

Temporal and spatial variation of a winter soundscape in south-central Alaska

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Abstract

Context Winter soundscapes are likely different from soundscapes in other seasons considering wildlife vocalizations (biophony) decrease, wind events (geophony) increase, and winter vehicle noise (technophony) occurs. The temporal variation and spatial relationships of soundscape components to the landscape in winter have not been quantified and described until now.

Objectives Our objectives were to determine the temporal and spatial variation and acoustic–environmental relationships of a winter soundscape in south-central Alaska.

Methods We recorded ambient sounds at 62 locations throughout Kenai National Wildlife Refuge (December 2011–April 2012). We calculated the

normalized power spectral density in 59,597 recordings and used machine learning to determine acoustic–environmental relationships and produce spatial models of soundscape components.

Results Geophony was the most prevalent component (84 %) followed by technophony (15 %), and biophony (1 %). Geophony occurred primarily at night, varied little by month, and was strongly associated with lakes. Technophony and biophony had similar temporal variation, peaking in April. Technophony occurred closer to urban areas and at locations with high snowmobile activity. Biophony occurred closer to rivers and was inversely related to snowmobile activity. Over 75 % of sample sites had >1 recordings of airplane or snowmobile noise, mainly in remote areas.

Conclusions The soundscape displayed distinct patterns across 24-h and monthly timeframes. These patterns were strongly associated with land cover

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variables which demonstrate discrete acoustic–environmental relationships exhibiting distinct spatial patterns in the landscape. Despite the predominance of geophony, the presence of technophony in this winter soundscape may have significant negative effects to wildlife and wilderness quality.

Keywords Alaska · Biophony · Ecoacoustics · Geophony · Soundscape · Technophony · Machine learning, GIS, winter soundscapes

Introduction

The emergent properties of ecosystems extend beyond that which can be seen. Plants and animals perceive and interact with their environment using all their senses (Kare 1970; Doty 1976; Wells and Lehner 1978; Voigt et al. 2008) and therefore attention should be given to these interactions to have a more holistic understanding of their roles in ecological processes. Sound is an intrinsic component of ecosystems and plays a significant role in how plants and animals interact with each other and with their surroundings (Hongbo et al. 2008; Dowling et al. 2011; Krams et al. 2012; Mazzini et al. 2013).

The field of soundscape ecology focuses its attention on the broader ecological significance of sound in the landscape (Pijanowski et al. 2011; Farina 2014) and landscape-scale soundscape research is proving useful in assessing relationships among soundscape components and landscape variables (Mennitt et al. 2014; Tucker et al. 2014; Fuller et al. 2015). The study of sound as an emergent property of ecosystems over extended periods of time and across large spatial extents contributes to a broader understanding of the role sound plays in the environment.

Three general components to a soundscape have been characterized: biophony (Krause 1998, 2001, 2002), geophony, and anthrophony (Qi et al. 2008; Pijanowski et al. 2011). All sounds made by animals like those from birds, frogs, insects and mammals make up biophony. All sounds made by geophysical phenomena such as rain, wind, and flowing water make up geophony and all human-made sounds are considered anthrophony. Although human-made sounds such as speaking, music, and machines can be grouped as anthrophony, for the purpose of this

study and further definition of soundscape components, we distinguish human-made sounds generated from machines and technology to be that of technophony, a subcomponent of anthrophony.

Biophony is generally the sounds produced by animals for communicating between individuals or within groups (Krause 1998, 2001, 2002; Stegmann 2013). Biophony also consists of information that enables animals to detect predators (MacLean and Bonter 2013) and prey (Konishi 1973), as well as, attract mates and defend territories (Collins 2004; Nowicki and Searcy 2004; Reichert 2012). Biophony also enables animals to locate suitable habitats or territories (Slabbekoorn and Smith 2002).

Geophony can influence animal behaviors that, in turn, directly affect biophony. For instance, Hüppop and Hilgerloh (2012) found that wind altered the call rates of migratory thrushes (*Turdus* sp.) while McNett et al. (2010) discovered that the occurrence of wind events determined the signal timing of Treehoppers (*Enchenopa binotata*). Background noise produced by geophonic sounds such as rain has also been known to influence the frequency at which some animals vocalize in order to increase the likelihood of attracting a mate (Moreno-Gómez et al. 2013). Geophony, therefore, is an important component that can influence the variation of biophony in the soundscape.

When technophony is introduced to a natural soundscape, significant changes can occur in the sonic environment that can be indicators of degrading natural systems (Stone 2000; Dooling and Popper 2007; Habib et al. 2007; Francis et al. 2012). Technophony produced from machinery and motor vehicles (e.g., cars, airplanes, snowmobiles) tend to create low frequency noise that can mask the calls and communication of terrestrial organisms (Barber et al. 2010). Masking occurs when a sound interferes with the detection of another sound. Low frequency noise produced by road traffic or oil compressors (1–4 kHz) has been observed to have a masking effect on the ability of organisms to hear vocalizing cohorts that call within this frequency range (Ortega and Francis 2012; Ortega 2012). Some bird species alter their calls in response to masking by increasing their call frequency (Dowling et al. 2011) while other species simply avoid noisy areas (Bayne et al. 2008; Francis et al. 2009; Ortega and Francis 2012). Hence, these behavioral responses to technophony can affect the acoustic

composition of biophony in specific habitats and alter the spatial distribution where biophony occurs.

Soundscapes vary temporally and spatially. Urban environments, for example, have a different sound configuration than soundscapes in rural or wilderness areas (Joo et al. 2011) and animal activity and their vocalizations vary on daily, monthly, and seasonal timescales (Krause and Gage 2003; Joo et al. 2011; Pieretti et al. 2011; Gage and Axel 2014). Much of the work done on soundscapes has focused on small spatial scales and on spring, summer, and/or fall seasons when biophony is at its peak (Krause and Gage 2003; Joo et al. 2011; Pieretti et al. 2011; Gage and Axel 2014). However, winter possesses a very different level of human and animal activity and noticeable changes in geophysical events that contrasts with all other seasons (Marchand 1996). It is conceivable that winter soundscapes would also differ spatially and temporally.

During winter in northern latitudes, wildlife diversity is reduced by the fall migration southwards. The reduction of daylight and decrease in temperatures also reduce the activity and associated sounds of wildlife that remain as winter residents (Marchand 1996). Geophony also changes. The babbling of a brook or the rush of water in a river is halted by freezing. The impacting sound of rain falling on leaves, water, and the Earth's surface is transformed into a soft muffle resulting from falling snow. Even the presence of snow on the ground can reduce the propagation of sound in the landscape (Nicolas et al. 1985). Wind is also stronger during winter due to the increase in temperature gradients and reduced vegetation that typically impede air currents. Human activity is even reduced and altered by winter's influences. However, in some areas, motorized noise from airplanes and winter recreational vehicles like snowmobiles can be prevalent.

All these factors have an effect on the timing and distribution of where sounds occur in the landscape. The locations of sound-producing wildlife are likely influenced by the distribution of resources associated with land cover variables like forested areas for cover and travel corridors along forest edges (Slagsvold 1977; Hurlbert and Haskell 2003). Similarly, anthropogenic activity is associated with urban developments and therefore machine noise is likely strongly associated with these environments. These urban areas may also serve as the origins of motorized vehicles

(e.g., airplanes, snowmobiles) and enhance activity into wilderness areas, emitting technophony into an otherwise natural soundscape.

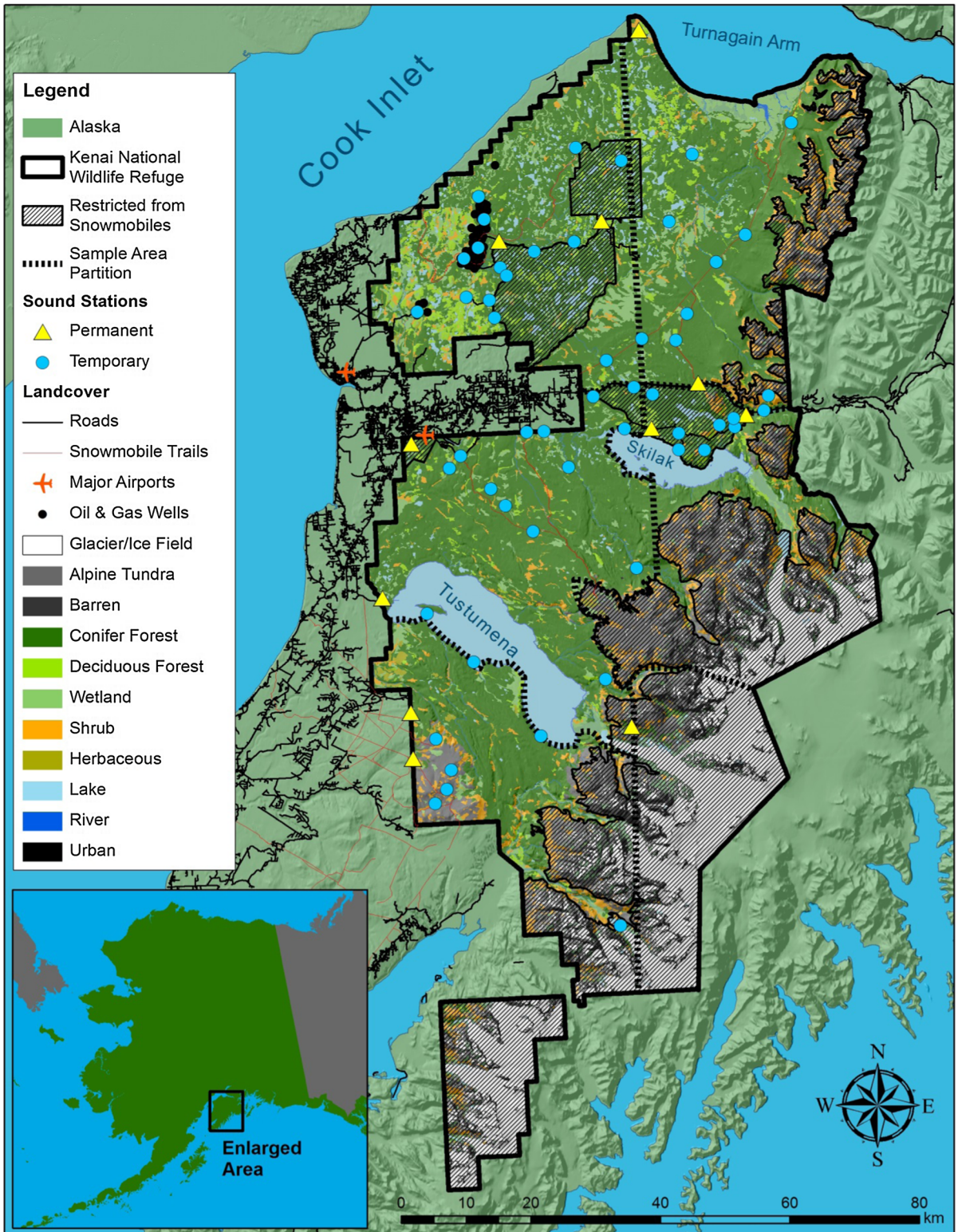
Because of the important role sound plays in natural systems and the impacts that human activity can have on the acoustic environment, conservation efforts are needed to preserve soundscapes as an inherent property and valuable environmental resource (Dumyahn and Pijanowski 2011). Knowledge of the composition, variation, and spatial distribution of soundscapes is essential for identifying where conservation efforts should be focused.

Due to the lack of research on winter soundscapes, their unique attributes, and the potential impacts of technophony, our aim in this study was to capture and describe variations in the winter soundscape of a subarctic ecosystem over space and time. Here we focus our attention on the temporal variation of biophony, geophony, and technophony over 24-h and monthly time frames and a suite of environmental factors that likely influence the distribution and occurrence of soundscape components in the landscape.

Methods

Study area

Our research was conducted in the Kenai National Wildlife Refuge (KENWR; 60.3333°N, 150.5000°S), 805,000 ha of public land located on the Kenai Peninsula in south-central Alaska, USA (Fig. 1). The area consists of a diverse array of subarctic ecosystems, including coastal wetlands, boreal forests, and alpine tundra. KENWR's lowland forests are dominated by white spruce (*Picea glauca*) and black spruce (*P. mariana*) with a mixture of aspen (*Populus tremuloides*), birch (*Betula neoalaskana*), willow (*Salix* sp.), and an extensive network of wetlands. Lichen, mountain hemlock (*Tsuga mertensiana*), and sub-alpine shrub (*Alnus* spp.) dominate areas above tree line in the Kenai Mountains and Caribou Hills. Temperatures rarely exceed 26 °C in the summer or drop below −18 °C in the winter. Over the past 3 years of monitoring, snow depth ranged between 26–162 cm above and 25–82 cm below 300 m elevation. The combinations of these diverse ecosystems make unique landscape patterns and provide habitats for a variety of subarctic wildlife.



◀ **Fig. 1** Geographical orientation and distribution of land cover variables of the Kenai National Wildlife Refuge, Alaska (60.3333°N, 150.5000°S) based on 2002 Landsat7 ETM+, USGS DEM (KENWR Geodatabase) in association with soundscape sample areas and permanent and temporary sound sampling stations

Additionally, KENWR has a major highway (Sterling Highway) running east to west through its center, and is bordered on the west by a significant urban interface that includes oil and gas development and a patchwork of residential, rural, and industrial complexes (Fig. 1). This infrastructure provides human access to many parts of KENWR. There are approximately 17 small airports that serve as hubs for commuter, charter, and personal aircraft traveling over KENWR and one commercial airport that supports flights traveling over KENWR's air space. In winter, snowmobiling is a popular means of winter activity that is permitted within 505,800 ha of KENWR during December through April. The combination of sounds from snowmobiles and airplanes have become a concern for its potential impacts on wilderness and wildlife.

Spatial sampling

We partitioned KENWR into six spatially explicit regions and established a permanent soundscape sample site within each region. To maximize spatial sampling, we also established 56 temporary sample sites distributed throughout each region. Temporary sites were sampled for 10 days, after which our sound sampling devices were moved to new temporary sites within their respective sample region. Accessibility to our sound recording sites throughout much of KENWR in winter was limited to roads accessed by vehicle and trails, rivers, wetlands, alpine tundra, and lakes accessed by snowmobile. Sites near lakes in lowland and alpine areas were accessed by ski plane. Locations along hiking trails were accessed by foot.

Overall, this enabled us to sample the soundscape at 62 locations within a variety of environments representative of our entire study area including the urban-KENWR interface, wetlands, mixed coniferous forests, deciduous forests, lakes, rivers, streams, alpine, and glaciers. We recorded the spatial coordinates of each soundscape sample site with a global positioning system (GPS) and subsequently associated each sound

recording to a spatially explicit location in the landscape for model building (Fig. 1).

Sound sampling and data acquisition

Ambient sounds were recorded during December 2011–April 2012 using Song Meter SM2 autonomous recorders (Wildlife Acoustics, Inc., Maynard, MA, USA). We scheduled the song meters to record for 1 min at 30-min intervals for a total of 48 samples per day. We recorded in monaural at 16 bits in a waveform audio file format (WAV) at a frequency of 22,050 hertz (Hz) for a total useable frequency range of 11 kHz. We confirmed the reliability of our microphones and sound recorders prior to sound sampling by conducting trial recordings and listening sessions to validate the sounds detected. Cold temperatures (−35–0 °C) during our field work substantially reduced battery life. Therefore, we visited each sound recorder site every 7–10 days to replace batteries. We accumulated a total of 120,500 sound files during the sampling period.

Sound is emitted from a source within a range of frequencies that vary over time. Ravens, for example call within a 250–1850 Hz frequency range (Conner 1985) while black-capped chickadees (*Poecile atricapillus*) call between 3000 and 4000 Hz (Hill and Lein 1987). Recordings of a sound event can be visualized in a spectrogram, where frequency is indicated on the y-axis and time on the x-axis. The energy of the sound recorded is visualized in a spectrogram by the intensity of the color representing that sound. Louder sounds (i.e., sounds with more energy) have brighter, more intense colors (Online Appendix 1). This sound energy can be quantified using power spectral density (PSD), a metric that can be expressed as watts/kHz and calculated using Welch's (1967) method. PSD describes the power of a sound event in the equivalent of 1-Hz bands in the domain of its respective frequency (Merchant et al. 2015).

To determine the PSD value in different frequencies, we partitioned each recording into 10, 1-kHz frequency intervals. PSD values for each frequency interval (1–11 kHz) were computed and vector normalized (0–1) using methods outlined by Kasten et al. (2012). We term this normalized PSD value as soundscape power (normalized watts/kHz). These data and their associated metadata (e.g., timing and

location of recording) were entered into the Remote Environmental Assessment Laboratory sound library (<http://www.real.msu.edu>), an open access website where all recordings and metrics can be accessed and downloaded for analysis (Kasten et al. 2012).

To determine whether we could automate the identification of sound sources into the categories of biophony, geophony, and technophony, we listened to 270 sound files with sound sources representative of these three categories and conducted a discriminate function analysis in R (R Development Core Team 2012) to identify what frequency intervals had the best potential for identifying soundscape categories. We found that a number of biophonic, technophonic, and geophonic sounds occurred in similar frequency intervals with 13, 70, and 71 % of biophony, geophony, and technophony records respectively occurring within the 1–2 kHz range. This made it impossible to automate accurate identification of biophony, geophony, and technophony by frequency intervals.

To classify sounds into the categories of biophony, technophony, and geophony, we listened to and identified the sounds recorded in 59,597 sound files representative of all 62 sample sites. These aurally identified sound files consisted of approximately 50 % of all sound recordings we accumulated over the entire winter. This provided an accurate data set of sound sources for each soundscape component.

We realize that there are limitations to the sensitivity of our microphones that likely prevented the detection of distant, quieter sound events. Merchant et al. (2015) mentions the commonality of these limitations in acoustic studies and we make no assumptions that our recordings detected all sounds within the landscape but rather were representative of what our microphones could detect. The 59,597 sound records we listened to and had identified to specific sound sources were the focus of our analysis.

Soundscape analysis

We used Minitab v16 (Minitab, State College, PA, USA) to summarize, graph, and analyze soundscape power for each soundscape component. We treated the audio recordings for each station as a temporal and spatial sample of the winter soundscape and summarized the information as the mean soundscape power for each soundscape component for the entire study area.

We calculated and visualized soundscape power within each frequency interval for each soundscape component and visualized the temporal variation of frequency intervals with the highest average soundscape power for each soundscape component over 24-h and monthly time frames. We considered frequency intervals with the highest average soundscape power more representative of the respective soundscape component than intervals with much lower soundscape power.

We used a Pearson correlation test to determine if average soundscape power of each soundscape component was correlated over 24-h and monthly time-frames ($p < 0.05$). We calculated a one-way ANOVA and 95 % confidence intervals (CI) to determine the differences of soundscape power of each soundscape component between months. We conducted an additional analysis to determine whether the constraints of sampling sound recording stations that were accessible by airplane, snowmobile, car, and by foot had an effect on the detection of biophony, geophony, and technophony by calculating an ANOVA and 95 % CI.

Building predictive models

A machine learning strategy was used to model each soundscape component. Machine-learning algorithms (e.g., boosted regression trees, CART, RandomForests, TreeNet) are useful tools for quantifying the spatial distribution of plants and animals and identifying species–environmental relationships (Guisan and Zimmermann 2000; Craig and Huettmann 2009; Drew et al. 2011). Our hypothesis was that the spatial distribution and environmental relationships of soundscape components could also be modeled using these tools. These algorithms do not require a priori assumptions regarding explanatory variables which provide more flexibility than traditional generalized linear or additive models.

Stochastic gradient boosting (TreeNet; Salford Predictive Modeler[®] v7.0; Salford Systems, Inc., San Diego, CA, USA) was used to build predictive models of biophony, geophony, and technophony using a weighted average (WA) of soundscape power for each sound recording station. Because each sound station and each soundscape component had a different number of sound records, we weighted the average amount of soundscape power for all recordings of each soundscape component for every sound station by its proportion to the total number of recordings.

The coordinates of each sound station were imported into ArcGIS 10.2.1 (ESRI, Redlands, CA, USA) and overlaid onto 17 associated environmental layers derived from data available in the KENWR geodatabase. We used two additional spatial layers of predicted snowmobile activity (snowmobile tracks/0.06 km²) and snow depth. These two predictive models were developed by methods outlined in Mullet (2014). Using the Extract Tool, we created a table of all sound stations, their respective soundscape components and associated soundscape power, and the spatial data of all 19 environmental layers (Table 1).

TreeNet fits a simple parameterization function (base learner) to pseudo residuals by least squares at sequential iterations to construct additive regression models. During each iteration, the pseudo residuals are calculated as the gradient of the loss function with respect to the training data being evaluated in each regression. To improve the accuracy of this process, a subsample of training data is selected from the entire data set at random with replication. The random subsample is then used to fit the base learner and update the model's predictions for the current iteration. The model's performance is more robust by randomizing the data used in each iteration (Friedman 1999). TreeNet is an effective predictive modeler of both complex categorical and continuous data sets and has proven an effective analysis method for ecological data (Popp et al. 2007; Craig and Huettmann 2009; Cai et al. 2014; Jiao et al. 2014).

We produced soundscape models in TreeNet using all 19 environmental variables then calculated the accuracy of each predictive model using the normalized root mean squared error (nRMSE). Normalized root mean squared error is the percent error between predicted values and observed values where a lower percentage indicates higher prediction accuracy.

The acoustic–environmental relationships learned by TreeNet between target (e.g., technophony) and predictor variables (e.g., distance to roads, distance to snowmobile trails) were visualized and compared by interpreting partial dependence plots produced in TreeNet. To create a spatial map of model predictions, target–predictor relationships were scored to a regular point grid (500 × 500 m) overlaid onto our study area derived in ArcGIS. These points were also attributed with all 19 predictor variables to which the scored predictions could be applied with the appropriate target–predictor relationship. The scored predictions were

Table 1 Environmental variables and abbreviations used to determine the acoustic–environmental relationships of biophony, technophony, and geophony in Kenai National Wildlife Refuge over winter (December 2011–April 2012)

Variable	Abbreviation
Distance to airports	AIR
Distance to barren land	NOV
Distance to coniferous forests	CON
Distance to deciduous forests	DEC
Distance to lakes	LAK
Distance to oil and gas compressors	OIL
Distance to rivers	RIV
Distance to roads	ROD
Distance to seismic lines	SEI
Distance to shrub land	SHR
Distance to snowmobile trails	SMT
Distance to streams	STR
Distance to urban areas	URB
Distance to wetlands	WET
Aspect	ASP
Elevation	ELE
Slope	SLO
Snow depth ^a	SNO
Snowmobile activity ^a	SNM

Distances are Euclidean distances measured in meters from the source

^a Derived from GIS predictive models

added to a map of KENWR in ArcGIS. For an improved continuous spatial visualization, the predicted soundscape power index values of each soundscape component at each point in the grid were interpolated between neighboring points across the extent of the study area using the interpolate-to-raster and inverse distance weighting (IDW) tools in ArcGIS Spatial Analyst. This yielded a continuous raster (500-m² resolution) of the predicted distribution of each soundscape components' soundscape power in KENWR over winter.

Results

Composition of soundscape components

Geophonic sounds were detected in 84 % (n = 50,141) of all sound records making it the most prevalent soundscape component. The majority of geophony was that from wind. Wind is defined as the

movement of air from high pressure to low pressure. We identified the sound of wind as the disturbance of the microphone from the movement of air across its surface or the sounds of wind moving through trees, canyons, diverted from the rock faces of mountains, or the sound of wind blowing snow across the land surface. The movement of air past the microphone of a recorder is similar to the sound of air movement past the ear and is therefore representative of the sonic experience an animal or person would have in the environment under such conditions. Therefore, we considered these events to be a component of geophony. More notably, 77 % of geophony recordings were of subtle, distant breezes blowing through forested areas, the creaking of branches, the cracking of ice, and the impact of snow on our microphones, trees, and the snow surface.

Technophonic sounds were detected in 15 % ($n = 8742$) of all recordings and an assortment of biophonic sounds were detected in 1 % ($n = 714$) of all recordings. Less than 0.5 % of all sound recordings were documented as having ≥ 2 detections of biophony, geophony and/or technophony within a single recording.

We identified the sounds produced by a total of 22 species in our recordings. Vocalizations produced by corvids made up 42 % of biophonic sounds ($n = 300$) and other passerines comprised 30 % ($n = 211$). The remaining 28 % of biophony recorded consisted of raptors [e.g., owls (*Strigiformes*), bald eagles (*Haliaeetus leucocephalus*)], ducks (*Anatidae*), woodpeckers (*Picoides* sp.), wolves (*Canis lupus*), coyotes (*Canis latrans*), ptarmigan (*Lagopus* sp.), and red squirrels (*Tamiasciurus hudsonicus*; Fig. 2).

Road traffic noise made up 42 % ($n = 3654$) of all technophony recordings. Airplane and snowmobile sounds consisted of 29 % ($n = 2568$) and 18 % ($n = 1583$) of technophony, respectively, while sounds emanating from oil and gas compressors made up 10 % ($n = 874$) of technophony (Fig. 2). Over 75 % of sample sites had >1 recordings of airplane noise and nearly 50 % of sample sites with recordings of noise generated by snowmobiles.

Comparison of site access methods and soundscape identification

Many of our sound sampling locations ($n = 26$) were accessed by car. However, we found no difference

between the proportion of biophony (95 % CI 0.005, 0.006), geophony (95 % CI 0.000, 0.012), and technophony (95 % CI 0.003, 0.015) sound sources recorded in these locations. Twenty-three of our 62 sound stations were accessed by snowmobile. Sound records were not distinguishably different when the proportion of biophony (95 % CI -0.008 , 0.010), geophony (95 % CI 0.007, 0.025), and technophony (95 % CI -0.008 , 0.001) were compared. Similarly, for sites accessed by airplane ($n = 7$), there was no difference in the proportion of biophony (95 % CI -0.028 , 0.028), geophony (95 % CI 0.016–0.068), and technophony (95 % CI -0.024 , 0.028). Of the six sample locations we accessed by foot, we found no difference in the proportion between sound records of biophony (95 % CI -0.072 , 0.072), geophony (95 % CI 0.016, 0.12), and technophony (95 % CI -0.072 , 0.072).

Soundscape power by frequency

The average soundscape power for biophony was highest in the 1–2 kHz interval (0.6998 normalized watts/kHz) which was comprised of the calls of corvid species [ravens (*Covus corax*), black-billed magpies (*Pica hudsonia*), and gray jays (*Perisoreus canadensis*)], the most common and wide-spread vocal winter residents. Soundscape power at frequency intervals between 2 and 11 kHz were much lower when visually compared to the 1–2 kHz interval, although the 2–3 kHz interval and intervals between 5 and 8 kHz had slightly higher soundscape power when visually compared to all remaining frequencies (Fig. 3). These intervals consisted of other passerine species such as common redpolls (*Carduelis flammea*) and black-capped chickadees, as well as red squirrels.

Soundscape power of technophony was largely within the 1–2 kHz interval where it averaged 0.9588 normalized watts/kHz (Fig. 3). There were a variety of anthroponic sounds (e.g., ice augers, gunshots, fireworks) but the main sources of low-frequency technophony were from road traffic, oil and gas compressors, airplanes, and snowmobiles (Fig. 2). The revving of snowmobile engines and noise produced from the propellers of low-flying, fixed-winged aircraft occasionally produced soundscape power that peaked within the 3–4 kHz interval.

Average soundscape power for geophony was highest in the low frequency interval of 1–2 kHz

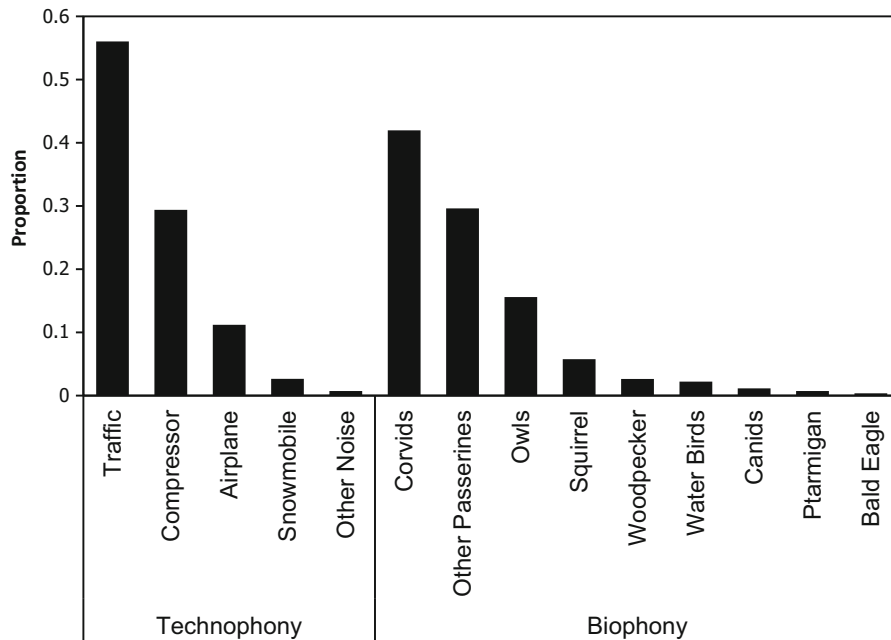


Fig. 2 Proportion of sound recordings of technophony and biophony sound sources recorded in the Kenai National Wildlife Refuge, Alaska over winter (December 2011–April 2012)

(0.6356 normalized watts/kHz). There was a significant reduction in soundscape power from the 1–2 kHz interval to the 2–3 kHz interval. However, soundscape power decreased more gradually from the intervals between 2 and 11 kHz (Fig. 3).

Temporal variation of soundscape components

Our analysis of daily patterns of soundscape power revealed that biophony and technophony occurred predominantly during daylight hours (0800–1600 h). Mean soundscape power of biophony began around 0600 h and peaked at 0800 h (0.0189 normalized watts/kHz). Biophony remained high and varied during the day until 1500 h (0.0218 normalized watts/kHz), after which it declined to low levels by 1700 h and decreased further after 1700 h (Fig. 4). Mean soundscape power of technophony gradually increased from 0500 h and remained high between 1100 (0.1904 normalized watts/kHz) and 1500 h (0.1953 normalized watts/kHz) then gradually decreased to its lowest (0.0579 normalized watts/kHz) at 0300 h (Fig. 4). Conversely, mean soundscape power of geophony was higher between 2200 and 0600 h peaking around 0400 h (0.5870 normalized watts/kHz) then declining sharply after

0600 h (Fig. 4). Geophony soundscape power was lowest between 1000 (0.05128 normalized watts/kHz) and 1500 h (0.5133 normalized watts/kHz; Fig. 4). Geophony had significantly higher soundscape power over a 24-h timeframe than biophony and technophony, with biophony having the lowest soundscape power of all three soundscape components.

Although mean soundscape power of biophony was significantly lower than technophony, their temporal patterns over a 24-h timeframe were positively correlated (Pearson = 0.879, $p = 0.000$). However, only 0.12 % of biophonic sound events occurred during the same recording as technophony. Additionally, detectable sound events of geophony occurred in 0.08 % of recordings where biophony was also detected. However, it is likely that quieter geophonic sound events occurred in a majority of sound recordings with biophony but were not detected through audible listening of recordings and, therefore, were not recorded.

We also found that mean soundscape power of biophony and technophony were positively correlated (Pearson = 0.886, $p = 0.046$) when their temporal patterns were compared by month (Fig. 5). December and February had similar patterns of soundscape

Fig. 3 Mean soundscape power (normalized watts/kHz) and 95 % confidence intervals within 10, 1-kHz frequency intervals summarized by biophony, technophony, and geophony identified from 59,597 sound recordings acquired over winter (December 2011–April 2012) in the Kenai National Wildlife Refuge, Alaska

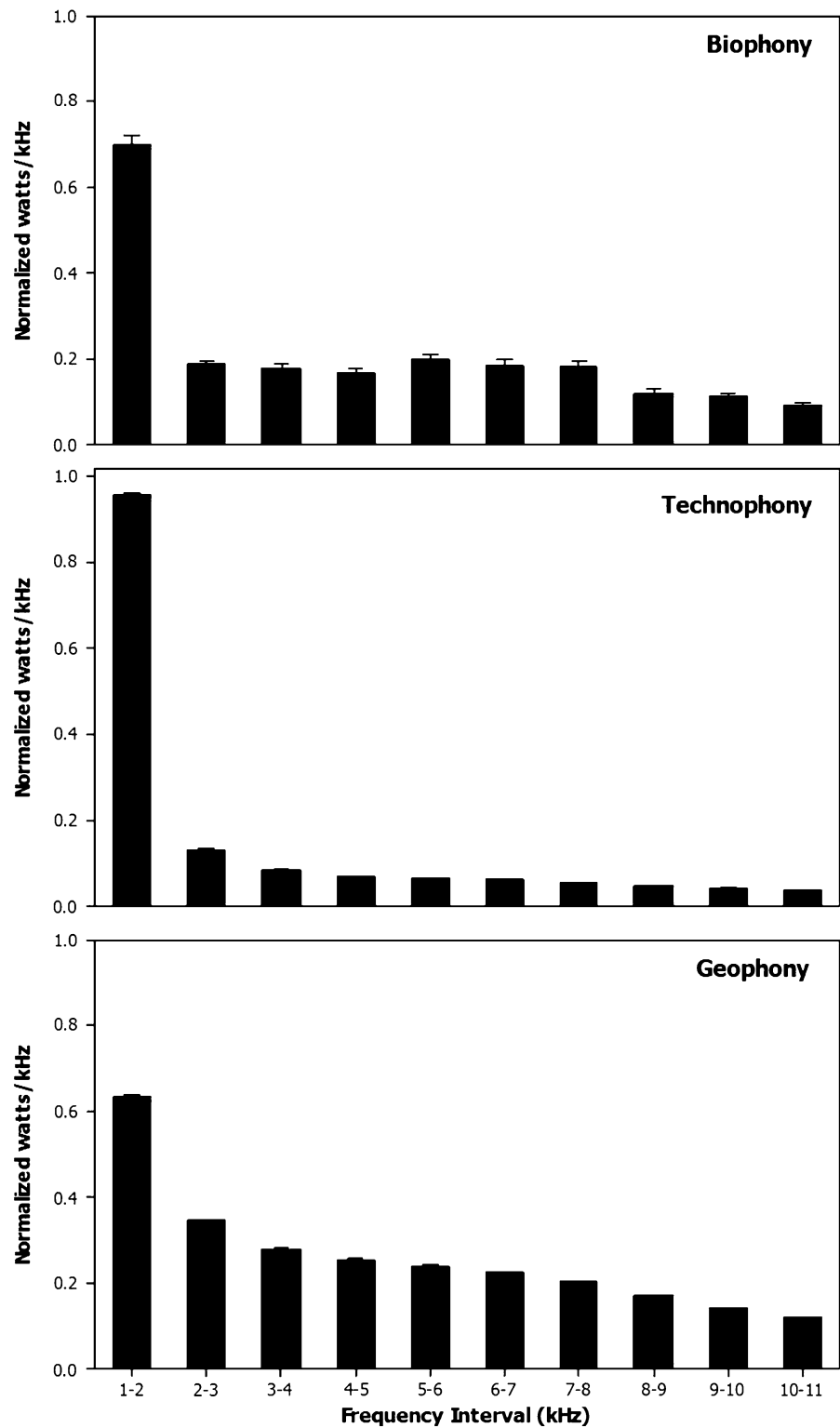
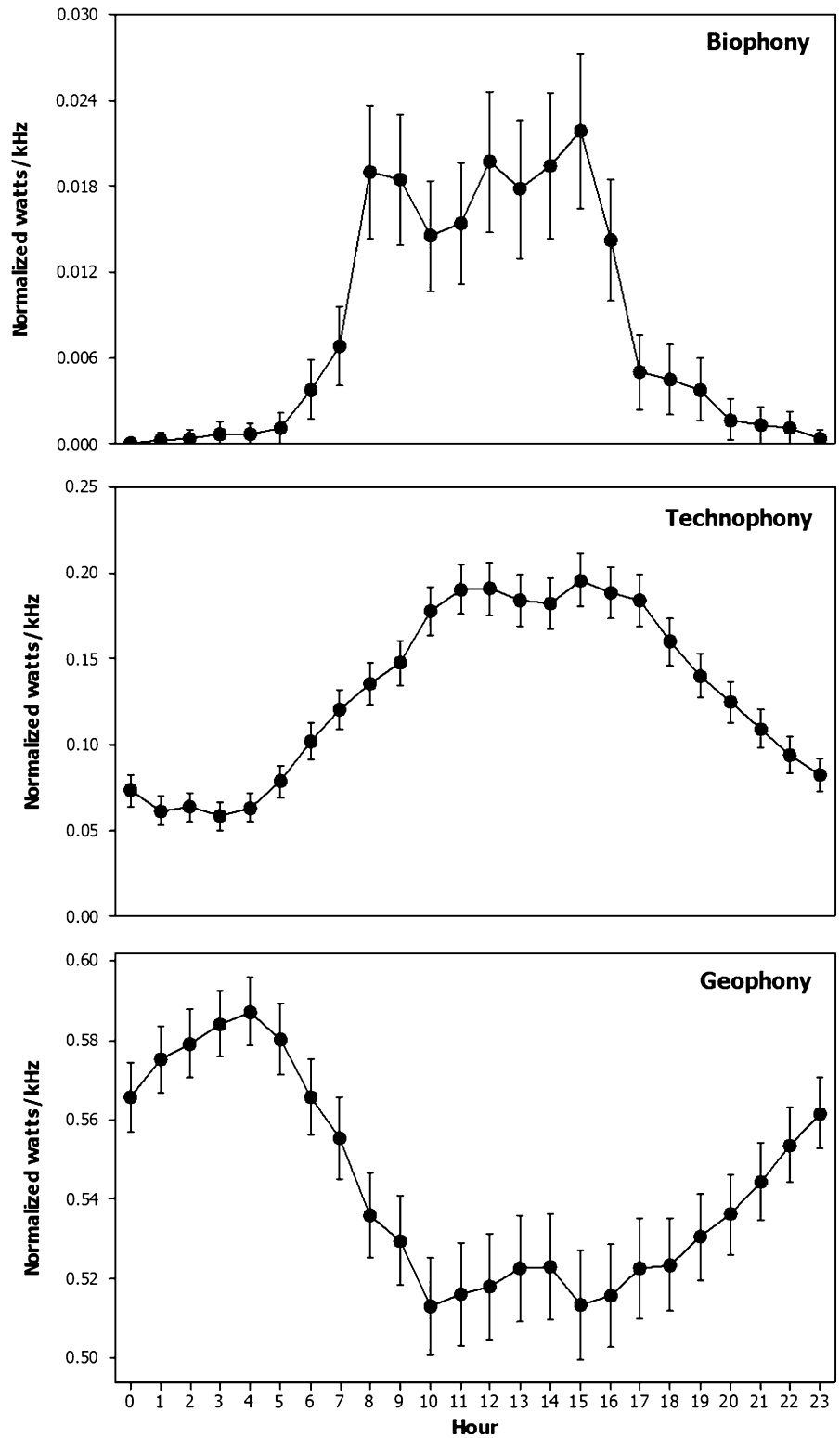


Fig. 4 Mean soundscape power (normalized watts/kHz) and 95 % confidence intervals of biophony, technophony, and geophony over a 24-h time period during winter (December 2011–April 2012) in the Kenai National Wildlife Refuge, Alaska. Time 0 is 12:00 a.m. and 23 is 11:00 p.m. The y-axis for all three soundscape components is not the same scale in order to reflect variation



power for biophony and technophony and were appreciably higher than January and March (Fig. 5). April had significantly higher soundscape power than all other months for both biophony and technophony (Fig. 5). Mean soundscape power of geophony peaked during the month of February with a gradual increase from December and January, declining then from March to April (Fig. 5).

Spatial variation of soundscape components

We produced spatially explicit predictive models to visualize the spatial distribution of biophony, technophony, and geophony in KENWR. Each model was based on the acoustic–environmental relationships of soundscape components in the landscape. We calculated the accuracy of our models using the nRMSE given in percentages. Low percentages indicated a more accurate model.

Biophony

The biophony model accuracy was fairly high with $nRMSE = 20\%$. The top three environmental variables associated with the spatial distribution of biophony were distance to rivers (RIV), distance to wetlands (WET), and snowmobile activity (SNM; Table 2).

The soundscape power of biophony was associated with areas ≤ 500 m from rivers and ≤ 1000 m from wetlands. Biophony did not occur in areas where snowmobile activity was >3 snowmobile tracks/ 0.06 km^2 (Online Appendix 2). Biophony occurred predominantly in the northern region of KENWR along river corridors and wetlands. High soundscape power index values of biophony in the southern part of KENWR also indicated that rivers were spatially representative of biophony in this region. These relationships can be visually identified by the sinuous nature of biophony hot spots (Fig. 6).

Technophony

Our model of technophony had $nRMSE = 21\%$. The top three environmental predictors of technophony were distance to urban areas (URB), snowmobile activity (SNM), and distance to lakes (LAK; Table 2).

Technophony showed a significant association with urban areas where it extended ≤ 2.5 km beyond the

urban–KENWR interface. Additionally, areas throughout KENWR where snowmobile tracks/ 0.06 km^2 were >8 were strongly associated with technophony. Technophony also occurred most often in areas >1.5 km from lakes (Online Appendix 3).

When predictions were projected to our study area, high soundscape power index values of technophony were strongly associated with roads, infrastructure, and oil and gas compressors in the northwest portion of KENWR (Fig. 7). High soundscape power index values were also indicated along the Sterling Highway that runs east–west through KENWR. High index values of technophony were predicted ≤ 3 km from this same highway where a number of vehicles travel through a mountain pass of the Kenai Mountains on the eastern side of KENWR. Technophony was also predicted along roads that extend into KENWR from urban areas on the western Kenai Peninsula. Technophony was spatially represented along a few scattered rivers in the north but more so with rivers in the southern part of the study area where these landscape features are commonly used corridors for snowmobile-related activity (Fig. 7).

Geophony

Our geophony model had comparable accuracy ($nRMSE = 20\%$) to our models of biophony and technophony. The top three environmental variables associated with the distribution of geophony were distance to RIV, distance to URB, and distance to LAK; (Table 2). The acoustic–environmental relationships of geophony with urban areas and lakes were inverse to those of technophony. Geophony was primarily associated with areas >1 km from rivers and >2.5 km from the urban–KENWR interface. Lakes in particular were an important landscape variable associated with the distribution of geophony (Online Appendix 4).

Geophony soundscape power index values were relatively high throughout most of our study area. Large hot spots of geophony were located in the northern and western portion of KENWR. However, proportionally smaller patches were predicted in the central and southern regions. All these areas are sites where a multitude of lakes are located and mostly inaccessible to human activity. Interestingly, very low soundscape power index values were associated with

Fig. 5 Mean soundscape power (normalized watts/kHz) and 95 % confidence intervals of biophony, technophony, and geophony over the months of winter (December 2011–April 2012) in the Kenai National Wildlife Refuge, Alaska. The y-axis for all three soundscape components is not the same scale in order to reflect variation

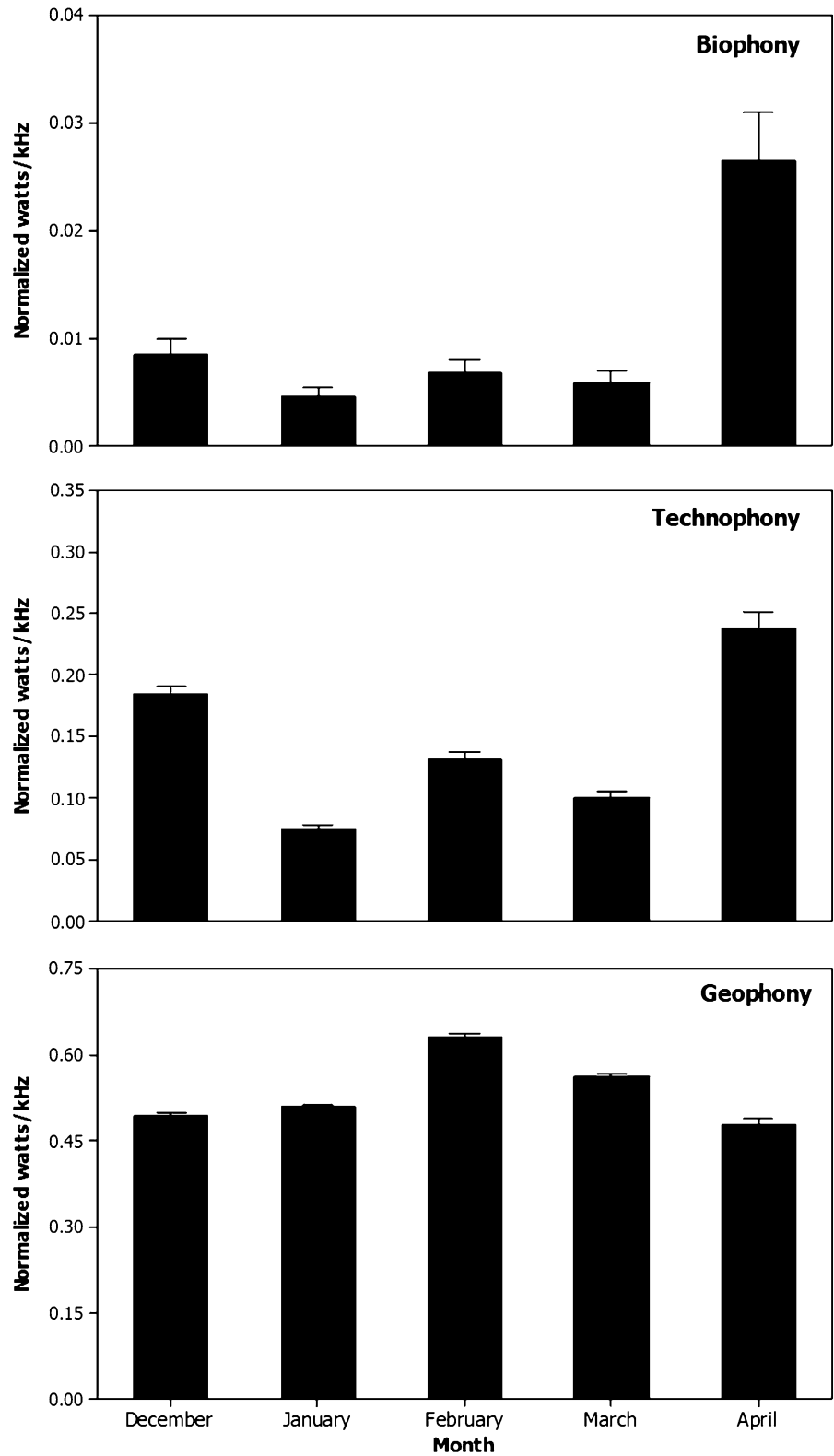


Table 2 Rank of importance of environmental variables associated with biophony, technophony, and geophony in the Kenai National Wildlife Refuge over winter (December 2011–April 2012)

Rank	Biophony	Technophony	Geophony
1	RIV	URB	RIV
2	WET	SNM	URB
3	SNM	LAK	LAK
4	LAK	RIV	SNM
5	DEC	ROD	ELE
6	AIR	OIL	OIL
7	NOV	ELE	ROD
8	SEI	STR	STR
9	SHR	SLO	SLO
10	STR	SEI	SMT
11	URB	SHR	DEC
12	SNO	DEC	SEI
13	ELE	SNO	WET
14	CON	WET	SHR
15	OIL	AIR	AIR
16	ROD	CON	ASP
17	SMT	SMT	NOV
18	ASP	NOV	SNO
19	SLO	ASP	CON

areas that appear to correspond to the high index values of technophony (Fig. 8).

Discussion

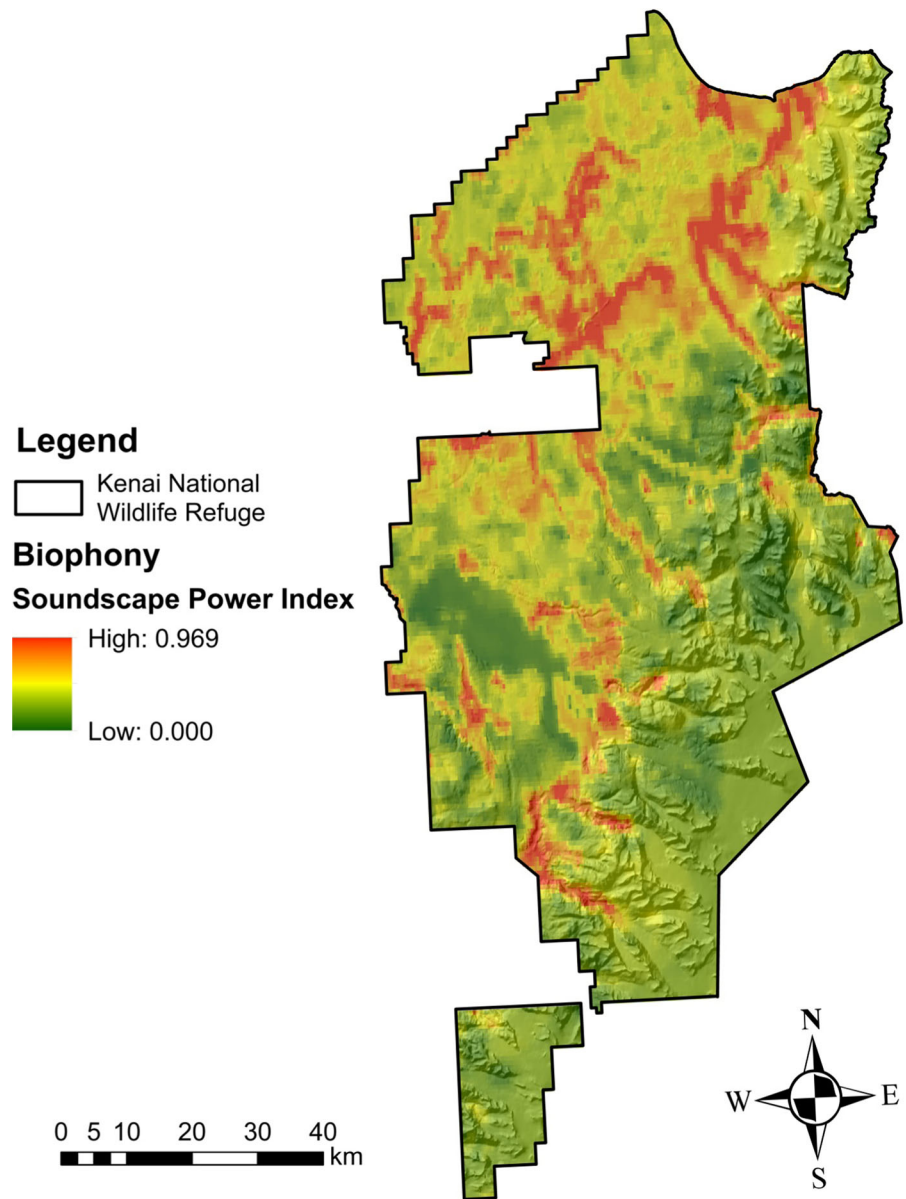
Our study provides a quantitative and visual description of the temporal and spatial variation of a winter soundscape in south-central Alaska. Biophony, geophony, and technophony displayed distinct temporal patterns across 24-h and monthly timeframes. Additionally, we found that the distributions of these soundscape components were strongly associated with land cover variables, and so demonstrate discrete acoustic-environmental relationships that present distinct spatially-explicit patterns in the landscape. Geophony contributed significantly to the winter soundscape while technophony and biophony were comparatively less represented. A large majority of geophony recordings were of subtle low-frequency sound events that describe this winter soundscape as a notably quiet time of year.

Mennitt et al. (2014) also found significant environmental relationships to sound pressure levels associated with anthropogenic (L_{10}) and background noise (L_{90}) throughout National Parks in the contiguous United States. They found a strong relationship between noise levels within the 1–2 kHz frequency range and developed areas. Background noise levels within the same frequency range were associated with average annual precipitation and the noise floor sound pressure levels of their equipment that ranged between 22 and 23 dB. Additionally, they found that sound pressure levels across a wide range of frequencies were much lower in winter than average summertime levels, a finding supported by our study.

Seasonal changes in the soundscape can largely be attributed to changes in wildlife and human activities coinciding with seasonal changes in daylight and food availability and the changing geophysical processes brought on by changes in temperature and air pressure (Slagsvold 1977; Hurlbert and Haskell 2003; Gage and Axel 2014). Gage and Axel (2014), who used a similar method of analysis to our own, found that a northern Michigan soundscape had significant temporal variation in soundscape power over all 10, 1-kHz frequency intervals between May and November which was defined by a distinct temporal pattern between the dawn and dusk choruses of spring and fall. Their findings also showed that soundscape power representative of biophony, geophony, and technophony, displayed similar patterns from year to year. Our findings extend this information to understand how the composition and temporal variation of winter soundscapes can contrast with that of other seasons.

Our results showed that biophony had the lowest proportion of sound recordings and soundscape power than all other soundscape components. A majority of our biophony sources were bird vocalizations. In northern latitudes, bird community composition changes and species richness decreases over winter as a result of resource availability (Hurlbert and Haskell 2003). Nearly 75 % of land birds that occupy summer breeding territories in Alaska over-winter outside the state (Boreal Partners in Flight 1999), while bird populations and vocal activity in northern regions increase during the spring (Slagsvold 1977). These observations would explain the low contribution and soundscape power of biophony throughout most of our sample period and the significant increase of biophony we recorded in April. Although it is not

Fig. 6 Predicted distribution of biophony soundscape power (normalized watts/kHz) in Kenai National Wildlife Refuge, Alaska (60.3333°N, 150.5000°S) over winter (December 2011–April 2012)

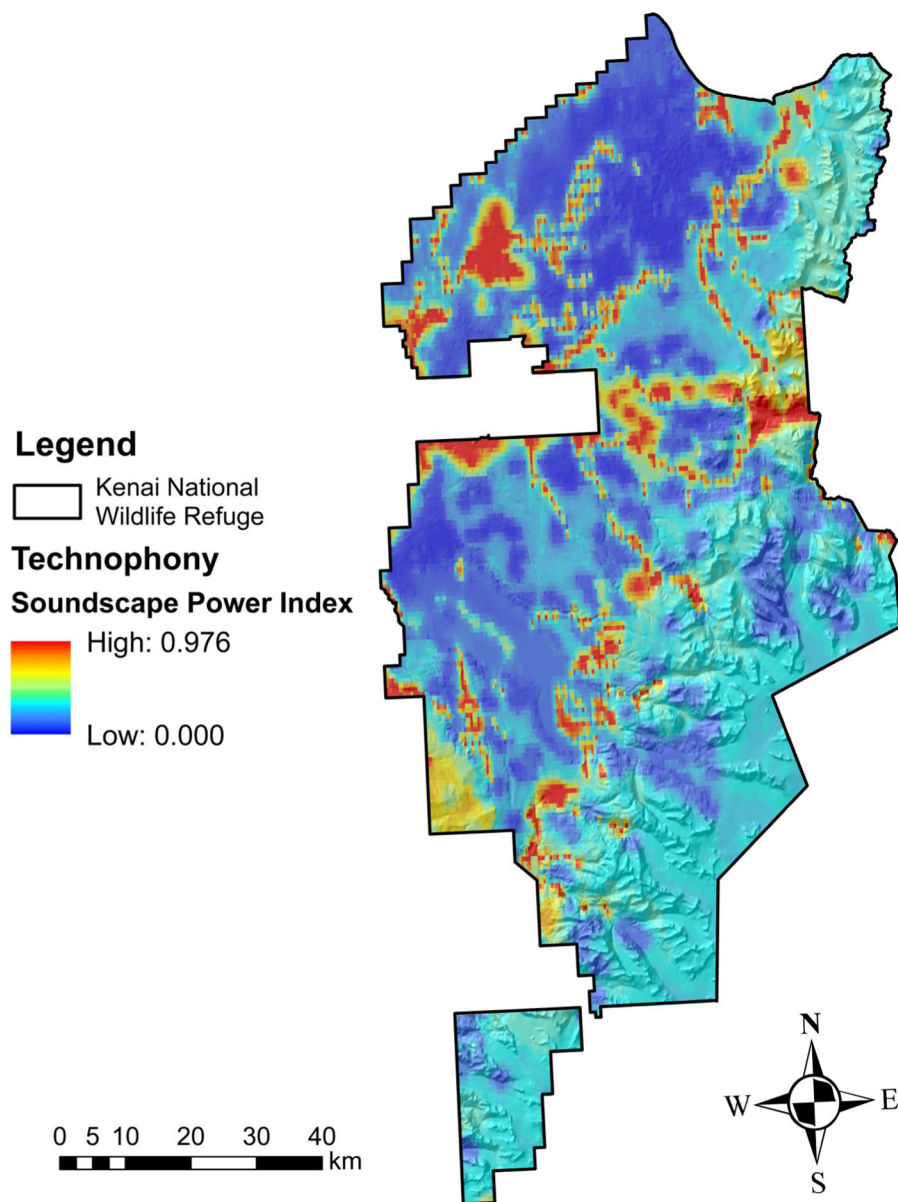


yet known how biophony specifically changes in KENWR seasonally, our results likely signify the oncoming seasonal changes in biophony from winter to spring (Fig. 5).

Biophony was strongly associated with rivers and wetlands, suggesting that edge habitats close to these landscape components are important predictors of vocal wildlife. These locations are known to serve as travel corridors and feeding locations for wintering birds (Desrochers and Fortin 2000). We found very few sound recordings in which biophony overlapped

with technophony, despite the high correlation in their temporal patterns and the presence of each at respective sound stations. Furthermore, we found that biophony and technophony primarily occurred at lower frequencies. Vocal animals in our study called at times when technophony did not occur to possibly negate the effects of masking (Dooling and Popper 2007; Habib et al. 2007; Barber et al. 2010; Ortega 2012; Ortega and Francis 2012) or because they were simply not present at the time technophony occurred. This may be especially important considering bird

Fig. 7 Predicted distribution of technophony soundscape power (normalized watts/kHz) in Kenai National Wildlife Refuge, Alaska (60.3333°N, 150.5000°S) over winter (December 2011–April 2012)



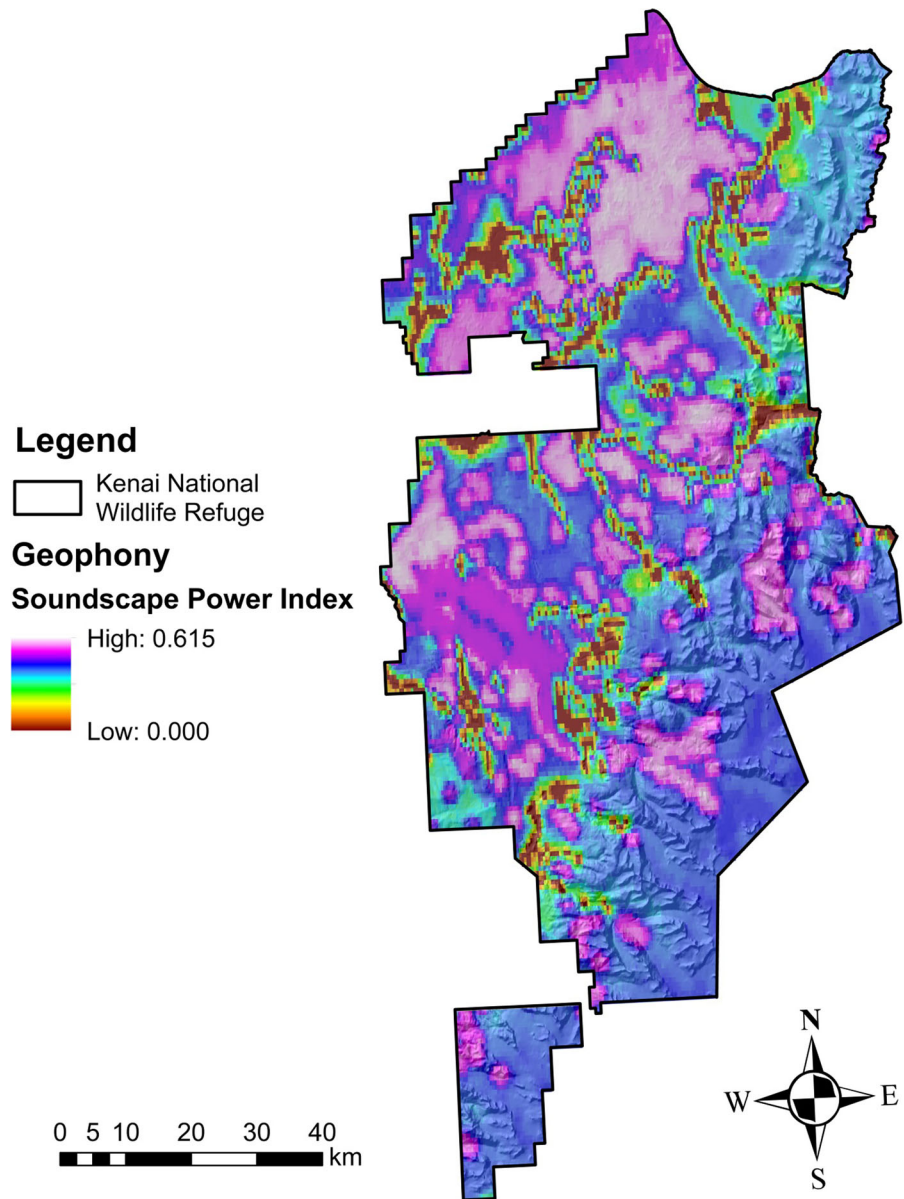
vocalizations in winter are used for communication between individuals to locate scarce food resources (Ficken et al. 1978; Ficken 1981).

We expected technophony to be strongly associated with areas of human development (e.g., urban areas, roads, snowmobile trails) but we found evidence that technophony also extended into natural areas of KENWR where development was nonexistent. The most common sources of technophony in our study were those emitted by road traffic, aircraft, snowmobiles, and oil and gas compressors. Low frequency

sounds emitted by these noise sources were centralized in urban areas, the most important predictor of technophony. Yet, technophony extended to areas ≤ 2.5 km from their source. This is likely explained by the fact that >75 % of our sample locations had ≥ 1 record of airplane noise and nearly 50 % had ≥ 1 record of noise produced by snowmobile activity. Noise from these sound sources were the only technophony recorded in remote areas.

Although it is difficult to associate airplane noise over KENWR with specific land cover variables in

Fig. 8 Predicted distribution of geophony soundscape power (normalized watts/kHz) in Kenai National Wildlife Refuge, Alaska (60.3333°N, 150.5000°S) over winter (December 2011–April 2012)



remote areas, the source of airplane noise can be associated with the urban areas where airports are located. Additionally, technophony had a positive relationship with increasing snowmobile activity, a covariate expressed as the number of snowmobile tracks/0.06 km² that occurred in remote locations of KENWR's interior (Mullet 2014). These remote areas are only accessible by snowmobile trails along the urban-KENWR interface. Our results suggest that urban areas from where airplanes and snowmobiles originate have a more significant acoustic footprint on

wilderness soundscapes than other technophony emitted along the urban-KENWR interface. The encroachment of technophony beyond urban areas have been found to occur in other parts of North America (Barber et al. 2010; Lynch et al. 2011) with significant impacts on wildlife behaviors and community structure (Forman and Deblinger 2000; Francis et al. 2012; Ortega 2012; Ortega and Francis 2012).

Another notable observation is the inverse acoustic–environmental relationship that biophony had with snowmobile activity. While our analyses cannot explain

the cause of this relationship, our results do suggest that vocal wildlife are exhibiting a distinct spatial separation and possible avoidance of areas where snowmobile activity is high. These findings raise important questions regarding the extent to which snowmobiling in KENWR is affecting wildlife habitat selection, their behavioral responses, and access to food resources.

Despite the encroachment of technophony into remote areas of KENWR, geophony dominated most sound records and occurred at all of our sample sites. The occurrence of geophony in the winter soundscape was primarily nocturnal with fewer recordings during daylight hours. Moreover, 77 % of our geophony recordings had subtle and nearly inaudible sound events (constrained by the sensitivity of our microphones) which provide evidence that winter in KENWR is exceptionally quiet. The significance of these quiet periods and areas to animal behavior or other ecological processes is not yet known. It could simply be an indicator of the decrease in animal activity attributed to bird migrations outside the region, as well as the dormancy and hibernation of many species (Marchand 1996). Quiet areas could represent time periods and areas with less food resources that make them less desirable for wildlife, suggested by the strong relationship geophony had with lakes that remained frozen all winter and its inverse relationship to river corridors commonly used by birds. It may also be an indicator of locations with little or no human impacts given geophony's inverse relationship to urban areas (Online Appendix 4).

An additional component to consider is that organisms audibly perceive their sonic environment at different frequency thresholds (Fay 1988). What one organism or species may be able to hear is not the same as it is for another. For instance, the hearing frequency range for humans is 22–22,000 Hz (Sivian and White 1933), for owls is 200–12,000 Hz (Konishi 1973), and for cats ranges between 64 and 44,000 Hz (Miller et al. 1963). We recorded at 22,050 Hz which is within many species' hearing range. However, there is some degree to which our microphones differ from the acoustic sensitivity of wildlife species to sounds present within areas we deemed as “quiet”. Merchant et al. (2015) also pointed out that there are significant differences in the sensitivity between microphones. The microphones we used were the standard microphones included with our SM2s that have been used in other published soundscape studies (Gage and Axel

2014; Sueur et al. 2014; Tucker et al. 2014; Oden et al. 2015; Pieretti et al. 2015). Although it is possible that sounds during our study could have occurred below and above this frequency range, as well as outside the range of detection by our microphones, the sounds we were able to detect provide a good description of the winter soundscape within this threshold range in KENWR.

The proportion, temporal variation, and spatial composition of KENWR's soundscape are likely to change significantly from winter to summer. The resident human population of the Kenai Peninsula is >50,000 (U.S. Census Bureau 2010). However, in summer, the influx of tourists, largely drawn to the Kenai Peninsula for its exceptional recreational opportunities, substantially increases the human population in the area. This sizeable increase comes with an intensification of technophonic sources associated with >1 million vehicles traveling the Sterling Highway, motor boating, and personal and chartered air tours that occur over the longer daylight hours of the subarctic (Comprehensive Conservation Plan 2010). The Kenai Peninsula is also home to, or a stop-over for, 176 migratory bird species whose numbers fluctuate throughout KENWR during spring and fall migrations (Kenai National Wildlife Refuge 2014). The significant increase and augmentation of human and bird activity in this region would clearly contribute a higher volume of technophony and biophony to the soundscape. An additional study on KENWR's summer soundscape would likely reveal these activity changes in comparison to our findings.

Our results and those of Mennitt et al. (2014) provide substantive evidence that soundscapes are closely linked to the characteristics of the landscape, and that sound levels and sound sources of the soundscape vary temporally at daily, monthly, and annual timescales. Although sound metrics alone do not provide information of sound sources, when they are combined with individually identified sound sources, sound metrics such as soundscape power (normalized watts/kHz), dB, and the acoustic complexity index (Pieretti et al. 2011) can provide useful information on the nature of the acoustic environment.

We found that winter in our study area is especially unique in that quiet geophony is a dominant and likely meaningful component to the winter soundscape. The rapid increase and expansion of mechanized human activity has led to an escalation in technophony in the

environment and it continues to threaten the naturalness of wilderness areas (Dumyahn and Pijanowski 2011). Our results clearly show that technophony produced by the mechanical activities of Kenai Peninsula's human population extends well beyond the spatial footprint of infrastructure in and around KENWR.

Soundscape conservation is increasingly becoming a focus on public lands in the U.S. (Miller 2008; Pilcher et al. 2009), as well as in endangered ecosystems around the world (Irvine et al. 2009; Dumyahn and Pijanowski 2011; Monacchi 2013). Management of soundscapes with the goal of conserving natural patterns and processes, and providing human generations with unimpaired soundscape experiences, should be considered before technophony intensifies any further in protected areas. We were able to use soundscape power, individually identified sound sources, and machine learning to produce spatially-explicit models that provide a valuable baseline for soundscape conservation and direction for additional soundscape studies in this region. Our work is particularly relevant as human populations grow and wintering bird communities redistribute in response to a rapidly changing climate (MacLean et al. 2008).

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Compliance with ethical standards

Conflicts of Interest The authors declare that they have no conflict of interest.

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