# Supplementary Online Material for Soundscape Ecology: The Science of Sound in the Landscape

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This supplement to the Pijanowski et al. (2011) *BioScience* article “Soundscape Ecology: The Science of Sound in the Landscape” describes the details of field and analysis protocols used in the four case studies.

**Krause case study.** The Krause recording archive contains 2692 recordings spanning over 40 years. Many are ambient dawn or dusk chorus recordings in remote areas of the world. Recordings are terrestrial and many are also marine (of marine mammals).

*Madagascar Dawn Chorus Recording.* Krause recording #1702. Recording made in southeastern Madagascar in the Andohahaela Nature Reserve. Habitat is lowland tropical forest located at 24°34’07.85”S/46°57’44.53”E (147 meters above sea level). Sound equipment used was a Sony TCD-D10 Portable DAT recorder and a Sennheiser MKH-30/40 MS combo microphone. Many different birds (most endemic to Madagascar) are present in this recording including Tylas vanga (also known as the blue vanga), Pollen’s vanga, white-headed vanga, red-tailed vanga-shrike, white-headed vanga, “white eyes,” cuckoo-shrike, Asian paradise flycatcher, common sunbird asity, Madagascar brush warbler, black bulbul, crested drongo, Ward’s flycatcher, and the Nelicourvi weaver.

*Central African Republic bai recording.* Krause recording #2599. Recording made at the Dzanga-Tsanga Rainforest (Sarno) in the Central African Republic on March 16, 1995. Microphone set near a bai with coordinates 3°21’55.50”N/16°01’28.41”E (497 meters above sea level). Time of recording was 00:30 local time. Several birds (unidentified), insects (unidentified) and frogs (unidentified) chorus during the bellowing and trumpeting of forest elephants (*Loxodonta cyclotis*). Recorded with an X-Y microphone pair and a Sony D7 DAT logger.

*Zimbabwe Predawn Recording.* Krause recording #1334. Habitat of this recording is a low veldt kopje riparian forest located at southeastern Zimbabwe (20°58’04.65”S/32°19”14.58”E and 176 meters above sea level). Sound equipment used was a Sony TCD-D7 Portable DAT recorder and a Sennheiser MKH-30/40 MS (Mid-Side) combo microphone. Recording was taken on September 30, 1996 at 04:22 local time. Birds and mammals occurring in the recording (in sequence that they appear) are barred owlet; scops owlet, barred owlet natal francolin, barred owlet/freckled nightjar, cape turtle dove, natal francolin/freckled nightjar/ground hornbill, freckled nightjar, Egyptian goose, freckled nightjar, spotted wood dove, baboons echoing off kopje, long baboon echoes, blue-eyed bulbul, bearded robin, fork-tailed drongo/terrestrial bulbul/yellow-billed bulbul, bleating warbler, hoopoe, buff-back shrike, bulbul shrike, african goshawk, black-headed oriole, crowned hornbill, trumpeter hornbill/black-headed oriole, trumpeter hornbill, striped kingfisher, chinspot battis, red rabbit, and the bearded woodpecker.

*Stridulating Ants Recording.* Krause recording #1804. Recorded with a Sony ECM-55 lavaliere microphone and a Sony D10 DAT recorder. Ants located in the New Mexico, USA desert (31°27’38.62”N/108°51’35.33”W) (1559 m.a.s.l.). Recorded on April 25, 1992 at 09:52 local time.

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*Algonquin wolves.* Krause recording #2898. Recorded with a Sony ECM-55 lavaliere microphone and a Sound Devices 722 recorder. Habitat is secondary boreal forest located in the Haliburton Forest bordering the Algonquin Park in Ontario, Canada. Wolves were vocalizing in the park. Recording was made on March 24, 2007 (temperature was –4 degrees Celsius). Located at 45°13'25.41"N/78°35'25.31"W (405 meters above sea level). Also present in the recording are barred owl, bushtit, and a raven.

**Tippecanoe "Rhythms of Nature" Study.** We conducted a year-long study to measure near continuous sounds in a variety of landscapes in northwestern Tippecanoe County, Indiana. We deployed Wildlife Acoustics (WA) Songmeters in seven different locations that varied in land use/cover characteristics and proximity to roads. Three recorders were deployed in forested habitats. One located in the Ross Biological Field Station; trees at this site were 50-80 years old and consisted of mature hickory and oak. The second forested site was in Purdue's Martell Forest with 20- to 30-year-old oak and hickory trees. The third forest site, McCormick Woods, was a 20-ha forest stand of 15 to 25-year-old oak and maples and was surrounded by apartment complexes and a golf course and is thus impacted by urban use. One recorder was placed on the edge of a 10-ha wetland in a 10- to 15-year-old maple stand (Wildlife Area). Three agricultural sites were also monitored. We placed one recorder in the Purdue Forestry and Natural Resources Farm (hereafter FNR Farm), which was a recently abandoned orchard, composed of apple trees and open grassland. We also placed a recorder alongside the edge of a cornfield (also called site Ag1 online), and another alongside a soybean field (called Ag2 online). Both recorders were placed along the edge of the field close to rural roads to ensure access and safety to the recorders.

The acoustic recorders used a stereo omni-directional microphone array attached to a digital data logger. We programmed the recorders for 15 minutes of active recording at the start of every hour (yielding 24 recordings per site per day). Songmeters were placed near the wetland and in forested sites in early April 2008, and in the agricultural fields in early May 2008. All seven continued recording until November 25, 2008, yielding 34,228 total 15-minute recordings representing over 5 TB of data. To effectively minimize confusion introduced by wind and rainfall, we selected recordings without precipitation during the recording period and with wind speeds that were less than 20 km/hr. The Wildlife Acoustics recorders used in this study were equipped with built-in stereo omni-directional microphones each of which have a sensitivity of –35 +/− 4dB, an acoustic frequency response of 20 Hz to 20Khz and a signal to noise ratio greater than 62dB. Microphones were calibrated by Wildlife Acoustics, Inc. prior to placing them in the field.

Hourly weather data were obtained from iclimate.org Web site and precipitation totals (> 0.0 mm) and maximum wind speeds (> 20 kph) were used to select out 15-minute recordings that could be impacted by rain and wind. In several instances, the recorder data disk filled in the field prior to a visit to swap out cards and the microphone stopped making recordings. In such occurrences, data from the other sites were excluded from analyses to ensure standardization between sites.

We decomposed the acoustic frequencies into spectral bands of 1 kHz widths and threshold the biological sounds above a specified base amplitude (viz. –50 dBFS), and calculated Shannon's diversity index to create acoustic frequency entropy values using:

$$H_{t,l} = -\sum_{i=1}^{N} p_i \ln p_i \tag{1}$$

where

$$H^{*}_{t,l} = g(dB^{'}_{i}, r, a_l, a_u, b, f_s) \tag{2}$$

such that $H_{t,l}$ is the diversity of acoustic frequencies at time $t$ and location $l$, $p_i$ is the proportion of the $i^{th}$ spectral band where sound is present, and $N$ is the number of spectral bands in the discretized spectrogram. To compare the values of $H_{t,l}$ at different locations and over different time periods, multiple recording measurements must be standardized; this is accomplished via Eq. 2. Here, the transformed value $H^{*}_{t,l}$ is expressed as a function of $dB^{'}_{i}$, the minimum $dB$ threshold used to assess whether sound is present in band $i$, the length of the recording $r$, the upper, $a_u$ and lower $a_l$ frequencies that are analyzed, the bit depth $b$, and the sampling frequency of the recording device $f_s$. For our study, we used N = 10, $dB^{'}_{i}$, = −50 dBFS, r = 900 seconds, $a_l$ = 20 Hz, $a_u$ = 10 kHz, b = 16, $f_s$ = 44.1 kHz.

We also calculated frequency band evenness using the Gini coefficient (figure S1). The Gini coefficient has been used by economists and ecologists to quantify the measure of dispersion across classes. Briefly, Gini coefficient is calculated by summing the rank proportional values and then plotting the rank cumulative values. The area under this curve (called the Lorenz curve) is calculated and then compared to the remaining area created by the idealized area for the case where all groups have the same proportions (see figure S1). Gini is calculated as such:

$$G = B / (A+B) \tag{3}$$

Values range from 1.0 (all acoustic activity occurs in one frequency band) to 0.5 (there is an equal amount of activity in each frequency band across all ten frequency bands).

We experimented with the use of different $dB^{'}_{i}$ values ranging from –65 to –10 dBFS. We found –50 dBFS to adequately filter out "white noise." A small sample of representative files was examined for different N discretization values to determine how N impacts temporal cycles. We discretized spectrograms using N values ranging from 10 to 1000. Other potential metrics of acoustic frequency diversity

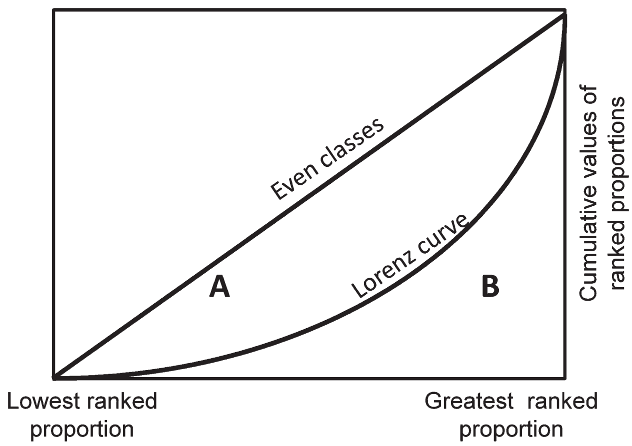


*Figure S1. Gini-coefficient calcultion is based on areas under two curves.*

were also examined, including: acoustic richness, average band activity and ratios between important biological acoustic frequency bands (e.g., the proportion of band 3 occurrence) relative to all other bands. In short, daily and seasonal temporal patterns of acoustic frequency diversity were not greatly affected by the selection of $dB_i^{'}$ , N or the use of alternative diversity metrics although other metrics provide slightly different information about the composition of sound in the landscape.

We used land use/cover maps derived from aerial imagery and Tiger line files for roads to quantify land use patterns around each recording site. Ross and Martell are surrounded by the least amount of roads (less than 5 km of roads within a 1 km buffer around the recorder). Two of the forest sites, Ross and Martell, are entirely forested within a close proximity to the recorder but become mixed further away. All sites contain some urban use within a kilometer of the recorder and experience occasional noise from airplane traffic from the Purdue airport.

A total of 4277 15-minute recordings were used per site to develop the monthly, hourly and habitat (i.e., land use) averages. Monitoring for these seven sites started May 13, 2008 and ended November 25, 2008.

**Sequoia National Park "Acoustic Niche Hypothesis" Study.** The following four sites were selected in conjunction with National Park Service personnel based on landscape heterogeneity and year-round accessibility: (1) Foothill Zone Riparian (Buckeye Flat, near Paradise Creek 2900 ft), N 36°31.185 & W 118° 45.692; (2) Foothill Zone Oak savanna (Sycamore Creek 2100 ft.); N 36° 29.470 & W 118°51.225; (3) Dry Savanna chaparral (Shepard's Saddle, 3000 ft.) N 36° 29.470 & W118° 51.142; and (4) Old Growth Site (Crescent Meadow) north end 7000 ft.) N 36 ° 33.364 & W 118°44.867.

We (BLK and SHG) used a protocol to optimize the sampling logistics while gathering a reasonable volume of data. We selected four seasonal recording periods based on typical weather patterns at approximate seasonal midpoints. Each of the four personnel on the project sampled one of the four sites simultaneously, resulting in simultaneous samples from each of the four sites at four times of day. We recorded daily samples of approximately 60 minutes of acoustic activity at dawn and dusk, which tend to be the most acoustically active periods, as well as at mid-day and two to three hours after sunset representing nighttime, totaling four samples from each location for each season.

We attempted to record in the same location during each of the four daily and seasonal samples. However, in the case of Buckeye Flats, we had to change the position of the recording location after the fall recordings, as we determined the initial site to be too near the stream.

Selection of equipment was based on a choice of professional quality equipment with low noise/high sensitivity/high transparency characteristics. While other types of systems might also be useful, we felt that the combination of the particular microphones, recorders, and preamplifiers we selected represented the best and most cost-effective for this type of bioacoustic site monitoring. The frequency response of the system ranged from 40 Hz to 20 kHz. The noise floor was calibrated to 12 dBA with a maximum level of 134 dBA.

Other considerations included flexibility of data based on the M-S (Mid-Side) microphone system format (Krause 2002). M-S systems consist of two separate microphone patterns. M stands for mid, and includes any pattern from cardioid to hypercardioid and which provides some directionality. S stands for side, and includes a figure-eight patterned microphone that splays out broad patterned lobes to each side in relationship to the front axis.

The data were first transferred from DAT (44.1 kHz sampling, 16 bit) M-S to matrixed stereo on both hard drive (.WAV format) and also backed up to stereo-encoded audio CDs. The data are stored in two separate locations for safety. After receiving the CDs, SHG's Lab copied the samples onto its terabyte server, and entered them into the database and digital library, for later publication on the Clickable Ecosystem project's Web site.

Randomly selected 11.5 second biophonic segments were chosen from each of the site recordings. By testing a number of different sample lengths, the period of time represented in each of the 11.5-second spectrogram samples (*x* axis) was determined to be within the temporal sample length range necessary to reveal the types of bioacoustic signal discrimination extant in a given biophony. The scale of the spectrogram on the *x* axis is germane to what is revealed in terms of discrimination. In the GW Instruments Superscope 5.1 software program used to produce the spectrogram examples in this report, 11.5 seconds across the horizontal width of the image display is the normal default setting. We have experimented with expanding and compressing time over the width of the display from 10 seconds to a maximum of 15 seconds and found that the default of 11.5 was most likely to reveal the discrimination necessary for preliminary evaluation. If the spectrogram across the width of the page length-wise was reduced in time to 10 seconds, the display began to fragment. Conversely, if compressed in time to 15 seconds the image began to appear too condensed. Thus, we picked a relevant interval of 11.5 seconds we felt to be appropriate for the proper visualization of the acoustic data. This visualization allowed us to examine the information in a manner that minimized errors incurred by compression or fragmentation of the signals. Specifically excluded for this preliminary examination were periods of time that featured noise (such as aircraft, automobiles, domestic animals, generators, gun-shots from the NPS practice firing range located within the park boundaries, etc.) occurring at intervals where these recordings took place.

A sample spectrogram typical of each of the four landscape/season/time recordings were made for a total of 190 spectrograms. One audio CD is included in this package featuring the recordings from which all of the spectrograms were generated. This type of spectrogram analysis is used to identify an organisms' vocalizations and a qualitative analysis was used to determine the degree to which vocalizations and geophonic sounds overlapped.

**Tuscany "Mapping Soundscapes Study."** This study was carried out from June 1 2008 to July 19 2008, totalling 11 recording sessions, in the Tuscan-Emilian Apennine National Park, Northern-Italy, Northern side of Mount La Nuda, at 1344 meters above sea level. A dense beech forest (*Fagus sylvatica*) is the dominant vegetation resulting from the abandonment 60 years ago of coppicing practices. A few conifer trees interrupt the homogeneity of beech cover at one corner of the study area.

Twenty digital recorders (Handy Recorder, H4) were located according to a grid composed of four rows and five columns, for 190 minute sessions at a distance of 100 m spacing ensuring a good spatial sampling and to reduce the interstation overlap. The H4 recorders were set at 44.1 kHz/16 bit/stereo mode. Eleven recording sessions were conducted in the morning (6 to 9 a.m., CET) during the breeding season, and in optimal meteorological conditions. The acoustic files were synchronized for each session using the Cool Edit Pro 2.1 software and processed by using Avisoft-SASLab Pro v4.40 (Avisoft Bioacoustics, Berlin) with a FFT size of 516 points. A numerical matrix composed of 310,078 temporal steps ($\Delta t_k$, 0.02321 second-length) and 255 frequency bins ($\Delta f_l$ , about 78 Hz) was created from each two hour recording.

A measure of sound complexity along frequencies was calculated using the Acoustic Complexity Index (ACI) (Farina and Morri 2008). ACI calculates the absolute difference ($d_k$) between two adjacent values of intensity ($I_k$ and $I_{(k+1)}$) in a single frequency bin ($\Delta f_l$):

$$d_k = \left| I_K - I_{(K+1)} \right| \tag{4}$$

and then adds together all of the $d_k$ encompassed in a temporal step of five seconds ($j$).

$$D = \sum_{k=1}^{215} d_k \quad \text{for:} \quad J = \sum_{k=1}^{215} \Delta t_k \tag{5}$$

where D is the sum of the 215 $d_k$ contained in five seconds. This result is then divided by the total sum of the intensity values registered in $j$, to reduce the effect of the distance of the birds from the microphones:

$$ACI = D / \sum_{k=1}^{215} I_k \tag{6}$$

ACI values at each of the 20 points where then used as inputs to Surfer interpolation program to create a surface map with BACI on the $y$ axis plotted against the length ($x$ axis) and width ($z$ axis).