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Short communication

A GIS tool for modeling anthropogenic noise propagation in natural ecosystems

Sarah E. Reed[a,b,*], Jennifer L. Boggs[c], Jacob P. Mann[d]

[a] Department of Fish, Wildlife, and Conservation Biology, Colorado State University, Fort Collins, CO 80523-1474, USA
[b] North America Program, Wildlife Conservation Society, 301 North Willson Avenue, Bozeman, MT 59715, USA
[c] Center for Landscape Analysis, The Wilderness Society, 655 Montgomery Street #1000, San Francisco, CA 94111, USA
[d] GIS consultant, PO Box 72953, Davis, CA 95617, USA

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A B S T R A C T

SPreAD-GIS is a tool for modeling spatial patterns of anthropogenic noise propagation in natural ecosystems. SPreAD-GIS incorporates commonly available datasets on land cover, topography, and weather conditions to calculate noise propagation patterns and excess noise above ambient conditions for one-third octave frequency bands around one or multiple sound sources. User-specified noise source characteristics, ambient sound conditions, and frequency-weighting make SPreAD-GIS flexible to incorporate field measurements and model noise propagation for any type of source, environment, or species. SPreAD-GIS is a free, open-source application written in Python and implemented as a toolbox in ArcGIS software.

Software availability

Name of software: SPreAD-GIS
Developer: Dr. Sarah Reed
Contact information: Center for Landscape Analysis, The Wilderness Society, 720 3rd Avenue, Suite 1800, Seattle, WA 98104, USA. Tel.: +1 206 624 6430; fax: +1 206 624 7101 E-mail: cla_info@tws.org.
Availability: free at http://purl.oclc.org/spread-gis
Available since: October 2010
Software required: ArcGIS 9.3 with the Spatial Analyst extension and Python

1. Introduction

Expanding urbanization, industrial development, natural resource extraction, and transportation networks have led to increasing levels of anthropogenic noise around the world, affecting species in terrestrial (Barber et al., 2009) and marine ecosystems (Slabbekoorn et al., 2010). Chronic exposure to anthropogenic noise can have deleterious physiological and behavioral effects on humans and other animals, including increased stress levels (Babisch, 2003; Campo et al., 2005) and decreased reproductive success (Habib et al., 2007). Flight from or avoidance of anthropogenic noise can alter the spatial distribution of organisms (Forman et al., 2002), leading to declines in habitat use or species abundance (Bayne et al., 2008; Francis et al., 2009). Introduced noise also disrupts animal communication systems, masking detection or discrimination of signals and prompting vocal adjustments (Patricelli and Blickley, 2006); these effects are well-documented for birds (Slabbekoorn and Ripmeester, 2007), anurans (Parris et al., 2009), and mammals (Rabin et al., 2003).

Several environmental factors influence the spatial patterns of noise propagation in natural ecosystems. In the absence of interference, sound waves propagate geometrically and sound levels decline as the square of the distance from the sound's source. Acoustic energy is absorbed by the atmosphere, as a function of elevation, air temperature, and humidity (American National Standards Institute (ANSI), 2004). Temperature and wind gradients cause sound waves to refract, altering the spatial pattern of propagation (Ingard, 1953). Sound is absorbed by the ground (Aylor, 1971) and scattered by vegetation aboveground (Fang and Ling, 2003). Terrain features determine the relative importance of ground versus atmospheric effects; noise may propagate long

* Corresponding author. Department of Fish, Wildlife, and Conservation Biology, Colorado State University, Fort Collins, CO 80523-1474, USA. Tel.: +1 970 491 8740; fax: +1 970 491 5091.
E-mail addresses: sarah.reed@colostate.edu (S.E. Reed), jboggs30@pratt.edu (J.L. Boggs), admin@jakemann.org (J.P. Mann).

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distances from hilltops or across valleys (Piercy et al., 1977), whereas a steep hill or ridgeline acts as a barrier to sound propagated from below (Embleton, 1996). The degree to which noise impacts humans and other species depends on the ambient acoustic environment, as well as a species' auditory sensitivity (Lohr et al., 2003).

Modeling the spatial patterns and temporal dynamics of noise disturbances could help ecologists to better understand and predict how anthropogenic noise affects species and ecosystems at a landscape level (Pijanowski et al., 2011). We reviewed seven existing software tools available for modeling noise propagation, and we evaluated them on the basis of their cost, ease of use, and incorporation of various factors likely to affect noise propagation in natural ecosystems. The tools we reviewed were either high-cost commercial products developed in proprietary software with limited capacity for the user to adjust model parameters and calculation procedures (Pamanikabud and Tansatcha, 2003), or they were low-cost or free products with limited functionality or user support available. Most of these tools were developed for modeling noise propagation in human-dominated ecosystems, including noise from urban and industrial areas (e.g., CadnaA, LIMA, NoiseMap, and SoundPLAN) or aircraft and highway traffic (e.g., INM, NMSim, TNM). Accordingly, many of these tools do not incorporate important factors that are likely to affect noise propagation in natural ecosystems (e.g., changes in vegetation cover over space) (Barber et al., 2011), and most present results in a summary sound level that corresponds to human auditory sensitivity (i.e., A-weighted sound level or dBA) and do not allow for alternate frequency-weighting to better represent the way that other animals hear noise (Delaney et al., 1999). Although some of the tools we reviewed permit input and output of data via common spatial data formats, none operates within a geographic information system (GIS), limiting the ease with which noise models can be integrated with other information in a research or resource management context (Tang and Wang, 2007). We determined that no single software tool was available that met all of our criteria for application to modeling anthropogenic noise propagation in natural ecosystems.

Thus, our objectives were to create a software tool to model spatial patterns of noise propagation in natural ecosystems, while accounting for the frequency-dependent effects of sound attenuation due to environmental factors, and to apply custom frequency-weighting to estimate the sound exposure or area affected for species with variable auditory sensitivity. We chose to develop SPreAD-GIS in a geographic information system (GIS) environment to provide scientists and resource managers with a user-friendly tool that could be implemented using their existing software at no additional cost. Additionally, implementing model calculations in a GIS facilitates the integration of acoustic data with other spatio-temporal environmental information in environmental research and decision making.

2. Development of SPreaD-GIS

SPreAD-GIS is a free, open-source GIS application for modeling anthropogenic noise propagation in natural ecosystems. SPreAD-GIS is based on the System for the Prediction of Acoustic Detectability (SPreAD), a model developed by the U.S. Forest Service (USFS) and Environmental Protection Agency (EPA) to predict potential acoustic impacts of human activities and plan for recreation opportunities in U.S. National Forests (Harrison et al., 1980). The SPreAD model was designed as a step-by-step guide – a series of worksheets with tables of data and explicit directions for computations – that would allow a resource manager without technical training in acoustics to calculate manually the propagation of sound from a single point source to a single point receiver for eight one-third octave frequency bands (0.4–2 kHz). Data and calculations used in SPreAD were drawn from the Acoustic Detection Range Prediction Model (ADRPM), a model developed under the sponsorship of the U.S. Army Tank Automotive Command (TACOM) for the purpose of estimating the acoustic detection range of motor vehicles. Calculations in the original ADRPM model combined theoretical models of acoustic propagation with statistical models fit to empirical data (Evans et al., 1989).

SPreAD-GIS automates the manual calculations of the SPreAD model to predict the propagation of sound from one or multiple point sources continuously throughout an area of interest. SPreAD-GIS is an open-source application written in Python and implemented as a toolbox in ArcGIS software (ESRI, Redlands, CA, USA). The required inputs for SPreAD-GIS are free and commonly available datasets, including a digital elevation model (DEM), land cover dataset (e.g., NLCD or GlobCover), and local weather conditions (e.g., air temperature, relative humidity, and wind speed and direction). Sound source characteristics (e.g., sound level by frequency and measurement distance) are specified by the user, chosen from a table of 'built-in' source types, or input manually from empirical measurements, making SPreAD-GIS flexible to model noise propagated from any type of source. Ambient sound conditions for the study area can be represented as a constant sound level by one-third octave band, or imported as a custom digital map of empirical field measurements. Alternatively, a tool is available uses the land cover dataset and a table of background sound spectra from the original SPreAD model to create a dataset that estimates sound spectra by land cover type and environmental conditions.

SPreAD-GIS calculates noise propagation patterns for one-third octave frequency bands (0.125–2 kHz) around a point sound source. An octave is the interval between a simple tone and half or double its frequency; the human ear hears an octave as the perfect interval between the same note up or down the chromatic scale. In sound measurement and modeling applications, continuous sound spectra are commonly represented as one-third octave bands, which summarize the acoustic intensity over the bandwidth at its center frequency and approximate the auditory filter widths of humans (Barber et al., 2011). Integration time is the time interval over which an acoustic metric is calculated. Common acoustic metrics include L_{eq}, the level of a constant sound over a specified time period, and L_{max}, the maximum sound level measured or modeled during an event of specified duration. Integration time is not specifically addressed by the original SPreAD model; thus, we assume that the acoustic metric and associated integration time of noise modeled in SPreAD-GIS are determined by those characteristics of the sound source.

The SPreAD-GIS calculation process comprises six stages, each of which introduces an additional factor that influences how each sound frequency band propagates through space (Fig. 1):

1) *Spherical spreading loss* calculates the decline in sound level as a function of distance from the sound's source.
2) *Atmospheric absorption loss* calculates the decline in sound level due to absorption by the atmosphere. Atmospheric absorption is frequency-dependent and is a function of air temperature, relative humidity, and elevation.
3) *Foliage and ground cover loss* calculates the decline in sound level due to absorption by the ground and scattering by vegetation. The rate of foliage and ground cover loss is frequency-dependent and is a function of land cover type and distance from the sound's source.
4) *Downwind and upwind loss* calculates changes in sound level due to blowing wind. Downwind and upwind losses are

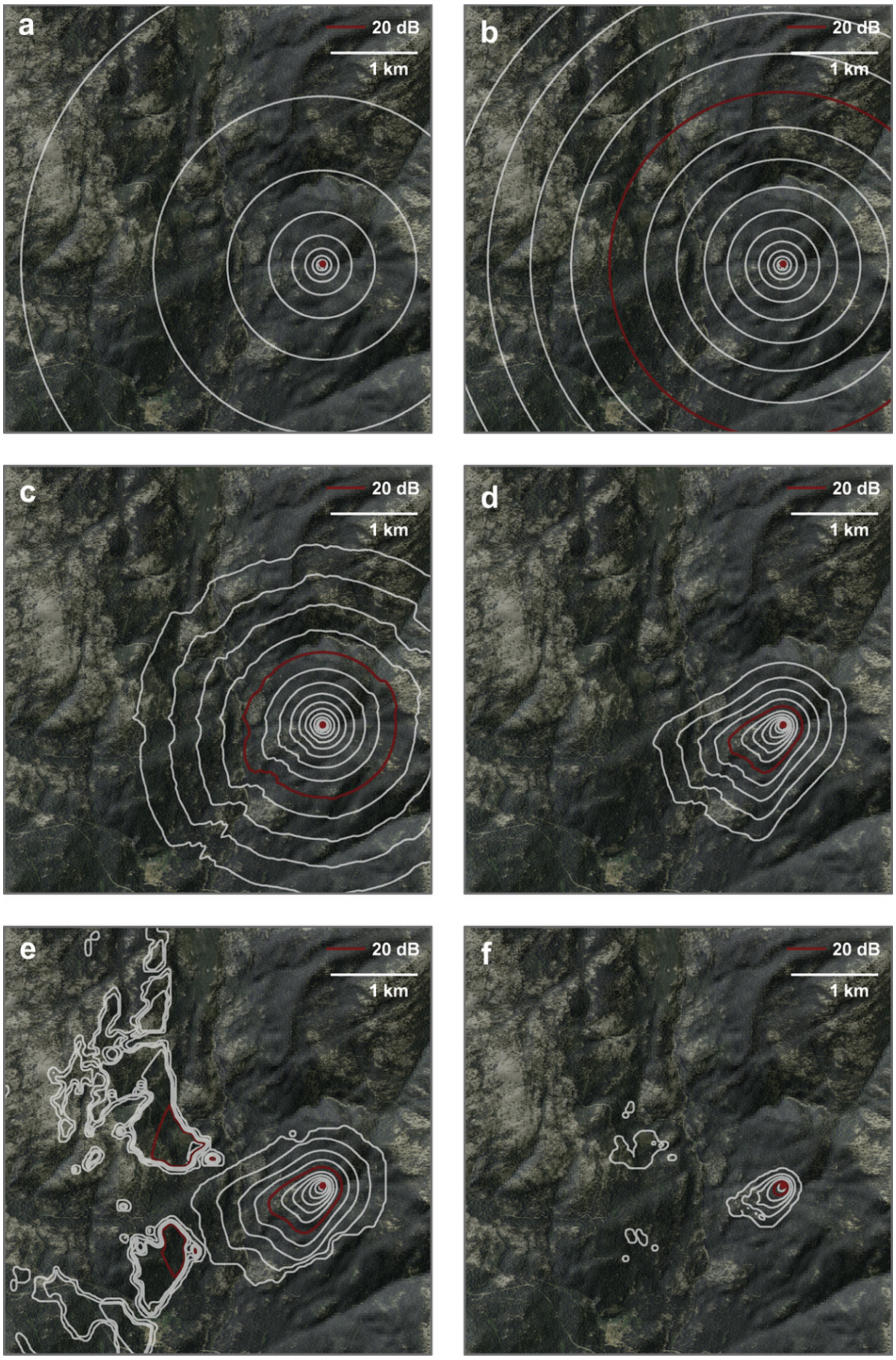

Fig. 1. Factors affecting environmental noise propagation and their implementation in SPreAD-GIS. Model calculations include: (a) spherical spreading loss, (b) atmospheric absorption loss, (c) foliage and ground cover loss, (d) downwind and upwind loss, (e) terrain effects, and (f) excess noise propagation. The example shown in the figure represents noise propagated at a frequency of 1 kHz from an all-terrain vehicle (ATV) in a mid-elevation mixed conifer forest on a summer day with a light northeast wind. Results for the cumulative stages of the SPreAD-GIS calculation process are shown in 5 dB contours around one stationary point source.

a function of the prevailing wind direction, wind speed, and seasonal conditions.

5) *Terrain effects* determines the areas of the landscape that are primarily influenced by atmospheric, ground, or barrier effects and calculates the decline in sound levels due to the barrier effects of ridgelines. Terrain effects are a function of topography.
6) *Excess noise propagation* identifies areas of the landscape where noise propagated from the source exceeds ambient sound conditions.

Adapting SPreAD to a GIS environment required several modifications to calculations from the original model. Data for the SPreAD model was provided in tables of discrete parameter values. Where possible, we used statistical software (JMP, SAS Institute, Inc., Cary, NC) to fit a continuous model to data in the tables and derive an equation for the relationship among variables. A continuous model is advantageous because it decreases computation time, does not require rounding of data values, and permits the user to input parameter values beyond those included in the original model. When variable relationships were too complex to fit a simple statistical model, we sought an alternate source for the equations. For example, we replaced the data tables for the atmospheric absorption calculations with equations from the ANSI S1.26-1995 (2004). We converted absorption by foliage and ground cover to a rate by distance, to allow for the possibility that sound would pass over multiple land cover types with different absorption rates in a study area. We applied topographic tools in GIS to identify the areas of the landscape that would be subject to barrier effects (e.g., the far side of a ridgeline), as well as the areas of the landscape that would be primarily subject to long-distance propagation through the atmosphere (e.g., within a viewshed). We expanded the frequency range of the original SPreAD model (0.4–2 kHz) to include an additional octave at the lower end (0.125–0.4 kHz), and we applied a local smoothing algorithm to minimize artifacts of the raster calculation process for the final noise propagation and excess noise calculations.

The outputs of SPreAD-GIS are raster datasets representing the predicted pattern of noise propagation around the source and the difference between introduced noise and background sound levels. The results can be visualized as a continuous surface of sound levels (e.g., Fig. 2), used as a basis for generating isodecibel noise contours (e.g., Fig. 3), or intersected with a point dataset to extract sound levels at receiver locations (e.g., Pamanikabud and Tansatcha, 2003). Both output datasets are produced for each one-third octave band, and a weighted sum of the frequency bands can be used to calculate a map of summary sound levels. The true composite sound level for a noise event is represented by a flat-weighted sum, which does not weight any frequency band relative to another. Users can also supply frequency weights to calculate a summary sound level that correspond to the auditory sensitivity of a particular species (e.g., A-weighted sound level for humans or O-weighted sound level for owls; Fig. 2). However, data on auditory sensitivity and frequency weights are currently available for only a small proportion of species, making this an important area for future research in bioacoustics.

SPreAD-GIS also includes tools that allow the user to batch-process the calculation of noise propagation from multiple point sources, or for multiple frequency bands, and combine the results. For example, summing acoustic energy from multiple points can be used to simulate noise propagated from multiple simultaneous sources (e.g., continuously operating oil and natural gas well compressors; Barber et al., 2011) or to simulate noise from moving source(s). At present, modeling dynamic or moving sources in SPreAD-GIS requires that the user supply sequential point locations, representing a source that is moving through space, or a series of source characteristics, representing a source whose sound spectrum changes over time. To simulate the propagation of noise from a 'linear' source (e.g., a road), the acoustic energy from many discrete points located along the line is summed together. This discretization is necessary to accurately represent the propagation of noise from a line that is not straight – for example, to account for the greater intensity of acoustic energy found at the inside of a curve. An example is given by Fig. 3, which illustrates simultaneous propagation from multiple vehicles traveling along a road at two points in time.

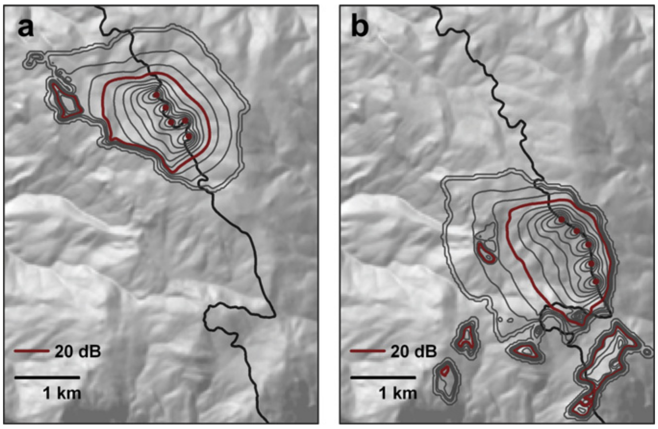

Fig. 3. Summation of acoustic energy from multiple noise sources. Cumulative maximum noise propagation at 1 kHz from five motor vehicles traveling along a forest road is shown in 5 dB contours for two points in time. Source spectra were derived from 'built-in' source types from the original SPreAD model (Harrison et al., 1980) and did not include information on integration time.

3. Applications and limitations of SPreAD-GIS

SPreAD-GIS was initially developed for application to the USFS Travel Management Planning process (36 CFR 212.55), which establishes guidelines for designating systems of roads and trails that are open to motor vehicle use in National Forests throughout the U.S. This process and other federal regulations (e.g., E.O. 11644) require USFS land managers account for the impacts of motor vehicle noise on wildlife, wildlife habitats, and human visitors when designating motorized routes. However, the high cost and complexity of commercial software tools has limited the application of noise modeling to recreation and transportation planning. Developed as an ArcGIS toolbox with a graphical interface and help files, SPreAD-GIS provides a user-friendly alternative that can be implemented by researchers and land managers using their existing GIS software at no additional cost.

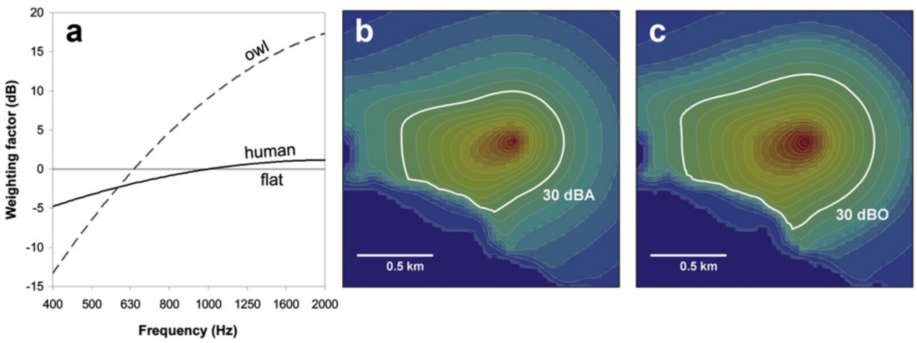

Fig. 2. Illustration of alternate frequency-weighting of complex anthropogenic noise. In the first panel, (a) weighting factors are compared for owls, humans, and flat (unweighted) sound levels over the frequency range 0.4–2 kHz. These weighting factors are used to calculate summary sound levels for noise propagated from a motor vehicle for (b) humans (A-weighting, or dBA) and (c) owls from the order Strigiformes (owl-weighting, or dBO). Although the majority of acoustic energy from motor vehicle engines is concentrated at lower sound frequencies, owls have greater auditory sensitivity than humans at higher frequencies within this range. In this example, the area affected by a composite noise level of >30 dB is 45% greater for an owl than for a human. Data on owl auditory sensitivity and approximate frequency-weighting factors are derived from Delaney et al. (1999) and Delaney and Grubb (2003).

Allowing the user to specify sound source characteristics, import a custom map of ambient sound conditions, and assign frequency weights makes SPreAD-GIS flexible to model noise propagation for many other research and management applications in bioacoustics (Blumstein et al., 2011) and soundscape ecology (Pijanowski et al., 2011). Users who have downloaded SPreAD-GIS to date report that the tool has been used to model potential noise propagation from roads, recreational activity, heavy equipment, residential and urban development, and natural resource extraction. SPreAD-GIS can also be used in the design of field experiments and analysis of the resulting data. For example, one user reported applying SPreAD-GIS to estimate the area affected by an animal vocalization playback experiment. Members of our research group are currently using SPreAD-GIS and field measurements of motor vehicle noise to forecast the area affected for bird and mammal communities in Sierra National Forest, California, USA (Reed et al., unpublished data).

An important limitation of SPreAD-GIS is that, to date, its predictions have not been validated with empirical measurements of noise propagation in a natural environment. This is similarly a limitation of most major noise modeling software packages (Barber et al., 2011), and further testing, field validation, and comparison of model predictions should be priorities for future research (Kaliski et al., 2007). Other limitations of SPreAD-GIS include its restricted frequency range and the computational efficiency of large-scale or multi-point model runs. Although we expanded the range of the original SPreAD model to include an additional octave of frequency bands (0.125–0.4 kHz), this range is still quite narrow when compared to the spectra of many sound sources as well as the auditory sensitivity of many species. In the future, we aim to expand the range of frequency bands available in the model above the current limit of 2 kHz. In addition, a complete model run of SPreAD-GIS for a single point source and one frequency band requires approximately 80 raster calculations. When these calculations are run for a large modeling extent, or repeated for multiple point sources and many frequency bands, processing time increases substantially. Future versions of SPreAD-GIS could increase the efficiency of model runs by combining sequential equations, reducing the resolution of the input data, or preserving intermediate datasets for use in multiple model runs.

4. Summary

SPreAD-GIS is the first free, open-source tool available for modeling the propagation of anthropogenic noise in natural ecosystems within a GIS environment. Although SPreAD-GIS is currently a static model (i.e., the model illustrates potential noise propagation for a snapshot in time), it could be integrated with traffic, recreational visitation, or other dynamic models to forecast the frequency and duration of noise disturbances over time. We anticipate releasing future versions of SPreAD-GIS to increase the efficiency of model calculations, expand the range of source types, sound frequency bands, and environmental settings that can be modeled, and ensure the toolbox's compatibility with future versions of GIS software. Additionally, we encourage other users to participate in the continued development, refinement, and testing of the SPreAD-GIS toolbox. The toolbox, a detailed user's guide, and sample datasets are available for download from the SPreAD-GIS website <http://purl.oclc.org/spread-gis>.

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