WHITE PAPER

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Development and Application of Environmental Acoustics for Monitoring Bird Pathways in Wind Resource Areas

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Summary

Development and Application of Environmental Acoustics for Monitoring Bird Pathways in Wind Resource Areas

Wind-generated energy is considered to be one of the most advanced renewable energy technologies and has become one of the fastest growing energy industries. Although it is widely accepted that development of renewable energy resources is to reduce greenhouse gas emissions, a better understanding of the unintended impacts of wind farms on wildlife is needed. For instance, the increased mortality rate of raptors and migrating passerines due to impact with turbine blades has been investigated by several research teams. The increased awareness of wind farm environmental impacts has prompted state and federal agencies to put forth guidelines for evaluating the potential effects that a wind farm deployment might have on wildlife. Automated monitoring, using in-situ sensor systems, enables timely delivery of data from sensor-to-user, enabling better decision making. However, further study is still required to best understand the correlation between sensor data and the flow of life through wind resource areas.

Acoustic signatures constitute a source of information that can be used to measure the spatial and temporal distributions of vocal organisms in ecosystems. Measuring and tracking those species that produce sounds can reveal important information about the environment. Acoustic signals have been used for many years to census vocal organisms. For example, the North American Breeding Bird Survey, one of the largest long-term, national-scale avian monitor programs, has been conducted for more than 30 years using human auditory and visual cues. The North American Amphibian Monitoring Program is based on identifying amphibian species primarily by listening for their calls. Recent advances in sensor networks enable large-scale, automated collection of acoustic signals in natural areas. The systematic and synchronous collection of acoustic samples at multiple locations, combined with measurements of ancillary data can produce an enormous volume of ecologically relevant data that can be used to measure and compare the quality of habitats and to serve as indicators of environmental change.

This white paper describes an operational framework to enable the deployment of acoustic sensors, manage and access the observations, interpret the general and specific information in the signals and specifically address elements of habitat usage, species diversity, ecological disturbance, species census, and species migration and timing. Our intent is to assist wind energy organizations to implement and deploy an habitat evaluation procedure and sensor technology for evaluating and monitoring wind resource area wildlife habitats to better enable decision making with respect to wind turbine site selection and operation. Specifically, we intend to do on-site reconnaissance studies, continuous and periodic monitoring using acoustic and other sensors and propose standards for monitoring species migration, census, and mortality in wind resource areas.

Project Description

1. Introduction

Wind-generated energy is considered to be one of the most advanced renewable technologies (Exo et al. 2003) and has become one of the fastest growing energy industries (Pasqualetti et al. 2004, National Research Council 2007a, Kunz et al. 2007). Although it is widely accepted that development of renewable energy resources is to reduce greenhouse gas emissions, a better understanding of the unintended impacts of wind farms on wildlife is needed. For instance, the increased mortality of raptors and migrating passerines due to impact with turbine blades has been investigated by several research teams (Erickson et al. 2001, Morrison and Sinclair 2004, Manville 2005, Drewitt et al. 2006, Kunz et al. 2007). The large number of reported raptor fatalities at Altamont Pass in California (Orloff and Flannery 1992) and at Tarifa and Navarre in Spain (Barrios and Rodriguez 2004) helped increase awareness and concern about the potential impacts of wind turbines on avian communities (Estep 1989; Orloff and Flannery 1992, 1996; Drewitt et al. 2006; and Kunz 2007). Moreover, increased awareness has prompted state and federal agencies to put forth guidelines for evaluating the potential effects that a wind farm deployment might have on wildlife (Michigan Department of Labor and Economic Growth 2005; United States Fish and Wildlife Service 2003; Anderson et al. 1988, 1999).

With the growth and expansion of human populations has come an increasingly greater need to understand the dynamics of ecosystems and their complex interactions (Michener *et al.* 2001). As urban areas continue to expand, fragile surrounding ecosystems are often affected as they are redesigned to support urban infrastructure. For instance, the fragmentation of forests within the National Parks and Reserves, and its effects on animal habitats, is becoming a significant problem. In Michigan, urban populations are estimated to increase 180 percent by the year 2040 (Skole *et al.* 2002). When human development impacts critical components or linkages within an ecosystem, the function and structure of that ecosystem is dramatically altered (Vitousek 1997). The need to better understand these effects has led to the development of ecological indicators, which are variables measured within an ecosystem that contain information regarding the degree of ecosystem stress and perturbation. Dale and Beyeler (2001) argue that these ecological indicators need to capture the complexities of the ecosystem, yet need to be routinely and easily monitored. They note that ecological indicators should: (1) be sensitive to stresses on the system; (2) respond to stress in a predictable manner; (3) be anticipatory, integrative, and have a known response to disturbances, anthropogenic stresses, and changes over time; and (4) have low variability in response. Indicators that meet these criteria can provide information important for making decisions on how people and organizations can use the Earth's natural resources responsibly.

This white paper describes an operational framework to enable the deployment of acoustic sensors, manage and access the observations, interpret the general and specific information in the signals and specifically address elements of habitat usage, species diversity, ecological disturbance, species census, and species migration and timing. Our intent is to assist wind energy organizations to implement and deploy an habitat evaluation procedure and sensor technology for evaluating and monitoring wind resource area (WRA) wildlife habitats to support better risk assessment and decision making with respect to wind turbine site selection and operation. The following project description is intended to provide background and insight into the potential for acoustic monitoring of wind resource areas. Although the following description proposes an extensive evaluation and assessment protocol, smaller projects that comprise a subset of the proposed activities may also provide significant information about the potential impact of wind resource area development on existing habitats and migration pathways.

2. Proposed Deployment

We propose a research project to improve knowledge about the use of acoustic signals as a means to measure and interpret the status of ecological systems in wind resource areas. The project will exploit state-of-the-art sensor technologies, previously developed and tested by the investigators, for the capture and transmission of acoustic data from field sites to data processing centers. The main focus of the project is on the collection and analysis of sensor data and the use of the results to assess risk and enable informed decision making with respect to wind farm placement and operation. First, we plan to monitor first arrival events for detection of migratory bird species, and detect and identify raptors and passerine night calls. Second we will focus on more general measurement, interpretation, characterization and comparison of reference sites with those sites monitored in wind resource areas. We intend to refine our Acoustic Habitat Quality Index (AHQI) to better represent specific habitat types, and develop new metrics for comparing and measuring how the quality of a habitat is impacted by wind farm presence. Third, we will plan to correlate landscape cover and habitat types, characterized through on-site studies, with acoustic and other sensor data to better enable measurement and interpretation of ecosystems in wind resource areas. Four key system components will be implemented to accomplish these goals and assess the impact imposed on wildlife by wind energy facilities.

On-site reconnaissance studies. When possible, On-site studies will be conducted before deployment of wind-turbine towers, after deployment but before turbine operation begins, and after turbine operation has begun. Conducting an on-site study at each of these three junctures enables comparison of site characteristics and populations to better understand how the site has changed as the wind farm is developed. On-site reconnaissance studies will comprise: mortality counts, point count avian census surveys, survey and mapping of land cover and habitat type, and completion of the US Fish and Wildlife Service's (2003) Potential Impact Index (PII) checklist forms.

Periodic monitoring. In addition to reconnaissance studies, we intend to conduct periodic on-site monitoring. Similar to reconnaissance studies, periodic monitoring will enable comparison of site characteristics and populations as the change over time. In addition, periodic on-site monitoring will help verify the results produced during continuous monitoring using automated sensor stations. On-site periodic monitoring will comprise: mortality counts, point count avian census surveys, survey of land cover and habitat type and change, and completion of the US Fish and Wildlife Service's PII checklist forms. In addition we plan on investigating the utility of using marine radar and infrared imagery for estimating the volume of birds and bats flying over the wind resource area under study.

Continuous monitoring. We propose to leverage sensor technologies, infrastructure, and on-line, automated analysis techniques to identify the relationship between acoustics and ecological indicators. The acoustic monitoring system will focus on identifying species based on their acoustic signatures. A sensor data stream is a time series comprising continuous or periodic sensor readings. Typically, readings taken from a specific sensor can be identified and each reading appears in the time series in the order acquired. These sequences can be clustered and fused with other data to support species detection and classification. *Classification* attempts to accurately recognize which species produced a particular vocalization, while *detection* indicates the likelihood that an acoustic clip contains a the vocalization of a particular species (Kasten et al. 2007). Visual and other representations of acoustic and other sensor signals can be used to enable automated classification and detection of acoustic events, including classification and detection of vocalizing species. Moreover, such signal processing and analysis enables the computation of indices and fusing of different sensor data types that can be used for ecosystem assessment.

We will standardize the collection of acoustic samples at 30 minute intervals for 30 second duration sampled at 16 bits at a frequency of 22 kHz. The data set will amount to 250 MB of acoustic samples per day from each cluster of 4 sensors (4x48x1.3 MB). This data rate will provide the capacity to examine the diurnal cycle of: (a) arrival events and (b) disturbance regimes. We will enable sensor observations to be stored locally and transferred to remote servers through either manual collection or transmission using standard satellite technology, like that used to provide internet connectivity. Acoustic sensor platforms can collect large data sets, so automated processing will be used to facilitate the organization and searching of the resulting data repositories. Without timely processing, the sheer volume of the data will preclude the extraction of information of interest. We will address this challenge directly by implementing a systems approach to the cyberinfrastructure challenges to ensure that a functional acoustic digital library will be accessible for monitoring the flow of life through wind resource areas, and enabling analysis and interpretations. A regional server system will receive raw and processed sensor observations from sensor clusters and will store these observations and associated metadata in a digital library. Analytical systems, housed on the regional server, will enable the analysis of sensor observations and correlate the results with other information, such as that acquired through on-site studies, landscape type or meteorological observations.

Ecosystem assessment and reporting. We will apply data mining techniques to detect the presence of specific sentinel species to recognize the first arrival of migratory birds and the presence of raptors and passerines. We will further develop and refine acoustic metrics, such as AHQI, to better measure and characterize specific habitats, and use these metrics to investigate the correlation between acoustic habitat quality and other metrics for measuring, comparing and interpreting habitats and ecosystems. Moreover, we will marry the results of our on-site studies with information obtained through analysis of collected sensor data to produce reports characterizing habitats and their inhabitants to help assess the risk associated with a specific wind farm deployment and provide guidance on its operation.

2.1 Justification for Automated Monitoring

Documentation of the potential impacts of wind farm development on avian species requires field monitoring prior to establishment of wind resource areas (US Fish and Wildlife Service 2003, Kunz et al. 2007, National Research Council 2007b). The National Wind Coordinating Committee (NWCC) recommends that bird biological information must be sufficiently documented by on-site surveys and monitoring of birds including species of special concern. Birds of interest include: endangered or threatened species listed by the federal or state governments, breeding birds, migrating birds, wintering birds and species known to be susceptible to collision (e.g., raptors and ravens). Moreover, efforts to minimize the potential risk to birds early in the pre-construction process are important because of the potential for incurring greater expense and delay if problems occur after construction of wind energy facilities (Anderson et al. 1999).

Traditionally, one of the most commonly used survey methods used for identifying bird species and estimating abundance has been the point count survey (Ralph et al. 1995, Rosenstock et al. 2002, Thompson 2002). The point-count method depends on a human observer to identify birds using acoustic and visual cues within a fixed distance at a specific points in an area block or along a line transect during the breeding season (Hutto et al. 1986, Ralph et al. 1995). Several studies have expressed concerns about using the point count method to survey birds because of inconsistencies in detection probability among species and across habitats or over time (Thompson 2001, Rosenstock et al. 2002). They also noted that even highly skilled observers cannot detect every bird that is present or singing simultaneously. Others have raised concerns regarding the high variability found among observers with respect to their ability to accurately conducting surveys (i.e., experience and survey skills, age, and hearing loss) (O'Connor et al. 2000). Point-count results can vary considerably due to diurnal and seasonal changes that occur during survey periods (Canada Wildlife Service 2006). In addition, when using only the point-count method, there is no validation of the species identified by an observer.

We propose to deploy an array of automated acoustic recording platforms that will record the sounds of migrating and resident species of vocalizing organisms at frequent regular intervals and 24 hours per day. The recordings will be archived in a digital acoustic library for subsequent analysis, interpretation and access. There are several advantages for using automated recording of biological acoustic signals over traditional point-count methods in to support evaluation of wind turbine impacts on migratory species of birds. The traditional point count method, although valuable, has several deficiencies that must be supplemented by automated recording sensors. The advantages of using automated acoustic sensor platforms are:

1. Avian species can and do migrate at all times of the day and night. It is necessary to measure at regular intervals to capture the dynamics of migration. Our automated recorders can be programmed to record at any time interval for any length of time.
2. Migratory activity occurs over large geographic areas and it is necessary to make simultaneous measurements spanning the extent of the wind farm to interpret the passage of migrants through and over the wind farm. Our automated recorders are designed to make simultaneous measurements with appropriate archival and access technology.

3. Minimal variability in recording quality is necessary to capture subtle migratory bird calls, especially at night. Our automated recorders and parabolic microphones are designed to capture standardized high quality digital recordings.
4. Sounds produced by migratory species are distinct but are difficult to identify. Our analytical pattern matching system system can distinguish unique signatures and search the wind farm acoustic library to match vocalization frequencies.
5. Resident birds and other organisms that communicate via acoustics will occur within the wind farm landscape. Our acoustic recorders will record these organisms and will provide an exceptional digital dataset of resident and migratory organism vocalizations at high temporal resolution.

One of the main concerns in developing wind energy facilities is the collision risk to migratory birds. As previously noted, point counts are limited to recording species presence and and estimates of population, primarily for resident (breeding) bird populations (Canada Wildlife Service 2006, Kunz 2007). During the migratory period (mostly during the spring and fall), many passerines and waterbirds migrate at night whereas point-count surveys are typically conducted during the day when visual cues are available to the observer. The number of migratory birds can vary considerably during the migration period, depending on local climate conditions. Thus, highly intensive surveys are required to get a quantitative evaluation of avian migration at a site. Although little is known about the flight call rate of migratory birds at night, research has shown that the number of radar objects is significantly correlated with the number of flight calls recorded (Evans 2000, Larkin et al. 2002, Farnsworkth et al. 2004). These results indicate that species surveys conducted using acoustic recordings can be used as an index of avian migration activity.

In addition, it is essential to investigate whether migratory birds are in the height range of the rotor-swept zone when they are flying through the site, descending, or taking off from the ground. The point-count method is not intended to estimate the flight altitude of migration birds. Quantification of flight altitude for nocturnal migration can be documented using radar technology. Moreover, multi-microphone arrays with accurate multi-channel recording equipment can provide an estimate of the direction and distance of bird calls (Evans 2000). Thus, the radar and acoustic monitoring technology can provide powerful tools for intensively monitoring and quantifying migratory bird activity even at night when migrating birds use night calls for communication.

2.2 Project Outcomes

Implementation of our four key system components will enable assessment of the impact imposed on avian wildlife in the wind energy area (WRA) under study and is expected to produce at least the following 7 outcomes.

1. A procedure and protocol to assess the impact of WRA development procedure and protocol to assess the impact of WRA development on migrating avian populations to include:

a. Background (literature) searches to capture existing information on regional avian species, migration pathways and important habitats.
b. On-site assessment of avian (passerine and raptor) census, diversity, and mortality conducted before and after WRA development.
c. Continuous monitoring of the WRA, including acoustics and, potentially, marine radar, optical or other monitoring systems.
d. Correlation of WRA avian populations with habitat type.
e. Detection of seasonal arrival and occupation by WRA avian inhabitants.
f. Calculation of potential impact indices for different WRA habitat types.
g. Construction of habitat maps that cover the WRA under study and indicate areas of greatest potential impact.

2. Extension of the above procedure and protocol as a methodology for evaluating wind farm installations in the Great Lakes, including a documented approach for assessing a potential wind farm development site with respect to the potential impact on avian populations.
3. A framework for designing and deploying an automated monitoring system in a WRA. This framework will address the technological and communications needs for establishing sensor stations within a WRA and for harvesting the collected observations.
4. A database of avian observations to support innovative bird migration research. Automated monitoring collects large amounts of data that can be mined to enable better mapping of migration pathways and enable better understanding of the environmental conditions that affect avian migration.
5. A near real-time bird migration observatory. Acoustic and other observations collected during continuous, automated monitoring can be transmitted to REAL servers to support near real-time monitoring of changing temporal, spacial and phenological dynamics as they affect local populations. These data and related analysis results can be accessed via a secure web site.
6. Reports, maps and other supporting documentation to enable WRA operators to better understand the risk associated with developing a specific WRA, and help guide wind farm operation.
7. Workshops and research publications on evaluation and assessment of the impact of WRA development on avian populations and migration in WRAs. Workshops are intended to educate WRA operations and students on the automated monitoring and assessment of WRAs, and recommended procedures and protocols for mitigating potential impact on avian communities.

2.3 Site Selection

As shown in Figure 1 and in greater detail in Figure 2, we plan to deploy 4 sensor stations at the cardinal positions around on-site meteorological stations. By installing our acoustic monitors in close proximity to the existing meteorological stations, we hope to better correlate raptor and passerine behavior with current weather conditions at wind resource facilities. Studying how weather affects avian behavior may provide insight that enables prediction of periods where high avian mortality rates are likely.   Moreover, by positioning 4 sensor stations at the cardinal compass points (north, south, east and west), we plan on capturing information about the flight direction of migrant populations. In addition to sensor stations installed in proximity to the weather stations, we will deploy additional sensor clusters at reference sites for comparison. As recommended by the US Fish and Wildlife Service (2003), reference sites will be high-quality wildlife areas that can be used for determining the comparative risks of developing other potential sites. Comparison of reference sites with potential development sites enables the calculation of potential impact indexes (PIIs) that can be used to guide tower placement. We will develop an acoustic PII and study how it correlates with the the PII computed using the US Fish and Wildlife Service protocol.

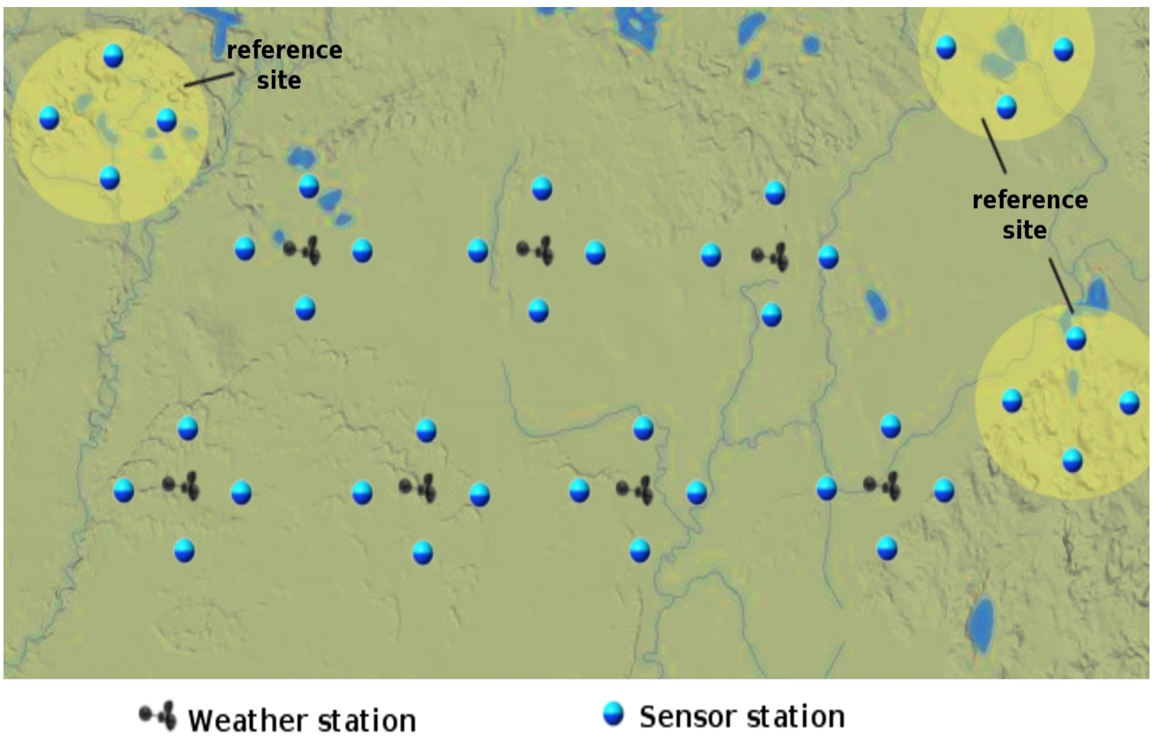

Figure 1: Pictorial of proposed monitoring site. Sensor units outfitted with upward oriented parabolic microphones will be positioned at four cardinal positions (north, south, east and west) within 100 meters of each meteorological stations and at reference sites for comparison.

Each acoustic sensor will be equipped with a parabolic microphone oriented to record vocalizations from above by birds during flight. As such, the sensor stations are intended to monitor the passage of birds as they fly through the wind farm. We intend to investigate the relationship between the types of birds present in the airscape, indices of biological activity, as measured using acoustics, and the avian mortality rate (established using on-site surveys). We also plan to conduct on-site point count and other surveys to ground our surveys conducted using automated acoustic recordings. Resources permitting, we intend to automatically transmit collected sensor data to REAL servers using commercial satellite technology, like that used for providing residential internet access. We anticipate that each wind resource area will only require a single satellite station coupled with a small computer for storage and relay of sensor data received from sensor stations over a local wireless sensor network. If there is insufficient electrical or satellite service, we intend to fall back to periodic manual collection of collected sensor recordings.

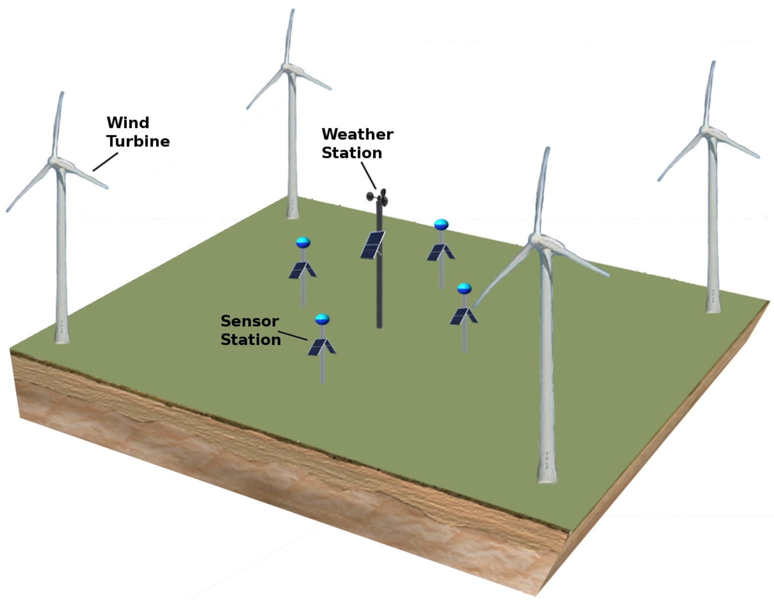

Figure 2: Pictorial of proposed sensor deployment. Sensor units outfitted with upward oriented parabolic microphones will be positioned at four cardinal positions (north, south, east and west) within 100 meters of each weather station.

3. The Environmental Impact of Wind-Generated Energy

The potential impact on avian communities resulting from the construction of a wind farm typically fall into two main categories: direct and indirect (Kunz et al. 2007). Direct impact refers to avian fatalities or lethal injury due to collision with wind turbine rotor blades and poles (Desholm et al. 2006, Drewitt et al. 2006). In addition, it has been reported that the vortex created by wind rotors can be lethal for birds (Winkelman 1992). Since the implementation of large-scale wind resource facilities in California, incidents of avian collisions have been increasingly reported. The California Energy Commission (1989) documented that there were 108 fatalities across 7 raptor species at Altamont over a 4-year period from 1984 to 1988. Avian fatalities due to collision with wind turbines affected several species of special concern, including 26 golden eagles and 20 red-tailed hawks. One study on wind farm bird fatalities due to collision documented 182 bird casualties, comprising 68% raptors and 26% passerines (Orloff and Flannery 1992). Affected raptor species included the red-tailed hawk, American kestrel, and the golden eagle. Orloff and Flannery (1992) indicated that the number of raptor fatalities may be as high as 567 over 2 years. In Carbon County, Wyoming, Johnson et al. (2001) estimated that there were 159 bird fatalities per year due to collision in a wind farm comprising 95 wind turbines. Of these fatalities 91% were passerines and 5.2 % were raptors.

Indirect impacts of wind farms on birds refers to disturbance of foraging and resting behaviors, breeding activities, and migratory patterns due to altered habitat and landscape structures. Indirect impacts include: displacement, habitat loss or modification, and flight avoidance responses. Direct and indirect impacts on birds can lead to high mortality, changes in food and nest availability, high probability of predation, and altered population viability and genetic structure (National Research Council 2007a). Birds can be displaced from a preferable foraging and resting area by the disturbance of turbines, or avoid flying near wind turbines during migration (Desholm et al. 2006, Drewitt and Langston 2006). In general it is assumed that displacement may occur during both the construction and operational period of wind farms. Bird displacement can be caused by noise, visual, and vibration disturbance of wind turbines, and the presence of human activities including vehicles and personnel movements (Drewitt and Langston 2006). So far, little research has been conducted to investigate the types and degree of disturbance causing bird displacements. Pendersen and Poulsen (1991) recorded that disturbance distance (i.e., the distance from a wind farm at which birds are absent or fewer in number) was approximately 600 to 800 meters for wintering waterfowl at onshore wind farms. Leddy et al. (1999) documented that densities of breeding grassland passerines increased with distance from wind turbines.

Although the actual amount of habitat loss resulting from the implementation of wind energy facilities is expected to be from 2% to 5% of the total wind development area (Fox et al. 2006), physical habitat loss could contribute to the creation of novel feeding, resting, and breeding opportunities that actively attract birds to the turbines, and to loss or alterations in habitat elements such as hydrological flows and wetland sites (Drewitt and Langston 2006). To date, most wind turbines in the US have been implemented in grassland, agricultural, and desert landscapes in western and mid-western regions. Construction of wind farms on agricultural landscapes can lead to declining populations of grassland and shrub-steppe bird species that are already suffering from significant habitat loss, fragmentation, and degradation (Erickson et al. 2007). There is much uncertainty about the scale and the size of habitat changes or loss due to wind energy development. In addition, few studies have been conducted to investigate the significance of wind farm placement on wildlife habitat. Therefore, long-term and on-going research should be done to reveal the potential impacts of wind farm placement on avian habitats.

4. Acoustic Monitoring

Acoustic signatures constitute a source of information that can be used to measure the spatial and temporal distributions of vocal organisms in ecosystems (Kroodsma et al. 1996, Gage 2001). Communication is a fundamental property of many types of animals. The exchange of biological information requires energy expenditure by organisms to produce as well as capture kinetic energy transmitted as sound. Measuring and tracking those species that produce sounds can reveal important information about the environment. Ecosystem sounds create a *soundscape*, comprised of acoustic periodicities and frequencies emitted from the ecosystem's biophysical entities (Qi et al. 2008; Sueur et al. 2008; Truax 1978, 1999; Schafer 1977).

Acoustic signals have been used for many years to census vocal organisms. For example, the North American Breeding Bird Survey, one of the largest long-term, national-scale avian monitor programs, has been conducted for more than 30 years using human auditory and visual cues (Bystrak 1981). The North American Amphibian Monitoring Program is based on identifying amphibian species primarily by listening for their calls (Weir and Mossman 2005). Recent advances in sensor networks enable large-scale, automated collection of acoustic signals in natural areas (Estrin *et al.* 2003). The systematic and synchronous collection of acoustic samples at multiple locations, combined with measurements of ancillary data such as light, temperature, and humidity, can produce an enormous volume of ecologically relevant data. Transmuting this raw data into useful knowledge requires timely and effective processing and analysis. Acoustics as an ecological attribute has the potential to increase our understanding of ecosystem change due to human disturbance, as well as provide a measure of biological diversity and its subsequent change over time (Truax 1984, Wrightson 2000). The analysis of entire soundscapes may also produce valuable information on the dynamics of interactions between ecological systems in heterogeneous landscapes (Charles et al. 1999). Moreover, timely analysis and processing enables rapid delivery of important environmental information to those responsible for conservation and management of our natural resources, and can promote public involvement through public access to ready information about the environments in which we live.

Acoustic measurement exhibits several desirable properties. First, soundscape analysis simplifies biological measurements. Whereas traditional approaches to measuring biological complexity are labor intensive, the infrastructure used to collect acoustic data can be managed by non-expert field staff (Thompson *et al.* 2001, Michener *et al.* 2001, West *et al.* 2001, Hobson et al. 2002). Second, continuous and stationary acoustic monitoring reveals spatiotemporal patterns that cannot be captured in site-by-site observations. By remaining in one location and monitoring continuously, acoustic information can reveal changes in ecosystems over diurnal, monthly, seasonal, yearly, and other temporal scales (Truax 1984). Third, because acoustic monitoring systems can simultaneously monitor in multiple locations, acoustical variances can be compared to environmental heterogeneity (Thompson *et al.* 2001, Michener *et al.* 2001, West *et al.* 2001). Fourth, microphones can collect data from all directions simultaneously despite occlusions, such as trees or buildings, and cover of darkness. Finally, ecological acoustics can be measured automatically with minimal human interference. Recording technology operates independently in the field, thereby allowing observation to take place without interference generated by human presence (West *et al.* 2001).

Over the past few years, great strides have been made in the following areas: sensor platform development; interpretation of acoustic signals; using data mining techniques for identification of vocalizing species; and the use of cyberinfrastructure to collect, disseminate, and store acoustic libraries. The microphone is a sensor that can capture the presence of many vocalizing species of mammals, birds, amphibians and insects, and yet, is non-invasive. Moreover, the microphone can enable the measurement and monitoring of changing patterns of acoustics over long periods that can then be correlated with ecological change.

4.1 Cyberinfrastructure: From sensor-to-user

Automated collection of acoustic and ancillary data is an important goal of this project. As shown in Figure 3, for a deployment at the Kellogg Biological Station, each sensor cluster comprises two or more sensor platforms and an optional cluster server. Each sensor platform collects data at pre-programmed times with minimal site disturbance or regular human intervention. The platform comprises a pole-mounted sensor unit and a solar panel coupled with a deep cycle battery for providing power over extended periods. Acoustic clips or other sensor observations are collected by sensor units and transmitted over a wireless network either directly to the sensor data depot or to a cluster server for later relay to Remote Environmental Assessment Laboratory (REAL) servers (http://www.real.msu.edu).

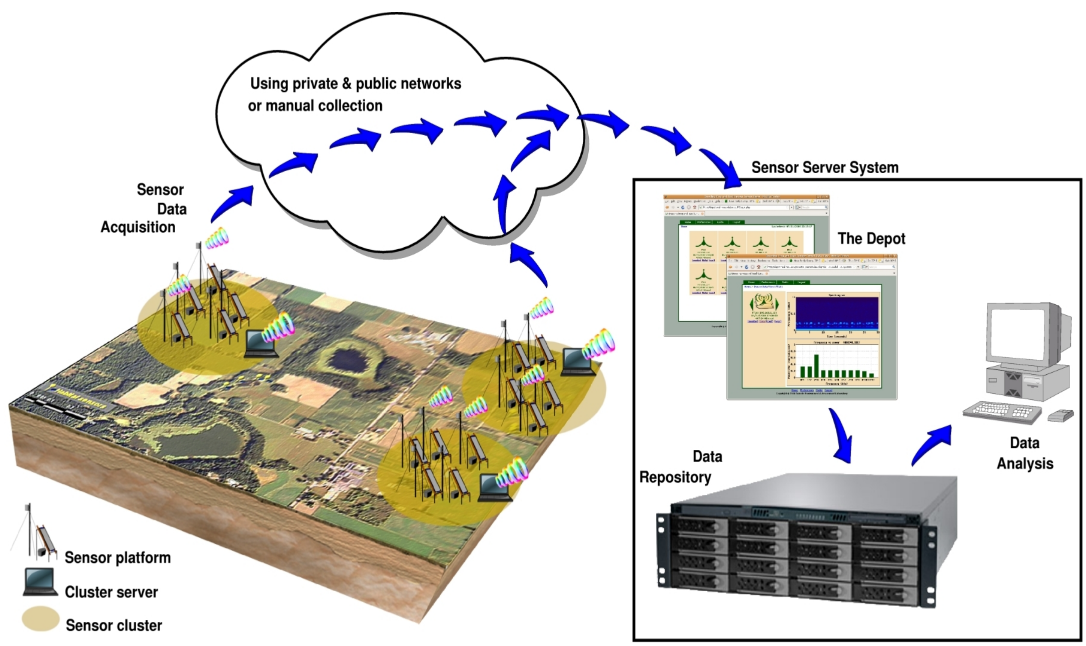

Figure 3: Acoustic sensor deployment at the Kellogg Biological Station in Hickory Corners, MI. Sensor units collect observations that are transmitted over private and public networks to the REAL sensor data depot. The framework also supports manual collection of sensor observations where network infrastructure is not available. Once data arrives at the depot, it can be vetted and automatically cataloged in REAL data repositories.

The sensor data depot provides near real-time processing and analysis of sensor data as it transmitted from sensor units and cluster servers, enabling early vetting of sensor unit operation and data collection. The user can access specific sensor observations based on time of observation. Finally, attributes of the data (acoustic sample) are displayed (oscillogram, spectrogram, frequency vs. power) and the sound clip can be listened to. After sensor data arrives in the depot, it is subsequently processed for cataloging and included in the REAL digital library. We implemented a relational database schema to enable rapid access to large sensor data sets. For example, one of our long term databases of acoustic observations contains 106,164 files and is 127.72 Gigabytes (as of 9/23/08) and is growing at a rate of 60 Megabytes per day. Coupled with the recordings is metadata describing the characteristics of the site, instrumentation and sensor observations. The digital library contains approximately 350 Gigabytes of digital acoustic files that can be accessed on-line. Our real-time data acquisition system has the capacity to automatically populate this acoustic library at our Regional Sensor Observatory as data is transmitted from in-field deployments. Currently, several projects deposit about 60 Megabytes per sensor platform each day.

4.2 Processing and Analysis

One of our goals is to develop a system that enables access to the large array of acoustic observations that our sensor platforms can collect and deliver to the regional sensor server. Depicted in Figure 4 is a framework designed for enabling analysis of observations in a regional repository of sensor observations. Our relational database design enables the rapid extraction of sets of specific sensor observations based on location, sensor, date and time of day. We have built a data access framework to enable users to immediately download the selected sensor data collections to a local computer for customized analysis, or provide general analysis of selected observations through a web-based workbench.

Analytical Advances. We have been investigating techniques for automatic and immediate visualization and interpretation of acoustic signals in a variety of different environmental settings. Figure 5 illustrates a few of the visualization and analytical methods possible using data from selected projects, including using principal components analysis and an acoustic habitat quality index for plotting soundscape metrics. An Acoustic Habitat Quality Index (AHQI) is one technique that we have developed to quantify the soundscape based on the occurrence of selected frequencies in the soundscape. Values are based on computations of the power spectral density (Welch 1968) for each 1 kHz frequency band in the sound sampled from a location in the environment. An analysis of the frequency of biological and technical sounds revealed that biological sounds of birds, amphibians and insects generally occur at higher frequencies (> 2 kHz) in the sound spectrum (Napoletano 2006) compared to technical sounds (1-2 kHz) caused by motors and other mechanical and technological devices. Therefore the ratio of biological and technical sounds provides an indication of the amount of biological or technical information in the signal. Since we are more interested in the relative intensity and position of power of different frequencies in the soundscape and less interested in the overall intensity across all frequency bands (i.e., sound pressure level) of the soundscape, it is useful to normalize the power spectral density values for each computed 1 kHz frequency interval. This alleviates issues with different recording levels. Also, our calculation of AHQI produces a standardized value that ranges from -1 to +1 (Joo 2008), where values are negative when technology is dominant and values are positive when biology is dominant. This index can be applied to any soundscape and enables comparisons within and between locations.

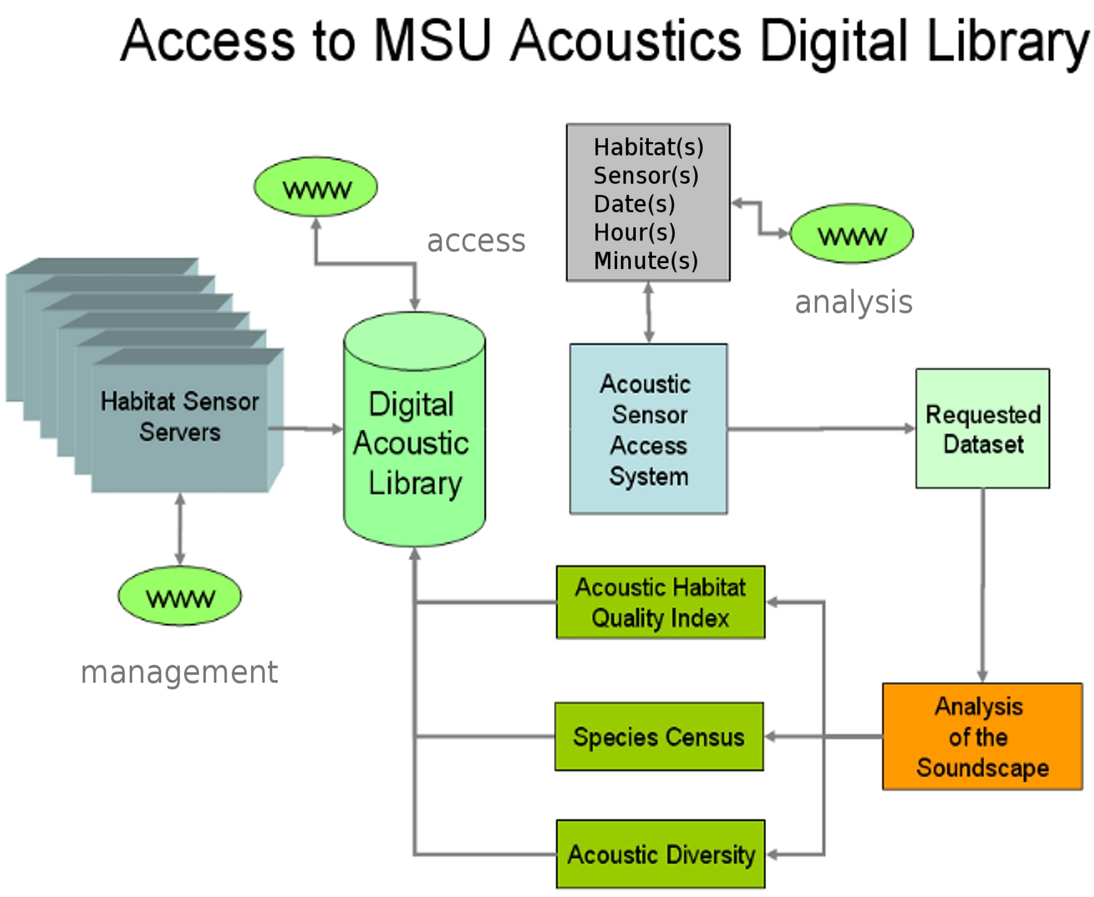

Figure 4. A framework for digital access to acoustic observations acquired by automated sensor platforms.

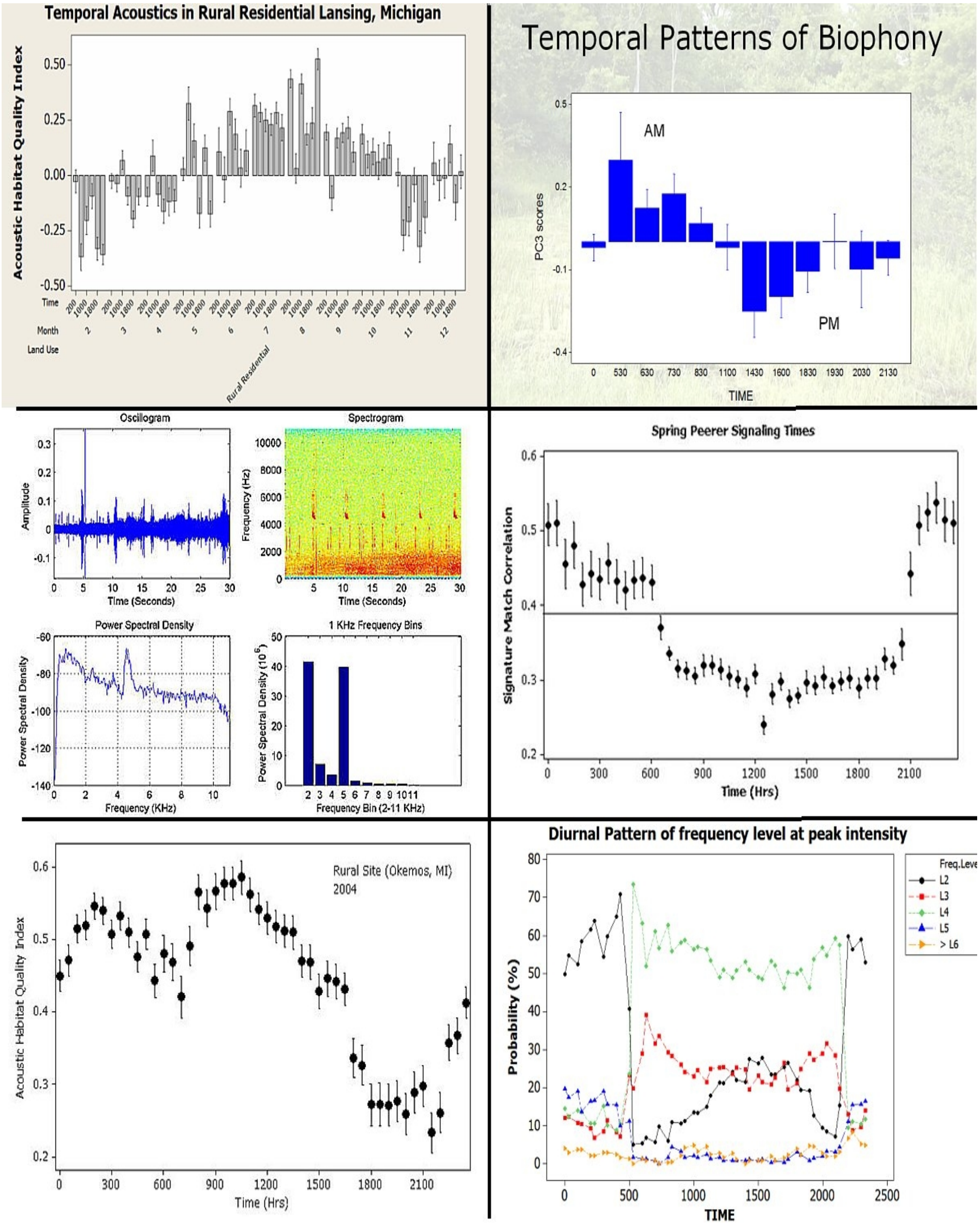

Figure 5. Array of analytical examples to visualize patterns of acoustic observations over time.

5. Example Sensor Deployments

As depicted in Figure 6, REAL has deployed sensor platforms in several locations for collecting environmental acoustics. Figure 6(a) depicts a sensor platform at the Michigan State University Lakes site. The acoustic signaling of water fowl and other wetland inhabitants are recorded and transmitted to REAL servers on the MSU campus. Data has been collected at this site since 2006. Figure 6(b) depicts a deployment at the Kellogg Biological Station (KBS) pond laboratory site in 2007. Platforms were deployed in three different sites at KBS, including: the pond laboratory, bird sanctuary, and an agricultural field. Figure 6(c) is one of seven platforms deployed in Okemos and DeWitt, Michigan in April, May and June 2008. This deployment was a collaboration between REAL, the Michigan Department of Natural Resources, and survey volunteers during Michigan's annual DNR Frog and Toad Survey (Michigan Department of Natural Resources 2008) to study the use of automated collection of acoustics to support frog and toad census. Finally, Figure 6(d) depicts a buoy deployed on a bog in northern Wisconsin. A REAL acoustic sensor unit was installed on this buoy in 2008 to monitor the acoustics of the wetland inhabitants. Acoustics collected by this sensor unit are transmitted directly to REAL servers in East Lansing, Michigan. These and other deployments have collected large (on the order of many gigabytes) data sets of acoustic recordings that are candidates for automated processing, annotation and cataloging. Moreover, REAL has used sensor platforms like these to transmit acoustic observations from sites as far away as Australia to servers in Michigan in near real-time. Next we will describe two REAL projects in greater detail.

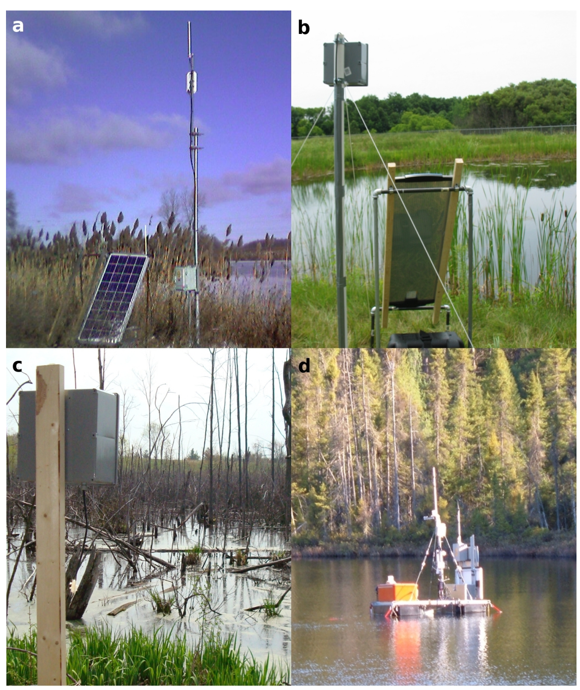

Figure 6: Example sensor platform deployments. Deployment locations: (a) Michigan State University Lakes site, East Lansing, MI; (b) Pond Laboratory at the Kellogg Biological Station, Kalamazoo, MI; (c) Frog and Toad Survey project wetland site, DeWitt, MI; and (d) Crystal Bog buoy deployment, Trout Lake, Wisconsin.

The Heartbeat of the City. We monitored the acoustic patterns of various landscapes along an urban-rural gradient over diurnal and seasonal changes, and investigated the impact that anthropogenic sounds have on biological acoustic properties (Joo and Gage in submission). As shown in Figure 7, we established 19 recording locations across the city of Lansing, Michigan from February to December, 2006 to measure the acoustic signatures. Automated recorders at each site collected sound samples simultaneously.

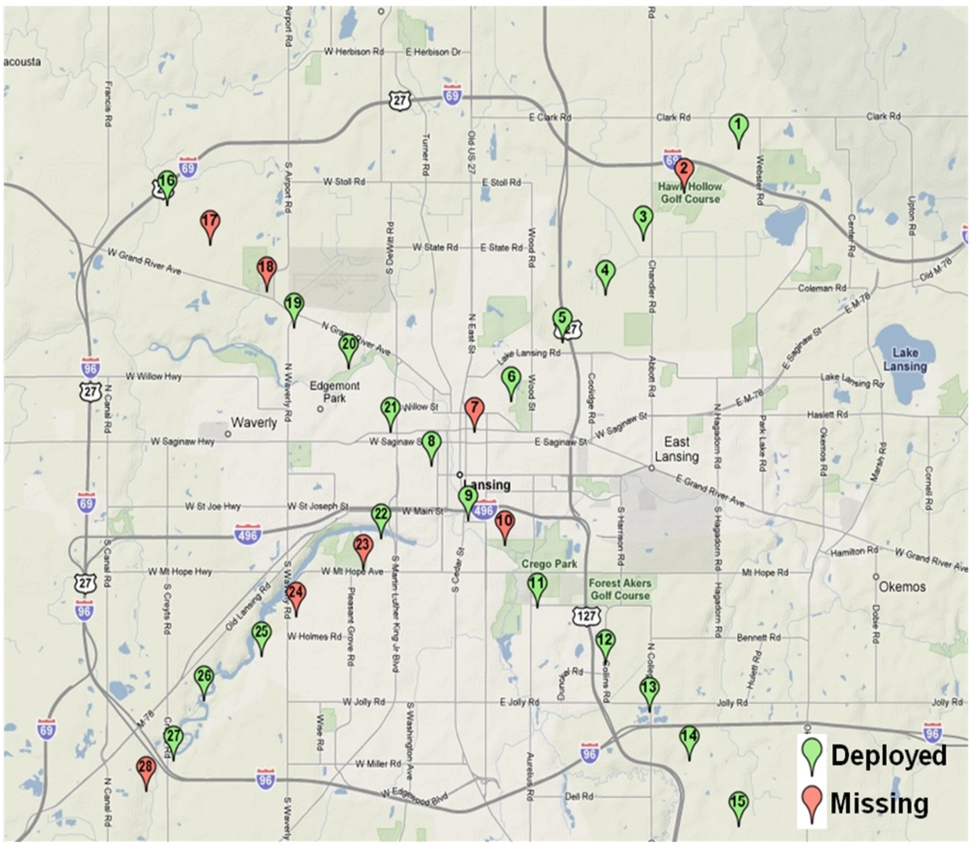

Figure 7. Map of the study area in the Greater Lansing area, MI. Each named symbol in the map represents the location where an acoustic monitoring unit was deployed along an urban- rural gradient. The green symbols represent data that were collected from February to December 2006, and the red symbols are the locations where the recording devices were lost during the study period.

We used the Acoustic Habitat Quality Index (AHQI) to classify a site relative to its biological composition and human disturbance. We found that the acoustic power of human-induced sounds was negatively associated with that of biological sounds, and that the value of AHQI increased along the urban-to-rural gradient in the study area. Given the relationship between Biological and anthropogenic sounds along the urban-to-rural gradient, a “Soundscape map” was produced based AHQI values to better understand the relationship between urban landscapes and environmental sounds. As shown in Figure 8, the soundscape map shows that negative values of AHQI occur at the city center and along main roads, whereas less developed areas have positive AHQI values, indicating higher levels of Biological sounds. This suggests that such soundscape maps can be used to visually assess temporal dynamics of urban acoustic environments.

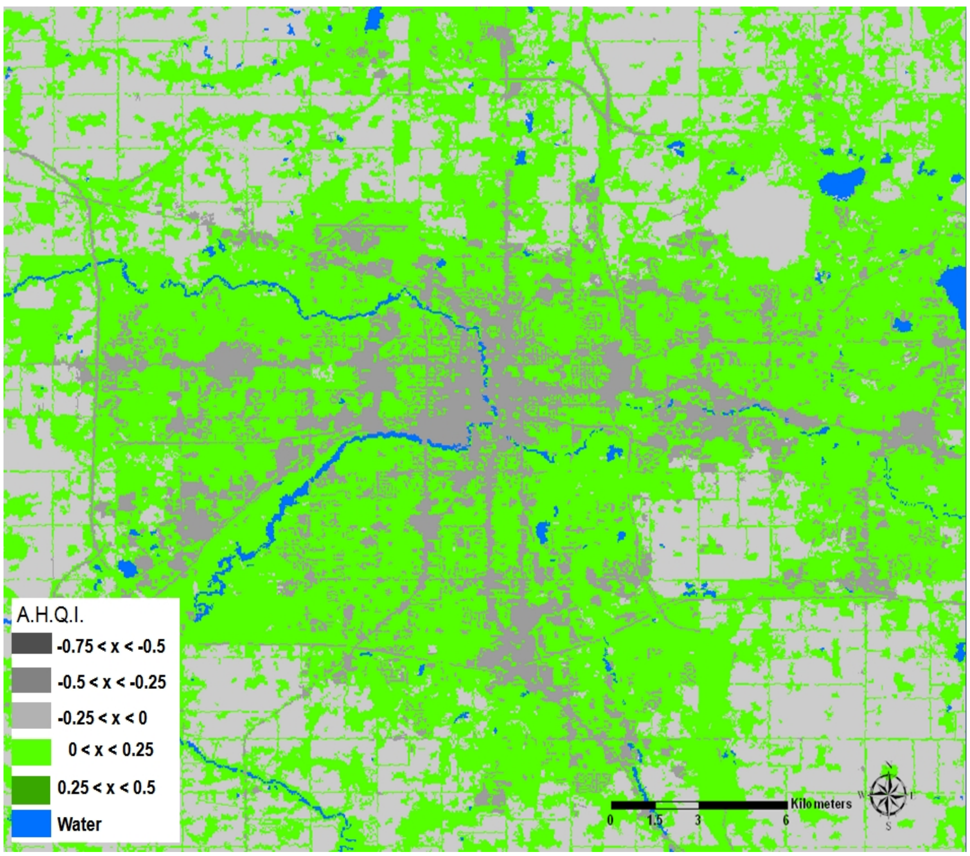

Figure 8. Expected distribution of the acoustic habitat quality index (the normalized ratio of biological sounds to anthropogenic sounds) based on National Land Cover Data map 2001 and analysis of acoustic data acquired during the Heartbeat of the City project. The index ranges from -1 to 1; positive values indicate that the intensity of biological sounds is higher than one of anthropogenic sounds.

The Muskegon River Watershed. Sound has played in 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 have been identified and interpreted (Kroodsma and Miller 1996). Gage et al. (2001) proposed that understanding the structure and components of environmental acoustic signals enables better understanding of changes in ecosystem quality and structure. Moreover, this project investigated how patterns in acoustic activity can be influenced by several environmental factors (e.g. precipitation and solar radiation), and that landscape indexes (e.g., patch size, composition, and diversity) can be important variables in interpreting acoustic information at a landscape scale.

As shown in Figure 9, REAL conducted acoustic surveys in the Muskegon River Watershed to collect a rich and informative dataset containing spatial, temporal and ecological information within a landscape context (Napoletano 2004). The research team recorded and analyzed environmental acoustics and ecological and spatial characteristics of river bank and wetland areas along the Little and Lower Muskegon Rivers. We found that there was a significant difference in environmental acoustic intensity within the 2-3 kHz frequency range between the human-disturbed and wetland locations. We also discovered that relatively pristine wetland habitats had the highest acoustic intensity within the 4-6 kHz acoustic frequency range. This study provided evidence that eventually helped support use of the REAL acoustic habitat quality index.

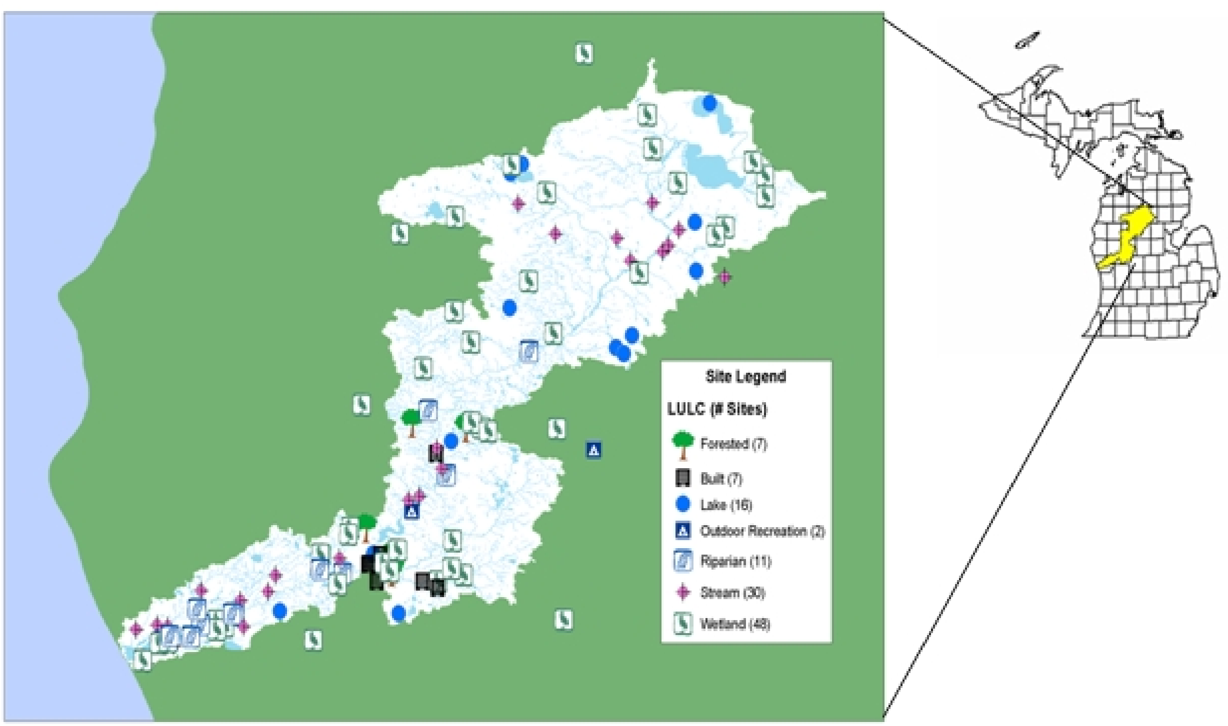

Figure 9. Map of acoustic observation sites in the Muskegon River Watershed, Michigan.

6. Collaborator Biographies

Dr. Stuart Gage is an Emeritus Professor at Michigan State University with his primary appointment in the Department of Entomology, College of Agriculture and Natural Resources. He is an Adjunct Professor in Zoology, College of Natural Science and an Adjunct Professor at Queensland University of Technology, Institute of Sustainable Resources in Brisbane, Australia. Gage has received recent honors including University Distinguished Faculty (2005) and University Outreach and Engagement Campus Fellow at Michigan State University (2008). Gage is Director of the Computational Ecology and Visualization Laboratory, which focuses on large scale ecological analysis and synthesis of long time series of biophysical processes, and is Co-Director of the Remote Environmental Assessment Laboratory which focuses on ecological sensors, analysis of sensor observations and cyberinfrastructure.

Dr. Eric Kasten conducts research in remote sensing using acoustics, time series data processing, and dynamically adaptive computing systems. He has 10 years of experience in developing software for real-time data stream processing for scientific applications, and more that 16 years of experience designing and deploying computer systems and networks. He has published research on applying automated data processing and machine learning to recognition and detection of bird species based on their vocalizations. His current research interests include adaptable software, mobile computing, autonomous decision making in software, time series and data stream analysis, and automated monitoring of environments and ecosystems using acoustics and remote sensing technology.

Wooyeong Joo is a Ph.D. candidate in the Department of Zoology at Michigan State University (graduation in 2009). He conducts research on the role acoustics play in understanding the characteristics of ecosystems and landscapes and how acoustics can be used to measure human-induced disturbance and stress on vital ecosystems. He has played a key role in many projects, including: "Analysis and Interpretation of the Heartbeat of the City using Acoustic Signatures" and "Comparison of Acoustic Bird Surveys with Point Count Surveys."

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