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ENVIRONMENTAL ACOUSTICS AS AN ECOLOGICAL VARIABLE TO UNDERSTAND THE DYNAMICS OF ECOSYSTEMS

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WOOYEONG JOO

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Major Professor's Signature

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ENVIRONMENTAL ACOUSTICS AS AN ECOLOGICAL VARIABLE TO UNDERSTAND THE DYNAMICS OF ECOSYSTEMS

By

Wooyeong Joo

A DISSERTATION

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ABSTRACT

ENVIRONMENTAL ACOUSTICS AS AN ECOLOGICAL VARIABLE TO UNDERSTAND THE DYNAMICS OF ECOSYSTEMS

By

Wooyeong Joo

Although acoustic variables play a key role in understanding the ecology and behavior of vocal organisms, little work has been done to investigate whether acoustic signals can serve as an ecological variable to assess the current state of ecosystems. Our research was guided by two overarching questions. The first question is can environmental acoustics be used as ecological attributes that reflect ecosystem structure and processes? The second question is can environmental acoustics provide a key means to measure and monitor the biodiversity and distribution of vocal species? The study first developed analytical methods to understand acoustic properties including: 1) development and refinement of an Acoustic Habitat Quality Index using the distribution of acoustic power across different frequency spectrum bands; and 2) measurement and analysis of vocalizing species diversity using multiple methods of recording acoustic signals. The second part of the study investigated a new approach to surveying avian species using acoustic recordings. This analysis revealed that automated acoustic recordings facilitated simultaneous breeding bird surveys at multiple locations with minimal variability and high accuracy of bird community measures. Third, the study characterized the urban-rural variability using environmental sounds based on quantification of environmental acoustic properties across a gradient of ecosystems and landscapes. Finally, the study illustrated that using wireless sensor networks as a new sampling tool in ecology and environmental science provides tremendous opportunities to measure and monitor

complex ecological variables at relevant spatial and temporal scales. The integration of acoustic research with the multi-science communities and advances in wireless sensor networks will potentially enable and enhance our understanding of ecological change and our ability to forecast changes in complex, interconnected ecosystems at scales ranging from the ecosystem to global level

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Introduction to Soundscape and Acoustic Ecology

Introduction

It has long been recognized that research on acoustic signals has enabled us to understand behavior and communication of vocal species. For instance, the North American Breeding Bird Survey (BBS), one of the largest long-term, national-scale avian monitoring programs, has been conducted for more than 30 years, based on auditory and visual cues observed by humans (Bystrak 1981, Robbins et al. 1986, Ralph et al. 1993, Sauer et al. 1994, Ralph et al. 1995). Weir and Mossman (2005) noted in their discussion of the North American Amphibian Monitoring Program (NAAMP) that identifying amphibian species has been done primarily by listening to their calls. Thus, identifying vocal organisms by auditory cues enabled the BBS and the NAAMP to monitor the abundance and distribution of bird and amphibian species and their phenological patterns. Acoustic signaling of vocal organisms can enable us to further investigate the effects of habitat transformation and climate variability on biodiversity.

Kroodsma et al. (1996) established a theoretical framework and clear demonstrations describing the diversity of vocal development in avian species and the extent of spatial variation of bird songs within and among populations. Other studies provided clear evidence that vocalizations in birds and frogs were highly influenced by and adapted to their habitat structures (Wiley and Richards 1978, Ryan et al. 1990).

Although acoustic signals have provided a great deal of biological information in many ecological studies, acoustic research has focused primarily on the significance of species-specific sounds in nature with a few attempts to interpret the implications and mechanisms of songs and calls at population or community levels (Warren et al. 2006).

It has been proposed that acoustic signals could contain some dimensions of ecological information about the environment (Truax 1984b) and therefore could be used to measure the dynamics and patterns of ecosystems (Gage et al. 2001, Napoletano 2004). Little work, however, has been done to investigate whether acoustic signals can serve as an ecological attribute for describing the characteristics of ecosystems and the changes in animal biodiversity, and to demonstrate whether soundscapes can reflect the current state of various ecosystems.

Concept of Soundscape

A dictionary defines the term soundscape as 'an acoustic environment or an environment created by or with sound' (The American Heritage Dictionary 2000). According to this definition, the soundscape is related to many areas such as music and acoustics, social science, and physics. However, from an ecological perspective, the term soundscape refers to the collection of sounds emanated by acoustic forces in a given place including abiotic, anthropogenic, and biological acoustics including human voices (Schafer 1994, Napoletano 2004).

Schafer (1977) first introduced the idea of the soundscape, defined as the biophysical environment or place where sounds are emitted, and stated that measuring and understanding the structure and function of soundscapes could provide a key means in environmental assessment. The dominant soundscapes in pristine ecosystems include the sounds of flows of abiotic components (e.g., wind, water, thunder, rain, etc.), and acoustic activities of vocal organisms (e.g., birds, frogs, insects, and mammals). In contrast, highly urbanized areas are dominated by the industrial and mechanical acoustic forces produced by anthropogenic activity. The soundscape in agricultural areas will result in an intermediate intensity of sounds both from anthropogenic and biological activity. The structures and components of the soundscape have thus far been qualitatively described, but the quantitative measure and analysis of the soundscape is necessary to understand ecological interactions between biological and human activities within heterogeneous landscapes.

According to Schafer (1994), the soundscape consists of three different elements: *'keynote sounds,' 'sound signals,'* and *'soundmarks'*. *Keynote sounds* are originally borrowed from a musical term that identifies the key of a piece. The keynote sounds may not always be heard consciously, they are mostly produced by physical and biological events such as movement of air (wind), flow of water, signaling of birds and insects. Traffic and other mechanic sounds are also the keynote sounds in urban areas. On the other hand, *Sound signals* are the acoustic signatures that can be heard consciously (such as bells, whistles, horns, sirens, etc.). Lastly, s*oundmark* originated from the term landmark, and refers to a unique acoustic signature produced from a particular area.

The soundscape can also be classified into three primary components by an acoustic frequency spectrum: biophony, anthrophony, and geophony (Gage et al. 2001, Napoletano 2004) (see Figure 1.1). The term "biophony", originally coined by Krause (1998), describes the complex chorus of ambient biological sounds. This category encompasses the natural sounds produced mostly by vocalizing birds, amphibians, insects and mammals. The acoustic frequency spectrum of most biophony generally ranges from 2.5 kHz to 8 kHz. The biophony also include two characteristic signals: 1) intentional signaling, which is transmitted to exchange information about mating, territory defense, etc., and 2) incidental, referring to the signals that propagate but do not include the explicit purpose of communication. In addition, because humans have had a significant impact on natural environment, the term, Anthrophony, was devised (Gage et al. 2001). Anthrophony refers to any acoustic signals created by human activities such as musical performance and oral conversation, or mechanical sounds resulted from operations of machinery and automobiles. The frequency spectrum of anthrophony ranges from approximately 40 Hz to 2 kHz. The last category, geophony, refers to the set of sound generated by physical processes including wind, rain, river flow, and so forth. Geophony generally includes the frequency spectrum of interest from approximately 40 Hz to 11 kHz, depending on intensity of the physical sound.

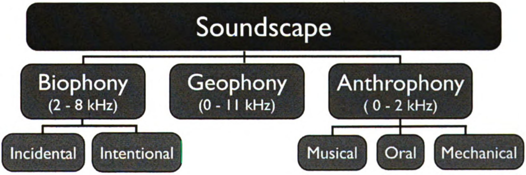


Figure 1.1 Diagram of the classification of a soundscape classification (modified from Gage et al. (2001)

These acoustic components have less distinct boundaries than landscape elements and often overlapping ranges of sound frequency. The spatial scale of the soundscape can vary, depending on the number and the detection capacity of acoustic sensors and recording devices. The frequency spectrum of the soundscape considered in this study ranges from 20 to 11,000 kHz, because this spectrum range is audible to the human ear; and many vocal organisms utilize this spectrum range for their communication.

The functions of the soundscape are to provide organisms with a sonic environment to communicate intra- and interspecific interactions, and to indicate the current states of acoustic sources. It is unlikely that changes in soundscape structures have a significant influence on transformation or alteration of landscape configurations. Rather, the properties of soundscapes will respond to alteration of spatial patterns in landscapes and the associated movements of landscape objects. The soundscape thus can function to provide critical information about landscape change. However, few studies have attempted to identify the potential functions of soundscapes and thus they still remain little known (Napoletano 2004).

Soundscape changes may occur as the consequences of movements of acoustic resources as well as any disturbance to an acoustic environment. Soundscape dynamics can substantially vary among different temporal scales from day to season to year. However, the repeated dynamic patterns of the soundscape can be observed over a long time period. Overall, anthropogenic disturbances will commonly amplify changes both in landscapes and soundscapes.

Interrelationships between the landscape and the soundscape

The relationships between soundscapes and landscapes have been little studied and rarely documented. In order to investigate the relationships between the landscape and the soundscape, several conceptual hypotheses are posed.

The first hypothesis states that spatial patterns and structures of a landscape do not have a direct relation to the characteristics of the soundscape (null hypothesis). Rather, potential processes of acoustic sources are more likely to have a critical influence on changes in soundscape structures. However, this hypothesis is unlikely to be accepted because acoustic sources are likely to be closely related to the spatial configuration of the landscape.

The second hypothesis states that greater heterogeneity of a landscape will produce a more diverse soundscape. Acoustic diversity refers to the patterns of frequency and temporal variability of the acoustic spectrum, indicating the degree that different vocalizing organisms will utilize different frequency niches to propagate information within a soundscape. It was shown that birds and amphibians make selective use of an acoustic frequency when attempting to communicate information such as mating potential, territory size, and potential predation (Catchpole and Slater 1995, Narins 1995, Kroodsma and Miller 1996). This hypothesis assumes that more diverse features of a landscape will result in diversity of acoustic environments where unique soundscapes are established. Furthermore, when the communication of vocalizing species is disrupted by human activities, the organism contributing to the soundscape can be adversely influenced. In contrast, habitats with less human activities tend to exhibit the more complex biological sounds in terms of acoustic frequency and periodicity.

In connection with the concept of the acoustic diversity, Krause (1997) proposed the "Acoustic Niche Hypothesis" in which each vocal species can develop a dynamic niche by adjusting the temporal and frequency properties of its respective signals to unfilled portions of the soundscape in order to avoid competition for spectral or temporal resources.

Although variability and diversity of soundscapes occur, dependent on spatial configuration of landscapes and the extent of disturbances, these suggested hypotheses need to be validated so that robust relationships between soundscape and landscape attributes can be established.

Given that environmental acoustics has played a key role, not only in inferring the ecology and behaviors of vocal organisms, but in understanding the dynamics of ecosystem structure and processes, it was proposed that environmental acoustics can be used as an ecological indicator of the state of the ecosystems (Napoletano 2004). To meet the requirements of ecological indicators, the acoustic variable has several advantages. First, sounds can reflect the degree of stress and perturbation in an ecosystem, and can be routinely and easily monitored; Second, current technology enables us to deploy acoustic monitoring systems with relative ease and minimum cost, leading to less interruption of the sites by human activities. Lastly, measuring environmental sounds provides integrated ecological information by interpreting their complex structures and identifying sound sources.

The overall objectives of this research are to investigate whether environmental acoustics can be used as an ecological attribute to indicate the current ecosystem status and to determine if sound can be used to measure and monitor the biodiversity and distribution of vocal species. To understand the acoustic characteristics in an ecosystem, numerous acoustical data were collected at many locations in different ecosystems over varying lengths of time. The specific goals of the study are:

- Develop an analytical framework to characterize the structures of environmental acoustics.
- Understand spatial distribution and temporal variability of environmental acoustics.
- Compare accuracy and efficiency of methods used to conduct acoustic surveys.
- Assess the state of varying ecosystems and landscapes using metrics of biological acoustic activities and anthropogenic acoustical disturbance.
- Establish and develop long-term ecological monitoring and observation systems based on environmental acoustics.

To accomplish the specific goals, the study is organized into five chapters. Chapter One introduces the concept of the soundscape, and provides a overview of acoustic ecology. Chapter Two describes the framework to enable understanding of the structures and components of environmental acoustic signals proposed by Gage et al. (2001). This chapter also includes the conceptual process of quantification and extraction of ecological information from acoustic signals. Chapter Three investigates whether acoustic recordings have the potential to survey abundance and distribution of breeding birds. In this chapter breeding birds were surveyed using automated and manual acoustic recordings to compare the accuracy of this method with the traditional point count survey method using the human ear as the sensor. In Chapter Four, I investigate whether a quantitative acoustic index could be used to describe the characteristics of different landscapes along an urban-rural gradient. This part of the research investigates and describes the relationships between anthropogenic noise and biological acoustics. In addition, I investigate how the acoustic index can be associated with social and economic variables. Chapter Five examines the concept of environmental cyberinfrastructure and the application of an automated sensor system in terrestrial ecosystems. Here I describe the design, development and application of an automated wireless sensor system to monitor and transmit environmental acoustics to a remote location for subsequent analysis and interpretation. Chapter Five provides a summary and conclusions about the findings of this research. In addition, I describe the accomplishments and challenges associated with this study as well as suggest future directions and potential research.

Chapter Two
Development of Analytical Framework to Understand the Structure and Components of Environmental Acoustic Signals

Sound has played a critical role in understanding the behavior of vocal aquatic and terrestrial animals, because vocal communication is a fundamental means of interaction within and between species. Sound has been used in ecology to census organisms (i.e. birds, amphibians, and mammals), and sound signatures of complex ecological communications has been identified and interpreted(Kroodsma and Miller 1996). This chapter will address the background of acoustics, and describe the data process and the analytical framework to understand the structure and components of environmental acoustic signals. Lastly, case studies are described to provide evidence of how acoustic signals can be applied to describe changes in different ecosystems.

Background of acoustics

Sound refers to vibration or compression waves transmitted through a solid, liquid, or air, and encompasses three main types determined by the acoustic frequency spectrum: 1) infrasound, 2) ultrasound, and 3) audio/sound (Rossing 2007). Infrasound is located in the frequency below 20 Hz, and is not audible to the human ear. In general, infrasound is generated from the natural events such as avalanches, earthquakes, and volcanoes (Tempest 1976). Ultrasound is sound with the frequency spectrum above 20 kHz, and is also beyond the upper limit of human auditory sensitivity (Larkin et al. 1996, Hopp et al. 1998). Ultrasound has been used in many fields, especially in medical science using ultrasonography. Ultrasound is also produced by some animals for communication, navigation, and predation, including marine mammals, bats, some rodents, and even a few amphibians (Feng et al. 2006). Lastly, audio refers to sound that can be heard by human ears, including frequencies from 20 Hz to 20 kHz. Vocalizations of many song birds, terrestrial mammals, amphibians, and insects fall into the audio-frequency spectrum similar to those of humans (Dooling 1982, Fay and Wilber 1989).

Sounds have physical properties of waves including frequency, wavelength, period, amplitude, intensity, speed, and direction (Rossing 2007). 'High pitched' or 'lower pitched' thus refer to sounds with high frequency (the number of cycle per a given time) or low frequency. Wavelength or period represents the distance or time of one cycle unit of sound wave. Because wavelength has an inverse relationship with frequency, longer wavelengths have lower frequencies and vice versa. Using these acoustic properties, sounds can be sampled, measured, and quantified. A common process in acoustic measurement is to record sound samples using a microphone and to analyze the acoustic signals based on frequencies and amplitude in a given time.

To analyze and interpret the characteristics of acoustic signals, there are two techniques in measuring sounds: 1) sound pressure level (SPL), and 2) sound power level (SWL). Both methods are computed with the same SI unit, "dB" but use different acoustic properties. Firstly, SPL is measured using the sound pressure (defined as the amplitude of an actual pressure of the sound wave in atmosphere, Pa). SPL is expressed as follows:

$$L_p(SPL) = 20\log_{10}\left(\frac{p}{p_{ref}}\right)dB$$

where p is the average sound pressure in a given period and p_{ref} is a reference sound pressure, commonly 20 μPa (threshold of human hearing) in air. This measurement represents the degree of sound loudness or amplitude, also called 'sound volume'. Because this equation is a logarithmic measure of the ratio between the root-mean-square sound pressure and the reference sound pressure, increasing 10 dB of a given sound means a 10 fold increase in the sound. In general, the SPL of traffic noise produced 10 m away from a highway is in the range of 80 to 90 dB and the SPL of jet engine sound 100 m distant is in the range of 110 to 140 dB. Sound pressure has been typically used to investigate the effects of noise on humans and wildlife because they are responsive to sound waves as pressure (Larkin et al. 1996). The perception of sound pressure in animals varies by different frequencies. Thus, it is important to estimate a sound pressure level (dB) with filtering or weighting of sound amplitude at different frequencies. The well-known method is called 'A-weighting (dBA)', approximating the threshold of human ear's response to sounds at different frequencies. Another common method of estimating SPL is 'C-weighting', cutting off the entire sound amplitude below low frequencies (about 50 Hz).

Sound power level (SWL) refers to a measure of sound power or sonic energy (watt), and is computed by the following equation:

$$L_w(SWL) = 10\log_{10}\left(\frac{p_1}{p_{ref}}\right)dB$$

where p_1 is the sound power, and p_{ref} is the reference sound power, commonly 10-12 watt in air. Sound power is not equivalent to the sound pressure but is proportional to the square of the sound pressure (Pw ∝ p2). Because the sound power is independent from the distance of the sound source, SWL can be employed to measure the sound power without knowing the distance from the source. Because both methods were developed to measure the noise of mechanical sound sources generated by human activities, they are not likely to be applied to measure the characteristics of entire soundscape.

Analytical tools to quantify and analyze environmental sounds

Although there has been pioneering research on the potential of soundscape to understand characteristics of environmental acoustics based on descriptive and qualitative analysis of sounds (Schafer 1977, Krause 1998), little work has been done to quantify and analyse the properties of environmental sounds and to extract ecological variables to indicate the various states of habitats and ecosystems. Analytical tools to compute and interpret acoustic data sets have been developed (Gage et al. 2001, Napoletano 2004, Qi et al. 2008), and consist of two main categories: Generalized Sound Classification Analysis (GSCA) and Acoustic Identification Analysis (AIA).

Generalized Sound Classification Analysis

This acoustical analysis was developed based on the hypothesis that every soundscape would have its unique acoustic signature, and the soundscape would have a common pattern of acoustic signatures in ecosystems with the same physical and biological components. Thus, this method characterizes the physical structure of environmental acoustic signatures from the data set, based on sound intensity with a particular combination of acoustic spectrum ranges.

Acoustic signal processing

There are two techniques used to process and quantify the values of sound intensity in a soundscape: the relative intensity value from a spectrogram and power spectrum density from digital sound samples.

***Quantification of spectrograms*:** Sound samples collected from a study site can be processed to extract acoustical information. To analyze and interpret the characteristics of acoustic signatures, a new analytical means was developed by quantifying the acoustic properties of the spectrogram (Gage et al. 2001, Napoletano 2004). Spectrograms are generated by digital signal processing based on the short-time Fourier transform (STFT)(Truax 1984a). In a spectrogram, time and spectrum frequency are plotted on the horizontal and vertical axis, respectively. The amplitude of the sound is represented by the intensity of each point in an image. This new acoustic processing technique enabled quantification of the spectrogram (Figure 2. 1). To accomplish this, the spectrogram image is divided into 1 kHz frequencies and then the intensity of sounds in each of three frequency ranges is computed. In this process, spectrograms are converted to 8 bit images with possible intensity values in the range from 0 to 255. For example, if a spectrogram visualizes acoustic signatures of the entire acoustic frequency filled with the maximum sound amplitude, the average intensity value is 255. As quantification and analysis of spectrograms is based on image processing techniques (Gage et al. 2001, Napoletano 2004), the method requires signal and image processing computation tools, a complex procedure, and a long duration for completing the entire process.

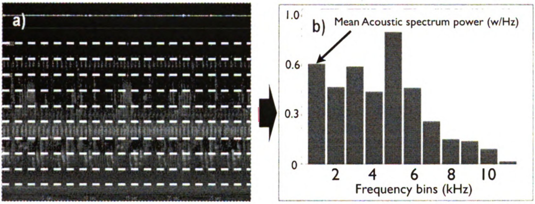


Figure 2. 1. The acoustic frequency slicing procedure. a) Each sound wave file is divided into 11 frequency bands, and b) the relative mean intensity is calculated for each band. Note that 5 kHz band has the highest mean intensity among 11 frequency bands.

Power spectrum density: In contrast to the spectrogram analysis, an approach was developed to directly process and quantify acoustic signals from sound data stored into a digital format (Gage et al. in submission). The sound samples were divided into 11 frequency bands (0-1 kHz, 1-2 kHz, ……, 10-11 kHz), and the power spectrum density (PSD) for each frequency band was calculated using MATLAB's signal processing tool based on Welch's algorithm (Welch 1967). PSD is computed with the unit, 'watt/Hz', and the values of PSD at each frequency band vary by the amount of the sound power in the sound sample. This method requires less computation time and eliminates the need to produce a spectrogram and subsequently apply image analysis techniques to quantify the mean number of pixels in each frequency interval.

Acoustic Habitat Quality Index

An Acoustic Habitat Quality Index (AHQI) was developed to interpret acoustic data from soundscape characterized by biological sounds (biophony) and mechanical sounds (anthrophony), based on the amount of acoustic energy in different frequency intervals. By analyzing a large number of environmental sound recordings, Napoletano (2004) found that the frequency spectrum of environmental sounds is concentrated into two main soundscape categories: Anthrophony and Biophony. Anthrophony consists of mechanical sounds mostly occurring at a frequency range from 1 to 2 kHz, whereas biophony (biological sounds) are prevalent between 3 to 8 kHz (Figure 2.2). Based on the method used to compute the Normalized Differential Vegetation Index (Myneni et al. 1995), normalized ratios of frequency levels were then employed to estimate the relative amounts of biophony or anthrophony in an acoustic sample.. The equation for AHQI is:

$$AHQI = \frac{\beta - \alpha}{\beta + \alpha}$$

where α, β represent the total amount of acoustic energy in biophony and anthrophony respectively. The value of AHQI ranges from -1 to 1. If the value of AHQI is 1, the sound sample is all biophony, while anthrophony is totally dominant in a sound sample when the value is -1.

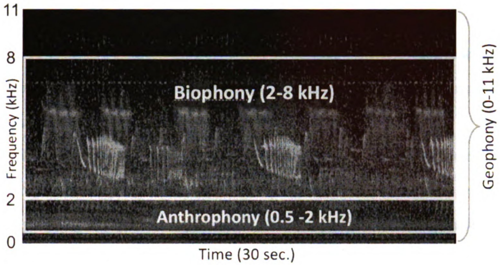


Figure 2.2. Three main classes of environmental sounds: 1) biophony, 2) anthrophony, 3) geophony, based on the location of the spectrum frequency bands.

This index provides an indication of the relative amount of biological and anthropogenic sounds occurring at a place, thus indicating the degree of human disturbance in an ecosystem. Patterns of the occurrence of these acoustic elements can be analyzed and trends assessed to develop estimates of acoustic signal types. The computation of these indices requires moderate processing capacity.

This method was employed to characterize and compare the relative contributions of biophony and anthrophony in soundscapes, and the results and applications of this index are addressed using specific examples provided in Chapter Three, 'Analysis and interpretation of the "Heartbeat of the City" using acoustic signatures along an urban-rural gradient'.

Principal component analysis (PCA)

To establish a statistical protocol to analyze acoustic signatures and characterize the combination of frequency bands for biological acoustics, a feasible statistical method to describe patterns of covariation in each acoustic signature is to calculate the eigenvalues and eigenvectors of the temporal covariance matrix among the different frequency bands using Principal Component Analysis (PCA). PCA has been widely used in many areas of ecology and biosystematics (James and McCulloch, 1990), and reduces the dimensions of observed variables by producing a smaller number of abstract variables. PCA is based on maximization of the variance of linear combinations of variables (Legendre and Legendre 1998). This statistical method is able to summarize patterns in the correlation matrix among the different frequency bands across the temporal extent at which the acoustic data was recorded. In the correlation matrix from the acoustic data set, eigenvectors are weightings of individual frequency bands contributing to sources of variability across the entire data set, and eigenvalues represent the variances of these sources. Thus, it is anticipated that each principal component will correspond to a set of contiguous frequency bands which characterize different classes of environmental sounds.

Our research shows that PCA can be used to separate the intensity of biological sounds from other types of acoustic signals (See Figure 2. 3). A large acoustic data set was collected from the Long Term Ecological Research (LTER) site at the W. K. Kellogg Biological Station, Hickory Corners, MI. from May 18 to July 15, 2005. Automated acoustic recording systems were deployed in 13 sites classified into two major land use types: agricultural (4 sites) and forested (9 sites). Note that when PCA was performed on the acoustic intensity data set, the first three principal components were determined as the key components because those components explained nearly 80 % of the variance in the acoustic signature data. The first Principal Component (PC) has negative loadings for all frequencies, implying that it indicates the amount of sound power across the entire frequency spectrum. The second PC has negative loadings at low to mid frequency bands (anthrophony) and is dominated with positive loadings in the sounds with high frequency bands (biophony). These patterns suggest that the distribution of high frequency sounds is relatively independent of low frequency sounds. In contrast, the third PC has high positive loadings for low frequencies (1 to 3 kHz), and moderately negative loadings for the mid to high frequency spectrum. The results show that when low frequency sounds are inversely correlated with high frequency sounds, there is a negative relationship between anthrophony and biophony.

The PCA method was further used to compare sounds recorded both within sites and between them, providing the capacity to separate the temporal and spatial dimensions of biological and mechanical sounds. The third Principal Component was selected because this PC includes the abstract information indicating which acoustic frequency band was highly associated with the intensity of biophony and anthrophony. Thus, PC3 scores on the Y-axis represent integrating acoustic variables from frequency 1 to 11 kHz. The positive PC3 scores contain biological signals (3 to 6 kHz) while the negative scores contain anthropogenic sounds (1 to 2 kHz). Note that the PC3 scores varied at different times and locations (Figure 2. 4), indicating the temporal and spatial variability of biophony and anthrophony. Note that high positive scores occurred in the morning and low negative PC3 scores occurred in the afternoon, providing evidence of the diurnal pattern of environmental sounds in the study site.

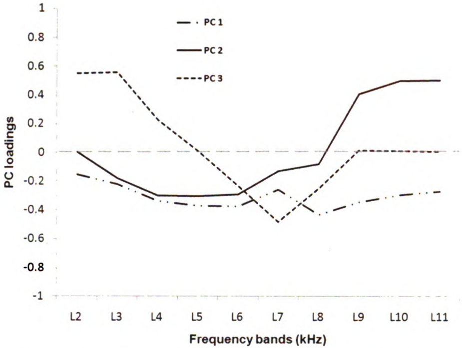


Figure 2. 3. Principal Component loadings of different frequency bands on the first three principal components from the acoustic data collected at the Long Term Ecological Research site in W. K. Kellogg Biological Station. The labels on X axis represent the acoustic frequency bands (e.g., L2 refers to the frequency band ranges from 1 to 2 kHz).

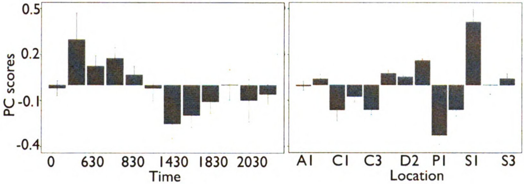


Figure 2. 4. Using principal component analysis, the temporal patterns of ecological sound intensity are shown on the left and the variability of biological or anthropogenic acoustic intensity at each site is shown on the right. The first letter of the location labels refers to one of five different habitats (A=Alfalfa fields, C=Coniferous forests, D=Deciduous forests, P=Poplar stands, S=Succession). The second letter of the location labels refers to one of three replicates. Means (+/- s.e).

Acoustic identification analysis

One advantage of quantifying acoustic samples to identify and census vocal organisms from recordings is that it provides a measure of the dynamics and patterns of vocal organisms in an ecosystem (Gage et al. 2001) as well as providing a permanent record of the observation. An analysis of the acoustic data set recorded at each site includes computing the PSD for each frequency level, visualizing the acoustic signatures in the spectrograms, listening to the songs and calls of vocal organisms, and then identifying species in the sound recordings.

The number of species present and the frequency of songs and calls made by each species were compiled resulting in an estimate of the relative species richness and abundance of vocalizations for each site. In addition to community measures including the number of species and vocalizations, bird species diversity was calculated using a modified Shannon-Weaver Index (Shannon and Weaver 1963, Magurran 1988, Blair 1996), thus providing an indication of biological acoustic diversity.

To illustrate the power of quantifying acoustic recordings of bird species, their acoustic signatures were identified from the sound recordings made at the W. K. Kellogg Biological Station, Hickory Corners, MI from May 18 to July 15, 2005. The number of species and their vocalizations varied in the different habitat types (

Figure 2. 5). The results show that more complex habitat types (e.g., early succession) had a higher avian species richness value and more frequent song occurrences. We were then able to characterize each habitat sampled in terms of the dominant bird species (Apendix 2.1).

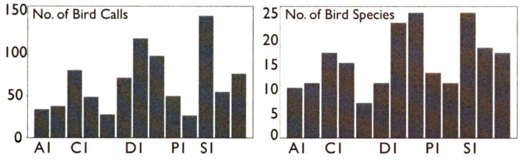


Figure 2. 5. Avian species were identified by listening to the recordings. The number of bird species identified is shown on the left and the number of calls identified is shown on the right.

Furthermore, the relationship between species richness and the abundance/intensity of biological sounds was examined. The results indicated that the number of avian species determined from the sound samples was positively related to the number of bird vocalizations in these recordings (Figure 5.a); Acoustic biodiversity was also positively related to the PC3 scores which indicate the intensity of biological sounds (Figure 5.b)

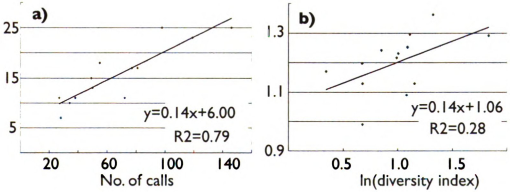


Figure 2. 6. a) The relationship between avian species richness and the number of calls, and b) the relationship between acoustic species diversity and PC3 scores (indicating the biological acoustic energy).

Chapter Three
Use of acoustic recordings for surveying avian species richness and distribution

Introduction

Surveying birds has provided ornithologists and wildlife biologists with a great opportunity to quantify species richness, abundance and spatial distribution of species, to illustrate the avian-habitat relationship, and to monitor changes in avian populations and communities (Rosenstock et al. 2002, Thompson 2002, Williams et al. 2002, Bart 2005). For example, the North America Breeding Bird Survey (BBS), one of the largest regional biological data sets across North America, has been conducted more than 30 years to monitor populations and communities of breeding birds at regional and national levels (Robbins et al. 1986). The BBS was established in 1966, in response to the concern over pesticides resulting in less reproductive success and increasing death of animals (Carson 1962, Patuxent Wildlife Research Center 2001), and so far has contributed data for more than 270 scientific publications up until 2002 (Peterjohn and Pardieck 2002). Moreover, many studies in support of the BBS data revealed a significant decline in populations of North American breeding birds, particularly species that inhabit forest-interior and grassland areas (Robbins 1979, Whitcomb et al. 1981, Herkert 1995). The declining trends of some avifauna populations might be caused by lack of breeding, wintering, and migration stopover habitats due to the extensive reduction and fragmentation (isolation) of their habitats (Robinson and Wilcove 1994, Herkert 1995, Robinson et al. 1995).

Although the BBS has played a key role in monitoring and understanding trends of breeding bird populations and communities across North America, some concerns about the quality, validity and variability of the BBS data have been raised. The BBS has used the point-count method; one of the most commonly used survey methods in identifying and counting birds (Ralph et al. 1995, Rosenstock et al. 2002, Thompson 2002). The point-count method consists of an observer listening to, seeing and identifying all birds within a fixed distance at a certain points in an area block or along line transect during the breeding season (Hutto et al. 1986, Ralph et al. 1995). Several studies have addressed concerns about using the point count method to survey birds, because of the inconsistency of detection probability among species and habitats or across time (Thompson 2001, Rosenstock et al. 2002), Others have raised issues due to different levels of observer ability (i.e., experience and skills of survey, age, and hearing loss) (O'Connor et al. 2000). It has been suggested that the method should be improved (O'Connor et al. 2000) or supported by other methods (Parker III 1991, Haselmayer and Quinn 2000, Zimmerling and Ankney 2000, Hobson et al. 2002, Rosenstock et al. 2002, Thompson 2002, Conway and Gibbs 2005, Acevedo and Villanueva-Rivera 2006). Given that animal vocalizations serve as a fundamental means for many vertebrates and invertebrates to communicate with each other, using acoustic recording technology for breeding bird surveys has been suggested to increase detection and reduce variability (Parker III 1991, Hobson et al. 2002, Conway and Gibbs 2005, Acevedo and Villanueva-Rivera 2006). In addition, when using only the point count method, there is no validation of species identified by an observer. However little work has been done to investigate the potential utility and applications of automated sound recordings and comparing species counts using these methods to those obtained by the point count method.

There are several advantages in the use of automated recording of biological acoustic signals in support of the BBS point-count method including: 1) reduced variability of detection probability within and among observers; 2) calibration and cross-validation of data; 3) higher detection rate for identifying secretive birds in grasslands and marsh areas (Parker III 1991, Allen et al. 2004, Conway and Gibbs 2005), 4) discovering new taxa in remote regions (Haselmayer and Quinn 2000), and 5) establishment of an archive and inventory of avian species thus building a birdsong digital library (Parker III 1991).

Several studies have attempted to take advantage of acoustic signals for measuring the abundance and distribution of bird species. Hobson et al. (2002) used arrays of omni-directional microphones to survey breeding bird species in mature deciduous stands areas in Canada. Allen et al. (2004) and Conway and Gibbs (2005) compared detection rates of breeding marsh birds in passive and sound-playback surveys in South Dakota. Recently, the effectiveness of using automated digital recording systems was investigated for avian and amphibian surveys in the north coast of Puerto Rico (Acevedo and Villanueva-Rivera 2006). However, there are limitations regarding the accuracy of acoustic recordings for detection of breeding birds across various habitats in temperate regions.

To address some of the issues, we investigated the detection probability of breeding birds using acoustic recording technology, in addition to following the protocol for the conventional point-count method to survey breeding birds. While recording the soundscape on digital media during the time in which the observer conducted the point count method, we set up automated recording units at each stopping position along the transect to monitor the temporal variability of surveying birds.

Methods

Study area

This investigation was conducted in two locations in Clinton County, Michigan. The study sites were selected based on the Michigan Breeding Bird Atlas mapping system which consists of township, range, and section to identify location (Kalamazoo Natural Center 2002). Two blocks were identified for the survey sites: one in Essex Township (T08N R03W, Block 2) and the other in Westphalia Township (T06N R04W, Block 4) (Kalamazoo Nature Center 2002). According to the Michigan Breeding Bird Atlas protocol, 25 points per block were selected from the point map which the MiBBA provides to surveyors. The sites were classified into five habitats: wet and dry forests, row crop fields, grasslands, and shrubs, representing typical habitat types in this temperate region.

Survey methods

The Essex Township block and the Westphalia Township block were surveyed on June 12 and on June 22, 2007, respectively (Figure 3. 1). Each study consisted of three different breeding bird survey methods: 1) Point Count Surveys (PCS), 2) Manual Acoustic Surveys (MAS), and 3) Automated Acoustic Survey (AAS). PCS was performed according to the survey protocols of the Michigan Breeding Bird Atlas II program (similar to the Breeding Bird Survey-style point counts) (Kalamazoo Nature Center). While conducting PCS for 5 min at each station, a field observer used a standard point count data form to record the following observations: geographic and meteorological observations, the name and the abundance of all avian species, and the time and distance of when and where each bird was first detected. The observer also noted whether the bird observed was within or beyond 50 m. This survey also recorded whether the bird identified was heard or seen (Haselmayer and Quinn 2000). The survey was conducted for 5 minutes at each of the 25 locations along the transect.

As PCS was being conducted at each location, a digital recording was made simultaneously for 5 minutes. In Essex Township a Sony® Mini Disk with a Sony MS957 microphone was used and in Westphalia Township, we used a Tascam digital recorder (HD-P2) with an Omni-directional microphone (ATR55, Audio-Technica Inc.). Recordings were captured in Waveform Audio (.wav) with a 22 kHz frequency sampling rate and a monaural channel. In general, a sampling rate is determined to double the highest frequency spectrum (Hartmann 1998), because most avian songs and calls are generated in frequency spectrum ranging from 2.5 to 8 kHz.

To capture the temporal variability of the avian survey we placed an automated recording unit (Sangean VersaCorder®, C. Crane Co with an Omni-directional boundary microphone, RadioShack Co. Model 330-3020) at each point count location. Each of the 25 recorders was programmed to automatically record ambient sounds for 5 minutes each hour from 0500 to 1000 hrs. The recordings were digitized from audio tapes employing the same protocol used for manual acoustic recording (22 kHz with monaural channel in waveform format). Once sounds from acoustic surveys were all digitized and archived in a digital acoustic library, bird species were identified by listening to bird songs and calls in the recordings.

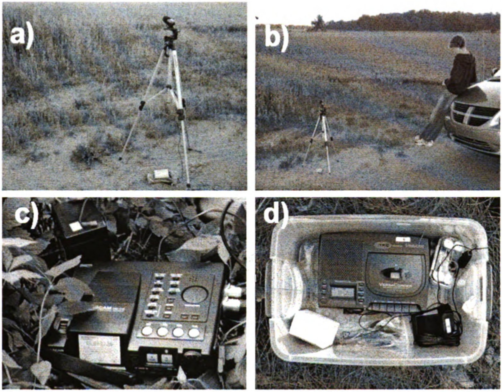


Figure 3. 1. Field bird survyes using a point count method and acoustic recordings in Clinton County, Michigan during June 2007: a) field configuration of the Manual Acoustic Recording (MAR) method using an Omni-directional microphone and a digital acoustic recorder; b) simultaneous bird surveys by human observation and MAR; c) a digital acoustic recorder (Tascam HD-P2) deployed in a point; and d) field deployment of an acoustic recording unit including an audio cassette-tape recorder with a timer (SanGeanVersaCorder) and a omni-directional microphone (330-3020) for Automated Acoustic Recording (AAR).

<u>Data Analysis</u>

The first objective of the study was to test the similarity of the three survey methods based on the number of bird species identified by point counts (human ear) and by digital audio recording including manual recordings and the automated recordings at each location. Prior to comparing the observations using the three different methods, the bird counts observed as "flying over" by point count method were excluded from the analysis because it was difficult to compare this type of observation with the other methods.

The primary objectives were to test the similarity of bird species detection using the three survey methods and to examine the total number of bird species identified by each method. Community similarity measures including the Jaccard's coefficient and the Sorensen's quotient of similarity were used to compare composition and number of species among three surveys is in the study sites (Hobson et al. 2002). The similarity indices were initially developed for comparing the communities with number of species (Krebs 1998), but the indices were modified to compare the species data among the survey methods instead of communities.

We investigated the results of the three survey types in terms of avian species richness. The number of bird species identified by each survey method was estimated at each location. As the species richness data set was normally distributed, a one-way analysis of variance (ANOVA) was performed. The Tukey's pairwise comparison method was conducted to examine mean difference of species richness among the bird detection methods.

The acoustic recordings cannot be used to identify the number of individuals of each species observed at each point unless microphone arrays were established at each location and this was beyond the scope of the study. Instead, it was assumed that one individual of a species identified at each location by all methods was considered as an encounter regardless of how many individuals of the species were seen or heard at each point. A paired t-test was performed to test whether there was a significant difference of avifauna species occurrence among the three survey methods used to determine avian species presence.

The number of bird species identified in the automated acoustic recordings was determined for each hour (e.g., 5am, 6am… 10 am). We thus investigated the temporal pattern of avian species richness during the survey time.

Results

The number of avian species detected in the acoustic recordings was almost the same as those identified using the point count survey. All survey methods combined identified 64 and 60 bird species in Maple Rapids and Westphalia respectively (Table 3. 1). The highest number of bird species was identified using the point count method in both Essex Township and Westphalia Township. Automated acoustic recordings failed to identify 7 and 6 species in Essex Township and Westphalia Township respectively. There were 14 and 9 species identified by human observation, but not by manual acoustic recordings in Essex Township and Westphalia Township, respectively.

Avian community similarities among the survey types

Bird community estimates between point count surveys and the two recording surveys had high similarity indices ranging from 0.71 to 0.89 (Table 3. 3). Similarity measures between point count surveys (PCS) and automated acoustic surveys (AAS) had consistent similarity indices in both sites (0.75 based on Jaccard's coefficient and 0.85

based on Sorenson coefficient in Essex and Westphalia sites), whereas similarity measures between PCS and manual acoustic recordings (MAS) differed in two study sites (0.70 and 0.80 of Jaccards' coefficient and 0.83 and 0.89 of Sorenson's coefficient in Essex and Westphalia sites respectively).

Table 3. 1. The number of bird species identified by point count survey (PCS), manual acoustic survey (MAS), and automated acoustic survey (AAS) in Essex and Westphalia Township.

Site	Number of species in all surveys	Number of species in PCS	Number of species in MAS (%)	Number of species in AAS (%) (500 – 1000 hrs)
Essex	64	59	45	52
Westphalia	60	54	45	48

Table 3. 2. Bird detection accuracy of all three survey types, based on the total number of species identified in Essex and Westphalia Township.

Site	Detection accuracy in PCS (%)	Detection accuracy in MAS (%)	Detection accuracy in AAS (%)(500 – 1000 hrs)
Essex	92.19	70.31	81.25
Westphalia	90.00	75.00	80.00

Table 3. 3. Community similarity measures (Jaccard's coefficient / Sorensen coefficient) to investigate similarity of avifauna community between Point Count Survey (PCS) and counts from two acoustic recordings: Manual Acoustic Surveys (MAS) & Automated Acoustic Surveys (AAS).

Jaccard's coefficient / Sorensen coefficient				
	Essex		Westphalia	
	AAS	MAS	AAS	MAS
PCS	0.75/0.85	0.70/0.83	0.75/0.85	0.80/0.89
AAS		0.75/0.85		0.71/0.83

Relationship between the survey types and species richness

The bird survey methods had a significant effect on bird species richness in Essex Township ($F=9.10$; $df = 2$; $p < 0.01$) and Westphalia Township ($F=3.66$; $df = 2$; $p < 0.05$). The average number of species per location between Point Count Survey (PCS) and Automated Acoustic Recording (AAS) was not significantly different ($p > 0.05$), whereas there were significantly fewer species identified in the Manual Acoustic Recordings (MAS) than in the PCS and the AAS in Essex Township ($p < 0.05$) and Westphalia Township ($p < 0.05$) (Figure 3. 2 1).

Species abundance estimate analysis

The number of encounters, defined as the number of locations where each species was identified, was used to determine the relative abundance of bird species. For instance, if the number of encounters for the American Robin is 23, this means that this species was identified in 23 out of 25 locations in the Township. In Essex Township, the point count survey methods (PCS) identified Indigo Bunting and Song Sparrow as the most abundant species, whereas the Song Sparrow and the American Robin were the most abundant species according to manual acoustic recordings (MAS) and automated acoustic recordings (AAS), respectively. In Westphalia Township, Song Sparrow was the most abundant species based on all methods (See Appendix 3.1 and 3. 2).

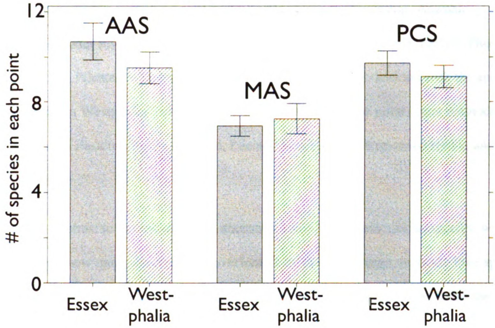


Figure 3. 2. Mean (± SE) of number of bird species at 25 survey points where all three surveys were conducted in Essex Township and Westphalia Township, MI. PCS, AAS, and MAS refer to three bird survey methods: Point Count Survey, Automated Acoustic Survey, and Manual Acoustic Survey, respectively.

The comparative analysis of bird species occurrence measures indicated that there was no significant difference between the number of encounters by point count surveys (PCS) and automated acoustic recording method (AAS) in Essex Township (t-value = 1.67, n = 50, P = 0.101) and Westphalia Township (t-value = -0.08, n = 50, p = 0.935). However, fewer encounters were measured using the manual acoustic recording methods

(MAS) compared to the point count survey method (t-value = 4.42, $n = 40$, $p < 0.001$ in Essex Township and t-value = 3.43, $n = 48$, $p = 0.001$ in Westphalia Township) and automated acoustic recordings (t-value = -2.21, $n = 40$, $p < 0.05$ in Essex and t-value = -2.30, $n = 48$, $p < 0.05$ in Westphalia).

There were 13 species identified by the point count survey but not by the two acoustic recording methods in the two study sites. In Essex Township, Acadian Flycatcher, Alder Flycatcher, Blue-winged Warbler, Common Grackle, Eastern Phoebe, Green Heron, Pileated Woodpecker, and Wild Turkey were not detected with the acoustic recordings. In Westphalia Township, the birds identified by the point count methods only were the Eastern Phoebe, Mallard, Pileated Woodpecker, Red-tailed Hawk, and Wild Turkey.

In contrast to the use of digital acoustic recordings to detect avian species, we also investigated how many species were overlooked by the point count method. Five species, including the Brown-headed Cowbird, Eastern Bluebird, House Sparrow, Ruby-throated Hummingbird, and Sandhill Crane were identified using the two acoustic recording methods, but not by the point count method in Essex Township. In Westphalia Township, 7 species, including the Brown-headed Cowbird, Eastern Towhee, House Finch, Hairy Woodpecker, Scarlet Tanager, Yellow-billed Cuckoo, and Yellow-throated Vireo, were detected only by the recording methods.

Temporal pattern of bird species richness

The relationship between sampling time and cumulative species richness from automated acoustic recordings is shown in (Figure 3. 3). The cumulative number of species recorded from 5 am to 8 am accounted for 91 and 92 % of the total species richness in Essex Township and Westphalia Township, MI respectively. There were only 4 additional species identified after 8 am in the automated acoustic recordings in both Township surveys (See Appendix 3. & 3.4).

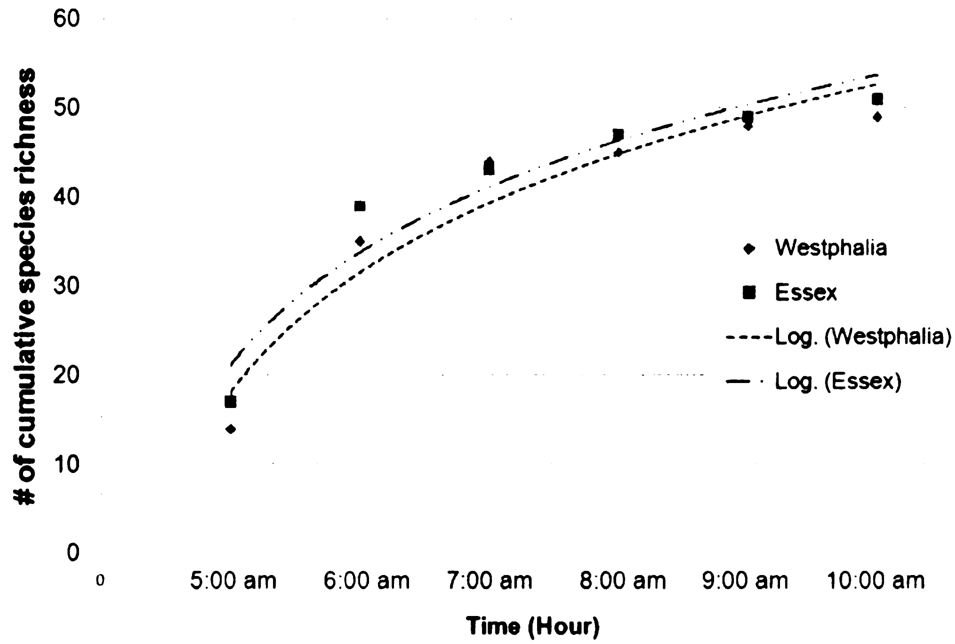


Figure 3. 3. The relationship between cumulative species richness and time of observation using automated recorders

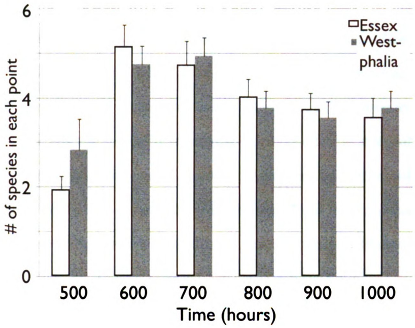


Figure 3. 4. Mean (± SE) of number of bird species at 25 survey points where AASs were conducted in Essex Township and Westphalia Township from 500 to 1000 hours.

Discussion

The study showed that overall there was no significant difference between point count surveys and automated acoustic surveys as methods to estimate species richness, and abundance of the avian community. Between the two acoustic recording surveys, however, automated acoustic recordings were more effective at identifying bird species than were the manual acoustic recordings. Automated acoustic recordings were made 6 times at hourly intervals at each location between 5 and 10 am, compared to manual acoustic recordings which were made for 5 minutes while the birds were being identified by the observer. Thus, as expected, automated acoustic recordings were more likely to capture vocal activities of bird species than manual acoustic recordings.

Although automated acoustic surveys indicated no statistical difference in species richness per location from point counts, some species were not identified among the survey methods. This lack of species detection by the acoustic recordings occurred in part due to the distance of the vocalization from the recording source and the fact that human observation can see birds that are infrequently vocalizing. Of the 13 species identified by human observation, 10 of these species were identified beyond 50 m, and 4 species were seen but not heard. When the species identified by human observation within 50 m were compared with those species identified in the acoustic recordings, the detectability of acoustic recordings accounted for 100 % and 95 % of all the species by point counts in Essex and Westphalia Township, respectively. These results show that all vocalizations by avian species can be identified using acoustic recordings if the detection distance is set to 50 m. The results also supported the suggestion by Schiek (1997) that 50 m detection distance is appropriate for identifying bird species based on the vocalizations among forest habitats in temperate region. He compared the ability to detect bird vocalizations among varied forest habitats and investigated the appropriate detection distance of bird songs, using the broadcast vocalization experiment. He found that all of the vocalizations were heard at 50 m from the broadcast whereas 27 % of the bird songs were not identified at 100 m. We found that the ability to detect species using acoustic recordings can be improved in multiple ways and future studies should investigate the variability of bird species detection in a diversity of physical environments and at different times (Schieck 1997). In addition, improvement in sensor technology, types of sensors, and sensor arrays all can improve detection range.

There were 5 and 7 species detected in the acoustic recordings but not in point count surveys in Essex Township and Westphalia Township respectively. One of the plausible reasons is that bird observers can overlook some bird species at locations with high species richness during the dawn chorus in the breeding season when peak of avian vocal activities occur (Bystrak 1981). The species only detected by acoustic recordings from 5 to 7 am (sunrise time is 6 am in this study area) accounted for 64 % of all 11 species above (Brown-headed Cowbird commonly found in both sites). Thus, acoustic recordings are less affected by observer confusion because recordists can repeatedly listen to the recordings. We can then use visual and auditory cues to detect bird species from the recordings by the aid of a spectrogram, a visualization of an acoustic signal with frequency, time, and intensity domains. Even so, the estimates can be verified by other field experts or ornithologists (Haselmayer and Quinn 2000). Moreover, in the study area, there are three species whose population status is of special concern in Michigan (Kalamazoo Nature Center 2002): the Dickcissel, Grasshopper Sparrow, and the

Prothonotary Warbler due to their rare status. In our study, these three species were detected by all three methods.

The results of the study support the "dawn chorus" hypothesis which states that the peak of avian vocal activity occurs at or near sunrise. Our results found that the number of species detected by the automated acoustic survey from 5 to 8 am accounted for more than 90 % of all species in the study area. There were only 2 additional species identified after 9 am including Easter Bluebird and Ruby-throated Hummingbird. Easter Bluebird is known as a "late riser" or sings softly so only a nearby female hears songs (Kroodsma 2007). Indeed, these two species were only detected by automated acoustic recordings but not by point counts.

Although point counts have played a key role in understanding avian species richness, abundance, and distribution across North America, the validity and variability of point count surveys have been questioned over years (Bystrak 1981, Thompson 2002). This study showed that by using an automated acoustic survey there was improved detection of species and reduced biases in observer errors. Moreover, automated acoustic recordings decreased the temporal variations by simultaneous recordings at multi-locations. Automation of acoustic recordings facilitated monitoring bird vocal activities without human interruption.

Despite the advantages of using automated acoustic recordings, some limitations are evident. First, acoustic recordings cannot easily estimate abundance of avian communities at locations. It is not feasible to distinguish different individuals of each species only by auditory cues. However, the development of new computer tools such as pattern matching and speech recognition to detect the unique acoustic signatures of individuals is progressing (Mills 1995, Chesmore and Nellenbach 1997, Chesmore 2004, 2007, Chesmore and Ohya 2007, Kasten et al. 2007). In addition, deploying a multi-array of microphones at a location can help to estimate the distance and direction of the sound sources, leading to an estimation of abundance and distribution of bird communities (Asano et al. 2001, Otsuki et al. 2007).

Since the automated acoustic surveys were conducted using cassette tape recorders in the study, it required many hours to digitize the tapes and to archive the recordings into an acoustic digital library. Moreover, it takes significant time for researchers to repeatedly hear and identify bird species. Thus, while the current study provides proof-of-concert, the development of automated acoustic sensor systems is necessary for wider application of these techniques (Gage et al. in submission).

In conclusion, the results provided evidence that acoustic recordings can be used as an alternative means to survey avian communities. Our study shows that automated acoustic recordings facilitate breeding bird surveys at multiple locations with minimal variability and high detectability of bird community measures, leading to correct interpretation of a long term pattern of avian species composition and distribution in regional scale (Rosenstock et al. 2002, Thompson 2002).

Chapter Four
Analysis and Interpretation of the "Heartbeat of the City" using Acoustic Signatures along an Urban-rural Gradient

Introduction

Urbanization causes substantial alteration of ecosystem structure and function (Vitousek et al. 1997). Noise, defined as "unwanted or detrimental sound or consistent level of background sound" (Stutz 1986, Forkenbrock and Schweitzer 1999), can be considered one of the main pollutants that causes degradation of human health and has negative impacts on animal communication. The impact of noise can vary depending on individuals; noise causes a variety of physical and psychological stresses from disturbance of sleep and communication to noise annoyance and even hearing loss (Forkenbrock and Schweitzer 1999, Ouis 2001, Warren et al. 2006). With this recognition of noise pollution, the European Union (EU) passed legislation that required member countries to provide the public with noise maps of all major or industrial cities, highways, and airports by 2007 (Butler 2004).

Recently, several studies have attempted to investigate the effects of urban noise on the reproductive success and distribution of animals. The breeding success of many avian and amphibian species appears to be impaired near roads with high traffic such as highways (Brumm and Todt 2002, Slabbekoorn and Peet 2003, Sun and Narins 2005). Extensively growing urbanization not only causes alteration of habitat structure and function, but also provides a novel acoustic environment where animals must either adapt or emigrate to communicate and reproduce. Warren et al. (2006) provided a conceptual overview of how some avian species have adapted to the acoustic environment of urban systems. Their study classified the modifications of bird calling behaviors by human noise into three categories: 1) "Amplitude shifts": sound amplitude of animal vocalizations increases when human noise occurs; 2) "Frequency shifts": many species produce their songs at higher acoustic frequencies than normal since most anthropogenic sounds have lower frequencies; 3) "Temporal shifts": birds shift the timing of their songs in order to avoid traffic noise. These adaptations of birds to the urban acoustic environment can make their reproduction successful. However the reproductive rate of most amphibians was drastically reduced near roads with heavy traffic, because amphibian vocalizations are masked by traffic noise (Sun and Narins 2005). Although some studies have addressed urban noise as a critical impact on the communication of vocal organisms and their reproductive success (Reijnen and Foppen 1994, Rundus and Hart 2002, Rabin et al. 2003, Katti and Warren 2004, Warren et al. 2006), little work has been done to understand the acoustic characteristics and the interaction between biological communication and anthropogenic sounds across various landscapes.

The structure of urbanized systems generally includes heterogeneous landscape patterns, ranging from rural to suburban to highly developed areas across the 'urban-rural gradient', depending on the density of human population. The urban-rural gradient can be characterized by several factors including: distance, land use types, vegetation structure, and landscape attributes (Blair 1996). The characteristics of environmental sounds can also vary depending on habitat type, the mosaic of habitats within the landscape, the time of day, and season of the year. Patterns of acoustic signals therefore reflect the dynamics of biological, social, and physical systems within each landscape.

Many groups of animals use acoustic signals to communicate information such as breeding condition, territory size, and predator alerts. Typically, ecosystems with a lesser degree of anthropogenic interference exhibit greater complexity in terms of sound frequency and periodicity. When anthropogenic noise disrupts this communication, critical information is not relayed and may result in population declines (Krause 1997). With the growth of human populations and their subsequent expansion away from urban centers, dramatic changes in the acoustic environment may occur. Therefore, investigation of how changing acoustic patterns along urban-rural gradients influence habitat quality and reflect that habitat's capacity to sustain its array of organisms is of critical importance.

Since human-induced noise has a critical impact on animal communication, reproductive rate, and the abundance and distribution of species, there should be an inverse relationship between Anthrophony (human-induced sounds) and Biophony (biological sounds) (Figure 4. 1). Biophony is expected to be greater in rural areas whereas Anthrophony is expected to be greater in the city where there is more human activity. Given the hypothetical relationship between anthropogenic and biological sounds, the various soundscape patterns will be dominant in different land types at different times of the day and vary depending on the season. Highly urbanized areas (e.g., commercial sites) are expected to have human-induced sounds outcompeting biological sounds over all seasons. In contrast, places with low development (e.g., rural sites) should retain higher biological sounds in breeding seasons than anthropogenic sounds (Figure 4. 1). Assuming that the theoretical relationship is applicable to any urban-rural gradient, we can investigate the urban-rural gradient by measuring several acoustic attributes including acoustic frequency, acoustic energy, and diversity (acoustic patterns) in an urban-rural landscape at different times of day over seasons.

The main objective of the investigation of acoustics in urban systems is to quantify the acoustic patterns in different landscapes across an urban-rural gradient. To meet the objective, we investigated whether: 1) characteristics of acoustic signals vary along urban-rural gradients and over different seasons; 2) urbanization adversely affects animal vocalizations; and 3) acoustic properties of urban systems are correlated with the structure and composition of landscapes.

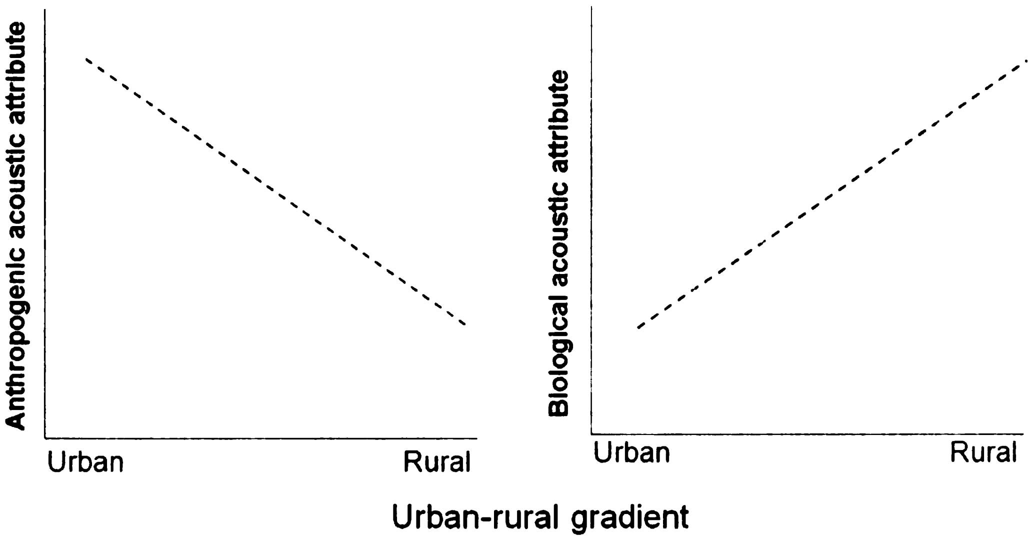


Figure 4. 1. Conceptual relationship between biological and anthropogenic acoustic attributes including acoustic energy at different acoustic frequency range, the number of species and vocalizations identified along urban-rural gradients. (Modified from Stevenson et al. (2004))

Methods

Study area

This study was conducted in the Greater Lansing area where Lansing is the capital of Michigan, and the sixth largest city in the state (Census 2006). Nineteen sampling sites were selected along two transects: one crossing from northeast Lansing (Bath Township) to southwest Lansing (Delta Township), and the other crossing from northwest Lansing (DeWitt Township) to southeast Lansing (Mason Township). The two transects cross at the Capitol Building in downtown Lansing. Most sites were spaced at 1.6 km (one mile) intervals. The distance from the most central urban site to the furthest rural site at each transact was about 10 to 11 km. The 19 sites were classified into five land use types: (1) rural areas, (2) urban parks, (3) urban residential areas, (4) agricultural areas, and (5) commercial areas (Figure 4. 2). An urban-rural gradient was defined with the five land use types ranked from the highest to lowest degree of urban development. The amount of land cover types was calculated at each site in a 100 m-radius circle (as determined from the maximum distance of microphone capacity to capture acoustic signals) using 2001 National Land Cover Data provided by the U. S. Geological Survey and 2005 aerial imagery by the Michigan Center for Geographic Information. The area of land cover areas at each site was converted to percentage of total site area (Blair 1996).

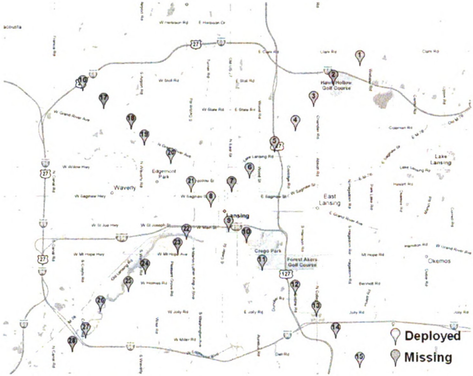


Figure 4. 2. Map of the study area in the Greater Lansing area, MI. Each named symbol in the map represents the location where an acoustic monitoring unit was deployed along an urban- rural gradient. The green symbols represent data that were collected from February to December 2006, and the red symbols are the locations where the recording devices were lost during the study period.

Survey methods

Environmental acoustic samples were collected once a month from February to December in 2006. At each location an acoustic recording unit was deployed. The recording technology used was an audio cassette-recording device (Sangean VersaCorder®, C. Crane Co.) and one powered Omni-directional boundary microphone (Model 330-3020, RadioShack Co.). The recording device was equipped with a timer which enabled automated collection of acoustic samples six times per day without human interaction. The microphone selected was able to capture the acoustic frequency range from 40 to 14,000 Hz within which most songs and calls of vocal organisms are produced.

Each acoustic unit was set to record for 3 minute duration, three times in the morning at 2:00, 6:00, and 10:00, and three times during the day and evening at 14:00, 18:00, and 22:00 for two consecutive days.

The recordings were digitized and transferred to a wave file with a 22 kHz frequency sampling rate and a monaural channel for quantification and analysis of environmental acoustic signals. The size of the data files was large and required a high-performance computer and extensive analysis. Each recording was divided into six 30-second sound clips. Only the 3 middle sound clips were analyzed because the first and last part of the raw sound files had recording variability such as recording duration and technical sounds due to the recorder start-stop cycle.

Data Analysis

Two analytical methods were used to extract the acoustical information from sound samples (Gage et al. 2001): (1) Acoustic Intensity Analysis, used to classify environmental sounds into three main categories (biological, anthropogenic, and geophysical sounds) by acoustic intensity and frequency range; and (2) Acoustic Identification Analysis, which identifies sound sources or vocal organisms from sound recordings.

(1) Acoustic Intensity Analysis

Each sound sample was analyzed to determine the spectral energy in 1-kHz frequency intervals by developing a program based on the Welsh algorithm (Welch 1967), using MATLAB software (Mathworks 2005). The numerical values resulting from this process provided a quantitative measure of how the energy is distributed across the acoustic spectrum. Based on analyzing a large number of acoustic recordings (Napoletano 2004), it was determined that the mechanical sounds (Anthrophony) were most prevalent between 1-2 kHz, and biological sounds (Biophony) were most prevalent between 3-8 kHz. Biophony was computed by the sum of acoustic power values at frequency range from 3 to 8 kHz. Similarly, Anthrophony is the acoustic power values between 1 and 2 kHz.

Based on the formula of Normalized Differential Vegetation Index (Myneni et al. 1995), an Acoustic Habitat Quality Index (AHQI) was developed to provide a classification of a place relative to its biological composition and human disturbance based on the amount of acoustic energy in different frequency intervals. Mechanical sounds produced by most machines (cars, airplanes, trains) occur at lower frequencies (average 1.5 KHz) whereas most biological sounds occur at higher frequencies (average 4.5 KHz). The distribution of sound frequencies in acoustic samples was computed to determine what types of sounds occurred (e.g., mechanical, biological or physical). Normalized ratios of frequency levels were then calculated to evaluate the relative amounts of biological or mechanical sounds in a sample or set of samples. The equation for AHQI is:

$$AHQI = \frac{\beta - \alpha}{\beta + \alpha}$$

where α, β represent the total amount of acoustic energy of mechanical sounds and biological sounds, respectively. The value of the index ranges from -1 to 1. If the value is negative, mechanical sounds are dominant at a sampling place. If the value approaches 1, biological sounds dominate at the site.

An Analysis of Variance and Tukey's multiple comparison method were performed to test whether acoustic variables, particularly the total sound level, the percent of both biological and anthropogenic sound intensities, and the AHQI, exhibit significant difference across different land use types. In addition, we investigated whether temporal pattern of AHQI varied across the land use types.

(2) Acoustic Identification Analysis

The recording process enabled the identification of species specific vocalizations. Bird species were identified from the acoustic recordings at each site, and the relative number and the calling frequency of species were quantified. Four acoustic samples were selected per site, recorded at 6 am on May 17-18, and June 14 -15 2006. In general, peak vocalization of bird species occurs about sunrise during their breeding season (Staicer et al. 1996). Regardless of how many calls and songs by the same species repeatedly occurred in one sample, these vocalizations were considered as one "encounter" in the sample (see Chapter 3). The maximum number of encounters per species was four because the total number of samples analyzed per site was four. By estimating the number of encounters per species, the relative occurrence probability of each species was calculated based on the ratio of the number of encounters in four acoustic recordings per site. For example, the House Finch was identified from all acoustic samples at site E05 (commercial area), so the number of encounters of the House Finch at that site was four. In contrast, because the American Robin was recorded two times in the samples, the number of the encounters was two. Accordingly, the probability of the House Finch and the American Robin was 1 and 0.5, respectively.

Bird species diversity was calculated by using a modified Shannon-Weaver Index (Shannon and Weaver 1963, Magurran 1988, Blair 1996). The equation used to compute biological diversity is:

$$H' = \left| \sum_{i=1}^{c} p_i \log(p_i) \right|$$

where H' is the Index of biodiversity and c is the number of bird species. Pi is the proportion of encounters of the *ith* species to total encounters of all species at each site. The mean values of species diversity for different land use types were calculated and compared. In this study, species richness was defined as the total number of bird species identified in the recordings.

The effects of urbanization on the composition of communities and distribution of individual species were analyzed in basis of Canonical Correspondence Analysis using R statistic package software (Blair 1996, R Development Core Team 2007). This analytical model has been applied to investigate how species respond to environmental gradients by separating the distribution of species in an ordination plot (ter Braak and Prentice 1988, Blair 1996). For this analysis, the number of encounters of each species at a site was used, and the environmental factors consisted of percentage area covered by forest, pasture/crop, lawn, and buildings/paved roads at each site (Blair 1996).

Results

The percent of area covered by forest, lawn, pasture/crops, and buildings/pavement varied with land use type (Figure 4. 3). Rural residential sites had the highest percent area covered by forest (49.2 ± 16.6) and the least amount of area covered by buildings/pavement. In contrast, commercial sites had the highest percent area covered by buildings/pavement (99.3 ± 0.7) and the least percent area covered by forest. The percent of land covered by lawn and pasture/crops was highest in the urban park and agricultural sites respectively (60.3 ± 14.4; 53.8 ± 7.8).

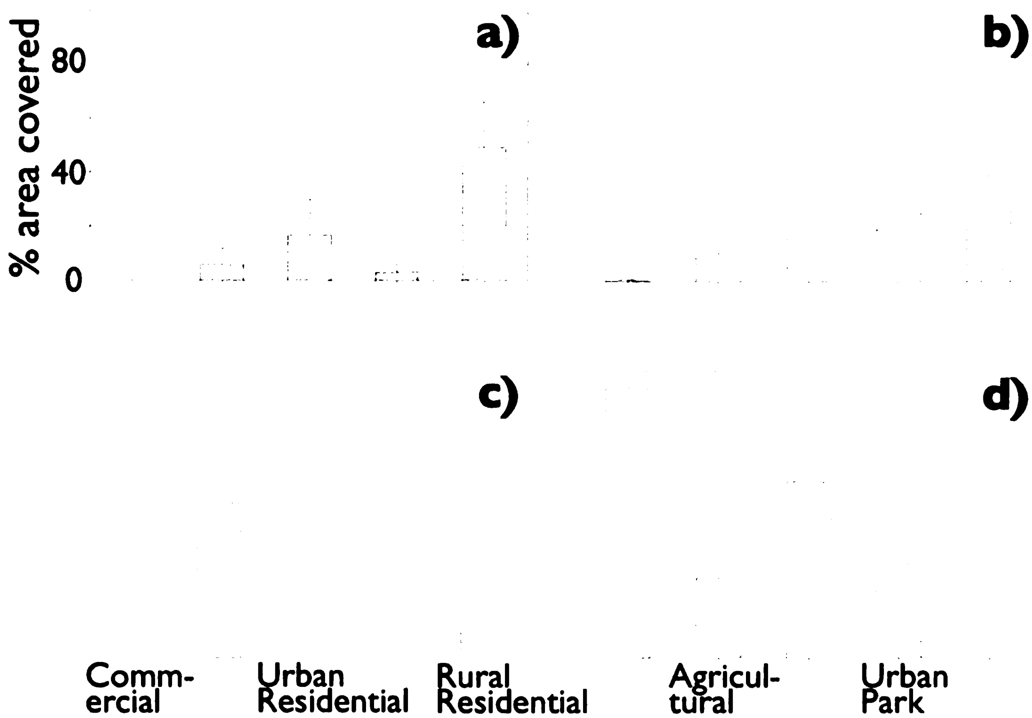


Figure 4. 3. Average percent of land covered by a) forest, b) lawn, c) pasture/crops, and d) buildings/pavement estimated by land cover maps and aerial photo imagery (mean + standard error)

Average total sound levels (dB) varied across all land use types (Figure 4. 4a). Land use type was ranked from the highest (left) to lowest (right) based on the degree of urban development, the urban-rural gradient. Commercial land use had significantly higher sound levels among sites (65.31 ± 0.104), and lower sound levels were found in agricultural, urban park, and rural residential land uses (One-way ANOVA, F = 506.1, p ≤ 0.05). Urban residential land use had moderate sound levels and sound level was significantly different from other land uses (62.78 ± 0.12).

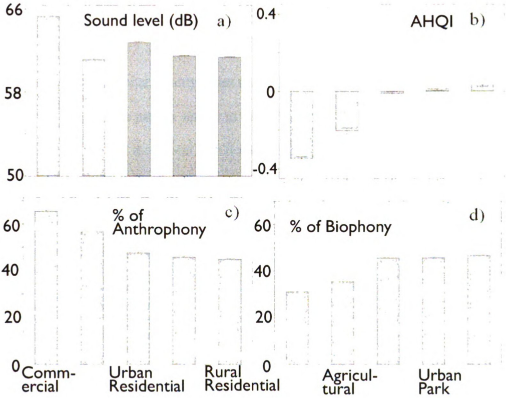


Figure 4. 4. a) Average sound levels, b) Acoustic Habitat Quality Index (AHQI), c) proportion of anthropogenic sounds (Anthrophony), and d) proportion of biological sounds (biophony) of 5 different land use types where the acoustic samples were recorded from February to December, 2006. The land use types was listed on x-axis along an urban-rural gradient, defined by ranking the land use types in order from the highest (left) to lowest (right) degree of urban development.

The bars represent mean ± SE (n = 8475). Lowercase letters refer to means contrasts among different land use types using Tukey's HSD tests.

The proportions of biological and anthropogenic acoustic intensity varied along the urban-rural gradient. Based on computation of Anthrophony and Biophony from February to December, 2006 (Figure 4. 4b and 4.4c), the average percent of Anthrophony gradually decreased along the urban-rural gradient, whereas the proportion of Biophony increased along the gradient. The proportion of Anthrophony was highest in commercial land use and lowest in urban park and rural residential land use; whereas the proportion of Biophony was highest in rural residential, urban residential, urban park land use and lowest in commercial land use ($p < 0.05$).

The Acoustic Habitat Quality Index (AHQI), a normalized ratio of Biophony and Anthrophony, showed the pattern similar to the Biophony measure (Figure 4. 4d). Commercial land use had the lowest AHQI value (-0.34 ± 0.01), and rural residential and urban park land use had the highest values of AHQIs across all land use types (0.03 ± 0.007; 0.01 ± 0.009). Although the AHQI values in rural residential and urban park land use were the highest in the study area, the values were small positive numbers, indicating that these land uses had only slightly more Biophony than Anthrophony.

Environmental sounds exhibited temporal variability across the different land use types examined. Because acoustic samples were made multiple times per day we were able to examine the diurnal and seasonal changes. Temporal patterns of AHQI in commercial and agricultural land uses were clearly different from those in rural residential land use types (See Figure 4. 5). The negative trend of AHQI in commercial and agricultural land uses occurred during most of the sampling period, whereas AHQI values were positive in rural residential land use except during winter. of AHQI showed high variability in urban residential and urban park land uses depending on time of day or season of the year.

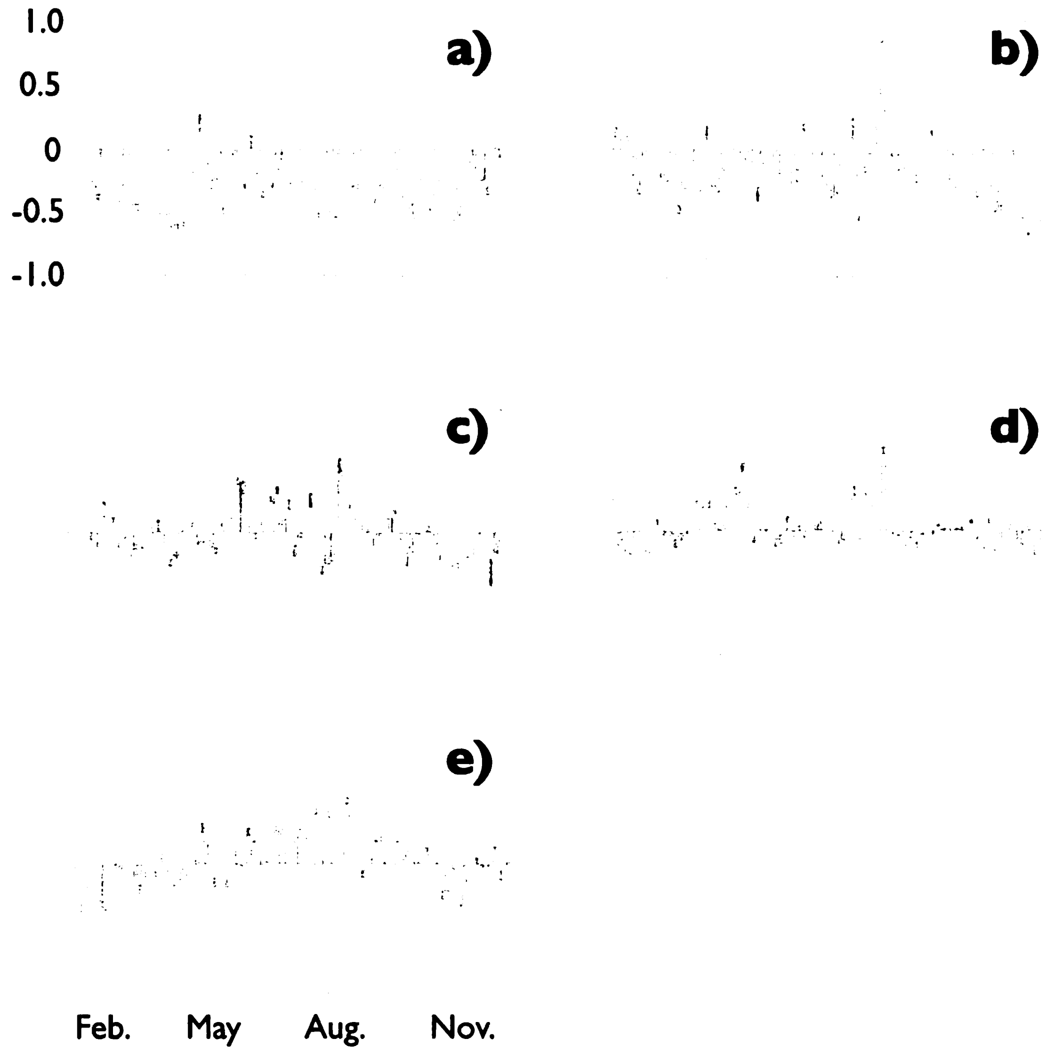


Figure 4. 5. Temporal changes in Acoustic Habitat Quality Index (AHQI) at 5 different land use types: (a) commercial; (b) agricultural; (c) urban residential; (d) urban park; and (e) rural residential sites. Data were collected 6 times a day for two consecutive days at each month from February 14 to December 12, 2006. Bars indicate average values of AHQI at each time of day during the month.

Twenty eight species of birds were identified from the recordings. Avian community species richness, abundance, and diversity were not significantly different between the sites (Figure 4. 6). However, commercial sites had the lowest values of species richness and diversity and rural residential exhibited the greatest richness and diversity.

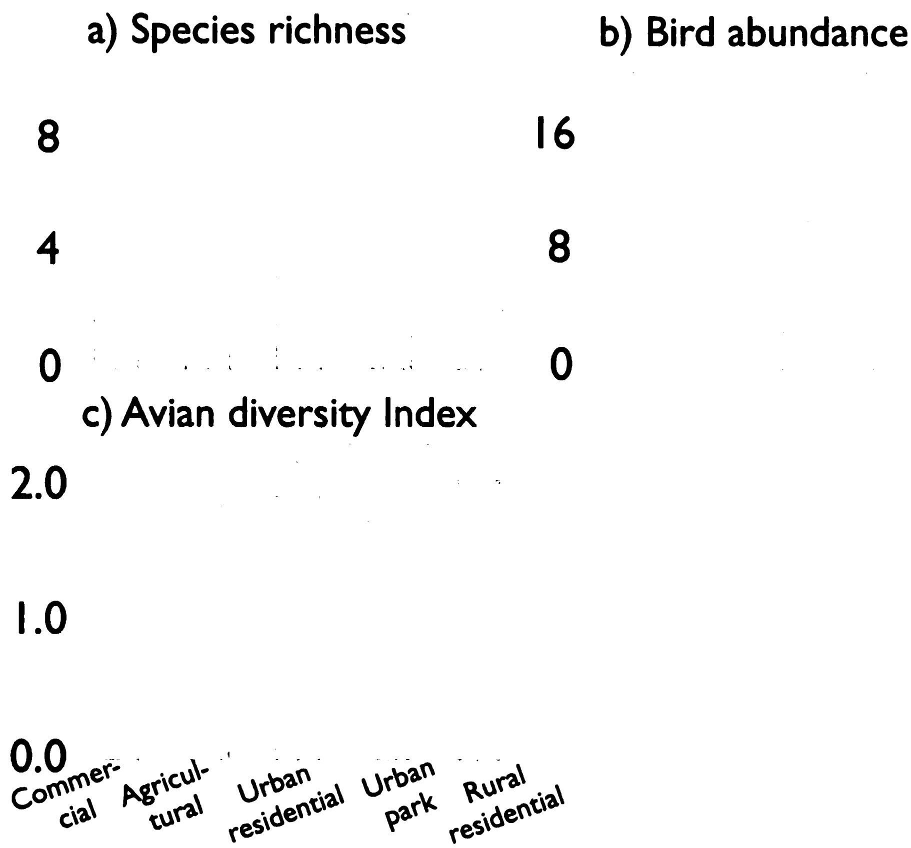


Figure 4. 6. Avian community measures along the urban-rural gradient from May and June 2006: a) mean number of bird species, b) mean number of encounters, and c) mean value of Shannon's diversity index at each landscape. Note that the bird species and their vocalizations were identified from 4 acoustic samples at each site during the period.

The relative occurrence probability of all avian species varied along the urban-rural gradient based on bird species identified by listening to the acoustic recordings

(Figure 4. 7). Four "urban adaptable" species were found in highly to moderately urbanized land uses: Cedar Waxwing (only detected in the commercial area); House Sparrow, House Finch, and European Starling (> 0.75 probability in the commercial area). Fourteen species were "suburban adaptable" (Blair 1996). These included the Song Sparrow, Northern Cardinal, American Robin (found in all types of land uses); Red-winged Blackbird, Chipping Sparrow, Gray Catbird, Yellow Warbler, Baltimore Oriole, American Goldfinch, Brown-headed Cowbird, Blue Jay, Common Yellowthroat, Horned Lark, Willow Flycatcher (the maximum occurrence probability of all species in urban residential land use). Seven species were "urban avoiders" with the maximum occurrence probability in rural land use (Tufted Titmouse, Black-capped Chickadee, House Wren, and American Crow), or only found in rural land use (Downy Woodpecker, Great Crested Flycatcher, and Red-eyed Vireo). The most abundant birds in the agriculture land use were the Canada Goose and Mourning Dove.

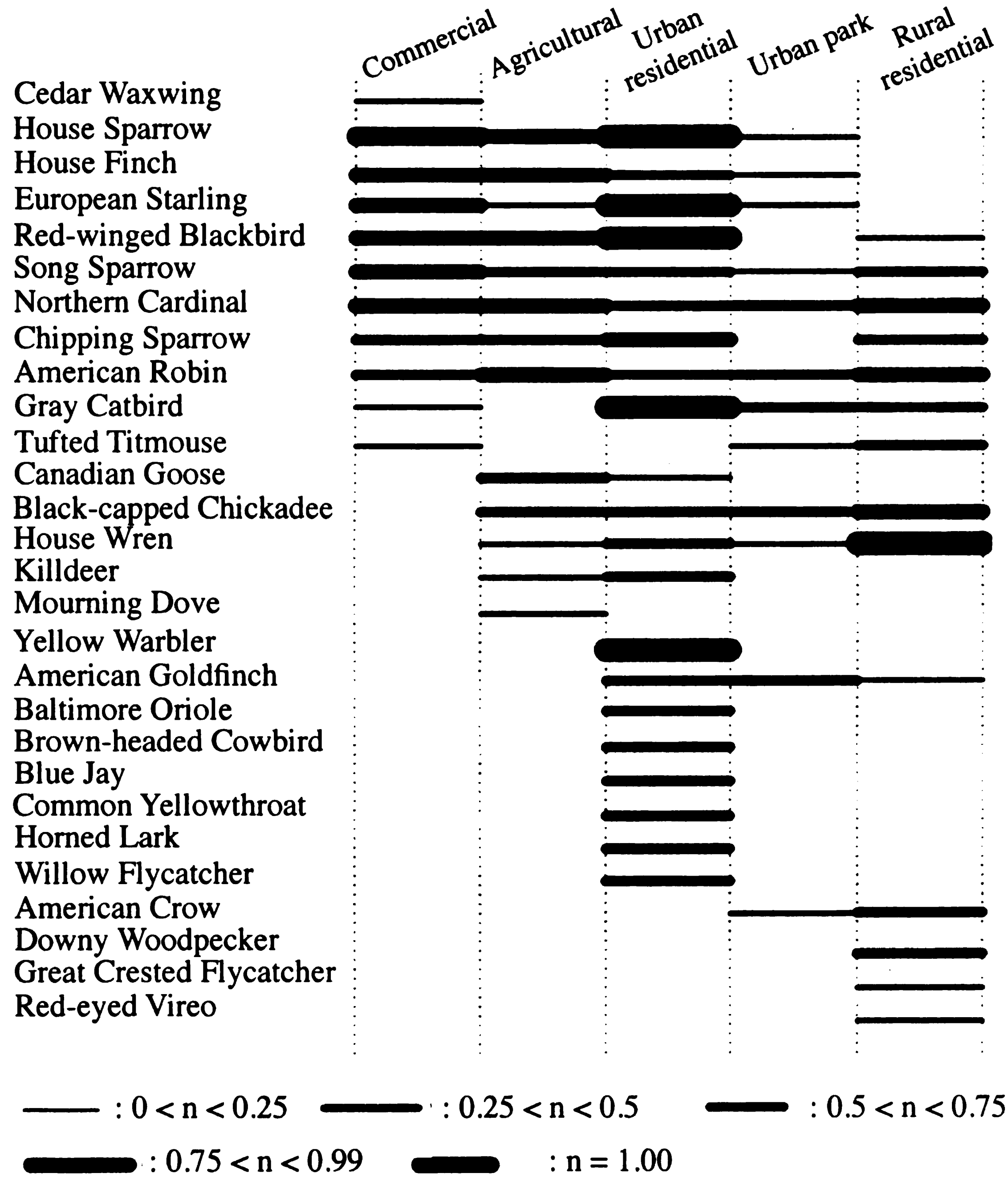


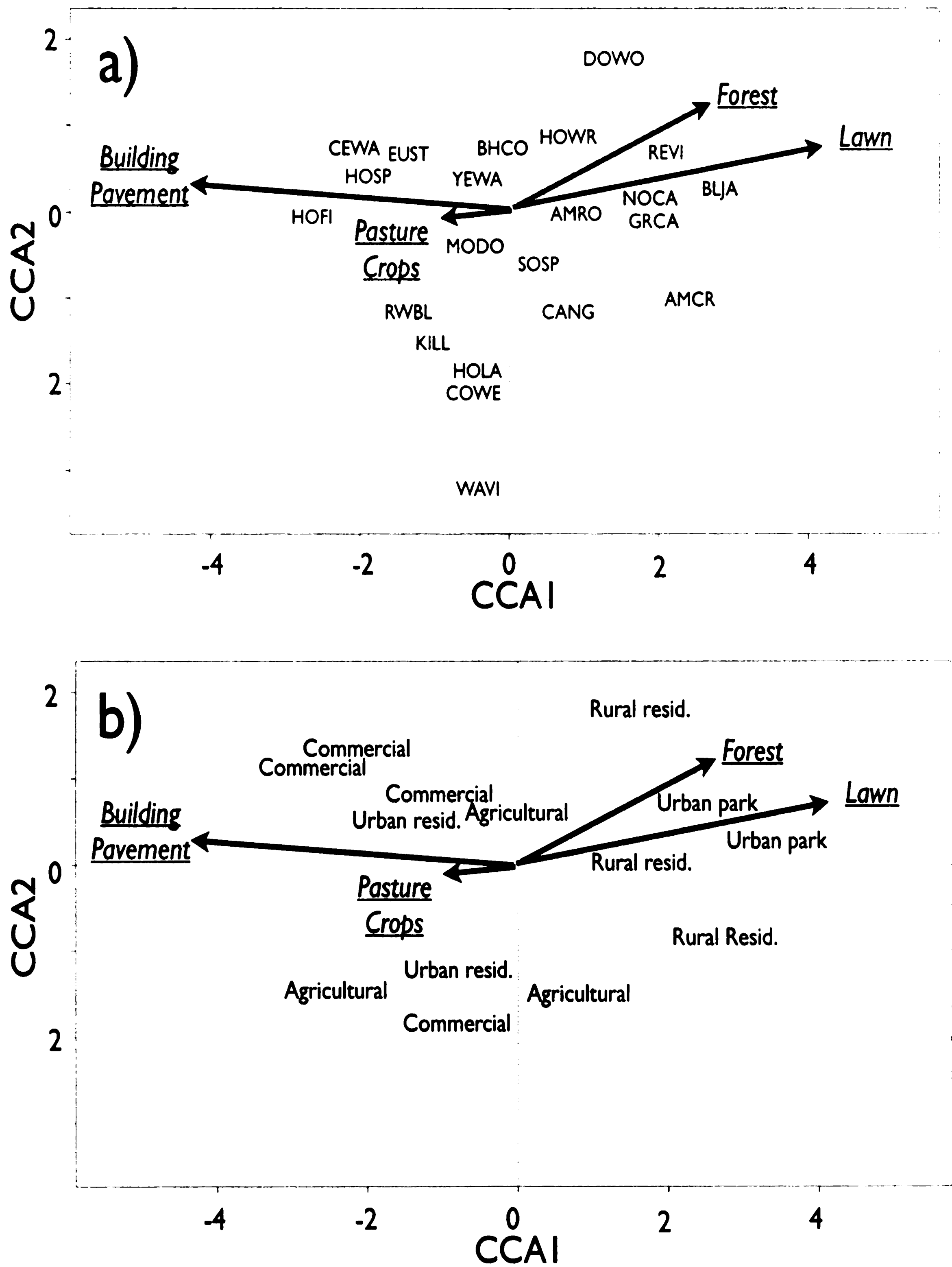
Figure 4. 7. Relative occurrence probability of avian species across all sites, listed in order from highest occurrence probability in commercial sites to greatest occurrence probability in rural residential sites (n = number of encounters/ total acoustic surveys)

A Canonical Correspondence Analysis (CCA) was performed to quantify the distribution of bird species in relation to the percent of land cover type. There was a significant relationship between the number of encounters of bird species and land cover types (Figure 4. 8). The direction and length of the arrows in the ordination diagram indicate the changes of environmental variables and the extent of correlation between the variables and the ordination axes (Blair 1996). The distribution of bird species in relation to the arrows (environmental variables) represents the preference of each species for a land cover type.

The canonical axes (the first two ordination axes) accounted for 26% of the variation in the bird species presence/absence data, which explained the percentage variance of the weighted average scores distributed in the ordination plot. The first two axes had species-environment correlations of 0.90 and 0.79. The correlations were calculated in combination with linear combination scores of environmental variables (here, the percent area of four different land cover types) and site scores that measured the weighted average of species scores (ter Braak 1986, Blair 1996, Oksanen et al. 2007). The first canonical axis in the plot separated bird species into groups by the extent of urbanization. The second canonical axis partitioned species into groups by open field (grassland and agricultural land uses) or non-open field (forests and building land uses).

The overall analysis and the first axis were marginally significant with more than 50 permutations (CCA: $p = 0.08$, Axis-1: $p=0.06$). This analysis demonstrates that the most important variables for relating bird species and land uses were the amount of area covered by building/pavement, forests, and pasture/crops.

Figure 4. 8. Ordination diagrams of canonical correspondence analysis (CCA) using bird survey data with environmental variables. (a) CCA ordination of 28 bird species (points) against 6 environmental variables (arrows; the percent areas of different land cover types: forests, lawn, pasture/crops, and buildings/pavement). The contribution of each environmental variable to the ordination axes is represented as the length of the arrow. The direction and distance of species scores to the arrows indicate how well the abundance of each species is related to each environmental variable (ter Braak 1986, Palmer 1993, Blair 1996). The angle between the arrows represents correlation between environmental variables. The smaller angle the arrows have, the greater the environmental variables are correlated. For example, the Forest and Lawn variables are highly correlated to one another. Four letter abbreviations represent species alpha code(Sharpe 1886). (b) CCA ordination of 18 sampling sites and linear combinations of environmental variables. The orientations of the site scores to the arrows represent how strongly the sites are related to environmental variables. See Appendix I for bird names and AOU codes


a)
DOWO
Forest
Lawn
Building
Pavement
CEWA
EUST
HOSP
BHCO
HOWR
REVI
YEWA
BLJA
NOCA
GRCA
AMRO
HOFI
Pasture
Crops
MODO
SOSP
AMCR
RWBL
CANG
KILL
HOLA
COWE
WAVI
CCA2
CCA1
b)
Rural resid.
Commercial
Commercial
Forest
Commercial
Urban park
Lawn
Building
Urban resid.
Agricultural
Pavement
Urban park
Rural resid.
Pasture
Crops
Rural Resid.
Urban resid.
Agricultural
Agricultural
Commercial
CCA2
CCA1

Discussion

The results show that acoustic properties are associated with the structure and composition of urban landscapes in several distinct ways. In general, biological acoustic energy increased along a gradient from highly urbanized to rural land uses, whereas anthropogenic acoustic energy was inversely correlated with the urban-rural gradient (See Figure 4. 4). Warren et al. (2006) showed that ambient noise levels, mostly consisting of motor vehicle traffic volume, were inversely correlated with the distance from an urban center to a suburban area in Phoenix, Arizona, and suggested further study to show how ambient noise or anthropogenic sounds affect animal vocalizations. However, that study did not reveal the source of ambient sounds. The environmental sound levels in our study did not show the same pattern as the measure of Anthrophony or biophony. Rather, simultaneous measures of biophony and Anthrophony strongly indicated that human-induced sounds were negatively associated with biological sounds.

On closer examination of the temporal patterns of AHQI values (Table 4. 1), commercial and agricultural land uses had negative AHQI values from February to December in 2006, whereas rural residential land uses had positive AHQI values, especially during the breeding season of vocal organisms. These results illustrate that high level of human activities and urban development can be negatively associated with animal vocalizations. Although agricultural land use includes large amount of vegetation, negative values of AHQI were caused by frequent mechanized cultivation activities (plowing, fertilizing, and harvesting) that overlapped with biological activities. In addition, agriculture land use did not provide suitable habitat for vocal animals because most agriculture land use in the study area planted in monoculture (low plant diversity).

In land uses with moderate development, including urban residential and urban park land uses, variability of AHQI values was high over all seasons, whereas AHQI values were positive in rural residential land use and remained consistent except in winter. The results imply that vocal species can respond differently to various levels of anthropogenic sounds. In general, vocal activities of bird species are most intense in habitats with the least human disturbance. However, high variability of biophony and Anthrophony occurring in land uses with moderate development suggests that some bird species in urban land use may modify their vocalization levels. Given that ambient noise influences communication of breeding birds, some studies have shown that male birds had higher song amplitude in a noisier environment than birds in natural habitats (known as the Lombard effect) (Brumm and Todt 2002, Brumm 2004, Katti and Warren 2004, Warren et al. 2006).

Table 4. 1. Temporal pattern of mean Acoustic Habitat Quality Indices (AHQIs) over months and at six times of day in all land use types.

Months	Commercial	Agricultural	Urban Residential	Urban Park	Rural Residential	ANOVA *P*
Feb	-0.37a	-0.09 a	0.02 a	-0.17 a	-0.24 a	0.01
Mar	-0.39 a	-0.27 b	-0.10 c	-0.03 c	-0.06c	< 0.001
Apr	-0.57 a	-0.17 b	-0.07 b	0.17 c	-0.08 b	< 0.001
May	-0.22 a	-0.12 a	-0.05 a	0.18 b	0.06 b	< 0.001
Jun	-0.20 a	-0.11 ab	0.19 c	-0.04 b	0.11 c	< 0.001
Jul	-0.26 a	-0.26 a	0.14 c	-0.01 b	0.26 d	< 0.001
Aug	-0.46 a	0.09 b	-0.01 b	0.29 c	0.30 c	< 0.001
Sep	-0.31 a	-0.15 b	0.05 c	-0.07 b	0.13 c	< 0.001
Oct	-0.32 a	-0.17 ab	-0.03 b	0.02 bc	0.11 c	< 0.001
Nov	-0.49 a	-0.32 b	-0.17 bc	-0.04 c	-0.17 b	< 0.001
Dec	-0.15 a	-0.49 a	-0.22 a	-0.08 a	0.00 a	< 0.001
Time of day						
02:00	-0.30 a	-0.05 b	0.15 c	0.09 c	0.10 c	< 0.001
06:00	-0.28 a	-0.24 a	0.07 b	0.03 b	0.00 b	< 0.001
10:00	-0.34 a	-0.14 b	-0.04 b	0.02 bc	0.08 c	< 0.001
14:00	-0.38 a	-0.28 b	-0.10 c	-0.02 bc	0.03 c	< 0.001
18:00	-0.40 a	-0.36 a	-0.17 b	-0.05 c	-0.02 c	< 0.001
22:00	-0.37 a	-0.16 b	0.01 c	0.03 c	0.00 c	< 0.001

* Mean AHQIs with the same superscript letter in each row are not signifinicantly different from one another (Tukey's multiple comparison)

The results suggest that vocal animals might overcome ambient noise in order to effectively exchange information with their conspecifics (Brumm 2004). However, not all animals show this type of behavior. Some birds shift either the song frequency range from low pitch to high pitch, or the timing of their songs, to counteract intense acoustic disturbance generated by human activities. Some species are not affected by ambient noise for their communication (Warren et al. 2006).

Given the relationship between Biophony and Anthrophony along the urban-rural gradient, it is possible to characterize urban landscapes using environmental sounds. A "Soundscape map" was produced based on the values of the Acoustic Habitat Quality Index. The average values of AHQI at the sampling sites were joined to attributes of each land cover class in the National Land Cover Data map (NLCD) 2001, and a map of the AHQI values were overlaid on the land cover classes in the study area. The spatial variability of the mean AHQI values is shown in Figure 4. 9. Negative values of AHQI occur in the center and main roads of the city, whereas the areas with less development have positive AHQI values, indicating higher levels of Biophony. This soundscape map showed how a cityscape can be characterized using environmental sounds. The accuracy of the map of AHQI values can be enhanced with an increase in the number and distribution of sampling sites and with additional ground verification (Gage et al. 2004). However, such soundscape maps can also be used to visually assess temporal dynamics of urban acoustic environment because our acoustic samples were made multiple times of day and over several seasons.

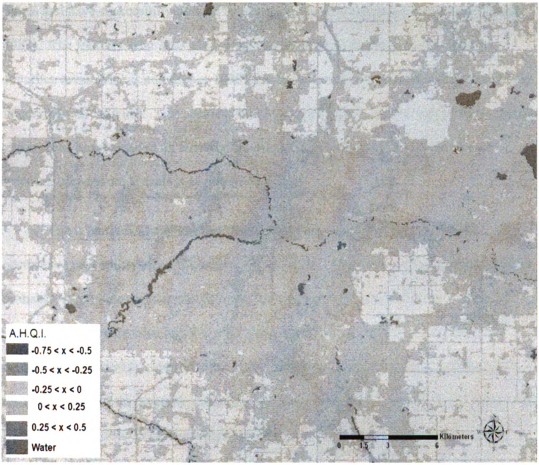


Figure 4. 9. Distribution of Acoustic Habitat Quality Index (the normalized ratio of biological sounds to anthropogenic sounds) based on National Land Cover Data map 2001. The index ranges from -1 to 1; positive values indicate that the intensity of biological sounds is higher than one of anthropogenic sounds, and vice versa.

The pattern of relative bird occurrence probability (encounters in a land use type/total encounters) demonstrates that the response of bird species to land use type can vary depending on the extent of urbanization (Blair 1996). Five species appeared to be highly adapted to urban areas. Three species, House Sparrow, House Finch, and European Starling, accounted for more than 75 % of bird occurrence probability in land use with high or moderate development. These species were introduced to the United

States and have successfully utilized resources in human-dominated ecosystems (Long 1981). The fourth, Cedar Waxwing, is known to be more common in open rural or suburban areas (Stokes and Stokes 1996), but in this study this species was detected only in commercial land use. This species, which generally feeds on a variety of fruits, berries, and insects, has expanded its territory to urbanized areas because serviceberries or weeping cherries are abundant as ornamental trees.

The urban residential land use had the highest species richness and bird occurrence probability along the urban-rural gradient. These suburban adaptable species probably utilize resources available in both urban and rural sites. This type of habitat structure can provide edge habitats with high primary productivity and diversity of resources (Cody 1985). Most classic studies in bird ecology conclude that urban sites resulted in lower bird diversity and abundance than natural sites (Graber and Graber 1963, Batten 1972, Guthrie 1974, Beissinger and Osborne 1982, Green 1984, Degraaf and Wentworth 1986). In contrast, Blair (1996) demonstrated that moderate levels of urbanization had the maximum species richness, bird occurrence probability and biomass, and that the Shannon diversity index peaks across various land use types in Palo Alto, California. He argued that the contradictory conclusions were drawn because previous works focused on comparisons of bird community measures in only two locations rather than in sites with various degrees of urbanization.

However, we conclude that moderate levels of urbanization provide a suitable habitat structure and abundant resources for bird species. The study did not investigate whether high occurrence probability and diversity of birds resulted in high reproductive success, and thus whether the population of each species can be sustained within the site

(Blair 1996). In addition, the edge habitats provided by urbanization can result in higher cowbird parasitism and nest predation than, for example, the interior of forest habitats (Gates and Gysel 1978, Johnson et al. 1990).

This study revealed that it is more critical to investigate the relationship between the biological and anthropogenic sounds rather than only the measure ambient noise levels. The study also provides clear evidence that biological sounds (biophony) are inversely correlated with anthropogenic sounds (Anthrophony) along an urban-rural gradient. This study also shows that recording and interpreting environmental sounds in human-dominated systems can offer enormous opportunities to not only measure ambient noise levels, but to also understand the components of the acoustic environment and how each component is related to another. It is suggested that urbanization affects not only the transformation of habitat structure for vocal organisms but also changes the soundscape, which can cause impairment of animal communication and breeding success.

Chapter Five
Development of Automated Acoustic Sensor Observation System via Wireless Networks

Introduction

Humanity has profoundly altered and degraded the biosphere in many ways (Vitousek et al. 1997). Pervasive human activities have resulted in the perturbation of the main biogeochemical processes and the transformation of about 40 to 50 % of the land surface on Earth. In addition, human domination and modification of earth systems have led to the massive loss of biological diversity (Vitousek et al. 1997, National Research Council 2001).

Given the drastic modification and degradation of ecosystems by human activities, the National Research Council (2001) proposed the "grand challenges of the environmental sciences": biogeochemical cycles, biological diversity and ecosystem functioning, climate variability, hydrologic forecasting, infectious disease and the environment, institutions and resource use, land-use dynamics, and reinventing the use of materials. Although those challenges in environmental science require measuring and monitoring complex environmental variables at various spatial-temporal scales, most ecological research has been conducted at small spatial scales and over relatively short-time periods (Porter et al. 2005).

Recently, several researchers argued that new advances in wireless sensor technology will help scientists to better understand the changes in ecosystem structures and processes at relevant spatial and temporal scales, providing a great deal of the spatially dense, near-real time observations in ways that were previously impractical and inaccessible to ecologists and environmental scientists (Estrin et al. 2003, Martinez et al. 2004, Porter et al. 2005, Butler et al. 2006, Collins et al. 2006, Hamilton et al. 2007, Kasten et al. 2007).

A wireless sensor network is a system with spatially distributed automated sensor arrays that monitor environmental conditions using wireless communication (Romer and Mattern 2004). Wireless sensor networks were initially developed for military applications and now have been used in many areas including agriculture, traffic controls, environmental monitoring, etc. (Estrin et al. 2003, Romer and Mattern 2004, Porter et al. 2005). In general, the sensor arrays used in environmental and ecological science can be classified into three main categories: 1) physical, 2) chemical, and 3) biological sensor arrays (Estrin et al. 2003). To date, physical sensors have been well developed and are relatively inexpensive. These sensors measure meteorological variables including temperature, moisture, and wind speed and direction, and photosynthetic active radiation (the spectral range of the sun light from 400 to 700 nanometers, which drives the process of photosynthesis in plants). Chemical sensors are used to monitor biogeochemical cycles including direct measurement of nitrate, carbon dioxide, and phosphorous. These types of sensors are expensive and require high power consumption. While the development of physical and chemical sensors has been relatively advanced and widely used in environmental science and ecology, animal studies posed challenges to scientific and engineering communities because most biological investigations require field surveys to directly measure community characteristics such as species richness, abundance, and population distribution. Today, advances in sensor technology and the widespread network infrastructure have facilitated animal scientists to exploit the advantages of wireless sensor networks such as tracking the movements of birds, small animals, and insect monitoring with infrared sensors (Mainwaring et al. 2002) or equipped with GPS sensor nodes to estimate animal location and speed of the movement (Juang et al. 2002). .

Acoustical sensor arrays are used to investigate the relevance and feasibility of the microphone as the sensor integrated with wireless sensor networks to conduct ecological research. Acoustic signals can provide fundamental information about communication of animals, potentially providing presence/absence data about vocal organisms (Kroodsma and Miller 1996, Gage et al. 2001, Gage 2004, Qi et al. 2008, Gage et al. in submission). Biological sounds have been used for many animal surveys (e.g., Breeding bird surveys and Breeding Amphibian surveys) (Bystrak 1981, Robbins et al. 1986, Bridges and Dorcas 2000, Haselmayer and Quinn 2000, O'Connor et al. 2000, Richter and Azous 2001, Hobson et al. 2002, Kendell et al. 2002). Furthermore, acoustic sensor nodes can not only record biological communications and environmental conditions, but also simultaneously sense anthropogenic activities (Gage et al. 2001).

To implement stationary and simultaneous measures of environment sounds at different locations, a recording system was developed, consisting of an audio cassette-recording device which could be programmed to record 6 time intervals (Sangean VersaCorder®, C.Crane Co.) and a powered Omni-directional boundary microphone (Model 330-3020, RadioShack Co.) (See chapter 3 & 4). The recording unit enabled 6 samples of environmental acoustics to measure temporal changes in a place. These initial acoustic surveys were conducted using the cassette tape recorder system, but the disadvantage was that it required many hours to manually digitize the tapes and then archive these recordings into an acoustic digital library. Moreover, it required enormous time to hear and identify bird species in the recordings.

Simultaneous observations using wireless acoustic sensor networks can revolutionize the ability to investigate the acoustic variability and diversity in complex ecosystems over a long-term period with minimal human effort and reduced processing duration. The "Clickable Ecosystem" developed by Stuart Gage and his research team in the Remote Environmental Assessment Laboratory (REAL) at Michigan State University, provided an online system to enable the public to hear sounds, visualize acoustic patterns, and interpret acoustic information for a specific ecosystem selected by users in near-real time (http://www.real.msu.edu).

This chapter describes the structure, deployment and functions of a wireless acoustic sensor network system. It also provides a case study of how the data can be remotely transferred from remote locations so observations can be analyzed and visualized within the remote research laboratory.

Design of an ecological wireless sensor network system

The overall goal of developing ecological wireless sensor networks is not only to monitor and collect ecological observations in near-real time, but to remotely manage and control the sensor system to minimize the loss of data. This development has coevolved with new advances in sensor technology and wireless network systems, and led to the development of an Ecological Wireless Sensor Network System (EWSNS) (Gage et al. in submission). EWSNS comprises of three main components: a Habitat Sensor Platform (HSP), a Habitat Server System (HSS), and a Remote Server System (RSS).

Habitat Sensor Platform (HSP): The acoustic habitat sensor platform was designed and developed by Gage, Biswas and Joo and their research teams, based on the Crossbow Stargate processing board (Gage et al. 2006). The Stargate processing board contains a 400 MHz Intel PXA225 processor and 64MB of RAM, and operates using TinyOS (a Linux-based operating system) (Crossbow 2006). The Stargate processing board requires relatively low power to operate (about 2.5 W). The main components of HSP are the Stargate processing board, an acoustic sensor and a web camera (Logitech pro 4000), a 2 GB flash card for local storage, a wireless communication card (802.11b), a power converter from 12 V input to 5 V output, and a weatherproof case (Figure 5. 1). Power is supplied via a 12 V deep cycle battery charged using a 18 W solar panel.

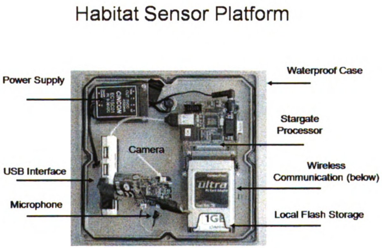


Figure 5. 1. Habitat sensor platform (HSP) hardware configuration.

Habitat Sensor Server (HSS): The main functions of the habitat sensor server are to monitor and manage an array of HSPs deployed in the field, and to transmit the sensor observations collected from HSPs into the regional server system. The HSS consists of a laptop operated by a Linux system. Access to habitat sensor platforms in the field is a critical function of the HSS. To achieve this, a habitat sensor management tool was developed to enable communication and manipulation of all HSPs. Once the sensor management application using a web-based program (a Perl CGI script) was embedded into each HSP, the HSP can be remotely invoked from the habitat server for sensor specific system configuration and programming applications (Gage et al. 2005) (See Figure 5. 2). This web based management application regulates all configurations of the habitat sensor platform including user login, setting time of day, sensor sample frequency, sensor parameters, sensor addition, file location on the habitat server, and process activities log. Note that since the HSP management application is developed using a web-based program, the service cannot only be accessed from the habitat server itself, but also from a regional server connected to the habitat server via the Internet.

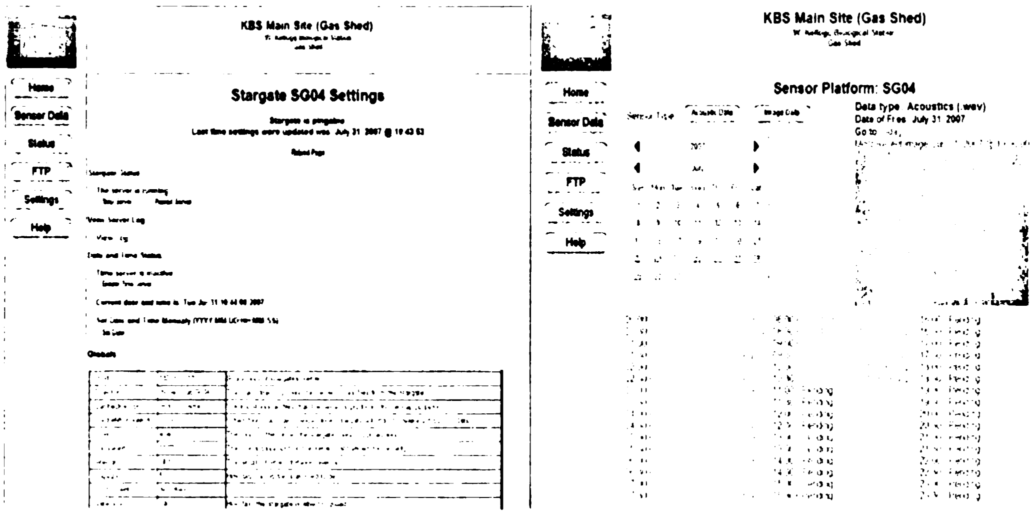


Figure 5. 2. Screen shots of the sensor management application developed with a web-based program (left) and near real-time sensor observations from an acoustic and image sensor from the KBS-LTER site (right).

Remote Sensor Server (RSS): Each HSS transmits the sensor data set to a digital archive of observations which reside on the RSS via wireless, broadband, satellite, or other means of communication. The main goal of the RSS is to store, manage, access, analyze, integrate, and distribute sensor observations from numerous arrays of the HSPs. The RSS contains the three main functions including: 1) Digital sensor data library, 2) Scientific query interface, and 3) Analytical processing tools (Gage et al. in submission). The sensor observations and the associated metadata transmitted from the arrays of the HPPs are deposited into the digital library. In addition, the digital library has a capacity to store the archive of the various types of ancillary observations (satellite imagery, meteorological and biogeochemical measures) from the ecosystems where arrays of the HPSs are deployed. The scientific query interface provides tools to access the database of the sensor observations and the associated metadata, and to select the sensor data set based on the researcher's interests, such as sensor types, locations and the time of the observation. Lastly, the analytical processing tool is employed, based on the researcher's queries, and provides results which can be downloaded as data tables for statistical analyses or can be visualized using graphic tools. The integration of the three main functions in the RSS thus provides researchers with near-real time sensor observations and their analytical products at appropriate spatial and temporal scales.

Case study

Deployment of Habitat Sensor/Server System

To understand the spatial and temporal patterns of environmental acoustics in various ecosystems based on the advanced habitat sensor system, 12 Habitat Sensor Platforms and one Habitat Server System were deployed within the Long Term Ecological Research (LTER) sites at W.K. Kellogg Biological Station (KBS) during June 2007. In addition, the study investigated the stability and efficiency of the Habitat Sensor/Server System, and the integrity and quality of the sensor observations.

The 12 locations in the agricultural ecosystems at the LTER site were classified into four different treatments: successional (T7, #4), poplar (T5, #3), and two wheat plots with different treatments (no tillage (T2, #2) and conventional tillage(T1, #1)). Each treatment consists of three replicates and one Habitat Sensor Platform was deployed in each replicate (Figure 5. 3). The acoustic sensor platform was programmed to collect environmental acoustic signals for 30 seconds every 30 minutes during the study period. The size of each sound file is 1.38 MB and 48 sound samples were recorded per day. Since 12 habitat sensor platforms collected and transmitted sound files for 30 days in June, the number of possible samples is 17,280 sound files which amounts to 22.46 GB.

Despite the integrity of habitat sensor system, the data set was incomplete due to severe weather and a power failure. However, the Habitat Sensor System operated at 83 % of capacity and successfully completed the data collection and transmission to a remote server during the study period.

Deployment of the Habitat Sensor System (HSS) at KBS revealed two main constraints: providing sustained power to the Habitat Sensor Platform (HSP) and the distance limitation of the sensor platforms due to wireless transmission. The Habitat Sensor Platform used at the KBS-LTER site was able to run for 14 days using one 12 V deep-cycle battery charged by one solar panel (18 watts), in typical Michigan summer weather. An improved Habitat Sensor Platform by Gage and his research team is able to continuously collect and transmit sensor observations for more than 30 days using a 12 V battery charged by two solar panels (36 watts) (Gage et al. in submission).

The HSS deployed at the KBS-LTER site supported wireless communication from the sensor platforms to a habitat server within the radius of 90 meters, causing us to increase the number of sensor platforms to cover the intended sampling area. To enhance the sensor observation communication system, we developed a "Wireless Bridge System" which relays sensor data from wireless hotspot to the wireless clouds of HSS (Figure 5. 4). The Wireless Bridge System consists of two antennas and one wireless access point. It was noted that when connected with omni-directional antennas, the Wireless Bridge System extended the communication to 235 meters with about 90% of wireless signal strength.

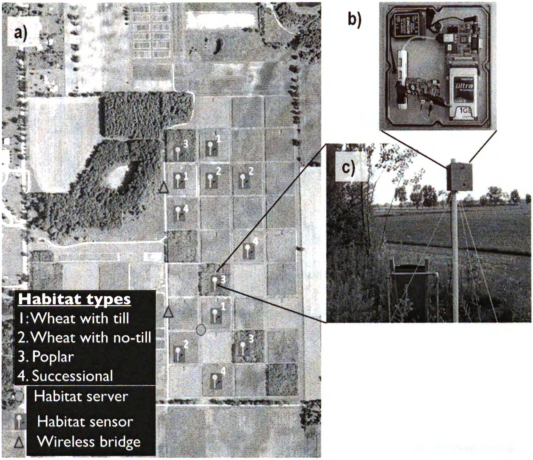


Figure 5. 3. a) Map of the distribution of Habitat Sensor Platforms and Habitat Server at KBS-LTER site (left). The Habitat Sensor Platform b) hardware components including a Crossbow Stargate processor, 12 to 5v power converter, an acoustic sensor and a web camera, wireless network card (802.11b), and a 1 GB Compact Flash storage device; and c) field configuration consisting of Habitat Sensor Platform, solar panel, and 12v deep cycle battery.

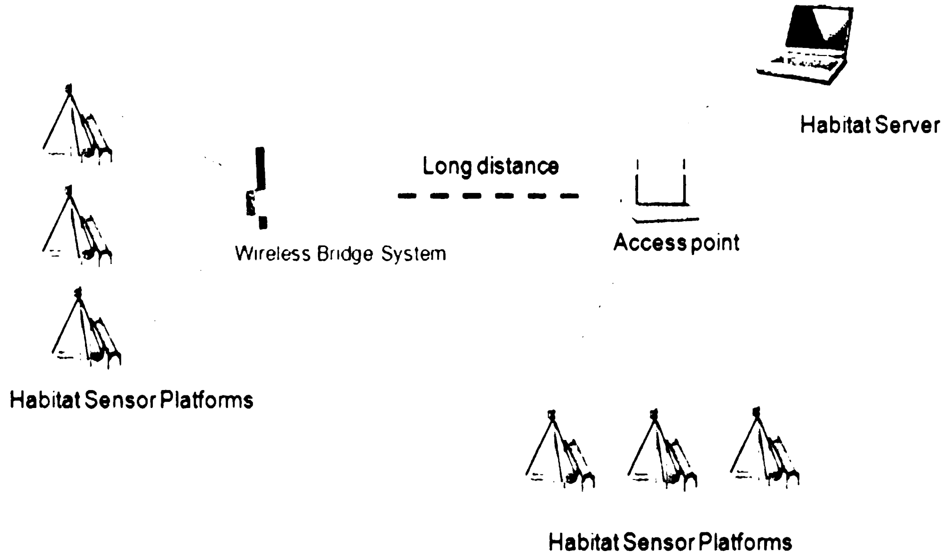


Figure 5. 4. Diagram of the advanced wireless Habitat Sensor Network System using a wireless bridge system.

Analyses and interpretation of sensor observations

The acoustic data collected by the sensor arrays in field were transmitted into a digital library embedded in the remote server system via the Internet. The data were processed by quantifying the spectral energy in one-KHz frequency intervals (See chapter 2). The numerical values resulting from this process provides a quantitative measure of how the acoustic energy is distributed across the acoustic spectrum.

To quantify environmental acoustics, the Acoustic Habitat Quality Index (AHQI) was computed to describe the temporal and spatial patterns of environmental acoustic signatures. The Acoustic Habitat Quality Index (AHQI) provides a method of classification of a place relative to biological sounds (biophony) and mechanical sounds (anthrophony), based on the amount of acoustic energy in different spectrum frequency intervals (See Chapter Two & Three for more details).

Acoustic Habitat Quality Index (AHQI) values varied with different habitat types (Figure 5. 5). The poplar plots had significantly higher values of AHQI (0.78 ± 0.006), and the no-till wheat plots had the lower values of AHQI (0.45 ± 0.008) ($p < 0.001$) in June 2007. There was no significant difference between the successional plots and the conventional-till wheat treatment. All the habitats measured in the KBS-LTER during the sample period had the positive AHQI values, indicating that every habitat measured in the KBS-LTER site exhibited dominance of biological sounds (biophony) during the acoustic sampling period.

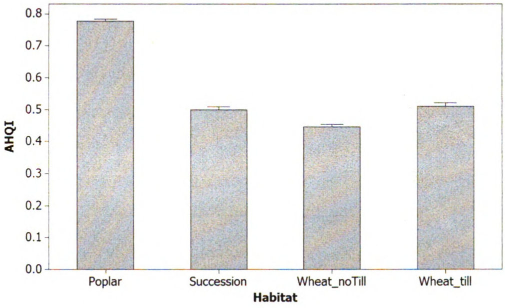


Figure 5. 5. The mean Acoustic Habitat Quality Indices at 4 different habitat types in the KBS-LTER site. The bars represent mean + SE (n=11,901).

The diurnal patterns of AHQI at each sensor location in the 4 habitat types were also investigated (See Figure 5. 6). The highest AHQI values commonly occurred at all habitats between 0530 and 0600 hrs in June, 2007. The Poplar habitats had high positive values of AHQI during most of the day and decreased between 2200 and 0430 hrs. On the other hand, positive values of AHQI in successional habitats and in two different wheat plots occurred during early morning (530 to 700 hrs) and in the early evening (1900 to 2100 hrs) during June. The high positive AHQI values in Poplar habitats accounted for more than 70 % of the time, whereas the positive AHQI values in successional habitats and two different wheat plots occurred less than 30 % of the time. The patterns show that frequent events of human acoustic disturbance are associated with the negative AHQI values in the wheat plots and the successional plots at mid-day, whereas biological vocalizations are dominant in the poplar plots from dawn to dusk.

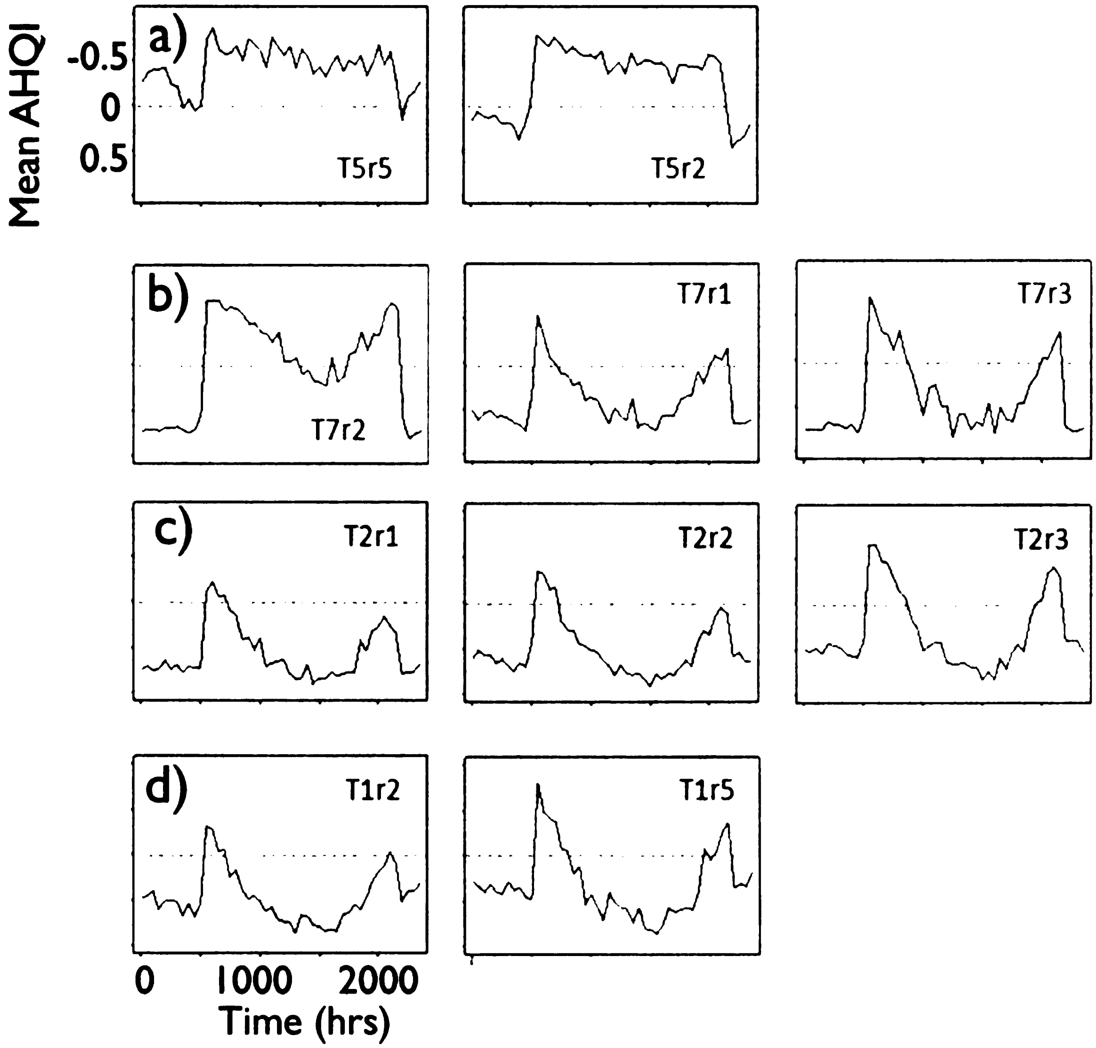


Figure 5. 6. The diurnal patterns of environmental acoustics based on computation of AHQI in 4 different habitats including a) poplar, b) successional, c) wheat with no-till treatment, and d) wheat with till treatment.

Conclusions

This component of the research has presented the concept, design, and development of wireless sensor networks for measuring and monitoring environmental acoustics. In addition, the model of the sensor network system, Ecological Wireless Sensor Network System (EWSNS) was introduced, and the specific components and functions of EWSNS were described. One representative case study, conducted at the KBS-LTER site, demonstrated the capabilities of wireless network systems for automatically collecting, transmitting, and analyzing a large number of sound samples from multiple points with a predetermined time schedule. Moreover, a simple analysis of data interpreted from the sensor system clearly exhibited the temporal and spatial variability of Acoustic Habitat Quality Indices in different ecosystems.

Although this study showed how EWSNS was able to be deployed to monitor the dynamics of environmental sounds, we identified ways to enhance the sensor system by solving some technical challenges including: power management, sensor network topology and scalability, and wireless network capacity (Estrin et al. 2003, Martinez et al. 2004, Porter et al. 2005). Electric power management for habitat sensor platforms can be one of the main constraints to sustain the operation of habitat sensor platforms over a long term period (Estrin et al. 2003, Porter et al. 2005). In our study, the habitat sensor platforms took advantage of solar energy and rechargeable batteries to extend power to the system. We still need to explore using a variety of new energy sources available in the environment such as wind, water, hydrogen, etc. (Biagioni and Bridges 2002). The efficiency of the sensor power consumption can be also increased by using low-power sensor processors or by programming to keep the operation of processors minimized using a 'hibernation' mode (Kasten, personal communication).

Although there are some challenges to be overcome in developing sensor network systems, using wireless sensor networks as a new sampling tool in ecology and environmental science will provide tremendous opportunities to measure and monitor complex ecological variables at relevant spatial and temporal scales, thus leading to forecasting changes in ecosystems and even to addressing some of the "Grand challenges" at a global scale (National Research Council 2001, Porter et al. 2005).

Chapter Six
Summary and Conclusions

The main goals of this research were to investigate whether environmental acoustics can be used as an ecological attribute to indicate the current state of varying ecosystems and to use acoustics as a key means to measure and monitor the biodiversity and distribution of vocal species. The study focused on four main research projects to accomplish the objectives: 1) development of analytical methods to understand acoustic properties; 2) investigation of a new method to survey avian species using acoustic recordings; 3) characterization of urban-rural gradient using environmental sounds; and 4) development of an automated acoustic sensor observation system.

Overall, this research has provided clear evidence that interpretation of environmental acoustics has tremendous potential to measure and interpret changes in ecosystems in space and time. By measuring and analyzing environmental sounds, key ecological information could be extracted from the measurement of the soundscape including; Acoustic Habitat Quality Index (Chapter 2 and 4); quantifying vocalizing species diversity measures (Chapter 2, 3, and 4); and analyzing the degree of human acoustical activities in various ecosystems (Chapter 2 and 4). Moreover, a wireless sensor network system enabled automated monitor of patterns and changes in environmental sounds at great spatial and temporal grain and extent (Chapter 5).

Based on a large number of acoustic observations, analyses of acoustic variables from environmental sounds may indicate the current states of ecosystem structure and processes. For instance, 14 grass-woodland sites in Australia were assessed using the habitat quality index developed by the Victoria Department of Sustainability and Environment (Straker and Lowe 2004). In addition, simultaneous acoustic recordings were made at the same 14 sites in the morning and evening on November 30, 2006. Preliminary results from the habitat assessment and acoustic recordings in Australia showed a positive relationship between Acoustic Habitat Quality Index and the ecological attributes determined by a habitat quality assessment across the sites (Gage et al. in submission) (Figure 6. 1). The results motivated me to test a hypothesis that there would be a relationship between acoustic attributes and ecological variables in various ecosystems in a future study. Moreover, the relationship will enable the development of an 'Index of Acoustic Integrity' (IAI) to assess the current quality of terrestrial ecosystems by measuring environmental acoustics.

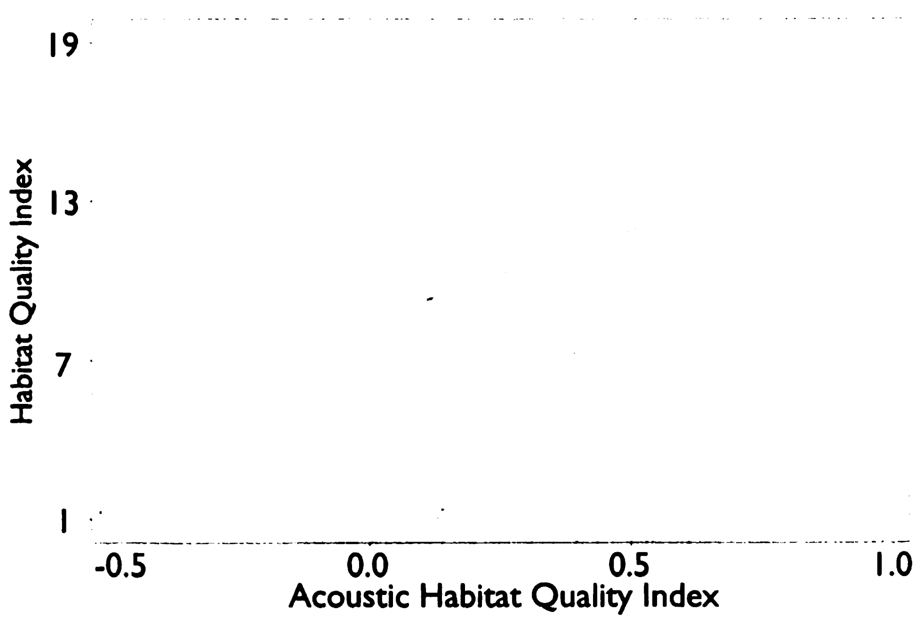


Figure 6. 1. A relationship between Acoustic Habitat Quality Index and Habitat Quality Index at 14 grass-woodland sites in Australia on November 30, 2006 (permitted by Gage et al.).

Although environmental acoustics is still a new research area to ecologists and environmental scientists, I suggest that environmental acoustics will offer exciting research opportunities in conjunction with development of wireless sensor networks in ecological sensing (Porter et al. 2005, Gage et al. in submission). In addition, to better understand the characteristics of environmental acoustics and their associated ecosystem structure and processes including human systems, acoustic research will require the multi-disciplinary science integration, including ecologists, acoustic engineers, computer scientists, statisticians, and sociologists. The integration of acoustic research in the multi science communities will enable an enhancement of our understanding and our ability to forecast changes in complex, interconnected ecosystems at scales ranging from the ecosystem to global level.

Appendices

Appendix 2. 1. The diversity of bird species identified from the automated recordings from five ecosystems.

LTER Sites	List of avian Species identified
Agriculture	
Alfalfa 1	Song Sparrow *, Field Sparrow, Savanna Sparrow, American Crow, Northern Flicker, American Robin, Killdeer, Cedar Waxwing, American Goldfinch
Alfalfa 3	Song Sparrow *, American Robin, Savanna Sparrow, American Crow, Red-winged Blackbird
Poplar 1	Indigo Bunting *, American Goldfinch, Northern Cardinal, American Crow, Yellow-billed Cuckoo, Killdeer, Common Yellowthroat, Tufted Titmouse, European Starling, Red-winged Blackbird, Song Sparrow, American Robin
Poplar 2	Song Sparrow *, Cedar Waxwing, Black-capped Chickadee, Northern Cardinal, Red-winged Blackbird, Chipping Sparrow, Indigo Bunting, American Robin, American Goldfinch
Coniferous forests	
Coniferous 1	Red-wing Blackbird *, Northern Cardinal, Warbling Vireo, American Robin, Rose-breasted Grosbeak, Baltimore Oriole, Black-capped Chickadee, Tree Swallow, Tufted Titmouse, Mourning Dove, Eastern Wood-pewee, Canada Goose, Gray Catbird, European Starling
Coniferous 2	Tufted Titmouse *, Hairy Woodpecker, Eastern Kingbird, Chipping Sparrow, Black-capped Chickadee, Indigo Bunting, Blue Jay, American Crow, Eastern Wood-pewee, Downy Woodpecker, Rose-breasted Grosbeak, Red-winged Blackbird, American Robin, Northern Cardinal
Coniferous 3	Northern Cardinal *, Chipping Sparrow, Black-capped Chickadee, Indigo Bunting, American Crow, Downy Woodpecker, American Robin

Appendix 2.1. Continued

Deciduous forests	
Deciduous 1	Scarlet Tanager *, Red-eyed Vireo, White-breasted Nuthatch, Red-bellied Woodpecker, Northern Cardinal, Hairy Woodpecker, Blue Jay, American Crow, Tufted Titmouse, Eastern Wood-pewee, American Robin
Deciduous 2	Baltimore Oriole *, Great Crested Flycatcher, Common Yellowthroat, Red-bellied Woodpecker, Scarlet Tanager, Northern Cardinal, Black-capped Chickadee, Blue Jay, American Crow, Tufted Titmouse, Eastern Wood-pewee, Canada Goose, European Starling, Rose-breasted Grosbeak, Red-winged Blackbird, Song Sparrow, Northern Flicker, American Robin, Eastern Towhee,
Deciduous 3	Eastern Wood-pewee *, Brown Thrasher, Field Sparrow, Baltimore Oriole, Great Crested Flycatcher, Red-eyed Vireo, White-breasted Nuthatch, Red-bellied Woodpecker, Scarlet Tanager, Northern Cardinal, Black-capped Chickadee, Indigo Bunting, Blue Jay, American Crow, Tufted Titmouse, Eastern Wood-pewee, Canada Goose, European Starling, Downy Woodpecker, Red-breasted Grosbeak, Red-winged Blackbird, Northern Flicker, American Robin, American Goldfinch, Eastern Towhee
Succession	
Succession 1	Song Sparrow *, American Crow, Black-capped Chickadee, European Starling, Baltimore Oriole, Eastern Wood-pewee, Northern Flicker, Indigo Bunting, Scarlet Tanager, Red-winged Blackbird, Field Sparrow, House Wren, American Crow, Chipping Sparrow, Northern Cardinal, Eastern Towhee, Canada Goose, American Robin, Yellow Warbler, Rose-breasted Grosbeak, Song Sparrow, American Goldfinch, Tufted Titmouse, Eastern Bluebird
Succession 2	Brown Thrasher *, Indigo Bunting, Northern Flicker, Eastern Wood-pewee, Gray Catbird, Eastern Towhee, Downy Woodpecker, Rose-breasted Grosbeak, Northern Cardinal, Black-capped Chickadee, Blue Jay, American Robin, American Goldfinch, Cedar Waxwing, Great Crested Flycatcher, American Crow
Succession 3	Northern Cardinal *, Northern Flicker, Downy Woodpecker, Scarlet Tanager, Yellow-billed Cuckoo, Baltimore Oriole, Song Sparrow, Black-capped Chickadee, Field Sparrow, Eastern Towhee, Veery, Northern Cardinal, American Robin, Rose-breasted Grosbeak, American Crow, Blue Jay, Tufted Titmouse, Brown Thrasher

: the dominant bird species determined by abundance of bird vocalizations

Appendix 3. 1. List of bird species identified by all survey types in Essex Township. Note that each species include its scientific name, AOU code, and the number of encounters in each survey type.

Common name	Scientific name	Code	PCS	MAS	AAS
Acadian Flycatcher	*Empidonax virescens*	ACFL	1	0	0
Alder Flycatcher	*Empidonax alnorum*	ALFL	1	0	0
American Crow	*Corvus brachyrhynchos*	AMCR	6	7	9
American Goldfinch	*Carduelis tristis*	AMGO	4	6	9
American Redstart	*Setophaga ruticilla*	AMRE	4	3	2
American Robin	*Turdus migratorius*	AMRO	14	16	16
Baltimore Oriole	*Icterus galbula*	BAOR	7	5	5
Bank Swallow	*Riparia riparia*	BANS	1	0	1
Black-capped Chickadee	*Poecile atricapilla*	BCCH	3	2	2
Blue Jay	*Cyanocitta cristata*	BLJA	3	3	7
Blue-gray Gnatcatcher	*Polioptila caerulea*	BGGN	2	0	3
Blue-winged Warbler	*Vermivora pinus*	BWWA	1	0	0
Bobolink	*Dolichonyx oryzivorus*	BOBO	1	1	2
Brown Thrasher	*Toxostoma rufum*	BRTH	4	2	2
Brown-headed Cowbird	*Molothrus ater*	BHCO	0	1	2
Cedar Waxwing	*Bombycilla cedrorum*	CEWA	2	1	2
Chipping Sparrow	*Spizella passerina*	CHSP	5	2	6
Common Grackle	*Quiscalus quiscula*	COGR	4	0	0
Common Yellowthroat	*Geothlypis trichas*	COYE	4	5	2
Dickcissel	*Spiza americana*	DICK	3	3	3
Downy Woodpecker	*Picoides pubescens*	DOWO	2	1	2
Eastern Bluebird	*Sialia sialis*	EABL	0	0	1
Eastern Kingbird	*Tyrannus tyrannus*	EAKI	1	4	1
Eastern Meadlowlark	*Sturnella magna*	EAME	7	0	4
Eastern Phoebe	*Sayornis phoebe*	EAPH	1	0	0
Eastern Towhee	*Pipilo erythrophthalmus*	EATO	2	1	2
Eastern Wood-Pewee	*Contopus virens*	EWPE	8	6	6
European Starling	*Sturnus vulgaris*	EUST	4	0	3
Field Sparrow	*Spizella pusilla*	FISP	10	6	7
Grasshopper Sparrow	*Ammodramus savannarum*	GRSP	2	1	1
Gray Catbird	*Dumetella carolinensis*	GRCA	6	1	3
Great crested Flycatcher	*Myiarchus crinitus*	GCFL	2	1	10
Green Heron	*Butorides virescens*	GRHE	1	0	0

Appendix 3.1. Continued

Common name	Scientific name	Code	PCS	MAS	AAS
Horned Lark	*Eremophila alpestris*	HOLA	1	1	2
House Finch	*Carpodacus mexicanus*	HOFI	1	1	0
House Sparrow	*Passer domesticus*	HOSP	0	0	4
House Wren	*Troglodytes aedon*	HOWR	5	2	5
Indigo Bunting	*Passerina cyanea*	INBU	15	8	5
Killdeer	*Charadrius vociferus*	KILL	3	5	2
Mourning Dove	*Zenaida macroura*	MODO	6	0	2
Northern Flicker	*Colaptes auratus*	NOFL	2	1	1
Nothern Cardinal	*Cardinalis cardinalis*	NOCA	11	10	10
Pileated Woodpecker	*Dryocopus pileatus*	PIWO	2	0	0
Prothonotary Warbler	*Protonotaria citrea*	PRWA	1	1	1
Red-eyed Vireo	*Vireo olivaceus*	REVI	3	0	2
Red-winged Blackbird	*Agelaius phoeniceus*	RWBL	11	10	13
Ring-necked Pheasant	*Phasianus colchicus*	RNEP	5	3	2
Rose-breasted Grosbeak	*Pheucticus ludovicianus*	RBGR	4	2	2
Ruby-throated Hummingbird	*Archilochus colubris*	RTHU	0	0	1
Sandhill Crane	*Grus canadensis*	SACR	0	1	0
Savannah Sparrow	*Passerculus sandwichensis*	SAVS	4	2	2
Scarlet Tanager	*Piranga olivacea*	SCTA	3	5	5
Song Sparrow	*Melospiza melodia*	SOSP	15	18	15
Tree Swallow	*Tachycineta bicolor*	TRSW	1	0	1
Tufted Titmouse	*Baeolophus bicolor*	TUTI	1	1	4
Vesper Sparrow	*Pooecetes gramineus*	VESP	2	1	0
Warbling Vireo	*Vireo gilvus*	WAVI	6	6	6
White-breasted Nuthatch	*Sitta carolinensis*	WBNU	3	3	4
Wild Turkey	*Meleagris gallopavo*	WITU	1	0	0
Willow Flycatcher	*Empidonax traillii*	WIFL	4	2	2
Wood Thrush	*Hylocichla mustelina*	WOTH	1	0	1
Yellow Warbler	*Dendroica petechia*	YWAR	12	11	7
Yellow-billed Cuckoo	*Coccyzus americanus*	YBCU	5	2	0
Total No. of species		64	59	45	52
Total No. of points			25	25	20

Appendix 3. 2. List of bird species identified by all survey types in Westphalia Township. Note that each species include its scientific name, AOU code, and the number of encounters in each survey type.

Common name	Scientific name	Code	PCS	MAS	AAS
American Crow	*Corvus brachyrhynchos*	AMCR	5	7	6
American Goldfinch	*Carduelis tristis*	AMGO	3	5	16
American Redstart	*Setophaga ruticilla*	AMRE	1	1	0
American Robin	*Turdus migratorius*	AMRO	17	12	19
Bank Swallow	*Riparia riparia*	BANS	3	1	0
Baltimore Oriole	*Icterus galbula*	BAOR	2	3	1
Black-capped Chickadee	*Poecile atricapilla*	BCCH	1	1	3
Brown-headed Cowbird	*Molothrus ater*	BHCO	1	0	2
Blue Jay	*Cyanocitta cristata*	BLJA	1	1	2
Bobolink	*Dolichonyx oryzivorus*	BOBO	2	1	1
Brown Thrasher	*Toxostoma rufum*	BRTH	3	3	4
Canada Goose	*Branta canadensis*	CANG	1	0	1
Cedar Waxwing	*Bombycilla cedrorum*	CEWA	1	1	0
Chipping Sparrow	*Spizella passerina*	CHSP	12	8	3
Common Grackle	*Quiscalus quiscula*	COGR	1	1	0
Common Yellowthroat	*Geothlypis trichas*	COYE	13	9	9
Downy Woodpecker	*Picoides pubescens*	DOWO	3	1	0
Eastern Kingbird	*Tyrannus tyrannus*	EAKI	3	2	3
Eastern Meadowlark	*Sturnella magna*	EAME	2	2	2
Eastern Phoebe	*Sayornis phoebe*	EAPH	1	0	0
Eastern Towhee	*Pipilo erythrophthalmus*	EATO	0	0	2
European Starling	*Sturnus vulgaris*	EUST	4	3	2
Eastern Wood-Pewee	*Contopus virens*	EWPE	8	5	4
Field Sparrow	*Spizella pusilla*	FISP	1	2	4
Great crested Flycatcher	*Myiarchus crinitus*	GCFL	5	2	2
Gray Catbird	*Dumetella carolinensis*	GRCA	4	3	4
House Finch	*Carpodacus mexicanus*	HOFI	0	1	0
Hairy Woodpecker	*Picoides villosus*	HAWO	0	0	1
Horned Lark	*Eremophila alpestris*	HOLA	3	2	8
House Sparrow	*Passer domesticus*	HOSP	4	4	11
House Wren	*Troglodytes aedon*	HOWR	5	2	2
Indigo Bunting	*Passerina cyanea*	INBU	6	3	5
Killdeer	*Charadrius vociferus*	KILL	4	5	9

Appendix 3.2. Continued

Common name	Scientific name	Code	PCS	MAS	AAS
Mourning Dove	*Zenaida macroura*	MODO	10	5	5
Nothern Cardinal	*Cardinalis cardinalis*	NOCA	9	5	11
Northern Flicker	*Colaptes auratus*	NOFL	2	1	2
Pileated Woodpecker	*Dryocopus pileatus*	PIWO	1	0	0
Rose-breasted Grosbeak	*Pheucticus ludovicianus*	RBGR	1	1	3
Red-bellied Woodpecker	*Melanerpes carolinus*	RBWO	1	0	1
Red-eyed Vireo	*Vireo olivaceus*	REVI	1	1	4
Ring-necked Pheasant	*Phasianus colchicus*	RNEP	10	7	6
Red-tailed Hawk	*Buteo jamaicensis*	RTHA	1	0	0
Red-winged Blackbird	*Agelaius phoeniceus*	RWBL	18	19	18
Sandhill Crane	*Grus canadensis*	SACR	1	5	3
Savannah Sparrow	*Passerculus sandwichensis*	SAVS	6	7	1
Scarlet Tanager	*Piranga olivacea*	SCTA	0	0	1
Sedge Wren	*Cistothorus platensis*	SEWR	1	1	1
Song Sparrow	*Melospiza melodia*	SOSP	20	22	21
Tree Swallow	*Tachycineta bicolor*	TRSW	1	0	1
Tufted Titmouse	*Baeolophus bicolor*	TUTI	1	1	2
Vesper Sparrow	*Pooecetes gramineus*	VESP	3	2	2
Warbling Vireo	*Vireo gilvus*	WAVI	3	3	6
White-breasted Nuthatch	*Sitta carolinensis*	WBNU	1	0	4
Willow Flycatcher	*Empidonax traillii*	WIFL	4	3	2
Wild Turkey	*Meleagris gallopavo*	WITU	1	0	0
Wood Thrush	*Hylocichla mustelina*	WOTH	4	1	3
Yellow-billed Cuckoo	*Coccyzus americanus*	YBCU	0	0	1
Yellow Warbler	*Dendroica petechia*	YEWA	6	6	4
Yellow-throated Vireo	*Vireo flavifrons*	YTVI	0	0	1
Total No. of species		60	55	45	48
Total No. of points			25	25	24

Appendix 3.3. List of bird species with the number of encounters identified by Automated Acoustic Surveys (AAS) in Essex Township. Note that each species includes the number of encounters at each recording sample from 5:00 am to 10 am every hour. Of 6 total recordings at each point, the number of species occurrence was calculated.

Species	5:00 AM	6:00 AM	7:00 AM	8:00 AM	9:00 AM	10:00 AM	Frequency
AMGO	1	3	4	5	7	7	6
AMRO	9	9	5	6	7	6	6
BLJA	1	1	5	1	2	1	6
EWPE	1	4	2	3	4	1	6
FISP	2	3	4	5	2	4	6
HOWR	1	3	4	3	2	1	6
NOCA	4	5	5	5	4	3	6
RWBL	1	9	5	7	7	5	6
YEWA	1	3	4	2	4	3	6
AMRE		1	1	1	1	2	5
BAOR	1		2	2	2	2	5
BOBO		1	2	1	1	1	5
DICK		2	1	2	1	2	5
GCFL	1	2	6	3	1		5
INBU		4	2	3	1	3	5
PROW		1	1	1	1	1	5
RBGR	1		1	2	1	1	5
SCTA		3	4	2	2	1	5
SOSP		10	9	11	8	7	5
TUTI		2	1	1	2	2	5
WAVI		4	3	1	2	2	5
AMCR		6	2	3		2	4
CHSP		3	2		3	2	4
HOSP	1	1	1	1			4
REVI		2		1	1	1	4
WBNU			1	2	2	1	4
BCCH		1	1			1	3

Appendix 3.3. Continued

Species	5:00 AM	6:00 AM	7:00 AM	8:00 AM	9:00 AM	10:00 AM	Frequency
BRTH			1	2	1		3
COYE		1	1			1	3
EAME	1	2	3				3
EUST	1	1				1	3
GRCA		2	2	1			3
RNGP		2	1		1		3
SAVS		2	1			1	3
WIFL	1			1		2	3
WOTH		1	1			1	3
BHCO		1			1		2
CEWA				1		1	2
DOWO			1			1	2
EATO		1				1	2
HOLA					1	1	2
MODO				1	1		2
BANS		1					1
EABL						1	1
GRSP			1				1
HAWO				1			1
KILL						2	1
NOFL				1			1
RTHU					1		1
TRSW	1						1

Appendix 3. 3. List of bird species with the number of encounters identified by Automated Acoustic Surveys (AAS) in Westphalia Township. Note that each species includes the number of encounters at each recording sample from 5:00 am to 10 am every hour. Of 6 total recordings at each point, the number of species occurrence was calculated.

Species	5:00 AM	6:00 AM	7:00 AM	8:00 AM	9:00 AM	10:00 AM	Frequency
EAKI	1	2	2	1	1	1	6
HOSP	1	5	7	5	5	3	6
AMGO	2	1	5	6	8	5	6
NOCA	2	3	6	1	2	3	6
COYE	2	7	4	1	1	3	6
KILL	4	1	3	1	1	2	6
SOSP	4	17	10	13	12	13	6
RWBL	5	14	11	12	11	13	6
AMRO	10	11	10	12	8	6	6
CHSP	1	1	2	1	1		5
BOBO		1	1	1	1	1	5
INBU		1	3	2	2	1	5
REVI		2	2	1	1	2	5
EWPE		2	3	1	1	1	5
YEWA		2	3	2	2	2	5
FISP		3	2	1	1	2	5
WAVI		3	5	4	2	5	5
HOLA	3		2	2	2		4
GCFL		1	1	1	1		4
MODO		2	1	1		1	4
SAVS			1	1	1	1	4
BLJA	1		1	1			3
TRSW		1	1		1		3
VESP		1	1		1		3
BCCH		1	1		2		3
EAME		1		2			3

Appendix 3.4. Continued

Species	5:00 AM	6:00 AM	7:00 AM	8:00 AM	9:00 AM	10:00 AM	Frequency
WOTH		2	2	3			3
RBGR		2			1	1	3
RNEP		3	4	2			3
AMCR		4	2	1			3
BRTH			1	2		1	3
GRCA			3	2	1		3
BHCO	1				1		2
TUTI		1				1	2
WBNU		2		2			2
EUST			1			1	2
YTVI			1			1	2
NOFL				1	1		2
EATO					1	1	2
WIFL	2						1
CANG		1					1
BAOR			1				1
SCTA			1				1
SEWR			1				1
SACR			3				1
HAWO					1		1
RBWO					1		1
YBCU						1	1

Appendix 4. 1. Common and scientific name and AOU code of bird species identified from acoustic recordings (see Figure 8).

Species Code	Common Name	Scientific Name
AMCR	American Crow	*Corvus brachyrhynchos*
AMGO	American Goldfinch	*Carduelis tristis*
AMRO	American Robin	*Turdus migratorius*
BAOR	Baltimore Oriole	*Icterus galbula*
BCCH	Black-capped Chickadee	*Poecile atricapillus*
BHCO	Brown-headed Cowbird	*Molothrus ater*
BLJA	Blue Jay	*Cyanocitta cristata*
CANG	Canadian Goose	*Branta canadensis*
CEWA	Cedar Waxwing	*Vombycilla cedrorum*
CHSP	Chipping Sparrow	*Spizella passerina*
COYE	Common Yellowthroat	*Geothlypis trichas*
DOWO	Downy Woodpecker	*Picoides pubescens*
EUST	European Starling	*Sturnus vulgaris*
GCFL	Great Crested Flycatcher	*Myiarchus crinitus*
GRCA	Gray Catbird	*Dumetella carolinensis*
HOFI	House Finch	*Carpodacus mexicanus*
HOLA	Horned Lark	*Eremophila alpestris*
HOSP	House Sparrow	*Passer domesticus*
HOWR	House Wren	*Troglodytes aedon*
KILL	Killdeer	*Charadrius vociferus*
MODO	Mourning Dove	*Zenaida macroura*
NOCA	Northern Cardinal	*Cardinalis cardinalis*
REVI	Red-eyed Vireo	*Vireo olivaceus*
RWBL	Red-winged Blackbird	*Agelaius phoeniceus*
SOSP	Song Sparrow	*Melospiza melodia*
TUTI	Tufted Titmouse	*Baeolophus bicolor*
WIFL	Willow Flycatcher	*Empidonax traillii*
YEWA	Yellow Warbler	*Dendroica petechia*

Bibliography

Acevedo, M. A. and L. J. Villanueva-Rivera. 2006. Using Automated Digital Recording Systems as Effective Tools for the Monitoring of Birds and Amphibians. Wildlife Society Bulletin **34**:211-214.

Allen, T., S. L. Finkbeiner, and D. H. Johnson. 2004. Comparison of Detection Rates of Breeding Marsh Birds in Passive and Playback Surveys at Lacreek National Wildlife Refuge, South Dakota. Waterbirds **27**:277-281.

Asano, F., M. Goto, K. Itou, and H. Asoh. 2001. Real-time Sound Source Localization and Separation System and Its Application to Automatic Speech Recognition. ISCA.

Bart, J. 2005. Monitoring the Abundance of Bird Populations. The Auk **122**:15-25p.

Batten, L. A. 1972. Breeding bird species diversity in relation to increasing urbanisation. Bird Study **19**:157-166.

Beissinger, S. R. and D. R. Osborne. 1982. Effects of Urbanization on Avian Community Organization. Condor **84**:75-83.

Biagioni, E. and K. Bridges. 2002. The Application of Remote Sensor Technology to Assist The Recovery of Rare And Endangered Species. International Journal of High Performance Computing Applications **16**:315.

Blair, R. B. 1996. Land use and Avian species diversity along an urban gradient. Ecological Applications **6**:506-519.

Bridges, A. S. and M. E. Dorcas. 2000. Temporal Variation in Anuran Calling Behavior: Implications for Surveys and Monitoring Programs. Copeia **2000**:587-592.

Brumm, H. 2004. The impact of environmental noise on song amplitude in a territorial bird. Journal of Animal Ecology **73**:pp. 434-440.

Brumm, H. and D. Todt. 2002. Noise-dependent song amplitude regualtion in a territorial songbird. Animal Behaviour **63**:891-897.

Butler, D. 2004. Sound and vision. NATURE **427**:480-481.

Butler, R., M. Servilla, S. Gage, J. Basney, V. Welch, B. Baker, T. Fleury, P. Duda, D. Gehrig, M. Bletzinger, J. Tao, and D. M. Freemon. 2006. Cyberinfrastructure for the analysis of ecological acoustic sensor data: a use case study in grid development. Challenges in Large Applications in Distributed Environments. IEEE:25-33.

Bystrak, D. 1981. The North American breeding bird survey. Studies in Avian biology **6**:34-41.

Carson, R. 1962. Silent Spring. Houghton Mifflin, New York.

Catchpole, C. and P. J. B. Slater. 1995. Bird Song: Biological Themes and Variations. Cambridge University Press.

Chesmore, D. 2004. Automated bioacoustic identification of species. Anais da Academia Brasileira de Ci?cias **76**:436-440.

Chesmore, D. 2007. The Automated Identification of Taxa: Concepts and Applications. CRC press, Boca Raton, FL.

Chesmore, E. D. and C. Nellenbach. 1997. ACOUSTIC METHODS FOR THE AUTOMATED DETECTION AND IDENTIFICATION OF INSECTS. Pages 223-231. ISHS.

Chesmore, E. D. and E. Ohya. 2007. Automated identification of field-recorded songs of four British grasshoppers using bioacoustic signal recognition. Bulletin of Entomological Research **94**:319-330.

Cody, M. 1985. Habitat selection in grassland and open-country birds. PHYSIOL. ECOL. SER.:191-226.

Collins, S. L., L. M. A. Bettencourt, A. Hagberg, R. F. Brown, D. I. Moore, G. Bonito, K. A. Delin, S. P. Jackson, D. W. Johnson, and S. C. Burleigh. 2006. New opportunities in ecological sensing using wireless sensor networks. Frontiers in Ecology and the Environment **4**:402-407.

Conway, C. J. and J. P. Gibbs. 2005. EFFECTIVENESS OF CALL-BROADCAST SURVEYS FOR MONITORING MARSH BIRDS. The Auk **122**:26-35.

Crossbow. 2006. Stargate developer's guide. Crossbow Technology, Inc., San Jose, CA.

Degraaf, R. M. and J. M. Wentworth. 1986. Avian guild structure and habitat association in suburban bird communities. Urban Ecology **9**:399-412.

Dooling, R. J. 1982. Auditory perception in birds. Pages 95-130 *in* D. E. Kroodsma and E. H. Miller, editors. Acoustic Communication in Birds.

Estrin, D., W. Michener, and G. Bonito. 2003. Environmental Cyberinfrasturcutre Needs for Distributed Sensor Networks. Scrippts Institute of Oceanography.

Fay, R. R. and L. A. Wilber. 1989. Hearing in Vertebrates: A Psychophysics Databook. The Journal of the Acoustical Society of America **86**:2044.

Feng, A. S., P. M. Narins, C. H. Xu, W. Y. Lin, Z. L. Yu, Q. Qiu, Z. M. Xu, and J. X. Shen. 2006. Ultrasonic communication in frogs. NATURE **440**:333-336.

Forkenbrock, D. J. and L. A. Schweitzer. 1999. Environmental justice in transportation planning. Journal of the American Planning Association **65**:96-111.

Gage, S., W. Joo, E. Kasten, F. Yu, T. Wu, and S. Biswas. in submission. Design, deployment and applications of a wireless sensor network for monitoring environmental acoustics. BioScience.

Gage, S., P. Ummadi, A. Shortridge, J. Qi, and P. K. Jella. 2004. Using GIS to develop a network of acoustic environmental sensors.*in* ESRI International User Conference 2004, San Diego, CA.

Gage, S. H., S. Biswas, W. Joo, T. Wu, and F. Yu. 2006. A sensor platform and local sensor server for capture andtransmission of acoustics and ancillary sensor observations toremote servers using wireless technology.*in* Long Term Ecological Research All Scientist Meeting at W. K. Kellogg Biological Station East Lansing, Michigan.

Gage, S. H., B. M. Napoletano, and M. C. Cooper. 2001. Assessment of ecosystem biodiversity by acoustic diversity indices. Page 2430 *in* 141st Meeting Acoustical Society of America. American Institute of Physics, Palmer House Hilton Hotel; Chicago, Illinois.

Gage, S. H., B. Subir, W. Joo, and F. Foust. 2005. Operation Manual: Habitat Sensor System. Computational Ecology and Visualization Laboratory, Michigan State University, East Lansing, Michigan.

Gage, S. H., Umadi, P.,Shortridge, A., QI, J., Kumar, J. 2004. **Using GIS to Develop a Network of Acoustic Environmental Sensors**. ESRI International Users Conference **1688**.

Gates, J. E. and L. W. Gysel. 1978. Avian nest dispersion and fledging success in field-forest ecotones. Ecology **59**:871-883.

Graber, R. R. and J. W. Graber. 1963. A comparative study of bird populations in Illinois, 1906-1909 and 1956-1958. Illinois Natural History Survey Bulletin **28**:377-527.

Green, R. J. 1984. Native and exotic birds in a suburban habitat. Australian Wildlife Research **11**:181-190.

Guthrie, D. A. 1974. Suburban bird opulations in southern California. American Mildland Naturalist **92**:461-466.

Hamilton, M. P., E. A. Graham, P. W. Rundel, M. F. Allen, W. Kaiser, M. H. Hansen, and D. L. Estrin. 2007. New Approaches in Embedded Networked Sensing for

Terrestrial Ecological Observatories. Environmental Engineering Science **24**:192-204.

Hartmann, W. M. 1998. Signals, Sound, and Sensation. Springer-Verlag, New York.

Haselmayer, J. and J. S. Quinn. 2000. A Comparison of Point Counts and Sound Recording As Bird Survey Methods in Amazonian Southeast Peru. The Condor **102**:887-893p.

Herkert, J. R. 1995. An Analysis of Midwestern Breeding Bird Population Trends: 1966-1993. The American Midland Natualist **134**:41-50p.

Hobson, K. A., R. S. Rempel, H. Greenwood, B. Turnbull, and S. L. V. Wilgenburg. 2002. Acoustic surveys of birds using electronic recordings: new potential from an omnidirectional microphone system. Wildlife Society Bulletin **30**:709-720.

Hopp, S. L., M. J. Owren, and C. S. Evans. 1998. Animal Acoustic Communication: Sound Analysis and Research Methods. Springer-Verlag Berlin Heidelberg, Germany.

Hutto, R. L., S. M. Pletschet, and P. Hendricks. 1986. A fixed-radius point count method for nonbreeding and breeding season use. Auk **103**:593-602.

Johnson, E. A., G. I. Fryer, and M. J. Heathcott. 1990. The influence of man and climate on the fire frequency of the Interior Wet Belt forest, British Columbia. Journal of Ecology **78**:403-412.

Juang, P., H. Oki, Y. Wang, M. Martonosi, L. S. Peh, and D. Rubenstein. 2002. Energy-Efficient Computing for Wildlife Tracking: Design Tradeoffs and Early Experiences with ZebraNet. Pages 96-107 *in* Proceedings of the 10 th international conference on Architectural support for programming languages and operating systems, San Jose, USA.

Kalamazoo Nature Center. 2002. Handbook of Michigan breeding bird atlas II. Kalamazoo Nature Center, Kalamazoo, MI.

Kasten, E. P., P. K. Mckinley, and S. H. Gage. 2007. Automated ensemble extraction and analysis of acoustic data stream.*in* Proceedings of the 1st International Workshop on Distributed Event processing, Systems and Applications (DEPSA), Toronto, Ontario.

Katti, M. and P. S. Warren. 2004. Tits, noise, and urban bioacoustics. Trends in Ecology and Evolution **19**:109-110.

Kendell, K., Fish, D. Wildlife, Alberta, R. Status, A. Branch, and A. Alberta Conservation. 2002. Survey Protocol for the Northern Leopard Frog. Fish & Wildlife Division, Resource Status and Assessment Branch, Alberta Sustainable Resource Development.

Krause, B. 1998. Into a Wild Sanctuary: A Life in Music and Natural Sound. Heyday Books, Berkeley, California.

Krause, B. L. 1997. The Niche Hypothesis: Creature Vocalizations and the Relationship between Natural Sound and Music. Nature Sounds Society:1-5.

Krebs, C. J. 1998. Ecological methodology. Addison-Welsey Longman, Inc., New York, New York.

Kroodsma, D. E. and E. H. Miller, editors. 1996. Ecology and Evolution of Acoustic Communication in Birds. Comstock Publishing Associates, Ithaca, New York.

Larkin, R. P., L. L. Pater, D. J. Tazik, and L. Construction Engineering Research. 1996. Effects of Military Noise on Wildlife: A Literature Review. US Army Corps of Engineers, Construction Engineering Research Laboratories; National Technical Information Service, distributor.

Magurran, A. E. 1988. Ecological diversity and its measurement. Princeton University Press, Princeton, New Jersey.

Mainwaring, A., D. Culler, J. Polastre, R. Szewczyk, and J. Anderson. 2002. Wireless sensor networks for habitat monitoring. Pages 88-97 *in* Proceedings of the 1st ACM international workshop on Wireless sensor networks and applications. ACM New York, NY, USA.

Martinez, K., J. K. Hart, and R. Ong. 2004. Environmental sensor networks. Computer **37**:50-56.

Mathworks. 2005. Power spectral density (PSD) using Welch's method.*in* Mathworks, editor.

Mills, H. 1995. Automatic detection and classification of nocturnal migrant bird calls. The Journal of the Acoustical Society of America **97**:3370.

Myneni, R. B., F. G. Hall, P. J. Sellers, and A. L. Marshak. 1995. The interpretation of spectral vegation indexes. IEEE Transactions on Geosicence and Remote Sensing **33**:481-486.

Napoletano, B. M. 2004. Measurement, Quantification and Interpretation of Acoustic Signals within an Ecological Context. Michigan State University, East Lansing.

Narins, P. M. 1995. Frog Communication Scientific American **273**:6 Page (s).

National Research Council. 2001. Grand Challenges in Environmental Sciences. Committee on Grand Challenges in Environmental Sciences

Oversight Commission for the Committee on Grand Challenges in Environmental Sciences, Washington, D.C.

O'Connor, R. J., E. Dunn, D. H. Johnson, S. L. Jones, D. Petit, C. R. Smith, and E. Welling. 2000. A Programmatic Review of the North American Breeding Bird Survey: Report of a Peer Review Panel. [Online] Available at www.mp2-pwrc.usgs.gov/bbs/index.html.

Otsuki, M., A. Kimura, T. Nishiura, F. Shibata, and H. Tamura. 2007. RealSound Interaction: A Novel Interaction Method with Mixed Reality Space by Localizing Sound Events in Real World. LECTURE NOTES IN COMPUTER SCIENCE **4551**:653.

Ouis, D. 2001. Annoyance from road traffic noise: a review. Journal of Environmental Psychology **21**:101-120.

Palmer, M. W. 1993. Putting things in even better order: the advantages of canonical correspondence analysis in ecology. Journal of Ecology **65**:85-94.

Parker III, T. A. 1991. On the Use of Tape Recorders in avifaunal surveys. Auk **108**:443-444p.

Patuxent Wildlife Research Center. 2001. North American Breeding Bird Survey. U. S. Geological Survey and Canadian Wildlife Service, [Online.] Available at http://www.pwrc.usgs.gov/bbs/.

Peterjohn, B. and K. Pardieck. 2002. A bibliography for the North American breeding bird survey.*in* USGS Patuxent Wildlife Research Center, editor. U.S. Geological Survey, Laurel, Maryland.

Porter, J., P. Arzberger, P. Hanson, T. Kratz, S. Gage, T. Williams, S. Shapiro, P. Bryant, F.-P. Lin, H.-b. King, T. Hansen, H.-W. Braun, and W. Michener. 2005. Wireless Sensor Networks for Ecology. BioScience **55**:p.561-572.

Qi, J., S. H. Gage, W. Joo, B. Napoletano, and S. Biswas. 2008. Soundscape characteristics of an environment: A new ecological indicator of ecosystem health. Pages pp.201-211 *in* J. W, editor. Wetland and water resource modeling and assessment. CRC press, New York, New York.

R Development Core Team. 2007. R: A language and environment for statistical computing. , Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org. R Foundation for Statistical Computing, Vienna, Austria.

Rabin, L. A., B. McCowan, S. L. Hooper, and D. H. Owings. 2003. Anthropogenic Noise and its Effect on Animal Communication: An Interface Between Comparative Psychology and Conservation Biology. International Journal of Comparative Psychology **16**:172-192.

Ralph, C. J., G. R. Geupel, P. Pyle, T. E. Martin, and D. F. DeSante. 1993. Handbook of field methods for monitoring landbirds. General Technical Report PSW-GTR-144, Pacific Southwest Research Station, Forest Service, U.S. Dept. of Agriculture, Albany, CA.

Ralph, C. J., J. R. Sauer, and S. Droege. 1995. Monitoring bird populations by points counts. USDA, Albany.

Reijnen, R. and R. Foppen. 1994. The effects of car traffic on breeding bird populations in woodland. 1. Evidence of reduced habitat quality for willow warblers (*Phylloscopus trochilus*) breeding close to a highway. Journal of Applied Ecology **31**:85-94.

Richter, K. O. and A. L. Azous. 2001. C Amphibian Distribution, Abundance, and Habitat. Wetlands and Urbanization Implications for the Future.

Robbins, C. S., D. Bystrak, and P. H. Geissler. 1986. The Breeding Bird Survey: Its first fifteen years, 1965-1979.

Robbins, D. S. 1979. Effects of forest fragmentation on bird populations.*in* R. M. Degraaf and N. Tilghman, editors. Proceedings of the workshop on management of North-Central and Northeastern forests for nongame birds. U.S. For. Serv. Gen. Tech. Rep. NC-51.

Robinson, S. K., F. R. T. III, T. M. Donovan, D. R. Whitehead, and H. Faaborg. 1995. Regional Forest Fragmentation and the Nesting Success of Migratory Birds. Science **267**:1987-1990p.

Robinson, S. K. and D. S. Wilcove. 1994. Forest fragmentation in the temperate zone and its effects on migratory songbirds. Bird Conservation International **4**:233-249.

Romer, K. and F. Mattern. 2004. The design space of wireless sensor networks. Wireless Communications, IEEE [see also IEEE Personal Communications] **11**:54-61.

Rosenstock, S. S., D. R. Anderson, K. M. Giesen, T. Leukering, and M. F. Carter. 2002. Landbird counting techniques: current practices and an alternative. The Auk **119**:46-53.

Rossing, T. D. 2007. Springer handbook of acoustics springer, New York, N.Y.

Rundus, A. S. and L. A. Hart. 2002. Overview: Animal Acoustic Communication and the Role of the Physical Environment. Journal of Comparative Psychology **116**:120-122.

Ryan, M. J., R. B. Cocroft, and W. Wilczynski. 1990. The role of environmental selection in intraspecific divergence of mate recognition signals in the circket frog, *Acirs Crepitans*. Evolution **44**:1869-1872.

Sauer, J. R., B. G. Peterjohn, and W. A. Link. 1994. Observer differences in the North America breeding bird survey. The Auk **111**:50-62.

Schafer, R. M. 1977. The Soundscape: Our Sonic Environment and the Tuning of the World. Destiny Books, Rochester, Vermont.

Schafer, R. M. 1994. The Soundscape: Our Sonic Environment and the Tuning of the World. Destiny Books, Rochester, Vermont.

Schieck, J. 1997. Biased detection of bird vocalizations affects comparisons of bird abundance among forested habitats. The Condor **99**:pp. 179-190.

Shannon, C. E. and W. Weaver. 1963. The mathematical theory of communication. University of Illinois Press, Urbana, Illinoise, USA.

Sharpe, R. 1886. The AOU Code and Check-List of American Birds. NATURE **34**:168-170.

Slabbekoorn, H. and M. Peet. 2003. Birds sing at a higher pitch in urban nise. NATURE **424**:267.

Stevenson, R. J., B. C. Bailey, M. C. Harass, C. P. Hawkins, J. Alba-Tercedor, C. Couch, S. Dyer, F. A. Fulk, J. M. Harrington, C. T. Hunsaker, and R. K. Johnson. 2004. Designing data collection for ecological assessments. Pages Pgs 55-84 *in* M. T. Barbour, S. B. Norton, H. R. Preston, and K. W. Thornton, editors. Ecological Assessment of Aquatic Resources: Linking Science to Decision-Making. Society of Environmental Toxicology and Chemistry, Pensacola, Florida.

Stokes, D. and L. Stokes. 1996. Stokes filed guide to birds: eastern region. Little, Brown and Compony, Boston, MA.

Straker, A. and K. W. Lowe. 2004. Native Biodiversity Resource Kit: Environmental management in agriculture. Department of sustainablility and Environment, Melbourne, Victoria, Australia.

Stutz, F. 1986. Environmental impact. Pages 329-343 *in* S. Hanson, editor. The geography of urban transportation. The Guilford press, New York.

Sun, J. W. C. and P. M. Narins. 2005. Anthropogenic sounds differentially affect amphibian call rate. Biological Conservation **121**:419-427.

Tempest, W. 1976. Infrasound and low frequency vibration. Academic Press, London.

ter Braak, C. J. F. 1986. Canonical Correspondence Analysis: a new eigenvector technique for multivariate direct gradient analysis. Ecology **67**:pp. 1167-1179.

ter Braak, C. J. F. and I. C. Prentice. 1988. A theory of gradient analysis. Advances in theological Research **18**:271-317.

The American Heritage Dictionary. 2000. The American heritage dictionary of the English language. Houghton Mifflin, Boston.

Thompson, J. N. 2001. Frontiers of ecology. BioScience **51**:15-24.

Thompson, W. L. 2002. Towards reliable bird surveys: Accounting for individuals present but not detected. The Auk **119**:pp.18-25.

Truax, B. 1984a. Acoustic communication. Ablex Publishing, New Jersey.

Truax, B. 1984b. Handbook for Acoustic Ecology. Cambridge Street Publishers.

Vitousek, P. M., H. A. Mooney, J. Lubchenco, and J. M. Melillo. 1997. Human Domination of Earth's Ecosystems. Science **277**:pp. 494 - 499.

Warren, P. S., M. Katti, M. Ermann, and A. Brazel. 2006. Urban bioacoustics: it's not just noise. Animal Behaviour **71**:491-502.

Weir, L. A. and M. J. Mossman. 2005. North American Amphibian Monitoring Program (NAAMP). Pages pp. 307-313 *in* M. J. Lannoo, editor. Amphibian Declines: Conservation Status of United States Species. Univ. of California Press, Berkeley.

Welch, P. 1967. The use of fast Fourier transform for the estimation of power spectra: A method based on time averaging over short, modified periodograms. Audio and Electroacoustics, IEEE Transactions on **15**:70-73.

Whitcomb, R. F., C. S. Robbins, J. F. Lynch, B. L. Whitcomb, M. K. Kliemkewicz, and D. Bystrak. 1981. Effects for forest fragmentation on avifauna of the eastern deciduous forest. Pages 125-205p *in* R. L. Burgess and D. M. Sharpe, editors. Forest island dynamics in man-dominated landscapes. Springer-Verlag, New York.

Wiley, R. H. and D. G. Richards. 1978. Physical constraints on acoustic communication in the atmosphere: implications for the evolution of animal vocalizations. Behavioral Ecology and Sociobiology **3**:69-94.

Williams, B. K., J. D. Nichols, and J. C. Michael. 2002. Analysis and management of animal populations. Academic Press.

Zimmerling, J. R. and C. D. Ankney. 2000. A technique that increases detectability of passerine species during point counts. Journal of Field Ornithology **71**:638-649.