**Title:** baRulho: an R package to quantify animal acoustic signal transmission and degradation

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**Abstract – 4 points, 350 words**

1. Animal acoustic signals are shaped by selection to convey information based on their time and frequency patterns. However, sound degrades as it transmits through various habitats, which affects communication potential. Transmission experiments are designed to quantify changes to signal structure in a given habitat by broadcasting and re-recording animal sounds at increasing distances.

2. We introduce ‘baRuhlo’, an R package designed to prepare signal transmission data sets to quantify degradation of animal signals. We highlight package features with a case study testing the effects of habitat, distance, and signal structure on transmission. Simulated pure tone and harmonic signals that varied in frequency and duration were broadcast and re-recorded at five increasing distances in open canopy and forest habitat. With this data, we show how ‘baRuhlo’ offers functions to prepare data sets for analysis as well as to calculate and visualize metrics that quantify degradation of acoustic signals in the time and frequency domain.

3. Signals transmitted over greater distances in open canopy compared to forest, and higher frequencies degraded more quickly…

4. The R package ‘baRuhlo’ provides an open-source, easily implemented suite of tools designed to quantify metrics of animal sound degradation…

**Keywords:** animal communication, attenuation, degradation, sound, acoustic adaptation; sound propagation

**1. Introduction**

Animal acoustic signals function to convey information from sender to receiver, which is encoded within their time and frequency patterns (Bradbury & Vehrencamp 2011; Catchpole & Slater 2003). However, over space, and particularly for long-distance communication, sounds degrade due to distance-related energy loss and distortion. The caller’s local habitat can add to degradation as sounds reverberate, scatter, or are absorbed depending on the structure of vegetation (Morton 1975; Marten and Marler 1977; Derryberry 2009). Thus, signals are shaped by selection to decrease the effects of distance and habitat-induced degradation, and presumably increase the probably of information transfer (Morton 1975; Wiley and Richards 1978). Understanding the physical properties of signal propagation and the factors that lead to degradation in space can help with link patterns of signal form to selection on songs and calls as well as behaviors that require communication.

Transmission studies seek to test hypotheses related to degradation of animal sounds, which can lead to an understanding of how selection influences signal form and function. Typically, this is achieved buy quantifying change to signal structure in a given habitat by broadcasting and re-recording animal sounds at increasing distances and quantifying changes to time and frequency patterns(reviewed by Hardt & Benedict 2020). *Generally, a loss of sound energy occurs through spread spherically, and declines by 6 dB with every doubling of distance. Energy loss further attenuates through atmospheric absorption, scattering, and ground attenuation. Temporally, sound degrades... Background noise also influences detectability of sounds, as ambient levels increase, sounds are more difficult to differentiate from noise (Grabarczyk & Gill, 2020; others). Distance of the signaler from the ground influences ground attenuation (Darden et al. 2008; Balsby et al. 2003).*

Thus, a combination of measurements can explain the effects of distance, habitat, and other environmental factors on the propagation of signals through space.

We introduce the R package ‘baRuhlo’, which is intended to facilitate acoustic analysis of animal sound transmission experiments. We highlight package features with a case study testing the effects of habitat, distance, and signal structure on transmission properties. Simulated pure tone and harmonic signals that varied in frequency and duration were broadcast and re-recorded at five increasing distances in open canopy and forest habitat. With this data, we show how ‘baRuhlo’ offers a workflow with functions to prepare the data set for analysis as well as to calculate and visualize metrics that quantity degradation of acoustic signals in the time and frequency domain (Fig. 1). The main features of the package include loops to apply tasks through acoustic signals referenced in a selection table, production of image files with graphic representation of sound in time and/or frequency, extended selection tables as the object format to input acoustic data and annotations as well as output results, and the use of parallelization to distribute tasks among several cores to improve computational efficiency. As proof of concept, we compare baRuhlo output to that of SIGPRO, a commonly used program for transmission studies (Dabelsteen et al. 1993; Holland et al. 1998; Balsby et al. 2003).

**2. Methods**

**2.1 Sound transmission experiment**

Quick paragraph on rational for case study.

*2.1**Synthesize sounds or compile test songs from recordings*

Test signals were synthesized in warbleR, pure tone and harmonic simulated songs were generated at four frequencies (list) and two durations (short: add length and long: add length). Amplitude was normalized for all signals (add in details for normalization).

The baRuhlo package builds on functions and data formats from the warbleR (Araya-Salas & Smith-Vidaurre 2017) and seewave packages (Sueur et al. 2008).

*2.2 Re-record signals*

Test signals were broadcast at increasing distances in open canopy and forest habitat at # sites. A reference signal was re-recorded at 1 m from the playback speaker and test signals recorded at ## m at ## m from the ground. Signals re-recorded with (what/settings). Signals broadcast with type of speaker at ## dB measured at 1 m (SPL meter info).

*2.3 Time sync re-recorded signals*

Recordings were imported into R and re-recorded signals from each distance aligned with the reference signal. To find the location of the start marker on the simulated re-recorded sound files, we used the functions search\_templates() to run a cross-correlation of one or more markers across the test (re-recorded) files to determine the exact time in which each marker is found:

**3. Quantify signal transmission with baRuhlo**

**Add package assumptions/data structure**

*3.1 Blur ratio*

Blur ratio quantifies the degradation of sound as a function of the change in signal energy in the time domain (Dabelsteen et al. 1993) and is measured as the mismatch between amplitude envelopes (expressed as probability density functions) of the reference signal and the re-recorded signal. Low values indicate low degradation of signals. The function blur\_ratio() measures the blur ratio of signals in which a reference playback has been re-recorded at different distances. The function compares each signal type to the corresponding reference signal within the supplied frequency range (e.g. bandpass) of the reference signal (‘bottom.freq’ and ‘top.freq’ columns in ‘X’). The ‘signal.type’ column must be used to tell the function to only compare signals belonging to the same category (e.g. song-types). All wave objects in the extended selection table must have the same sampling rate so the length of envelopes is comparable. Blur ratio can be calculated as follows:

R code for blur ratio

The output data frame is similar to input data, except that it includes two new columns (‘reference’ and ‘blur.ratio’) with the reference signal and blur ratio values. Note that NAs are returned for signals used as reference and ‘ambient’ noise selections. If img = TRUE it also returns 1 image file (in ‘jpeg’ format) for each comparison showing spectrograms of both signals and the overlaid amplitude envelopes (as probability mass functions (PMF)).

*3.2 Spectral blur ratio*

Spectral blur ratio quantifies degradation of sound as a function of change in signal energy across the frequency domain. This function is analogous to the blur ratio described above for the time domain. Low spectral blur ratio values indicate low degradation of signals. Spectral blur ratio is measured as the mismatch between power spectra (expressed as probability density functions) of the reference signal and the re-recorded signal. Similar to the blur ratio, each signal type is compared to the corresponding reference signal.

R code for spectral blur ratio

*3.3 Envelope correlation*

Amplitude envelope correlation measures the similarity of two signals in the time domain. The envelope\_correlation() function measures the envelope correlation coefficients between reference playback and re-recorded signals. Values close to 1 means very similar amplitude envelopes and suggest little degradation has occurred. If envelopes have different lengths, that is, when signals have different lengths, cross-correlation is applied and the maximum correlation coefficient is returned. Cross-correlation is achieved by sliding the shortest signal along the largest one and calculating the correlation at each step. As in the functions detailed above, the ‘signal.type’ column must be used to instruct the function to only compare signals that belong to the same category.

R code for envelope correlation

The output from the envelope correlation is also similar to those of other functions; an extended selection table similar to input data, but also includes two new columns (‘reference’ and ‘envelope.correlation’) with the reference signal and the amplitude envelope correlation coefficients. Note this function does not provide a graphical output. However, the graphs generated by blur\_ratio() can be used to inspect the envelope shapes and the alignment of signals.

*3.4 Spectral correlation*

Spectrum correlation measures the similarity of two signals in the frequency domain. This is similar to spectral\_correlation(), but no cross-correlation is applied as both signals are compared within the frequency range of the reference signal (so both spectra have the same length). Values near 1 indicate identical frequency spectrum or no degradation. To visualize spectral correlation, graphs generated by spectral\_blur\_ratio() can be used to explore the spectrum shapes and signal alignment.

R code for spectral correlation

*3.5 Signal-to-noise ratio*

Signal-to-noise ratio (SNR) quantifies signal amplitude level in relation to ambient noise and is a metric of overall signal attenuation. This method is implemented in the function snr(), which requires a measurement of ambient noise that which either be the noise just before each signal (noise.ref = "adjacent") or one or more ambient noise measurements per recording (noise.ref = "custom"). For the latter, selections on signal parameters in which ambient noise is to be measured must be specified. Alternatively, one or more selections of ambient noise can be used as reference (‘noise.ref’ argument). This can potentially provide a more accurate representation of ambient noise. When margins overlap with another acoustic signal nearby, SNR will be inaccurate, so margin length should be carefully considered. Any SNR less than or equal to one suggests background noise is equal to or overpowering the acoustic signal. SNR can be measured as follows:

R code for SNR

*3.6 Spectrogram distortion*

Finally, the function spcc() measures spectrogram cross-correlation as a metric of signal distortion. Values close to 1 means very similar spectrograms (i.e. little signal distortion). The function is a wrapper on warbleR’s xcorr() and can be run as follows:

R code for spectrogram distortion

*3.7 Statistical analysis for case study*

**4. Results**

4.1 Effects habitat on signal transmission over space

**5. Discussion**

**6. Conclusions**

The R package baRuhlo provides an open-source, easily implemented suite of tools designed to quantify metrics of animal sound degradation.

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**Conflicts of Interest:** The authors declare no conflicts of interest.

**Author contributions:**

**Data Availability Statement:**

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Table 1. Terms for understanding signal transmission.

|  |  |
| --- | --- |
| Term | Definition |
| Model signal | Signal in which transmission properties will be studied, usually found in the original field recordings or synthetic sound files. |
| Reference signal | Signal to use as a pattern to compare against. Typically created by re-recording a model signal broadcast at 1m from the source (speaker). |
| Test signal | Signals re-recorded away from source (speaker) to test for attenuation and degradation (also referred to as ‘re-recorded’ signals). |
| Signal type | Signal category. For example, song types (e.g., A, B, C), call types (alert, foraging, etc). |
| Ambient noise | Energy from background sounds in the recording, excluding signals of interest. |
| Degradation | Term used to describe change in the structure of the signal when transmitted in a given habitat. |
| Attenuation |  |
| SPL |  |
|  |  |
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Figure legends

Figure 1.

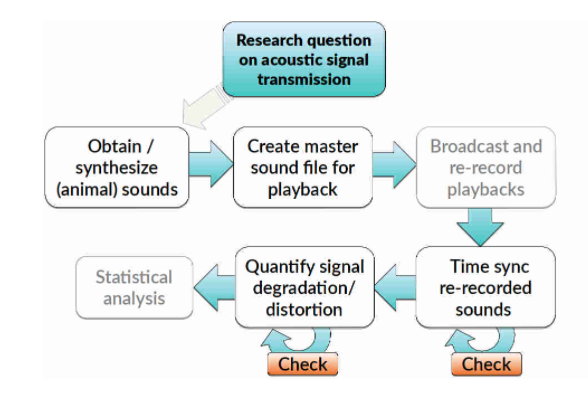


Figure 1. Diagram of typical sequence of steps to experimentally test hypotheses related to signal transmission.

Figure 2. Spectrogram of songs – maybe song alignment?