetland indicator variables were not selected for any of the models. The regression results for all of the explanatory variable combinations are provided in Online Resource 1.

Total spectrum analysis

The results for the regressions with the preferred specifications that describe the relation between LDI and the soundscape are provided in Table 4. The inband power regression model results indicate that a one-unit increase in LDI_{100} for a site was associated with a 0.32 decibel (dB) increase in inband power. This relation, scaled to the sample standard deviation of the LDI_{100} scores (Table 5), provides a reference for the impact of change. The model predicts that a one standard deviation change in a site's LDI_{100} score (15.27) results in an increase in inband power of 4.89 dB (50% of inband power's standard deviation).

In all four models, the LDI variables demonstrated a statistically significant ($p < 0.01$) relation with the acoustic metrics. LDI had a positive relation with inband power and a negative relation with delta power, aggregate entropy, and center frequency.

1 kHz frequency band analysis

The frequency band regression analysis described the average PSD and the relation between average PSD and other covariates in each band. The constant terms in the frequency band regression results (Table 6) reflect the pattern of average PSD across the frequency spectrum independent of controls included in the models. The average PSD was highest in the first band and generally decreased as frequency increased. The LDI_{100} coefficients in the models (Table 6) describe the relation between LDI and the average PSD of each frequency band. This relation was significantly ($p < 0.01$) different from zero in the first three frequency bands. The 3–4 kHz band was marginally significant ($p < 0.1$). The maximum positive relation occurred in the 1–2 kHz band and decreased in subsequent bands.

The Wald test indicated that the relation between LDI_{100} and average PSD was similar for frequency bands 1 and 2 and frequency bands 3 and 4 (Table 7). The first and second frequency bands and third and fourth bands were not significantly different ($p > 0.1$). The LDI_{100} coefficients between bands 3 and 1 were marginally different ($p < 0.1$). All other combinations between the first four frequency bands were significantly different ($p < 0.05$).

The LDI_{100} and hard ground variables were strongly and positively correlated (correlation coefficient = 0.856). LDI_{100} and hard ground had a positive relation with average PSD when either was a significant contributor to the model. Generally, LDI had a significant influence on average PSD below 3 kHz and hard ground had a significant influence above 4 kHz.

Discussion

The analysis reveals that the LDI index had a strong and statistically significant effect on soundscape characteristics even after controlling for important factors such as climate, season, and attenuation due to hard ground. There is a limited amount of research that

Table 4 Regression results for total frequency spectrum models

	Inband pwr	Delta pwr	Entropy	Cntr Freq
LDI ₁₀₀	0.32*** (0.08)			
LDI ₅₀₀		− 0.49*** (0.12)	− 0.06*** (0.01)	− 73.61*** (19.90)
% Hard ground	0.06* (0.03)	− 0.02 (0.06)	0.01 (0.00)	8.35* (4.64)
Temp	− 0.21 (0.18)	0.31 (0.25)	0.02 (0.03)	22.15 (46.38)
Rel humid	− 1.59 (4.78)	1.14 (6.31)	0.57 (0.56)	1,385.84 (913.59)
Winter				
Spring	− 0.67 (3.04)	− 5.13 (4.29)	− 0.72 (0.45)	90.40 (530.50)
Summer	0.05 (6.23)	− 3.05 (4.58)	− 0.29 (0.43)	− 736.24 (770.52)
Fall	− 3.25 (2.39)	− 2.51 (3.05)	0.04 (0.31)	− 110.93 (402.14)
Constant	108.96*** (5.13)	− 43.03*** (8.09)	3.63*** (0.75)	1076.01 (1316.46)
R-Sqrd	0.66	0.49	0.43	0.35

Asterisks indicate statistical significance: *p < 0.1, ***p < 0.01. Parentheses indicate the heteroskedastic robust errors

Table 5 Summary statistics for LDI and soundscape metrics

Variable	Mean	Std dev	Minimum	Maximum
LDI ₁₀₀	24.51	15.27	00.00	41.70
LDI ₅₀₀	26.71	13.58	00.00	41.00
LDI ₁₅₀₀	26.18	11.59	00.10	38.50
Inbnd pwr	113.07	09.69	89.60	136.20
Avg PSD	117.21	09.65	93.50	140.10
Delta pwr	52.86	09.97	− 73.10	− 30.90
Entropy	03.00	00.86	00.96	05.33
Cntr freq	962.69	1581.55	187.50	7125.00

establishes methods that describe landscape configuration as it is related to soundscapes (Fuller et al. 2015). Joo et al. (2011) used over ten variables to capture site variability with the surrounding landscape. Alternatively, the LDI index considers the presence and footprint of all LU/LC classes using one continuous variable versus a multiple variable LU/LC indicator. Additionally, LDI weights the land use configuration by the areal intensity of resource

consumption, which could be interpreted as an indicator of human sound production in this context.

The LDI index explained a substantial amount of variance in the sound metrics describing the total frequency spectrum. This was bolstered by the result that the supplemental landscape variables were not selected for inclusion in the models. Further, when the supplemental landscape variables were included in the models, the qualitative relation between LDI and the acoustic metrics and LDI’s statistical significance were robust.

The trends between LDI and the soundscape measures reflect the generally accepted concept that human generated sounds are loud, continuous, and occupy low frequencies. Specifically, the results confirmed the expectation of Pijanowski et al. (2011a) that soundscape complexity (as measured by aggregate entropy) decreased as human influence increased (as measured by the LDI index). The LDI index provides a promising framework for predicting the effect of anthropogenic development on soundscapes from easily available LU/LC data.

To the best of our knowledge, our study is the first to compare the impact of different sized contributing areas on ambient soundscape characteristics. Inband

Table 6 OLS regression results for 1 kHz band average PSD

	Band 1	Band 2	Band 3	Band 4	Band 5	Band 6	Band 7	Band 8	Band 9	Band 10
LDI ₁₀₀	0.45*** (0.09)	0.49*** (0.08)	0.25*** (0.08)	0.18* (0.10)	0.12 (0.09)	- 0.08 (0.08)	- 0.10 (0.08)	- 0.11 (0.10)	- 0.00 (0.15)	- 0.00 (0.14)
% Hard ground	0.05 (0.03)	0.03 (0.03)	0.09*** (0.04)	0.08* (0.04)	0.10*** (0.05)	0.16*** (0.05)	0.15*** (0.05)	0.13*** (0.06)	0.14*** (0.06)	0.15*** (0.06)
Temp	- 0.22 (0.18)	- 0.24 (0.22)	- 0.02 (0.22)	0.11 (0.24)	- 0.10 (0.28)	0.02 (0.29)	0.05 (0.27)	0.10 (0.28)	0.11 (0.27)	0.00 (0.26)
Rel humid	- 6.01 (4.97)	- 2.77 (4.59)	- 2.30 (4.55)	0.05 (4.52)	3.13 (5.04)	1.39 (5.52)	1.75 (5.22)	3.39 (5.93)	1.00 (5.79)	- 0.70 (4.83)
Winter										
Spring	1.31 (3.22)	- 0.49 (3.28)	- 0.10 (3.13)	- 0.92 (3.31)	3.47 (3.70)	2.01 (3.72)	0.61 (3.38)	1.40 (3.53)	1.45 (3.57)	2.89 (3.43)
Summer	- 7.14** (3.51)	- 5.654081 (3.78)	- 11.14*** (3.92)	- 14.61*** (4.53)	- 9.29 (5.58)	- 7.69 (5.25)	- 5.58 (4.56)	- 6.68 (4.53)	- 6.24 (4.56)	2.14 (5.07)
Fall	- 3.32 (2.37)	- 3.48 (2.73)	- 5.63* (2.90)	- 5.26 (3.15)	- 1.36 (3.62)	- 1.33 (3.57)	- 0.78 (3.36)	- 0.30 (3.35)	0.39 (3.50)	2.03 (3.46)
Constant	125.86*** (5.23)	113.71*** (5.39)	109.36*** (5.49)	104.18*** (5.58)	100.04*** (6.24)	100.51*** (6.74)	99.76*** (5.72)	97.36*** (6.17)	91.16*** (5.95)	88.55*** (5.53)
R-Sqrd	0.72	0.72	0.62	0.51	0.43	0.36	0.29	0.20	0.30	0.36
	Band 11	Band 12	Band 13	Band 14	Band 15	Band 16	Band 17	Band 18	Band 19	Band 20
LDI ₁₀₀	- 0.06 (0.14)	- 0.10 (0.14)	- 0.09 (0.15)	- 0.08 (0.15)	- 0.05 (0.14)	- 0.01 (0.13)	- 0.06 (0.13)	- 0.04 (0.13)	- 0.08 (0.13)	- 0.02 (0.12)
% Hard ground	0.17*** (0.06)	0.16*** (0.06)	0.13*** (0.06)	0.11* (0.06)	0.12*** (0.06)	0.10* (0.05)	0.09* (0.05)	0.07 (0.05)	0.08 (0.05)	0.05 (0.05)
Temp	0.15 (0.28)	0.07 (0.29)	0.05 (0.30)	0.06 (0.31)	0.06 (0.30)	0.03 (0.28)	- 0.04 (0.28)	0.00 (0.28)	0.01 (0.28)	0.04 (0.27)
Rel humid	- 1.57 (5.01)	- 0.74 (5.56)	- 0.10 (5.94)	- 1.38 (5.94)	0.28 (6.14)	0.53 (5.58)	- 0.08 (5.92)	1.69 (5.44)	- 0.35 (5.91)	- 0.37 (5.82)
Winter										
Spring	- 0.29 (3.73)	- 0.76 (3.85)	- 0.88 (4.04)	- 1.32 (4.09)	0.21 (3.98)	0.09 (3.90)	- 1.56 (4.06)	- 2.07 (3.87)	- 1.63 (3.92)	- 2.73 (3.69)
Summer	3.47 (5.18)	4.66 (4.62)	2.28 (6.69)	3.45 (6.92)	3.99 (5.90)	- 0.85 (5.97)	3.73 (6.25)	2.21 (6.01)	1.16 (6.21)	- 0.81 (6.50)

Table 6 continued

	Band 11	Band 12	Band 13	Band 14	Band 15	Band 16	Band 17	Band 18	Band 19	Band 20
Fall	0.64 (3.53)	0.95 (3.66)	1.09 (3.86)	0.42 (3.83)	0.80 (3.77)	0.65 (3.83)	- 1.08 (4.14)	- 2.37 (3.82)	- 4.19 (3.86)	- 5.70 (3.84)
Constant	85.46*** (6.17)	84.79*** (6.18)	84.22*** (6.44)	85.05*** (6.74)	81.35*** (6.47)	80.62*** (6.23)	83.20*** (6.26)	80.34*** (5.82)	82.73*** (6.17)	81.07*** (6.25)
R-Sqrd	0.33	0.28	0.21	0.14	0.18	0.19	0.15	0.14	0.12	0.14

Asterisks indicate statistical significance: *p < 0.1, **p < 0.05, ***p < 0.01. Parentheses indicate the heteroskedastic robust errors. Frequency band labels represent the highest extent of the frequency band in kHz. For example, Band 2 ranged from 1 to 2 kHz

Table 7 p values for results of Wald tests comparing the LDI coefficients in the 1 kHz band regression analysis

	Band 2	Band 3	Band 4
Band 1	0.718	0.060	0.024
Band 2		0.020	0.008
Band 3			0.585

power was most closely related to the surrounding area within a 100-m radius. The metrics that considered the distribution of sound across frequency (delta power, aggregate entropy, and center frequency) were more strongly correlated with LDI₅₀₀. This suggests that overall sound intensity was most influenced by sound sources within 100 m of the microphone but sound sources up to 500 m away were more important to how sound varied across the frequency spectrum.

The patterns observed between acoustic and landscape metrics in this study should be interpreted as resulting from the combined effect of differences in sound sources and attenuation from the landscape. In the 1 kHz band analysis, LDI₁₀₀ and hard ground had a positive relation with average PSD when either was a significant contributor to the model. Generally, LDI₁₀₀ had stronger significance in the models below 3 kHz and hard ground was a stronger influence above 4 kHz. These results highlight hard ground as an important control variable in the analysis.

The 1 kHz band analysis also described the relative PSD within each band independent of LDI₁₀₀ and hard ground (as indicated by the constants in the models). The coefficients for these variables indicated that the lower frequency bands had higher PSD than the higher frequencies, independent of LDI. This pattern could be the result of attenuation since higher frequencies are generally more susceptible to attenuation due to atmospheric absorption (ISO 1993), propagation through foliage (ISO 1996), and scattering due to industrial installations (ISO 1996).

The average PSD of the 20–3,000 Hz soundscape region had a statically significant relation with LDI₁₀₀, an indicator of human influence (Table 6). Further, there was evidence of a moderate relation between average PSD and LDI₁₀₀ in the 3–4 kHz band as well. This does not support the commonly used 2 kHz division between the anthropogenic and biologic sourced portions of the soundscape. The greatest

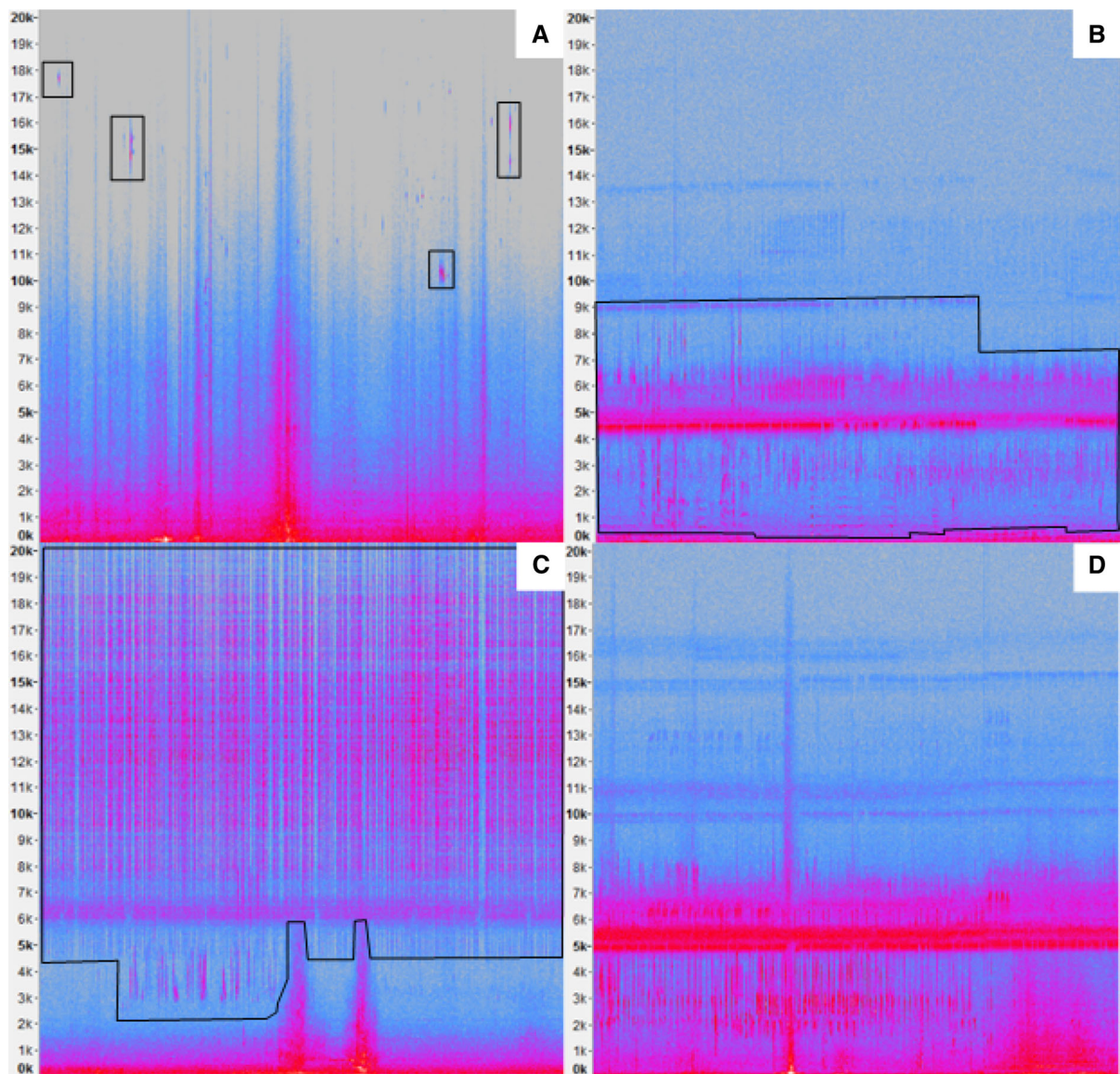


Fig. 2 Examples of spectrograms from study sample covering ten minutes from four different sites. **a** The black outlines highlight vehicular brake sound, **b** the black outlines highlight sounds sourced from insects, birds, and amphibians, **c** the black

outlines highlight sounds sourced from birds in lower frequencies and broad band insect sound up to 20 kHz, and **d** a spectrogram showing acoustic calls from wildlife overlapping with sound from a truck and boat

effect (as described by the LDI_{100} coefficients in the regression analysis) was within the 20–2000 Hz range and this effect was generally significantly larger than for the 2000–4000 Hz range. However, the LDI_{100} coefficients for frequency bands 1 and 3 were only marginally significantly different ($p < 0.1$). Further, Fig. 2a, c and d show examples of anthropogenic sounds present at frequencies higher than 2 kHz within the study sample. Our results suggest that

although ambient soundscapes below 2 kHz are the most influenced by surrounding land use development, higher frequency ranges are also be impacted by human influence.

The regions of the soundscape associated with LDI_{100} indicate regions with sound resulting from human footprint and therefore, areas of potential acoustic disturbance for animals. Anthropogenic sound can mask important acoustic cues for animals

that it overlaps in the frequency realm, such as calls or predator footfalls (Brumm and Slabbekoorn 2005; Dooling and Popper 2007). Animals use a broad range of frequencies for communication with a high concentration of acoustic activity between 1 and 9 kHz (Marler 1955; Napoletano 2004). Acoustic signals by amphibians, birds, and insects captured in this study's samples occupied frequencies from 300 to 20,000 Hz but were most concentrated from 4 to 8 kHz (see Fig. 2b, c for examples). The frequency overlap of these sounds with human sound suggests that a conflict exists that could inhibit the transmission of ecologically valuable information.

This study presented evidence of a strong relation between ambient soundscapes and landscape development intensity; however, the sample collection was limited. The study captured background sound but a more extensive sample collection could reveal additional details about specific sound events like rush hour traffic. Additionally, using automatic recording unites to expand the data collection at each site to encompass diurnal and seasonal temporal variation may provide additional findings.

Conclusions

Research within soundscape ecology and its umbrella discipline of ecoacoustics is trying to determine the extent and intensity of anthropogenic noise disturbance on wildlife. Tools that accurately predict soundscape characteristics from remote sensing data like the LDI index have high value in this pursuit. The results from this study have shown that ambient soundscape characteristics can be predicted by the landscape features surrounding a point. The applications of this tool are vast, ranging from site specific impact assessments to noise mitigation for pre-existing disturbance across vast areas. With increasing open access to remote sensing data, the ability to duplicate this study and characterize soundscapes on large scales is a reality. The LDI index could help identify locations where mitigation measures have the highest potential to resolve conflicts between anthropogenic noise and wildlife.

Acknowledgements The authors thank Gary Siebein, Peter Frederick, Barron Henderson, Erica Hernandez, and the anonymous reviewers for their helpful comments and

suggestions. This research project received support from the HT Odum Center for Wetlands.

References

- Barber JR, Crooks KR, Fristrup KM (2010) The costs of chronic noise exposure for terrestrial organisms. *Trends Ecol Evol* 25(3):180–189
- Bayne EM, Habib L, Boutin S (2008) Impacts of chronic anthropogenic noise from energy-sector activity on abundance of songbirds in the boreal forest. *Conserv Biol* 22(5):1186–1193
- Bee M, Swanson EM (2007) Auditory masking of anuran advertisement calls by road traffic noise. *Anim Behav* 74(6):1765–1776
- Bioacoustics Research Program (2011) Raven Pro: Interactive Sound Analysis Software (Version 14) [Computer software]. The Cornell Lab of Ornithology, Ithaca
- Bouchard M (2009) Wetland resources of Eastern South Dakota; drainage patterns, assessment techniques, and predicting future risks. South Dakota State University, South Dakota
- Brown MT, Vivas MB (2005) Landscape development intensity index. *Environ Monit Assess* 101(1–3):289–309
- Brumm H, Slabbekoorn H (2005) Acoustic communication in noise. *Adv Stud Behav* 35:151–209
- Brunni A, Daniel JM, Foote JR (2014) Dawn chorus start time variation in a temperate bird community: relationships with seasonality, weather, and ambient light. *J Ornithol* 155(4):877–890
- Can A, Leclercq L, Lelong J, Botteldooren D (2010) Traffic noise spectrum analysis: dynamic modeling vs experimental observations. *Appl Acoust* 71(8):764–770
- Charif RA, Waack AM, Strickman LM (2010) Raven pro 1.4 user's manual. The Cornell Lab of Ornithology, Ithaca
- Chen TS, Lin HJ (2011) Application of a landscape development intensity index for assessing wetlands in Taiwan. *Wetlands* 31(4):745–756
- Depraetere M, Pavoine S, Jiguet F, Gasc A, Duvaill S, Sueur J (2012) Monitoring animal diversity using acoustic indices: implementation in a temperate woodland. *Ecol Ind* 13(1):46–54
- Dooling RJ, Popper A (2007) The effects of highway noise on birds. Environmental BioAcoustics LLC, Rockville
- ESRI (2014) ArcGIS desktop: release 10.3. Environmental Systems Research Institute, Redlands
- Farina A, Pieretti N (2014) Sonic environment and vegetation structure: a methodological approach for a soundscape analysis of a Mediterranean maqui. *Ecol Inform* 21:120–132
- FGDL Metadata Explorer (2015) University of Florida GeoPlan Center, Gainesville
- Fonseca PJ, Revez MA (2002) Temperature dependence of cicada songs (Homoptera, Cicadoidea). *J Comp Physiol* 187:971–976
- Fore LS (2004) Development and testing of biomonitoring tools for macroinvertebrates in Florida streams. Statistical Design, Seattle, Washington. A report for the Florida Department of Environmental Protection, Tallahassee, p 62

- Fore LS (2005) Assessing the biological condition of Florida lakes: development of the lake vegetation index (LDV). Statistical Design, Seattle, Washington. A report for the Florida Department of Environmental Protection, Tallahassee, p 29 & Appendixes
- Forman RTT, Sperling D, Bissonette JA, Clevenger AP, Cutshall CD, Dale VH, Fahrig L, France R, Goldman CR, Heanue K, Jones JA, Swanson FJ, Turrentine T, Winter TC (2003) Road ecology: science and solutions. Island Press, Washington
- Fuller S, Axel AC, Tucker D, Gage SH (2015) Connecting soundscape to landscape: which acoustic index best describes landscape configuration? *Ecol Ind* 58:207–215
- Gage SH, Axel AC (2014) Visualization of temporal change in soundscape power of a Michigan lake habitat over a 4-year period. *Ecol Inform* 21:100–109
- Habib L, Bayne EM, Boutin S (2007) Chronic industrial noise affects pairing success and age structure of ovenbirds *Seiurus aurocapilla*. *J Appl Ecol* 44(1):176–184
- ISO (1993) Acoustics—Attenuation of sound during propagation outdoors—part 1: calculation of the absorption of sound by the atmosphere (Standard No. 9613-1). International Organization for Standardization, Geneva
- ISO (1996) Acoustics—Attenuation of sound during propagation outdoors—part 2: general method of calculation (Standard No. 9613-2). International Organization for Standardization, Geneva
- Joo W (2009) Environmental acoustics as an ecological variable to understand the dynamics of ecosystems. Dissertation. Michigan State University
- Joo W, Gage SH, Kasten EP (2011) Analysis and interpretation of variability in soundscapes along an urban–rural gradient. *Landscape Urban Plan* 103(3–4):259–276
- Kasten EP, Gage SH, Fox J, Joo W (2012) The remote environmental assessment laboratory’s acoustic library: an archive for studying soundscape ecology. *Ecol Inform* 12:50–67
- Kociolek AV, Clevenger AP, St Clair CC, Proppe DS (2011) Effects of road networks on bird populations. *Conserv Biol* 25(2):241–249
- Krause BL, Gage SH, Joo W (2011) Measuring and interpreting the temporal variability in the soundscape at four places in Sequoia National Park. *Landscape Ecol* 26(9):1247–1256
- Laiolo P (2010) The emerging significance of bioacoustics in animal species conservation. *Biol Conserv* 143(7):1635–1645
- Lane CR, Brown MT (2007) Diatoms as indicators of wetland condition. *Ecol Ind* 7:521–540
- Mack JJ (2006) Landscape as a predictor of wetland condition: an evaluation of the Landscape Development Index (LDI) with a large reference wetland dataset from Ohio. *Environ Monit Assess* 120:221–241
- Makarewicz R, Sato Y (1996) Representative spectrum of road traffic noise. *J Acoust Soc Jpn* 5:249–254
- Margritter SC, Bruland GL, Kudray GM, Lepczyk CA (2014) Using indicators of land-use development intensity to assess the condition of coastal wetlands in Hawaii. *Landscape Ecol* 29(3):517–528
- Marler P (1955) Characteristics of some animal calls. *Nature* 176:6–8
- Matsinos YG, Mazaris AD, Papadimitriou KD, Mniestris A, Hatzigiannidis G, Maioglou D, Pantis JD (2008) Spatiotemporal variability in human and natural sounds in a rural landscape. *Landscape Ecol* 23:945–959
- Mazaris AD, Kallimanis AS, Chatzigiannidis G, Papadimitriou K, Pantis JD (2009) Spatiotemporal analysis of an acoustic environment: interactions between landscape features and sounds. *Landscape Ecol* 24(6):817–831
- Mennitt DJ, Fristrup KM (2016) Influential factors and spatiotemporal patterns of environmental sound levels in the contiguous United States. *Noise Control Eng* 64(3):342–353
- Mitsch WJ, Gosselink JG (2007) Wetlands, 4th edn. Wiley, Hoboken
- Napoletano BM (2004) Measurement, quantification and interpretation of acoustic signals within an ecological context. Dissertation. Michigan State University
- Nega T, Yaffe N, Stewart N, Fu WH (2013) The impact of road traffic noise on urban protected areas: a landscape modeling approach. *Trans Res Part D* 23:98–104
- Odum HT (1996) Environmental accounting: emergy and environmental decision making. Wiley, New York
- Oliver L, Lehrter J, Fisher W (2011) Relating landscape development intensity to coral reef condition in the watersheds of St. Croix, US Virgin Islands. *Mar Ecol Prog Ser* 427:293–302
- Pieretti N, Farina A (2013) Application of a recently introduced index for acoustic complexity to an avian soundscape with traffic noise. *J Acoust Soc Am* 134(1):891–900
- Pijanowski BC, Farina A, Gage SH, Dumyahn SL, Krause BL (2011a) What is soundscape ecology? An introduction and overview of an emerging new science. *Landscape Ecol* 26:1213–1232
- Pijanowski BC, Villanueva-Rivera LJ, Dumyahn SL, Farina A, Krause BL, Napoletano BM, Pieretti N (2011b) Soundscape ecology: the science of sound in the landscape. *Bioscience* 61(3):203–216
- Qi J, Gage SH, Joo W, Napoletano BM, Biswas S (2008) Soundscape characteristics of an environment: a new ecological indicator of ecosystem health. Wetland and water resource modeling and assessment: a watershed perspective. CRC Press, Taylor and Francis Group, pp 201–214
- Reiss KC, Brown MT, Lane CR (2010) Characteristic community structure of Florida’s subtropical wetlands: the Florida wetland condition index for depressional marshes, depressional forested, and flowing water forested wetlands. *Wetl Ecol Manag* 18(5):543–556
- Schafer MR (1977) The tuning of the world. Knopf, New York
- SJRWMD (2012) St. Johns River water supply impact study (Technical Publication SJ2012-1). St. Johns River Water Management District, Palatka
- Slabbekoorn H, Ripmeester E (2008) Birdsong and anthropogenic noise: implications and applications for conservation. *Mol Ecol* 17(1):72–83
- Stacier CA, Spector DA, Horn AG (1996) The dawn chorus and other diel patterns in acoustic signaling. Ecology and evolution of acoustic communication in birds. Cornell University Press, pp 426–453
- StataCorp (2013) Stata statistical software: release 13. StataCorp LP, College Station

- Suer J, Sanborn AF (2003) Ambient temperature and sound power of cicada calling songs (Hemiptera: cicadidae: Tibicini). *Physiol Entomol* 28:340–343
- Sueur J, Farina A, Gasc A, Pieretti N, Pavoine S (2014) Acoustic indices for biodiversity assessment and landscape investigation. *Acta Acustica United with Acustica* 100(4):772–781
- Truax B (2001) *Acoustic communication*, 2nd edn. Ablex, Westport
- Tucker D, Gage SH, Williamson I, Fuller S (2014) Linking ecological condition and the soundscape in fragmented Australian forests. *Landsc Ecol* 29(4):745–758
- Ware HE, McClure CJW, Carlisle JD, Barber JR (2015) A phantom road experiment reveals traffic noise is an invisible source of habitat degradation. *Proc Natl Acad Sci USA* 112(39):12105–12109
- Warren PS, Katti M, Ermann M, Brazel A (2006) Urban bioacoustics: it's not just noise. *Anim Behav* 71(3):491–502

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.