

Use of an Acoustic Location System to Understand Songbird Response to Vegetation
Regeneration on Reclaimed Wellsites in the Boreal Forest of Alberta

by

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Abstract

Limited information exists on the recovery of different ecosystem components following reclamation of oil and gas wellsites in the boreal forest of Alberta. Songbird response to wellsite reclamation efforts in the boreal forest was previously unexamined, despite the abundance of wellsites, frequent use of songbirds to assess ecosystem state, and importance of the boreal forest as breeding habitat for songbirds. Determining local scale impacts of small disturbances characteristic of energy sector on songbirds in the boreal forest, and how these impacts change with regeneration requires spatially accurate data on use or avoidance of these features. Conventional methods for surveying songbirds in the boreal vary in their ability to provide these spatially accurate data. Many bird surveys now utilize bioacoustic approaches. Standard approaches to collect bioacoustic data do not overcome challenges associated with conventional methods for accurate estimation of bird singing locations. However, certain bioacoustic approaches, including the use of an acoustic location system have potential for collecting data with the spatial accuracy to determine where songbirds sing in relation to small boreal disturbances. The purpose of this thesis was to use an acoustic location system to determine how Ovenbirds (*Seiurus aurocapilla*), and songbird communities as a whole respond to vegetation regeneration on reclaimed wellsites in the deciduous boreal forests of Alberta, as a measure of ecological recovery. Songbird community similarity between reclaimed wellsites and the adjacent forest increased with vegetation regeneration on the wellsite. Understanding this relationship required data on relative use of the wellsite and adjacent forest by the songbird community provided by the acoustic location system, and could not be detected from presence/absence data on songbird assemblages detected only within the wellsite footprint, and from a standard

biacoustic survey. I used Ovenbirds as a focal species, as their response to recovery of disturbances in the boreal forest has been studied extensively. Individual Ovenbirds were identified by their songs, and tracked using the acoustic location system. Ovenbirds would sing from reclaimed wellsites and edges more frequently with increasing canopy cover on the wellsite, and less frequently with presence of conspecifics. Current wellsite reclamation practices result in vegetation recovery which facilitates use of wellsites by songbird communities in upland deciduous boreal forests. This thesis demonstrates that an acoustic location system can be used to provide precise spatial locations of multiple individual songbirds concurrently, and can be used as an effective alternative to conventional bird survey methods.

Preface

This thesis is an original work by Scott Wilson. Chapter 2 has been accepted pending revisions to *Restoration Ecology*, with Erin Bayne as a co-author. Chapter 3 was submitted to the *Avian Conservation and Ecology*, with Erin Bayne as a co-author. In both cases, Scott Wilson collected and analyzed data, and wrote the manuscripts. Erin Bayne assisted with project design, secured funding, and provided advice on analyses and edits to the manuscript.

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Chapter 1. General Introduction

The boreal forest makes up over half of Canada's land mass, and contains a mosaic of habitats which provide ecosystem services including carbon storage, maintenance of water quality, and biodiversity (Schindler and Lee 2010). North American songbirds are a large component of western boreal forest biodiversity, as this region provides breeding habitat for up to 3 billion individuals from 300 species (Wells 2011). Songbirds perform important ecosystem services to this region, including pollination, seed dispersal, and insect management (Wells 2011). The response of songbird communities in the boreal forest to fire and forestry is well documented, and songbird communities are often used to assess ecosystem state in response to vegetation regeneration on these disturbances. This response is due to differences in vegetation requirements for foraging and nesting by individual songbird species (Venier and Pearce 2005, Schieck and Song 2006, Lemaître et al. 2012). More recently, energy sector disturbances have expanded in the western boreal forest to facilitate extraction of oil and gas deposits (Schindler and Lee 2010). These disturbances may partially explain declining populations of songbird species that breed in this region, due to direct nest loss, and indirect impacts on behaviour and breeding success (Bayne et al. 2005a, Habib et al. 2007, Lankau et al. 2013, van Wilgenburg et al. 2013).

Wellsites are a large component of energy sector disturbance in the western boreal forest (Bott et al. 2016). Over 400,000 wellsites exist across Alberta. Generally, wellsites are one hectare in size and are used for extraction or exploration for oil and gas (Bott et al. 2016). Wellsites have been actively reclaimed since 1963, using criteria based on soil, vegetation, and hydrology with a focus on returning wellsites to 'equivalent land capability' as prior to disturbance (Powter et al. 2012, Bott et al. 2016). Recovery of vegetation on these disturbances following reclamation in forested lands is slow and unpredictable, due to changing development practices and reclamation criteria over time (Osco and Glasgow 2010). These factors have resulted in differing levels of soil disturbance, and availability of different plant propagules on reclaimed wellsites (Osco and Glasgow 2010, Frerichs et al. 2017). Practices for new oil and gas extraction wellsites have improved over time. However, following the initial issue of government reclamation certification, there is little information on the recovery trajectory of these

sites with regards to different ecosystem components, including songbirds. Current wellsite reclamation criteria in Alberta focuses on recovery of soil, vegetation, and hydrology in relation to an adjacent reference, with expectation of recovery of ecosystem function (Powter et al. 2012). Global standards in reclamation emphasize the importance of measurement of multiple ecosystem components (i.e. birds) to quantify recovery of ecosystem function (Ruiz-Jaen and Aide 2005). Examination of the long-term impact of these wellsites on different ecosystem components is necessary in order to understand the legacy of energy sector disturbances, and cumulative impacts on boreal forest songbirds (van Wilgenburg et al. 2013). Failure of these sites to follow a standard successional pathway towards a mature forest could have negative impacts on species which depend on a specific successional stage, and positive impacts on generalist or early successional species (Thomas et al. 2014, Mahon et al. 2016). Virtually no information is available on which species of birds use reclaimed wellsites in the boreal forest of Alberta.

Examining the response of the songbird community as a whole provides a comprehensive view of wellsite recovery. However, study of a focal species with a well documented response to human disturbance in the study region will provide insight into the relative impact and recovery of wellsites compared to other disturbances. Ovenbirds (*Seiurus aurocapilla*) are an abundant songbird in deciduous forests of the western boreal forest. The response of Ovenbirds to recovery of disturbances, such as forestry harvest and seismic lines has been studied extensively (Mazerolle and Hobson 2004, Bayne et al. 2005a, Bayne et al. 2005b, Machtans 2006, Lankau et al. 2013). Ovenbirds will avoid disturbances, including seismic lines on a local scale at early stages of regeneration (Lankau et al. 2013). With increasing vegetation regeneration, particularly greater canopy cover and leaf litter which facilitates increases in their insect prey, Ovenbirds will utilize these disturbances (Lankau et al. 2013). However, use of disturbances is also influenced by local conspecific density (Lankau et al. 2013). At increasing densities, Ovenbirds will utilize disturbances as territory boundaries, leading to decreased use of the feature (Heap et al. 2012, Lankau et al. 2013). These findings emphasize that factors beyond vegetation recovery should be considered when attempting to understand how songbirds respond to recovery of disturbances.

Various methods have been used to study how songbirds respond to small disturbances on a local scale in the boreal forest (Bayne et al. 2005b, Lankau et al. 2013, Bayne et al. 2016). These methods vary in resolution at which they can be used to accurately determine how songbirds use or avoid these disturbances. Point counts are a common method which rely on acoustic cues to determine presence of different species, which are often placed into estimated distance bins (Bibby et al. 1992, Bayne et al. 2016). However, challenges exist in accurate estimation of distance of birds from the observer, which can create difficulty when attempting to determine where birds sing in relation to a disturbance (Alldredge et al. 2007). Spot mapping involves an observer walking a route through a study plot and recording locations of birds. Several visits are performed, and territories are approximated from these visits where individuals may or may not be known (Bibby et al. 1992, Bayne et al. 2005b). Error in distance estimation also exists for spot-mapping but is assumed to be less than point counts. Finally, territory mapping involves following individual birds through their habitat, or use of telemetry to quantify their space use (Bibby et al. 1992, Bayne et al. 2005b, Lankau 2013). When determining how wildlife respond to recovery of these disturbances following reclamation, simple measures of presence/absence of different wildlife species can be relatively coarse measures of ecosystem recovery (Foster et al. 2016, Jones and Davidson 2016). Higher resolution metrics, such as spatial use of these features, or metrics that provide insight into animal foraging and breeding behaviour, provide better estimates of ecosystem recovery with respect to wildlife (Jones and Davidson 2016).

Songbird communities are increasingly surveyed using bioacoustic methods to understand impacts of human disturbances (Shonfield and Bayne 2017). Commonly used bioacoustic survey methods provide relatively coarse data due to difficulty determining the area sampled, and challenges with identification of individuals from recording data (Mennill 2011, Yip et al. 2017). Fortunately, methods exist which can overcome these challenges and provide spatially accurate data, through the use of an acoustic location system (ALS; Kirschel et al. 2011). An ALS is an array of microphones which can be used to estimate the location of a signal using time of arrival differences determined from cross correlations between channels (McGregor et al. 1997). Various

taxa including primates (Spillmann et al. 2015), marine mammals (Hayes et al. 2000), amphibians (Jones and Ratnam 2009), and songbirds (Kirschel et al. 2011, Stepanian et al. 2016) have been surveyed using localization. Using an ALS provides potential improvements on conventional bird survey methods which provide similar data, such as telemetry or spot mapping. These potential improvements include reduced bias due to absence of a human observer, and highly accurate spatial locations of many birds concurrently (Blumstein et al. 2011, Wilson et al. 2013). To date, most songbird research using localization has focused on validation of methodology, or examination of singing behaviour (Mennill et al. 2006, Fitzsimmons et al. 2008, Campbell and Francis 2012). Fewer studies have used localization to understand habitat associations or space use of individual songbirds in relation to human disturbance. An ALS provides singing locations, which indicate territorial songbird behaviour (Kroodsma and Byers 1991, Whitaker and Warkentin 2010). Therefore, placement of singing locations in relation to a disturbance can be used as an accurate measure of use or avoidance by songbirds. Increasing accessibility of ALS has created potential to identify and track individuals through time, which has been utilized infrequently, potentially due to equipment and logistical constraints of using this method. If these capabilities are successfully utilized, data from an ALS have high potential for providing information on how both songbird communities, and individual Ovenbirds respond to recovery of reclaimed wellsites, based on comparative use of the wellsite and adjacent reference forest.

The goal of this thesis is to demonstrate the potential of an ALS to collect data on how the impact of wellsites on songbird communities is mitigated with regeneration of vegetation following reclamation. The comparative use of wellsites and adjacent forest by the songbird community, and space use of individual Ovenbirds surrounding the wellsite will be used as measures of wellsite recovery. However, reclamation and reclamation monitoring are expensive. Therefore, the spatial resolution and cost of data required to understand how songbirds respond to current metrics used in reclamation criteria, specifically vegetation regeneration should be evaluated. This will be achieved by comparing inferences from different methods, which vary in their efficiency, as well as their ability to determine where songbirds sing in relation to wellsites, to localization data obtained from the ALS. Examination of songbird response to wellsite reclamation

is a step towards global reclamation standards, which suggest evaluation of multiple ecosystem components in relation to reference state. Information from this thesis will be used to gain insight into the legacy of wellsite disturbances on songbirds in the boreal forest, and the value of ALS as a method for studying songbird response to human disturbances.

Thesis Outline

In this thesis, I evaluate the use of an ALS to provide data on songbird response to vegetation recovery on reclaimed wellsites, presented as two independent manuscripts. In chapter two, I evaluate how inferences on songbird community response to regeneration of reclaimed wellsites change with data which vary in their ability to determine where songbirds sing in relation to reclaimed wellsites. Chapter three demonstrates the use of an ALS to track individual Ovenbird space use in relation to reclaimed wellsites, as a function of canopy cover and presence of conspecifics. General discussion and management implications are presented in chapter four. Appendix one contains a description of my approach to using an ALS. Appendix two contains additional information on wellsites used in this study.

Chapter 2. Use of Acoustic Methods to Quantify Songbird Community Response to Vegetation Regeneration on Reclaimed Oil and Gas Wellsites in the Boreal Forest of Alberta

Introduction

Modern reclamation uses multiple indicators of ecosystem function and state in comparison to a reference condition to evaluate recovery success (Ruiz-Jaen and Aide 2005, Shackelford et al. 2013). Previous emphasis during reclamation was placed on recovery of soil and vegetation attributes under the premise that animals will begin to use recovered areas if suitable habitat has been created (Cristescu et al. 2013, Jones and Davidson 2016). However, animals such as birds do not always return to reclaimed features in a predictable relationship with basic soil and vegetation parameters, as these metrics do not ensure recovery of specific features required by different bird species (Jones and Davidson 2016). There is growing evidence that measures of ecosystem function, rather than presence of species in relation to vegetation recovery are required to accurately understand how wildlife respond to reclamation treatments (Foster et al. 2016, Jones and Davidson 2016). Songbird communities require variation in woody plant structure for foraging and nesting, and are dependent on the presence of other taxa for food, making them good indicators of recovery of ecosystem function (Hobson and Bayne 2000, Schieck and Song 2006, Brady and Noske 2010). Thus, it is beneficial to assess how songbird communities recover following reclamation, as their presence can facilitate recovery through stimulation of ecological processes such as seed dispersal and insect management (Latja et al. 2016).

The boreal forest of Alberta is an important breeding habitat for North American songbird species. The relationship between songbird community composition and vegetation recovery following fire and forest harvesting has been well documented in this region (Hobson and Bayne 2000, Venier and Pearce 2005, Schieck and Song 2006). Populations of many songbird species in the western boreal region are declining, and concerns have been raised that extensive oil and gas development may be partially responsible (van Wilgenburg et al. 2013). Among the disturbances created by the energy sector are hundreds of thousands of one hectare oil and gas wellsites. Wellsites no

longer in production have been actively reclaimed in Alberta, Canada since 1963 using various criteria to characterize recovery (Powter et al. 2012). Current criteria measures similarity of soil, vegetation, and hydrology to a reference condition with the goal of returning to 'equivalent land capability' (Bott et al. 2016). Studies examining the impact of wellsite disturbances on birds have focused primarily on the effects at the landscape scale (Bogard and Davis 2014, Thomas et al. 2014). Limited information exists on the relationship between vegetation recovery on oil and gas disturbances, and local songbird community composition, with no data on wellsites available (Lankau et al. 2013, Foster et al. 2016). Failure of these sites to regenerate vegetation over a reasonable time frame will influence the amount of certain habitats available, potentially resulting in detrimental effects on songbirds in the boreal forest if reclamation is not effective (Venier and Pearce 2005).

Impacts of small disturbances in the boreal on songbirds, and how these impacts change with regeneration are often subtle, and may require metrics on local scale use or avoidance (Bayne et al. 2005b, Lankau et al. 2013). Reclamation and subsequent monitoring must balance effectiveness of ecological recovery with cost and time effectiveness (Richardson and Lefroy 2016). Point counts have been used extensively in bird monitoring programs, as they are time and cost effective (Hutto et al. 1986, Matsuoka et al. 2014). Point counts provide information on species occurrence, abundance, and community composition. A challenge with point counts is the inability to accurately estimate distance from the observer to a singing bird, and determine the area over which birds are sampled (Alldredge et al. 2007). This becomes a larger issue with new approaches that rely on audio recording technology to conduct surveys for birds in the absence of a human observer, in which the detection radius of a recording unit will depend on many factors (Shonfield and Bayne 2017, Yip et al. 2017). These issues may be less important when monitoring bird communities following recovery of larger disturbances, as the birds detected tend to be within the recovering area. However, the area that is accurately sampled by human point counts, and commonly used recording technology exceeds the size of the one hectare footprint of the reclaimed wellsites in this study. The consequence is that these methods also detect species living in the adjacent forest, and thus do not have the spatial accuracy to determine how birds

respond to wellsites alone, resulting in high variance for estimating their recovery success (Bayne et al. 2016, Yip et al. 2017).

An alternative method to measure songbird response to regenerating wellsites that can distinguish between use of the wellsite versus adjacent forest is an acoustic location system (ALS). Singing locations can be estimated using ALS based on the time of arrival difference of songs to an array of time synchronized microphones, termed localization (Blumstein et al. 2011). This method has been used extensively to study marine mammals (Watkins and Schevill 1972, Hayes et al. 2000) and communication in songbirds (Mennill et al. 2006, Fitzsimmons et al. 2008). Localization has been used less frequently to study habitat use, or response of birds to disturbance. Benefits of localization include accurate spatial locations of many birds concurrently, and reduced bias in assessment of bird behaviour due to the absence of a human observer (Blumstein et al. 2011, Wilson et al. 2013). Critics of localization suggest that equipment requirements, and requirement of detection of vocalizations on multiple microphones make the method impractical (Dawson and Efford 2009). However, when precise measures of location are required, as may occur with small disturbances such as wellsites, such a method may be critical. Few studies have examined community composition, or abundance of birds using localization relative to other methods such as point counts (Campbell and Francis 2012). We argue localization provides exact singing locations and reflects territorial behaviour in songbirds (Kroodsma and Byers 1991, Whitaker and Warkentin 2010). Singing locations within regenerating wellsite footprints indicates use of these habitats, and potential mitigation of this disturbance on songbird communities. However, localization data can be intensive to collect, and therefore the feasibility of more efficient methods, which may provide coarser spatial resolution, such as standard biacoustic surveys, should be investigated.

The overarching goal of this study was to examine use of reclaimed wellsites by songbirds across a gradient of vegetation recovery using multiple techniques. The first objective of this study was to use localization data to determine how community similarity of songbirds on reclaimed wellsites and the adjacent forest changed across a gradient of wellsite vegetation recovery, based on relative numbers of singing locations

on wellsite versus the adjacent forest. We hypothesized that as woody vegetation recovered on the wellsite, similarity of songbird use of the reclaimed wellsite to the adjacent forest would increase. Following reclamation, wellsites have limited vegetation structure and are primarily covered with grass and low shrubs. Increasing structural complexity associated with woody plant regeneration will increase the likelihood that wellsites will meet habitat requirements for a greater proportion of the songbird community, resulting in increased singing locations placed on the wellsite itself (Schieck and Song 2006, Brady and Noske 2010). The second objective was to determine if the same inferences about vegetation recovery on songbird community composition could be determined using presence/absence songbird community data from two types of bioacoustic data; songbird assemblages detected only from reclaimed wellsite footprints provided by an ALS and a standard bioacoustic survey using a single microphone placed in the centre of the wellsite. The ALS can provide singing locations within the wellsite footprint (similar to a point count with a constrained radius), while the standard bioacoustic survey is similar to an unlimited radius point count, and will detect individuals within the wellsite footprint, and adjacent forest. Human point counts constrained to the wellsite footprint (i.e., 50m radius) were previously shown to be more effective at determining the impact of wellsite disturbance relative to the forest interior on songbird communities, than larger radius point counts (Bayne et al. 2016). We hypothesized that the standard bioacoustic survey would be too coarse to determine the impact of vegetation regeneration on the songbird community, due to the detection radius of the microphone exceeding the footprint of the wellsite, and detecting individuals whose entire territories are in the adjacent forest. However, if the impact of a wellsite on the songbird community is large because songbirds completely avoid wellsites and this impact disappears quickly with vegetation regeneration on the wellsite, it may be possible to detect recovery in songbird communities using a standard bioacoustic approach or human point count, rather than using the more intensive localization approach.

Methods

Site Selection

Certified reclaimed wellsites ($n = 19$) were selected within the Central Mixedwood Natural Subregion of the Boreal Forest Natural Region, within 50km of the communities of Lac La Biche and Slave Lake, Alberta (Downing and Pettapiece 2006). Sites were located in mesic upland ecosites where the main soil type was grey luvisols (Downing and Pettapiece 2006). Wellsites were in deciduous forests dominated by trembling aspen (*Populus tremuloides*), and balsam poplar (*Populus balsamifera*). Common understory shrubs included alder (*Alnus spp.*), willow (*Salix spp.*), and beaked hazelnut (*Corylus cornuta*).

Wellsites ranged in age from 11 to 66 years since development, and 3 to 48 years since a reclamation certificate was issued. Various strategies have been used to set Alberta reclamation standards over time, which may confound regeneration, making the direct assessment of vegetation recovery necessary (Bott et al. 2016). Wellsites regenerate heterogeneously over time in part due to changing standards but also due to variability in successional processes. Thus, modelling recovery simply as a function of time since reclamation is not likely to inform how songbirds are recovering (Lankau 2014). For these reasons, sites were selected to sample a gradient of woody vegetation recovery, ranging from sites dominated by grass and forb cover ($n = 8$), to sites with intermediate levels of medium and tall shrub ($n = 5$), to sites dominated by woody vegetation greater than five meters in height ($n = 6$; Fig. 2.1). Sites were required to be accessible by a linear feature, and had no significant additional human disturbance within the area sampled (e.g. forestry harvest). Wellsite footprints covered an average of 1.01 ± 0.09 hectares (mean $\pm$ standard error), determined through digitization of survey diagrams and field measurements (Abacus Datagraphics Limited 2015).



Figure 2.1. Vegetation recovery on reclaimed well sites. From left to right, well sites are 14, 20, and 45 years since reclamation certificate was issued.

Acoustic Data Collection

The ALS used GPS enabled Wildlife Acoustics SM3 units equipped with external SMM-A1 microphones (Wildlife Acoustics, Inc., Maynard, Massachusetts, USA). At each site, microphones ($n = 25$) were deployed at a height of 1.5 m, and spaced an average of 33.9 ± 0.52 m apart in a 5 x 5 grid (Fig. 2.2). The ALS was rotated across 19 sites during the songbird breeding season in 2015 (May 25 – June 27) and 2016 (May 26 - June 27), resulting in a total of 475 unique microphone locations. Microphone arrays varied slightly in their design, covering an average area of 2.30 ± 0.25 hectares. Positions were determined using a Hemisphere S320 survey GPS, set to a horizontal accuracy of ± 3.0 cm. When not possible to obtain locations using the survey GPS due to dense canopy, positions were determined from the mounted Garmin 16x GPS attached to the recording unit (accuracy 3.28 ± 0.25 m). The ALS was deployed, and recordings were collected on 1 - 5 subsequent days from 05:30AM to 08:30AM at each site. Recordings were time synchronized to ± 1 milliseconds through the GPS clock of the Garmin 16x. A 48000 Hz sample rate was used, and recordings were collected in a compressed Wildlife Acoustics' WAC format.

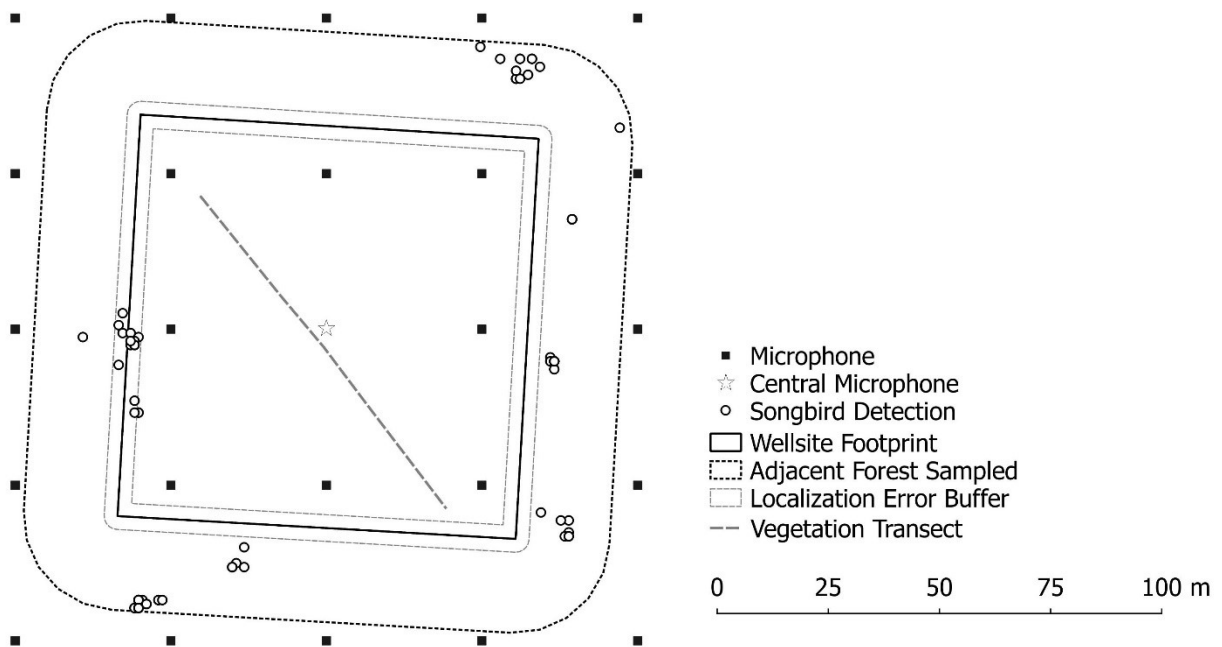


Figure 2.2. Schematic of study design. Songbird singing locations were determined within the wellsite footprint, and an area equivalent to the wellsite footprint in the adjacent forest between the wellsite and indicated buffer. Singing locations within the localization error buffer were removed from further analysis, and they could not be confirmed as within the wellsite footprint or the adjacent forest sampled. The microphone in the centre of the wellsite was used for the standard bioacoustic approach.

It was necessary to quantify error in positional estimates using acoustic localization, as error will vary based on habitat type and species (Wilson et al. 2013). Playback experiments were performed at one of the study sites to quantify error in localization for 14 common songbird species in the study region. The average error between the estimated position using localization, and a known speaker location was determined under slight differences in spacing of microphones and the GPS accuracy used to determine microphone locations. The average error in localization for microphone spacing and GPS accuracy at 7 study sites was determined as 2.97 ± 0.37 m, from 576 singing events across the 14 songbird species. Error increased with inter-microphone distance, and when microphone positions were estimated from the Garmin 16x GPS

attached to the recording unit, resulting in average error of 7.05 ± 0.84 m at 12 study sites, and 11.5 ± 1.78 m at 2 study sites.

Vegetation Data Collection

The point intercept method was used along a 90 m diagonal transect from a randomly selected corner of the wellsite to the opposite corner (Fig. 2.2; Floyd and Anderson 1987). Measurements were taken at 50 set distance intervals. At each interval, ground cover (i.e. bare ground, leaf litter, grass), and the maximum height of each woody plant which intercepted the pole was recorded. The diameter of each piece of coarse woody material (> 7 cm diameter) which intercepted the transect was recorded. Rectangular shrub stem (30 m^2 ; 30 m by 1 m) and tree density plots (60 m^2 ; 30 m by 2 m) were set up adjacent to the transect where the total number of shrubs and trees taller than one metre were recorded.

Data from the point intercept method were summarized into percent cover estimates for deciduous and coniferous woody plants less than 2 m, 2-5 m, and greater than 5 m (canopy) in height. The total volume of coarse woody material per hectare was calculated (Marshall et al. 2003). Percent litter and grass ground cover were calculated. Shrub stems and trees per hectare were calculated from rectangular plots. Sites ranged from 0 to 100% canopy cover, 0 to 98% litter cover, and 0 to 15667 shrub stems per hectare.

Acoustic Data Processing

Three recording periods that were three minutes long were selected within the dawn chorus on one day at each site for processing (i.e., 05:00-05:03 AM, 06:00-06:03 AM, and 07:00-07:03 AM). Recording files were converted to wav format and spectrograms were visualized using a 512 FFT hamming window in the program Audacity 2.1.3 (Audacity Team 2017). All files were grouped into four channel tracks based on spatial proximity, and scanned visually to locate songbirds performing territorial vocalizations within the microphone array. Vocalizations were included in further analyses if the entire song was detected clearly on four microphones, and did not coincide with other songs of greater amplitude, or overlap with any fainter singing events for 25% of the

duration of the target vocalization on any channel (Spiesberger 2004). Species identifications were confirmed by multiple trained observers through acoustic cues and visual cues from spectrograms. The multichannel track which contained the strongest signal for each identified bird was used in subsequent analyses.

Temperature data from the nearest Environment and Climate Change Canada weather station were summarized for each research site, and used for estimation of speed of sound (Wilson et al. 2013, Environment and Climate Change Canada 2017). The multichannel tracks, microphone positions, and speed of sound, were imported into the MATLAB based program XBAT for analysis (Figueroa and Robbins 2007, MathWorks Inc. 2014). Each vocalization that met the criteria mentioned earlier was annotated. The CSE location algorithm (version 2.3) was used for acoustic localization (Cortopassi 2006). This algorithm determines the time of arrival differences of a signal to different channels in the ALS using pairwise cross correlations of the signal between channels (Cortopassi 2006, Campbell and Francis 2012). These time of arrival differences are used to calculate the location of the signal under a known speed of sound and microphone locations (Cortopassi 2006). Each annotated vocalization was localized using a minimum of four channels to estimate positions, and a search radius of 100 m (Campbell and Francis 2012).

Spatial locations were validated to determine if they were closer to the channel with the greatest amplitude than to other channels used in localization. Observations were discarded if not closest to the channel with the greatest amplitude, however this only occurred for a few events, and mainly when partially obstructed by another vocalization. If singing locations did not occur within the multichannel track (resulting in positions outside the set of four microphones) but were still within the microphone array, they were rerun in the correct multichannel track based on the estimated locations. This was to achieve the most accurate positions, as accuracy of localization degrades with distance from the centre of the array (McGregor et al. 1997, Campbell and Francis 2012, Wilson et al. 2013).

Singing locations were exported from and visualized in QGIS 2.12.3 (Quantum GIS Development Team 2016). A buffer the equivalent size of the wellsite polygon was created around each site in the adjacent forest. Vocalizations occurring beyond this buffer were excluded from subsequent analyses. Error in localization was accounted for by creating a second buffer around wellsite footprints that was the size of error estimates based on GPS accuracy, and microphone spacing at different sites (Fig. 2.2). If singing locations occurred within the buffer they were excluded from analyses as their position could not be confirmed as on or off of the wellsite. Remaining singing locations were then classified as occurring within the wellsite footprint, or within the adjacent forest.

The microphone on the centre of each wellsite was used as a standard bioacoustic approach, to provide data similar to an unlimited radius point count at times concurrent to when localization data were processed. Spatial locations of songbirds in relation to the wellsite cannot be determined using this approach, only presence/absence of species. Three trained observers identified all territorial songbird vocalizations based on auditory and acoustic cues, according to the protocol of the Bioacoustic Unit (hereafter ‘standard bioacoustic survey’; Lankau et al. 2015). Recordings were visualized using a 2048 FFT Blackmann-Harris window in Audacity, and listened to at a standard volume.

Statistical Analyses

The Bray-Curtis dissimilarity index was calculated using the number of singing locations on each wellsite, and in the adjacent forest for each species from the localization data (R package ‘vegan’; Oksanen et al. 2017, R Core Team 2017). A score of ‘0’ indicated complete dissimilarity between the songbird assemblage on the wellsite in comparison to the adjacent forest, and a score of ‘1’ indicated complete similarity. An additional site by species matrix was created using presence/absence of species localized only within the wellsite footprint. Finally, data from the standard bioacoustic survey were summarized into a presence/absence, site by species matrix.

Several vegetation metrics were correlated (Pearson correlation > 0.6), therefore we condensed them using a Principal Components Analysis (PCA; Oksanen et al. 2017).

Vegetation attributes were standardized to zero mean and unit variance prior to PCA being applied. The first two axes explained 70.3% of variation in vegetation, and were used in subsequent analyses. A positive loading on principal component one indicates increasing litter cover, canopy cover, density of trees, and medium shrub cover (2-5 m tall). A positive loading on principal component two indicates decreasing low shrub cover (0.5-2 m tall), and shrub stem counts (Table 2.1).

Table 2.1. Loadings for the first two principal components from principal component analysis used to summarize vegetation data.

Vegetation Measure	Principal Component One	Principal Component Two
Litter	1.12	-0.31
Grass	-0.83	-0.67
Low Shrub Cover	-0.14	-0.97
Medium Shrub Cover	1.00	-0.29
Canopy Cover	1.15	-0.01
Conifer Shrub Cover	1.00	0.26
Shrub Stems	-0.03	-1.15
Tree Density	0.97	-0.35
Coarse Woody Material	0.28	-0.04

A beta regression, which allows proportions to be modelled as the response variable, was used to compare the songbird community similarity index between the wellsite and the adjacent forest and how this was influenced by vegetation recovery on the wellsite, accounting for Julian date of survey (R package 'betareg'; Cribari-Neto and Zeileis 2010). A value of 0.01 was added or subtracted from dissimilarity values of 0 or 1 so they could be accommodated by the beta regression. Canonical Correspondence Analysis (CCA) was then used to determine if the same trend in the influence of vegetation recovery on songbird community composition could be determined from presence/absence data from localization of only birds within the wellsite footprint, and the standard bioacoustic survey (Oksanen et al. 2017). Significance of individual terms on species compositions was assessed using an ANOVA permutation test (Oksanen et al. 2017). We chose to use CCA as it allows non-linear relationships between variables, and

constrains the ordination to variation explained by the environmental factors (Lindenmayer et al. 2012). A significance level of $\alpha = 0.05$ was used for all analyses.

Results

A total of 3995 vocalizations from 31 different songbird species were detected near reclaimed wellsites using localization. Of these vocalizations, 428 occurred within wellsite footprints from 16 different species. In the adjacent forest, 1096 vocalizations from 20 species were detected within an equal sized area as the wellsite (Table 2.2). Of the remaining 2,471 vocalizations, 806 were discarded as they occurred within the buffer, and 1,665 were discarded as they were detected beyond the area sampled in the adjacent forest. Alder Flycatcher (*Empidonax alnorum*), Clay-coloured Sparrow (*Spizella pallida*), Ovenbird (*Seiurus aurocapilla*), Red-eyed Vireo (*Vireo olivaceus*), Swainson's Thrush (*Catharus ustulatus*), Tennessee Warbler (*Leiothlypis peregrine*), and White-throated Sparrow (*Zonotrichia albicollis*) sang from three or more wellsite footprints. Clay-coloured Sparrow, Ovenbird, Swainson's Thrush, Mourning Warbler (*Geothlypis philadelphia*), Tennessee Warbler, and White-throated Sparrow sang more than 50% of songs detected on the wellsite footprint at more than one site. A total of 30 different species were detected near wellsites based on the standard bioacoustic survey, using the microphone in the centre of the wellsite. The species richness of songbirds detected on the wellsite footprint alone (mean $\pm$ 95% confidence interval) was 2.05 ± 0.28 . The 95% confidence intervals for the average number of species detected from the standard bioacoustic survey (7.90 ± 0.54) overlapped with those for the average number of species detected on the wellsite and adjacent forest using localization (7.05 ± 0.64).

Table 2.2. Summary of songbird species detections, based on singing locations in relation to reclaimed wellsites from localization data.

Common Name	Species Name	Number of Sites Where Species was Detected Within Adjacent Forest or Wellsite Footprint	Number of Sites Where Species was Detected Within Wellsite Footprint
Alder Flycatcher	<i>Empidonax alnorum</i>	4	4
American Redstart	<i>Setophaga ruticilla</i>	3	0
Black-and-White Warbler	<i>Mniotilta varia</i>	5	2
Bay-breasted Warbler	<i>Setophaga castanea</i>	3	1
Black-capped Chickadee	<i>Poecile atricapillus</i>	1	0
Blue-headed Vireo	<i>Vireo solitarius</i>	2	1
Clay-coloured Sparrow	<i>Spizella pallida</i>	2	2
Cedar Waxwing	<i>Bombycilla cedrorum</i>	2	1
Connecticut Warbler	<i>Oporornis agilis</i>	1	0
Common Yellowthroat	<i>Geothlypis trichas</i>	1	1
Dark-eyed Junco	<i>Junco hyemalis</i>	1	1
Hermit Thrush	<i>Catharus guttatus</i>	1	0
Least Flycatcher	<i>Empidonax minimus</i>	3	1
Magnolia Warbler	<i>Setophaga magnolia</i>	1	0
Mourning Warbler	<i>Geothlypis philadelphia</i>	4	2
Ovenbird	<i>Seiurus aurocapilla</i>	13	7
Philadelphia Vireo	<i>Vireo philadelphicus</i>	3	0
Pine Siskin	<i>Spinus pinus</i>	1	0
Red-eyed Vireo	<i>Vireo olivaceus</i>	16	5
Swainson's Thrush	<i>Catharus ustulatus</i>	3	3
Tennessee Warbler	<i>Oreothlypis peregrina</i>	8	7
Warbling Vireo	<i>Vireo gilvus</i>	1	0
White-throated Sparrow	<i>Zonotrichia albicollis</i>	9	4
Yellow Warbler	<i>Setophaga petechia</i>	1	1
Yellow-rumped Warbler	<i>Setophaga coronata</i>	3	0

Using presence/absence data alone collected using both the localization and the standard bioacoustic survey, vegetation regeneration on the wellsite explained limited variation in the community composition of songbirds. Songbird community similarity between the wellsite and adjacent forest increased with positive loading on both principal components according to the beta regression (pseudo $r^2 = 0.33$; Table 2.3, Fig. 2.3). This indicated that similarity between songbird detections on the wellsite, and the adjacent forest increased with greater litter cover, canopy cover, and medium shrub cover (2-5 m), and decreased with low shrub cover and shrub stem counts on wellsites.

Based on presence/absence species matrices, there was no effect of wellsite vegetation on songbird community composition using either localization data for only songbirds detected within the wellsite footprint or standard bioacoustic survey using CCA, according to a post hoc ANOVA test for individual terms (Table 2.4).

Table 2.3. Results from beta regression, using Bray-Curtis similarity index between wellsite and adjacent forest, based on singing locations from localization as the response variable. Phi is the precision parameter used in the beta regression model.

	Estimate	SE	Z	p
Intercept	4.53	2.89	1.57	0.12
Principal Component One	0.52	0.26	2.02	0.04
Principal Component Two	0.66	0.27	2.50	0.01
Julian Date	-0.04	0.02	-2.39	0.02
Phi	9.40	2.02	4.66	3.20×10^{-6}

Table 2.4. Results from Canonical Correspondence Analysis comparing influence of vegetation recovery on the songbird community composition detected using presence/absence data from the standard bioacoustic survey, and localization of only songbirds detected within the wellsite footprint.

		df	χ^2	F	p
Standard Bioacoustic Survey	Principal Component One	1	0.21	1.47	0.06
	Principal Component Two	1	0.09	0.64	0.93
	Residual	16	2.29		
Localization	Principal Component One	1	0.43	1.40	0.08
	Principal Component Two	1	0.38	1.25	0.25
	Residual	16	4.89		

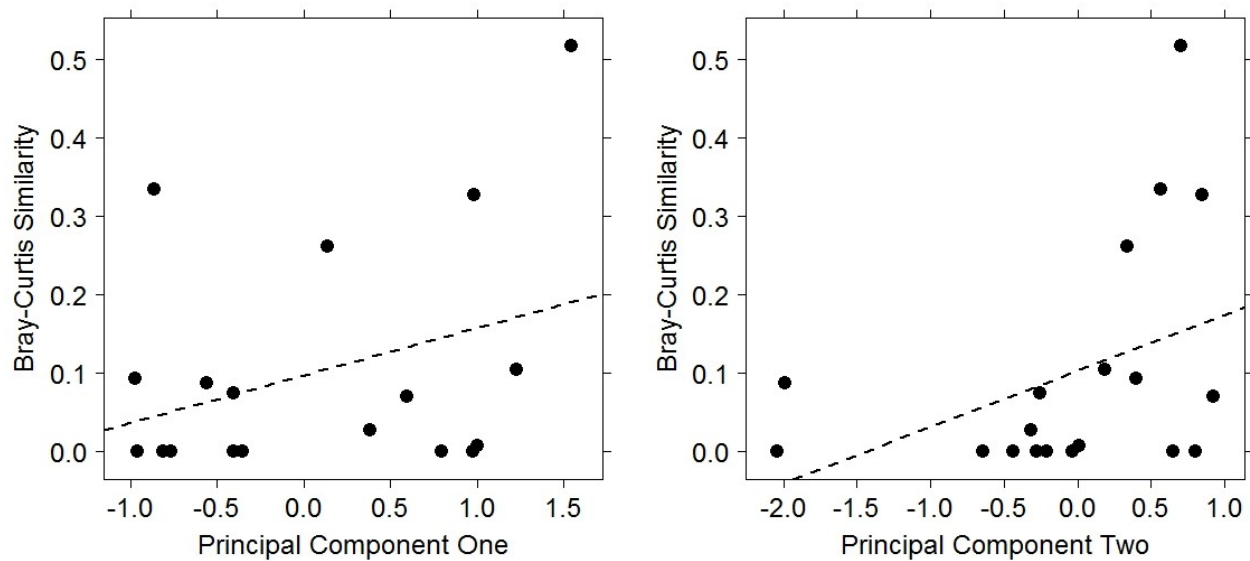


Figure 2.3. Plot of Bray-Curtis similarity for each wellsite, in relation to principal components. A positive loading on principal component one indicates increasing litter cover, canopy cover, and medium shrub cover. Increasing principal component two indicates decreasing low shrub cover and shrub stem counts.

Discussion

As woody plants regenerated on wellsites, we expected that the assemblage of songbirds on the wellsite would become more similar to the adjacent forest. We hypothesized that an increase in structural complexity of vegetation would meet habitat requirements for a greater number of species, leading to increased singing locations within the wellsite footprint (Schieck and Song 2006, Brady and Noske 2010). Songbird use of wellsites became more frequent with increasing canopy cover, and replacement of low shrubs with tall shrubs. Species known to be associated with regenerating and edge habitat, such as Mourning Warbler, Clay-coloured Sparrow, and Alder Flycatcher placed a majority of their singing locations within the wellsite footprint at some sites. Use of wellsites by these early-successional species associated with young forest created by fire and forestry harvest suggests that the plants growing on wellsites are creating an early-successional trajectory for songbirds that is consistent with other forms of disturbance. In addition, many species were detected close to wellsites at all stages of regeneration, and strong avoidance of these wellsites was not observed.

For most other species, when individuals sang from a reclaimed well, a limited number of singing events would be on the footprint, with the majority of singing events located in the adjacent forest. This suggests that these species included the wellsite as part of their territory but likely had most of their territory in the adjacent forest. This partially explains why the impact of vegetation regeneration could not be detected using presence/absence localization data of only birds that sang on the wellsite. Overall, communities remained distinct between the wellsite and the adjacent stand, even at highly regenerated wellsites. However, complete similarity between wellsite and adjacent forest was not expected. The forest adjacent to the wellsite was already established when the wellsite was created, such that the wellsite will always be younger than the adjacent forest. The longest time since reclamation for a wellsite in this study was 48 years, and sites were in stands generally greater than 75 years old. However, given differences between vegetation on the wellsite and the adjacent forest, some birds may have perceived wellsites as lower quality habitat than the adjacent stand, contributing to overall lower probability of defending territories within the wellsite (Lankau et al. 2013). Birds may have also viewed wellsites as boundaries for territories, promoting avoidance of these features over extended periods. This behaviour has been observed in Ovenbirds previously (Lankau et al. 2013).

Standard bioacoustic surveys detected a similar number of species overall as localization, supporting our expectation that the approximate detection radius of the microphone in the centre of the wellsite sampled a similar area as the ALS (Yip et al. 2017). However, the standard bioacoustic approach gave a less precise assessment of the direct impact of regeneration of wellsites on birds, as it was not possible to differentiate birds singing from the wellsite, and birds singing from the adjacent forest. Regardless of method, using presence/absence data alone, vegetation regeneration on the wellsite explained limited variation in the community composition of birds. Instead, detecting the impact of wellsite regeneration required comprehensive data on differences in use of the wellsite, and adjacent forest provided by acoustic localization. This finding supports growing literature that measures of presence of species alone may not accurately indicate recolonization of wildlife to reclaimed sites. Instead, functional measurements,

such as relative use of wellsites by the songbird community, may be more appropriate to assess benefits of reclamation on wildlife (Jones and Davidson 2016).

Comparing songbird community composition on the wellsite to the directly adjacent forest was aligned with local reclamation goals of promoting ‘equivalent land capability’ (Bott et al. 2016). Species composition was our focus rather than richness, as richness can remain similar across gradients of disturbance due to changes in presence of disturbance-tolerant species, exchanged with species associated with intact habitats over time (Thomas et al. 2014). However, a more complete assessment of foraging behaviour and reproductive success would be useful to further document habitat quality of wellsites for birds, as previous studies found that although vegetation was distinct between reclaimed and control sites, birds continued to forage at comparable rates in these treatments (Morrison and Lindell 2011).

Our ALS provided accurate information on songbird territory placement in relation to reclaimed wellsites. Localization has been used relatively infrequently to study songbirds, likely due to equipment requirements, and logistical constraints. In this study, microphones were spaced at similar distances to previous literature, but the size of arrays was larger, requiring greater numbers of microphones (Mennill et al. 2012, Campbell and Francis 2012). Studies which examine species composition using localization are uncommon, as optimal data require calibration of array layout based on individual species vocalizations, song perch heights, habitat type, and potential acoustic interference (Wilson et al. 2013). Accurate microphone positions are necessary, which can be challenging to obtain under dense canopies; this challenge resulted in high error in localization and therefore elimination of a large number of singing events in this study (Mennill et al. 2006). Some studies have also identified issues with masking of vocalizations during dawn chorus (Campbell and Francis 2012, Hedley et al. 2017). Although masking was common during dawn chorus in this study, a sufficient number of vocalizations met our criteria for localization. Due to the time intensiveness of processing localization data, a limited amount of dawn chorus recordings were processed at each site on a single day. Thus, these data may not represent a complete assessment of songbird space use in relation to wellsites, and future studies could

examine how inferences change using a greater amount of time processed, from multiple days.

Using the combination of methods provided the opportunity to validate, and demonstrate inflation of species counts using a standard bioacoustic approach, similar to an unlimited radius point count (i.e., species singing beyond the wellsite footprint), and provided insight into strengths and weaknesses of each method. These strengths and weaknesses are primarily related to the trade off between time and cost effectiveness of each method, and the spatial accuracy with which they were able to determine where birds sang in relation to wellsites. Collecting, and processing localization data was more time intensive and expensive (due to equipment costs) than data similar to point counts using bioacoustic approaches, but these data alone were too coarse to understand songbird community response to vegetation regeneration following wellsite reclamation. However, the ability to understand this relationship using a larger sample size of a standard bioacoustic approach or human point counts should be investigated in the future.

Reclamation monitoring will become increasingly important in the western boreal region, given the large volume of existing wellsites, and development projected to increase in coming years (Rosa et al. 2016). Given that upland mesic habitats have high potential for vegetation regeneration in the study region, habitats with lower probability of regeneration should be assessed (van Rensen et al. 2015). Many songbirds appeared to be resilient to small wellsite disturbances at the local scale, and utilized sites at various stages of vegetation regeneration. Determining this relationship required data on songbird use of wellsites, rather than presence/absence data. This finding should inform the type of data required to understand the response of the songbird community in the boreal forest to wellsite recovery on a local scale. However, the reasons songbirds use reclaimed wells, such as for foraging and nesting behaviour, and resulting breeding success should be assessed further. This information could be collected through a combination of behavioural observations, and acoustic localization (Taylor et al. 2016). Localization is an exciting technology which should become more accessible with the advent of sensor networks which could make field data collection more efficient, and

incorporation of automated species recognition to expedite data processing following collection (Taylor et al. 2016). Pairing these data with high resolution photogrammetry or LiDAR data could be used to answer questions on fine scale habitat use in birds (van Rensen et al. 2015, Cruzan et al. 2016). Based on results from this study, regeneration of vegetation on reclaimed wellsites in upland deciduous boreal forests mitigates impact on songbird communities, but communities remain distinct from the adjacent forest, highlighting the long-term effects of this disturbance even after they have been reclaimed.

Chapter 3. Use of an Acoustic Location System to Understand How Presence of Conspecifics and Canopy Cover Influence Ovenbird (*Seiurus aurocapilla*) Space Use Near Reclaimed Oil and Gas Wellsites in the Boreal Forest of Alberta

Introduction

Bird monitoring increasingly utilizes autonomous recording technology to collect data, without the requirement of a human observer present (Blumstein et al. 2011, Shonfield and Bayne 2017). Standard approaches in bioacoustic monitoring using autonomous recording units provides data that are the functional equivalent of an unlimited radius point count done by a human observer. Such data provide coarse information for understanding songbird behaviour, abundance, and habitat use (Bayne et al. 2016). The coarse nature of such data stem primarily from challenges in estimation of area sampled, and difficulty distinguishing individuals (Ehnes and Foote 2015, Darras et al. 2016, Yip et al. 2017). Certain research questions on songbird behaviour and habitat use require more precise spatial locations of birds, such as local scale response to disturbances (Bayne et al. 2016). While telemetry and spot mapping data can provide such information, field data collection for these methods is time consuming, and determining information on many birds concurrently is challenging. In addition, presence of a human observer, or use of certain tracking equipment can create behavioural bias in birds (Mennill et al. 2012, Wilson et al. 2013).

Localization can be used as an alternative approach to spot mapping or territory mapping, allowing collection of spatially accurate information on multiple individual birds concurrently through use of recording technology (Blumstein et al. 2011, Kirschel et al. 2011). Localization uses arrays of microphones to determine singing locations from time of arrival differences of songs to microphones in the array or ‘acoustic location system’ (ALS; McGregor et al. 1997, Blumstein et al. 2011). Various taxa including primates (Spillmann et al. 2015), marine mammals (Hayes et al. 2000), amphibians (Jones and Ratnam 2009), and birds (Kirschel et al. 2011, Stepanian et al. 2016) have been surveyed using localization. To date, most songbird research using localization has focused on validation of methodology, or examination of singing behaviour (Mennill et

al. 2006, Fitzsimmons et al. 2008, Campbell and Francis 2012). Fewer studies have used localization to understand habitat associations or space use of individual songbirds in relation to human disturbance.

Individuals must be consistently distinguishable by their song over time to determine individual space use patterns from localization data (Mennill 2011). Songbird studies typically use manual measurements of song characteristics from spectrograms to distinguish individuals (Foote et al. 2013). These measurements are then analyzed using various classification methods, which vary in terms of performance time, accuracy, and computational power required (Kirschel et al. 2009, Ehnes and Foote 2015). For species that display high variation in song between individuals, relatively simple and time efficient methods, such as spectrogram cross correlation (SPCC) can be used to provide a relative measure of similarity from pairwise comparison of signals (Cramer 2013, Foote et al. 2013, Ehnes and Foote 2015). These measures of similarity within and between groups of vocalizations can be used to validate estimates of which vocalizations belong to which individuals, and therefore the number of individuals present.

Populations of many songbird species in the boreal forest are declining, and concerns have been raised that extensive oil and gas development may be partially responsible (van Wilgenburg et al. 2013). This development includes hundreds of thousands of one hectare wellsites. Following production, wellsites are required to be actively reclaimed (Powter et al. 2012, Bott et al. 2016). Current reclamation criteria measures similarity of soil, vegetation, and hydrology to a reference condition with the goal of returning to 'equivalent land capability' (Powter et al. 2012, Bott et al. 2016). Following the issue of a reclamation certificate, limited information exists on the recovery trajectory of wellsites with respect to different ecosystem components, including songbirds. Whether current reclamation criteria results in regeneration of woody vegetation, which facilitates reduced avoidance or use of wellsites remains an unanswered question of interest to policy makers to assess ecological recovery of these sites. Increasing singing locations within the wellsite footprint should indicate that a bird is more likely to use this area as part of its territory, and thus a reduced impact of these sites from a songbird's perspective. Failure of these sites to regenerate vegetation over a reasonable time frame

will influence the amount of certain habitats available, potentially resulting in detrimental effects on songbirds in the boreal forest in the long term (Mahon et al. 2016). Fine scale data on songbird use and avoidance are required to detect subtle impacts of small disturbances characteristic of energy extraction in the boreal forest of Alberta (Machtans 2006, Lankau et al. 2013). Past assessments of songbird responses to wellsites have relied on point counts conducted by humans, and emphasize that the spatial precision at which songbirds are measured has a large effect on the conclusions about wellsite impact and recovery (Bayne et al. 2016). Methods that provide spatial information on songbird use of wellsites, such as telemetry, spot mapping, or localization are likely required to provide accurate estimates of songbird response to vegetation regeneration on reclaimed wellsites.

Our first objective was to track individual Ovenbirds (*Seiurus aurocapilla*) using an ALS comprised of commercially available omnidirectional microphones (Mennill et al. 2012, Ehnes and Foote 2015). We hypothesized Ovenbirds would be an excellent candidate to track using an ALS, based on their singing behaviour (Mennill 2011). Ovenbirds vocalize frequently, which provides an opportunity to determine many singing locations. The song of the Ovenbird is fairly broadband, which can be localized with greater accuracy than tonal songs (McGregor et al. 1997). Songs are produced from the lower canopy, which limits spatial error in localization due to disparity between microphone and signal height (Wilson et al. 2013). Finally, Ovenbirds display large individual variation in song, which may allow individuals to be distinguished using SPCC from omnidirectional microphones (Ehnes and Foote 2015).

The second objective was to determine if Ovenbirds sang from regenerating wellsites and/or wellsite edges. We were particularly interested in how this behaviour changed as a function of canopy cover on the wellsite and/or the presence of conspecifics, both of which influenced Ovenbird space use near regenerating seismic lines in the boreal forest (Lankau et al. 2013). Ovenbird response to energy sector disturbance, and resulting regeneration has been studied extensively using territory and spot-mapping (Bayne et al. 2005b, Machtans 2006, Lankau et al. 2013). Ovenbird singing locations indicate territorial behaviour, and placement in relation to the wellsite footprint should provide

evidence of reduced impact of this disturbance on their space use. Thus, we hypothesized that Ovenbirds should avoid wellsites at early stages of woody plant regeneration, presumably to limit predation risk and the lower quality foraging opportunities (Lankau et al. 2013). With increasing canopy cover, Ovenbird use of wellsites should increase, and distance from wellsite edge should decrease (Lankau et al. 2013). However, in areas with high densities of Ovenbirds, this species appears to use energy sector disturbances (e.g. seismic lines) as territory boundaries (Bayne et al. 2005a, Machtans 2006, Heap et al. 2012, Lankau et al. 2013). Thus, we hypothesized that use of wellsite edges as territory boundaries would become more evident with presence of conspecifics. In absence of conspecifics, there should be less competition for territory space and Ovenbirds will be less particular about territory placement in relation to the disturbance (Lankau et al. 2013). Decreased use of wellsites, and increased distance of singing locations from wellsite edge was expected with presence of conspecifics.

Methods

Site Selection

We selected certified reclaimed wellsites ($n = 13$) within 50km of the communities of Lac La Biche and Slave Lake, Alberta in the Central Mixedwood Natural Subregion of the Boreal Forest Natural Region (Downing and Pettapiece 2006). We focused site selection on mesic upland ecosites, in forests dominated by trembling aspen (*Populus tremuloides*), and balsam poplar (*Populus balsamifera*). Understory shrubs included alder (*Alnus spp.*), willow (*Salix spp.*), and beaked hazelnut (*Corylus cornuta*).

Wellsites ranged in age from 4 to 48 years since a reclamation certificate was issued. However, vegetation on wellsites regenerates heterogeneously over time, in part due to changing development and reclamation practices. Therefore, measuring recovery as a function of time since reclamation is unlikely to predict how songbird use of the wellsite will change (Lankau 2014). For this reason, we selected sites to sample a gradient of woody vegetation recovery, ranging from sites with predominantly grass and forb cover, to sites where woody vegetation exceeded five meters in height. Sites were required to be accessible by a linear feature, and have no significant additional human disturbance

within the area sampled (e.g. forestry harvest). Wellsite footprints were an average of 1.03 ± 0.12 (mean $\pm$ standard error) hectares in size, determined through digitization of survey diagrams and field measurements (Abacus Datagraphics Limited 2015).

Acoustic Data Collection

We used GPS enabled Wildlife Acoustics SM3 units equipped with external SMM-A1 microphones to construct the ALS (Wildlife Acoustics, Inc., Maynard, Massachusetts, USA). A total of 325 microphones were deployed over the 13 sites during the songbird breeding season in 2015 (June 5 – June 27) and 2016 (May 26 – June 27). Microphones were deployed at a height of 1.5 m, and spaced an average of 31.4 ± 0.44 m apart in a 5 x 5 grid (Fig. 3.1). Arrays covered an average area of 2.13 ± 0.08 hectares. We determined positions with a horizontal accuracy of ± 3.0 cm using a Hemisphere S320 survey GPS. Positions were determined from the mounted Garmin 16x GPS attached to the recording unit (accuracy 3.28 ± 0.25 m) when not possible to obtain locations using the survey GPS due to dense canopy. The ALS was deployed, and recordings were collected on 1 - 5 subsequent days from 05:30AM to 08:30AM at each site in compressed Wildlife Acoustics' WAC format with a 48000 Hz sample rate. The GPS clock of the Garmin 16x was used to synchronize recordings within the array to ± 1 milliseconds. Playback experiments were performed at one of the study sites to quantify error in localization for Ovenbirds. The average error between the estimated position using localization, and a known speaker location was determined under slight differences in spacing of microphones and the GPS accuracy used to determine microphone locations. The average error in localization for microphone spacing and GPS accuracy at 4 study sites was determined as 1.88 ± 0.41 m. Error increased with inter-microphone distance, and when microphone positions were estimated from the Garmin 16x GPS attached to the recording unit, resulting in average error of 6.06 ± 2.21 m at 9 study sites.

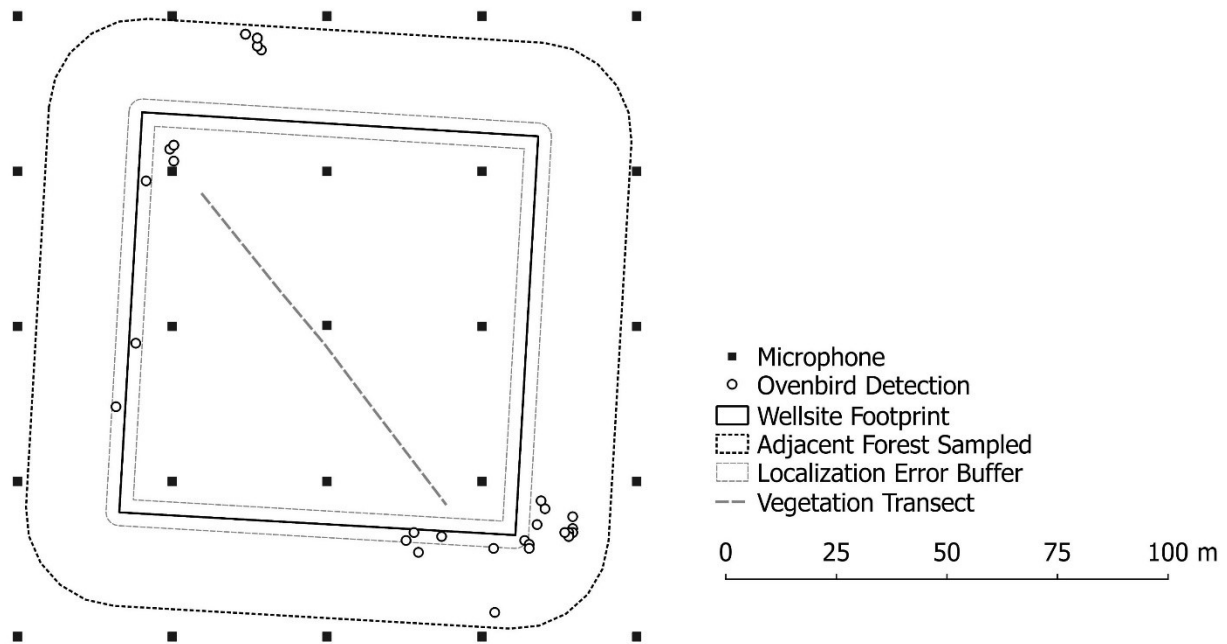


Figure 3.1. Schematic of study design. Ovenbird singing locations were determined within the wellsite footprint, and an area equivalent to the wellsite footprint in the adjacent forest between the wellsite and indicated buffer. Singing locations within the localization error buffer were removed from further analysis, and they could not be confirmed as within the wellsite footprint or the adjacent forest sampled.

Vegetation Data Collection

We used the point intercept method to measure canopy cover on reclaimed wellsites. A 90 m diagonal transect was laid out from a randomly selected corner of the wellsite to the opposite corner. Measurements were taken at 3 m increments for the first and last 30 m, and 1 m increments for the center 30 m (Fig. 3.1; Floyd and Anderson 1987). At each sampling distance, presence or absence of woody vegetation above five metres was recorded. These data were summarized into percent canopy cover, which ranged from 0 to 100% at reclaimed wells.

Acoustic Data Processing

We processed three hours of dawn chorus (i.e. 05:30-08:30 AM) at each site, to target when Ovenbirds are mostly likely to vocalize. Recording files were converted to wav format and spectrograms were visualized using a 512 FFT hamming window in the

program Audacity 2.1.3 (Audacity Team 2017). Recordings were visually scanned in groups to locate Ovenbird songs within the microphone array. Vocalizations were included in further analyses if the entire song was detected clearly on four microphones, and was not masked by songs of greater amplitude, or with any fainter singing events for 25% of the duration of the target vocalization on any channel (Spiesberger 2004). Ovenbird identifications were confirmed by multiple trained observers through acoustic and visual cues from spectrograms. The multichannel track which contained the strongest signal for each singing event was used in subsequent analyses.

Speed of sound was estimated using temperature data from the nearest Environment and Climate Change Canada weather station (Wilson et al. 2013, Environment and Climate Change Canada 2017). We imported the multichannel tracks, microphone positions, and speed of sound into the MATLAB based program XBAT for analysis (Figuerola and Robbins 2007, MathWorks Inc. 2014). Each vocalization that met the criteria mentioned earlier was annotated. We used the CSE location algorithm (version 2.3) for acoustic localization (Cortopassi 2006). This algorithm determines the time of arrival differences of a signal to different channels in the ALS using pairwise cross correlations of the signal between channels (Cortopassi 2006, Campbell and Francis 2012). These time of arrival differences are used to calculate the location of the signal under a known speed of sound and microphone locations (Cortopassi 2006). Each annotated vocalization was localized using a minimum of four channels to estimate positions, and a search radius of 100 m (Campbell and Francis 2012).

Spatial locations were validated to determine if they were closer to the channel with the greatest amplitude than to other channels used in localization. Observations (n=117) were discarded if not closest to the channel with the greatest amplitude, which mainly occurred when partially masked by another vocalization. If singing locations did not occur within the subset of microphones used for localization, but were still within the microphone array, they were rerun using the correct subset of microphones based on the estimated locations. This was to achieve the most accurate positions, as accuracy of localization degrades with distance from the center of the array (McGregor et al. 1997, Campbell and Francis 2012, Wilson et al. 2013).

Singing locations were exported from and visualized in QGIS 2.12.3 (Quantum GIS Development Team 2016). First, the distance of each vocalization from the nearest wellsite edge was calculated. Values within the wellsite footprint were assigned negative values. Next, a buffer the equivalent size of the wellsite polygon was created around each site in the adjacent forest (Fig. 3.1). Vocalizations occurring beyond this buffer were excluded from subsequent analyses. Error in localization was accounted for by creating a second buffer around wellsite footprints, that was the size of error estimates based on GPS accuracy, and microphone spacing at different sites. If singing locations occurred within the buffer they were excluded from analyses as their position could not be confirmed as on or off of the wellsite. Remaining singing locations were then classified as occurring within the wellsite footprint, or within the adjacent forest.

We clipped each localized singing from long recordings using the R package ‘tuneR’ on the recording of the microphone closest to the estimated position, adding a buffer of 0.25 sec on beginning and end of the song (Ligges et al. 2016). We manually estimated the number of individuals at each site based on song properties (length of song, frequency range of song, and song timing) and spatial clusters of singing events. We then assigned each vocalization to an individual, and removed individuals with less than 10 singing events from further analysis. Raven Pro 1.5 was used to perform SPCC to create a correlation matrix of pairwise comparisons of the vocalizations (Bioacoustics Research Program 2014). A 512 Hamming window spectrogram and bandpass filter of 1500Hz to 10500Hz was used for all processing. SPCC determines the similarity between two spectrograms, through shifting across time to find the point in time where amplitude is most similar between spectrograms (Terry et al. 2001, Cramer 2013). At this time instance, a correlation coefficient between ‘0’, indicating complete dissimilarity between spectrograms, and ‘1’ indicating complete similarity, is provided.

Statistical Analyses

To confirm that vocalizations had been assigned to the correct Ovenbird, an equal number of pairwise comparisons of vocalizations from a hypothesized individual against vocalizations of the same individual (‘Within’), and pairwise comparisons against

vocalizations of other hypothesized individuals ('Between') were subset from the SPCC correlation matrix. Duplicated pairwise comparisons were removed (i.e. the lower half of the matrix), as were comparisons of a vocalization to itself (i.e. the diagonal of the matrix). For example, if an individual produced 10 vocalizations, 40 'Within' and 40 'Between' scores from pairwise comparisons would be randomly selected for further analysis. The mean and 95% confidence interval of the SPCC score were calculated for 'Within' and 'Between' comparisons. If confidence intervals of SPCC score 'Within' and 'Between' individuals were not overlapping, vocalizations and associated spatial locations were assigned to these individuals for further analysis. These estimates were then used to calculate the number of Ovenbirds present at each site.

A mixed effects logistic regression was used to determine how canopy cover, and presence or absence of conspecifics at the site influenced placement of singing locations within the wellsite footprint ('1') or within the adjacent forest ('0'). A mixed effects generalized linear model (GLM) was used to determine how distance from edge was influenced by the same metrics (R package 'lme4'; Bates et al. 2015, R Core Team 2017). For both models, the individual (determined from SPCC) which produced the singing event was included as a random effect to account for repeated observations, and differences in singing behaviour among individuals. The conditional and marginal r^2 was calculated for models to assess fit (R package 'MuMIn', Barton 2016). A significance level of $\alpha = 0.05$ was used for all analyses.

Results

We localized 2052 Ovenbird vocalizations across the 13 wellsites, after removing vocalizations outside the wellsite and adjacent forest sampled. Following removal of vocalizations that were within the buffer accounting for error around the wellsite edge, 509 vocalizations occurred within wellsite footprints, and 866 occurred in the adjacent sampled forest (Fig. 3.1). Two individuals placed all of their singing locations detected within a wellsite footprint, while five individuals placed all vocalizations in the adjacent forest. The average correlation score from SPCC 'Within' individuals was $0.41 \pm <0.01$, and $0.17 \pm <0.01$ (mean $\pm$ margin of error) 'Between' individuals. After removing hypothesized individuals with less than 10 vocalizations, the data suggested 22 distinct

individuals, which demonstrated non-overlapping confidence intervals of correlations between their own vocalizations and other birds (Fig. 3.2, Table 3.1). Conspecific density ranged from one to four Ovenbirds across sites.

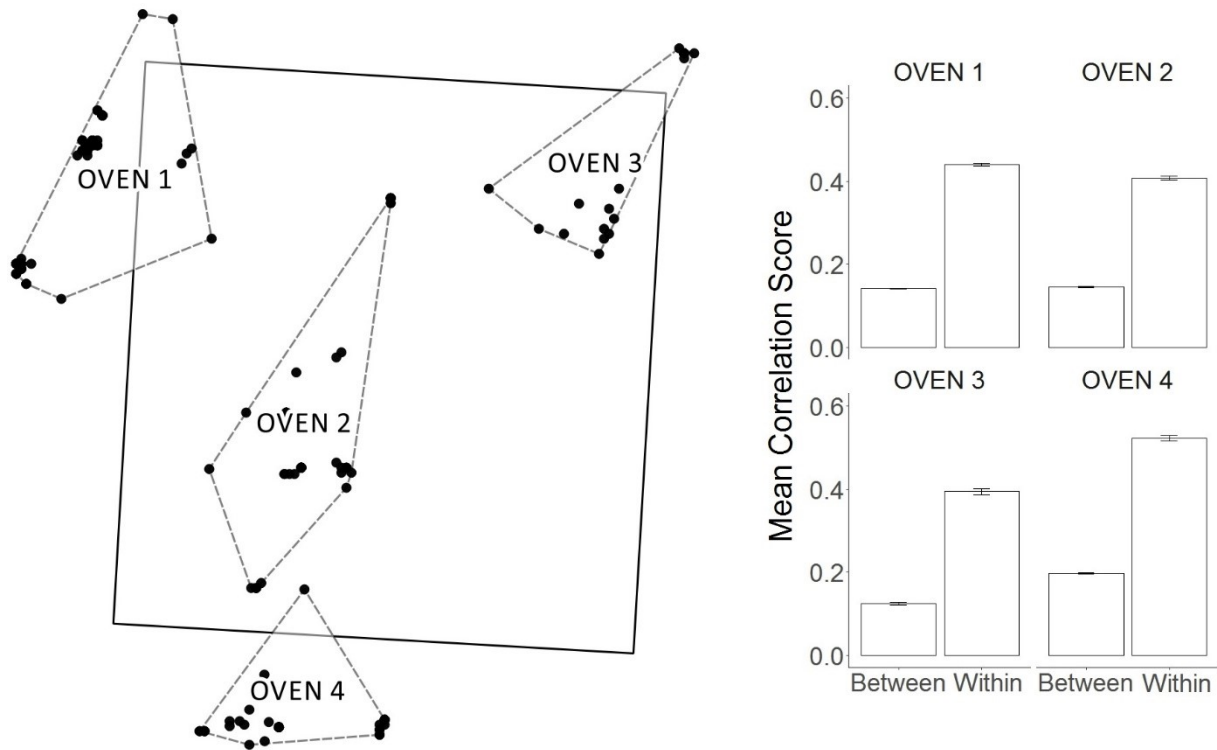


Figure 3.2. Ovenbird singing locations in relation to a reclaimed wellsite where four individuals were present, and associated mean correlation scores 'Within' and 'Between' individuals with 95% confidence intervals.

Table 3.1. Mean spectrogram cross correlation scores for Ovenbird vocalizations within individuals, and between individuals. Values are mean $\pm$ margin of error. Correlations of vocalizations assigned to each individual ('Within') had non-overlapping confidence intervals with an equivalent number of vocalizations from other birds ('Between') for all individuals.

Individual	Number of Vocalizations	Mean Within Score	Mean Between Score
OVEN 1	103	0.44 $\pm$ <0.01	0.14 $\pm$ <0.01
OVEN 2	67	0.41 $\pm$ <0.01	0.15 $\pm$ <0.01
OVEN 3	26	0.40 $\pm$ 0.01	0.13 $\pm$ <0.01
OVEN 4	53	0.52 $\pm$ 0.01	0.20 $\pm$ <0.01
OVEN 5	43	0.40 $\pm$ <0.01	0.18 $\pm$ <0.01
OVEN 6	100	0.43 $\pm$ <0.01	0.16 $\pm$ <0.01
OVEN 7	144	0.42 $\pm$ <0.01	0.22 $\pm$ <0.01
OVEN 8	11	0.41 $\pm$ 0.02	0.18 $\pm$ 0.01
OVEN 9	49	0.39 $\pm$ 0.01	0.17 $\pm$ <0.01
OVEN 10	24	0.48 $\pm$ 0.01	0.14 $\pm$ <0.01
OVEN 11	17	0.45 $\pm$ 0.02	0.21 $\pm$ 0.01
OVEN 12	20	0.31 $\pm$ 0.02	0.14 $\pm$ 0.01
OVEN 13	40	0.45 $\pm$ 0.01	0.20 $\pm$ <0.01
OVEN 14	278	0.45 $\pm$ <0.01	0.17 $\pm$ <0.01
OVEN 15	80	0.41 $\pm$ <0.01	0.17 $\pm$ <0.01
OVEN 16	21	0.43 $\pm$ 0.01	0.20 $\pm$ 0.01
OVEN 17	31	0.41 $\pm$ 0.01	0.18 $\pm$ <0.01
OVEN 18	24	0.47 $\pm$ 0.02	0.16 $\pm$ <0.01
OVEN 19	206	0.32 $\pm$ <0.01	0.16 $\pm$ <0.01
OVEN 20	11	0.39 $\pm$ 0.02	0.19 $\pm$ 0.02
OVEN 21	11	0.38 $\pm$ 0.01	0.24 $\pm$ 0.02
OVEN 22	16	0.36 $\pm$ 0.02	0.16 $\pm$ 0.01

According to the mixed effects logistic regression, Ovenbirds were more likely to sing from wellsites as canopy cover increased, and less likely with presence of conspecifics (Table 3.2, conditional $r^2=0.31$, marginal $r^2=0.80$). The distance that Ovenbirds would sing from wellsite edges (both within and beyond the wellsite footprint) decreased with increasing canopy cover on the wellsite, and increased with presence of conspecifics

based on results from the mixed effects GLM (Table 3.3, conditional $r^2=0.20$, marginal $r^2=0.62$).

Table 3.2. Results from logistic regression of Ovenbird singing locations placed on or off of reclaimed wellsite footprints.

	Estimate	SE	Z	p
Intercept	-1.80	1.52	-1.18	0.2369
Canopy Cover	6.93	2.55	2.72	0.0066
Presence of Conspecifics	-6.61	1.85	-3.58	0.0003

Table 3.3. Results from generalized linear model of distance of Ovenbird singing locations from wellsite edge.

	Estimate	SE	df	t	p
Intercept	8.98	4.32	23.02	2.08	0.049
Canopy Cover	-26.51	7.29	22.35	-3.64	0.001
Presence of Conspecifics	18.13	5.36	21.97	3.38	0.002

Discussion

We intended to demonstrate the potential of an ALS to determine how Ovenbird space use changes in response to vegetation recovery and presence of conspecifics, as a measure of ecological recovery of reclaimed wellsites. The ALS was successfully used to track individual Ovenbirds, without prior identification of individuals or territory boundaries. We hypothesized that increasing canopy cover on wellsites would decrease perceived predation risk, and increase leaf litter which is the main foraging medium for Ovenbirds. We also hypothesized that wellsites would be used as landmarks for territory boundaries when conspecifics were present. Our predictions that wellsite and/or edge use by Ovenbirds should increase with increasing canopy cover on the wellsite, and decrease with presence of conspecifics were supported.

Ovenbirds were an excellent species to study using an ALS. They were relatively abundant at study sites, and produced sufficient numbers of vocalizations to allow them to be tracked over the time and area sampled. However, territories constructed were not complete for all individuals, and were comprised of 11 to 268 singing locations. This is to be expected, as the ALS was not centered around Ovenbird territories, and focused on the wellsite disturbance itself. A longer period of time, with arrays centered over predetermined territories would have to be sampled to collect the approximately 60 singing locations required to construct complete Ovenbird territories (Zach and Falls 1978). Regenerating vegetation promoted use of wellsites, and appeared to ‘soften’ the impact of wellsite edge on placement of singing locations, resulting in more locations closer to the edge itself. Our results support the idea that Ovenbirds can tolerate energy sector disturbances once they are partially regenerated, and will utilize early successional habitats as part of their territories (Hache et al. 2013, Lankau et al. 2013). Further investigation should occur to determine if this local scale avoidance of wellsites at early stages of regeneration could be detectable on a broader scale, or if Ovenbirds are able to adjust territory placement in relation to these disturbances, as demonstrated in relation to seismic lines (Bayne et al. 2005a). Assessment of reproductive success of individuals which utilize wellsites is necessary to determine the full impacts of wellsite disturbance on Ovenbirds. In the future, it will be useful to assess how regeneration of wellsites influences species that partition territories more strongly, and are more sensitive to disturbance.

Determining the impact of small disturbances, including wellsites, on songbirds requires precise location estimates, such as those provided by acoustic localization (Bayne et al. 2016). Singing locations provided by the ALS were used to accurately assess how avoidance of wellsites and wellsite edges was reduced with vegetation regeneration. Relatively few species have been tracked through time using an ALS in terrestrial environments, despite potential for this technology to improve monitoring of various species (Kirschel et al. 2011, Spillmann et al. 2015). Similarly, identification of individuals based on song using omnidirectional microphones has been demonstrated in few species, as the majority of this literature is focused on data collected using directional microphones (Ehnes and Foote 2015). Our values support previous findings

that correlations from SPCC greater than 0.3 are generally vocalizations of the same individual Ovenbird (Ehnes and Foote 2015). Ideally, these estimates would have been validated in relation to spot mapping data, to confirm individual territories had been correctly assessed. Identification of individuals allowed us to account for behaviour of individual Ovenbirds, and determine presence of conspecifics, which were necessary for understanding space use near wellsites. This approach could also be very useful in providing validated estimates of density relative to those derived from point count or single microphone surveys (Matsuoka et al. 2012, van Wilgenburg et al. 2017).

Acoustic masking of Ovenbird songs occurred frequently during the dawn chorus, yet there were sufficient vocalizations available to perform the study. However, not all vocalizations can be localized, and the feasibility of this method based on the number of songs available for localization needs to be investigated prior to use (Araya-Salas et al. 2017, Hedley et al. 2017). The number of usable vocalizations available for localization will vary based on species, and total number of birds present. Development of automated species recognition should improve efficiency of this method, and ultimately localization could become more time efficient and accurate than conventional methods, due to more precise spatial estimates. However, efforts are needed to directly compare localization with conventional methods, such as spot mapping or telemetry to determine the effects of human observers on factors including territory size (Mazerolle and Hobson 2004). Ideally, individual estimates would have been validated in the field. However, we are confident with our approach of predetermining numbers of individuals, and validating assignment of songs to individuals given large differences in correlation scores between and within individuals. Even with small amounts of masking over song clips, and variation in amplitude, use of SPCC was still feasible, as Ovenbirds display high individual variation in song. The use of SPCC to discriminate individuals would not be applicable for species that display less variation and alternative approaches such as machine learning algorithms would be required (Kirschel et al. 2009).

Wellsite reclamation criteria in Alberta do not currently account for songbirds, but current criteria appear to facilitate vegetation recovery, which results in reduced avoidance of wellsites and edges by Ovenbirds. Future work should use localization to

understand the local scale impacts of other types of energy disturbances such as seismic lines and pipelines and associated edge effects. Localization is becoming increasingly accessible with the advent of sensor networks which will create more cost-effective arrays, and machine learning algorithms that make individual discrimination increasingly time efficient and accurate (Kirschel et al. 2009, Taylor et al. 2016). Pairing localization data with high resolution photogrammetry or LiDAR data will provide fundamental insights into fine scale habitat use by songbirds, territory establishment, and singing behaviour (van Rensen et al. 2015, Cruzan et al. 2016). These data could also be approached using spatially explicit capture-recapture models, or acoustic spatially explicit capture-recapture models to determine density of individuals, which remains a fundamental limitation of other approaches to avian monitoring (Dawson and Efford 2009, Campbell and Francis 2012, Stevenson et al. 2015). An ALS can be used to provide precise spatial locations of individual birds, and can provide an alternative to territory or spot-mapping, thereby freeing up field time to collect additional data including vegetation, food availability, and breeding success to determine factors influencing songbird use of specific habitats (Taylor et al. 2016).

Chapter 4. General Discussion

The purpose of this thesis was to demonstrate how an acoustic location system (ALS) could be used to collect data on response of songbird communities to vegetation regeneration on reclaimed wellsites in the boreal forest of Alberta. Few studies have used localization data to study songbird communities, or space use of individual songbirds in relation to human disturbance (Kirschel et al. 2011, Mennill 2011, Campbell and Francis 2012). Songbird response to wellsite reclamation in the boreal forest was previously unexamined, despite the magnitude of wellsite disturbance, frequent use of songbirds to assess ecosystem state, and importance of the boreal for breeding songbirds (Venier and Pearce 2005, Schieck and Song 2006, Lemaître et al. 2012). Current wellsite reclamation efforts result in regeneration of woody vegetation in upland deciduous forests, which facilitates use and reduced avoidance by the songbird community. In chapter two, the ALS provided the opportunity to create a community similarity index based on singing locations in relation to the wellsite footprint. Findings from chapter two indicate that data on songbird use of specific locations, rather than presence/absence data from a standard bioacoustic approach, or only songbirds detected on the wellsite using localization are required to quantify the impact of regeneration of woody plants on reclaimed wellsites on the songbird community. The ALS demonstrated that standard bioacoustic surveys on wellsites detected an average of 5.85 ± 0.26 more species within the adjacent forest than the 2.05 ± 0.28 species which sang from the wellsite alone. Although songbird community similarity between the wellsite footprint and adjacent forest increased with regeneration of tall shrubs (2-5 m), canopy cover (>5 m), and litter cover, overall average community similarity remained low. In chapter three, combining localization with other acoustic methods allowed identification of individual Ovenbirds (*Seiurus aurocapilla*) based on song alone, and quantification of individual behaviour and presence of conspecifics. Ovenbird space use near wellsites was influenced positively by canopy cover on the wellsite, and negatively by presence of conspecifics. In some cases, Ovenbirds sang from reclaimed wellsites equally or more frequently than the adjacent forest, notably at sites with greater than 25% canopy cover. These findings support that measurements, which account for songbird space use and behaviour, are necessary to detect the impacts of vegetation

regeneration due to wellsite reclamation practices on songbird communities in the boreal forest.

The ALS provided similar data to conventional spot-mapping, and even territory mapping when individual Ovenbirds could be identified. Although error in localization varied based on different array designs used in this study, similar accuracy to the ALS could be obtained using a handheld GPS to mark locations of birds in a spot-mapping grid. However, the benefit of the ALS is that the behaviour of multiple birds can be examined simultaneously, without bias from presence of a human observer, which is not possible during spot-mapping or territory mapping. Despite these benefits, obtaining the same data from the ALS was more expensive, and took a longer time to collect and process as data from a spot-mapping grid, based on time estimates from similar habitats (E. Bayne 2017, personal communication). It cost a minimum of ~ \$27,875 CAD to use the ALS in this study based on equipment costs alone, given that one ALS was rotated among sites. This does not include additional costs such as batteries to power the ALS, SD cards for data storage, or a survey grade GPS to obtain accurate locations of microphones. Conventional spot mapping would take on average 4.4 hours/hectare to get 10 locations of each individual, while the ALS took 7 hours/hectare to get an average of 11.9 ± 1.58 (mean $\pm$ SE) singing locations for each bird when three, three-minute time segments were processed. When a 3 hour period of time was processed for Ovenbirds, which took also took 7 hours/hectare to collect and process, an average of 62.5 ± 14.3 singing locations were obtained across identified individuals. Although field time for each method is similar, differences in time are related to processing data. Spot-mapping requires additional time to interpret maps and define territories. This can include entering data in a GIS or using map overlays. Further work is needed to assess processing time from conventional spot-mapping data to an ALS.

Singing locations from ALS do not necessarily represent unique song posts, rather individual songs. Song territories of Ovenbirds were estimated to be 0.21 ± 0.07 hectares, which are approximately 20% of the size of reported Ovenbird territory sizes in similar habitats using conventional territory mapping approaches (1.07 ± 0.10 hectares; Lankau et al. 2013). One individual was only detected singing over an area of 0.01

hectares during the time sampled, while another individual sang over an area of 1.51 hectares in the same amount of time. Although the ALS used in this study was larger and utilized more microphones than ALS used in previous studies, the area it sampled (2.30 ± 0.25 hectares) provided incomplete Ovenbird territories, resulting in many 'edge' territories (Bibby et al. 1992). To increase the number of singing locations and obtain a better estimate of space use, recording data from multiple days could be processed to simulate spot-mapping approaches (Bibby et al. 1992). However, due to equipment constraints, it is often infeasible to deploy the ALS at a single location for multiple days. In theory, localization could be used to collect infinite singing locations of songbirds, but careful consideration must be made on if the species of interest will be subject to masking by biotic and abiotic noise. I found that many songs were masked by other sounds, which limited the number of songs that could be localized accurately. This is because the time offsets used to calculate spatial locations by the ALS are determined when the signal is most similar between channels from cross correlations. Cross correlations of masked signals between channels will be less distinct, resulting in less accurate time offsets used in calculation of spatial locations. In the future, the proportion of songs that could not be localized should be quantified to determine the efficacy of this method for different songbird species in boreal forests, which are acoustically complex environments.

Although the ALS used in this study required more time and financial investment than conventional methods, this approach will become increasingly useful as equipment becomes more portable and cost effective, and workflows are developed that include automated recognition (Taylor et al. 2016). Use of localization should become more accessible, additional data can be collected to complement their use. With regards to this study, other data that indicates recovery of ecosystem function, such as foraging, age structure, or breeding success could be collected in addition to localization data to determine further mechanisms as to why songbirds would sing from reclaimed wellsites, and the impacts this has on their productivity (Foster et al. 2016, Jones and Davidson 2016, Taylor et al. 2016). For example, Ovenbirds could sing from wellsites as songs will suffer less from attenuation due to lower density of vegetation in relation to the adjacent forest (Lein 1981). Although Ovenbirds may include wellsites in their song territories,

the majority of their foraging could occur away from wellsites. Ovenbirds appear capable of this type of adjustment, with limited impact on breeding success in relation to intermediate levels of disturbance, as long as sufficient amounts of suitable habitat remains available (Hache et al. 2013). Ovenbirds display local scale avoidance of similar disturbances, such as seismic lines, but on a broader scale, these disturbances do not influence density of Ovenbirds until a high density of these features is met (Bayne et al. 2005b). As this study focused on local scale impacts of wellsite disturbances, the resilience of songbirds to these disturbances on a broader scale, and if a threshold is met at which this influences bird density should be examined in the future. In addition, the impact of wellsite disturbances on species which are less resilient to human disturbance, or highly dependent on a specific successional stage should also be examined both locally, and on a broader spatial scale.

Songbirds sang from wellsites more frequently with regeneration of woody plants to tree heights on wellsites (> 5 m), and therefore more canopy cover. Full songbird community similarity between wellsites and the adjacent forest was not expected, as even if recovery is not inhibited by wellsite development practices, not enough time has elapsed for vegetation to regenerate to the equivalent of the adjacent forest, which was generally older than 75 years in this study. However, songbird assemblages in wellsite and adjacent forest are unlikely to converge before an additional disturbance, such as fire or forestry harvest occurs. Although songbird community similarity between wellsites and adjacent forest was low in general, with 10 of 22 sites being completely dissimilar to the adjacent forest, different species would sing from wellsites at various stages of recovery. Songbirds associated with early successional habitats (e.g. Alder Flycatcher (*Empidonax alnorum*) and Tennessee Warbler (*Oreothlypis peregrina*)) sang from wellsites with no canopy cover, but at least 30% low shrub cover. Species associated with mature forest, such as Bay-Breasted Warbler (*Setophaga castanea*) were only detected at one reclaimed wellsite, with 90% canopy cover. However, wellsites were selected to obtain a gradient of woody plant regeneration, and may not represent the variation seen in wellsite recovery across the boreal forest of Alberta. The recovery of wellsites in other habitats within the boreal ecozone should be examined, as the potential for vegetation recovery in the upland deciduous habitats sampled is high in comparison to other

habitats such as organic wetlands (i.e. bogs and fens; van Rensen et al. 2015). A broad assessment of the state of wellsite recovery is necessary to determine the proportion of wellsites with vegetation maturing to tree heights, and those with limited establishment of woody vegetation. This assessment can occur through remote sensing technology such as LiDAR (van Rensen et al. 2015). Comparison of wellsite recovery to other disturbances with more heavily studied recovery trajectories, such as forestry harvest or fires, of similar age could provide insight into relative rate of recovery of wellsites (Schieck and Song 2006, Frerichs et al. 2017). Finally, this study focused on the local scale impact of wellsite regeneration, and future studies should examine the impact of wellsite regeneration on a larger spatial scale to determine impacts on songbird populations (Bayne et al. 2005b).

Management Implications

Global reclamation standards promote measurement of ecosystem function from multiple ecosystem components to assess reclamation success (Ruiz-Jaen and Aide 2005). Current wellsite reclamation standards in Alberta do not satisfy these recommendations. Given the number of wellsites across Alberta, this is unlikely to occur in the near future given time and financial constraints. Under current reclamation criteria, concerns have been raised over the slow and inconsistent vegetation regeneration of these wellsites in the boreal forest (Osko and Glasgow 2010). Fortunately, attempts have been made to improve development and reclamation practices to limit soil disturbance and therefore the potential persistence of new wellsite disturbances. These practices appear to have positive benefits on vegetation regeneration, but benefit on songbirds has not been assessed (Frerichs et al. 2017). Failure of existing wellsites to regenerate in the long term could result in less habitat for species which depend on a specific successional stage, and benefit generalists or species which prefer early successional habitats (Thomas et al. 2014, Mahon et al. 2016). However, these impacts should be assessed on a broader scale, to determine if a threshold is met at which songbirds are impacted by potential slow recovery of these sites, or if they are able to adjust space use in relation to these small disturbances. Insufficient recovery has occurred since reclamation of most wellsites in the boreal forest to determine when wellsites are no longer distinct from mature forest with

regards to different ecosystem components. However, current wellsite reclamation criteria results in regeneration of vegetation to tree heights, facilitating use of wellsites by the songbird community in upland deciduous forests. Songbirds utilized reclaimed wellsites at various stages of regeneration in upland deciduous forests. With increasing regeneration of woody plants, especially canopy cover (vegetation > 5 m in height) songbird community similarity between the wellsite and adjacent forest, and Ovenbird space use near reclaimed wellsites increased. In addition to vegetation recovery, songbirds should be measured directly, because behaviour of individual birds also played a role in their response to wellsite reclamation efforts.

Understanding the local scale impact of these disturbances requires metrics which determine where birds sing in relation to wellsite footprint itself. A standard bioacoustic approach is unsuitable to collect this information, and will inflate estimates of which species sing from wellsite footprints themselves, due to detection of species which are far beyond the wellsite edge. Appropriate data can be provided by an ALS, spot-mapping, or territory mapping. Preferably metrics which account for relative use of the wellsite by individual birds in comparison to a reference condition are used. The use of an ALS provided high quality data of songbird communities, but was not very efficient compared to conventional methods. Currently, use of an ALS is infeasible for applied approaches like reclamation monitoring given time and cost associated with this method. However, this technology is only expected to improve with development of sensor arrays, and improved automated species recognition algorithms which will expedite collection and processing of acoustic data.

Current reclamation criteria do not directly promote recovery of vegetation beyond 5 m in height in terms of when a reclamation certificate is issued, although this level of regeneration was observed within the study region (Environment and Sustainable Resource Development 2013). The time frame over which this level of recovery occurs, and the proportion of wellsites at different stages of regeneration in different habitat types requires further investigation. How this recovery compares to other types of disturbance, such as forestry and fire should be assessed as alternative reference conditions to a mature forest. Finally, this study focused on local scale use and

avoidance of these features and did not provide information on the ability of songbirds to adapt to these disturbances on a broader spatial scale as demonstrated in relation to similar disturbances.

The benefits of wellsite reclamation on songbirds in the boreal forest of Alberta was not assessed previously. Methodology used to measure songbird response to these small disturbances requires adequate spatial resolution to determine where songbirds are detected in relation to these disturbances. Reclamation has resulted in recovery of woody vegetation, which promotes use of wellsites by songbird communities.

Understanding this relationship is important, given the abundance of wellsites, frequent use of songbirds to assess ecosystem state, and importance of the boreal forest as breeding habitat for songbirds.

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Appendix 1. Acoustic Location System

Introduction

For the purpose of this thesis, an ‘acoustic location system’ (ALS) refers to an array of microphones which can be used to estimate the location of a signal using time of arrival differences determined from cross correlations between channels (McGregor et al. 1997). The term ‘localization’ will be used to describe the process used to locate birds using the ALS (Blumstein et al. 2011). The purpose of this appendix is to provide a brief overview of methodological considerations when using localization, and the workflow for localization used throughout this thesis (Fig. A1.1). My recommendations apply to songbird species in terrestrial environments, as ALS should be designed specifically to species of interest, and habitat type (Wilson et al. 2013).

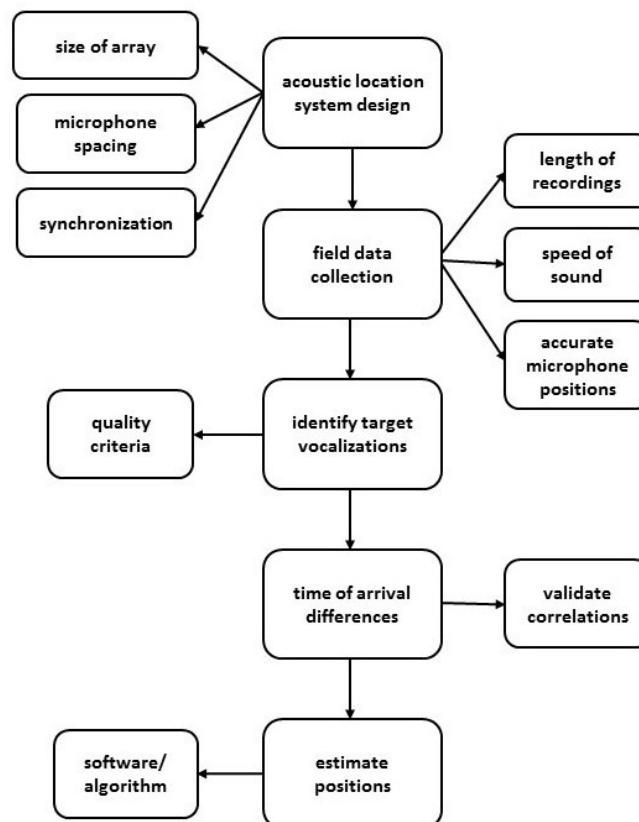


Figure A1.1. Overview of workflow and considerations for use of an acoustic location system.

Field Data Collection

Most ALS used to study songbirds utilize some form of ‘cross correlation’ (spectrogram or waveform) to determine time of arrival differences between channels (McGregor et al. 1997, Campbell and Francis 2012, Mennill et al. 2012, Wilson et al. 2013). Cross correlation compares two signals to determine the time offset when they are most similar in terms of frequency and amplitude. This time offset is used as the time of arrival difference between microphones for subsequent calculations. High quality vocalizations must be detected on multiple channels (≥ 3), with high enough amplitude that the cross correlations will yield accurate time offsets. Most songbird vocalizations degrade rapidly, requiring microphones to be densely spaced within an ALS (Mennill et al. 2012). Similarly, the ALS should be constructed over areas where sufficient vocalizations will be detected, as error in localization increases with distance of the target signal from the centre of the array (McGregor et al. 1997, Wilson et al. 2013). Arrays are ideally used in environments where masking by biotic and abiotic noise is limited so that sufficient target vocalizations are available for localization (McGregor et al. 1997, Bower and Clark 2005). For two dimensional arrays, error also increases with vertical displacement between target signals and the array. This means that the height at which microphones are placed needs to be consistent and should be evaluated for each circumstance (Wilson et al. 2013). Accurate microphone locations are required, often through use of a mapping or survey grade GPS. Position estimates from these GPS can be challenging to obtain in different environmental conditions, such as dense canopy cover (Mennill et al. 2006). The ability to obtain accurate microphone positions should be confirmed prior to data collection with the ALS.

Recordings must be time synchronized, and of high enough quality to obtain accurate time of arrival differences from cross correlations (Mennill et al. 2012). Previous studies have constructed ALS using microphones wired to a central recording device (Mennill et al. 2006). Such devices are more difficult to place in the field but are very accurate temporally. Commercially available, wireless recording units (e.g. Wildlife Acoustics products) have also been used successfully to construct ALS, in which recordings are synchronized through use of a GPS clock (Mennill et al. 2012, Wilson et al. 2013). Finally, factors which influence attenuation (i.e. temperature, humidity, barometric

pressure) should be collected to account for in calculation of speed of sound for data processing (Wilson et al. 2013).

The length of individual recordings, and overall time recorded, must be considered in terms of file storage, and constraints of computer used during processing. Ideally, the ALS is small enough (i.e. approximately 8 or fewer microphones) that all channels can be combined and visualized simultaneously during data processing. For large arrays, this is not feasible, and subsets of the array will have to be processed sequentially. This may result in challenges with double counting of individuals that are detected on multiple segments of the array.

The error associated with a given array should be assessed prior to use (Wilson et al. 2013). Localization is not always feasible to perform based on environmental conditions (i.e. topography, vegetation density, abiotic noise) and species of interest (i.e. song properties, amplitude, potential for masking by other biotic sounds; Wilson et al. 2013, Araya-Salas et al. 2017). Error can be evaluated using a playback speaker of known location, broadcasting vocalizations of similar amplitude, and from similar locations used by species of interest (Mennill et al. 2012, Wilson et al. 2013). Alternatively, live birds could be used with an observer present to collect locations and time stamps of vocalizations. Data from experiments should be used to inform feasibility, and optimum settings for species of interest.

The ALS in this study was constructed from GPS enabled Wildlife Acoustic SM3 units equipped with external SMM-A1 microphones. At each site, microphones ($n = 25$) were deployed at a height of 1.5 m, and spaced an average of 33.9 ± 0.52 m apart in a 5×5 grid. Use of external cables is not recommended, as they were more prone to wildlife damage than stand alone recording units, although such cables were significantly cheaper. Microphone positions were determined using a Hemisphere S320 survey GPS, set to a horizontal accuracy of ± 3.0 cm. When not possible to obtain locations using the survey GPS due to dense canopy, positions were determined from the mounted Garmin 16x GPS attached to the recording unit, which is not recommended as accuracy was lower (accuracy 3.28 ± 0.25 m). Four hours of data (05:00AM – 09:00AM) were

collected daily, in 29 minute long segments, separated by one minute segments to allow files to write properly. Recordings were time synchronized to ± 1 milliseconds through the GPS clock of the Garmin 16x. A 48000 Hz sample rate was used, and recordings were collected in the proprietary Wildlife Acoustics compressed WAC format.

Assessing accuracy

Error was evaluated using playback experiments. Songs of 85 dB amplitude were broadcast from a playback speaker at various locations in relation to an array of four microphones spaced 35, 37.5, and 50 m apart. Playbacks contained vocalizations from a subset of the following species: Alder Flycatcher (*Empidonax alnorum*), American Redstart (*Setophaga ruticilla*), American Robin (*Turdus migratorius*), Black-and-White Warbler (*Mniotilta varia*), Bay-breasted Warbler (*Setophaga castanea*), Canada Warbler (*Cardellina canadensis*), Chipping Sparrow (*Spizella passerina*), Clay-coloured Sparrow (*Spizella pallida*), Connecticut Warbler (*Oporornis agilis*), Common Yellowthroat (*Geothlypis trichas*), Dark-eyed Junco (*Junco hyemalis*), Hermit Thrush (*Catharus guttatus*), Least Flycatcher (*Empidonax minimus*), Lincoln's Sparrow (*Melospiza lincolnii*), Magnolia Warbler (*Setophaga magnolia*), Mourning Warbler (*Geothlypis philadelphia*), Ovenbird (*Seiurus aurocapilla*), Red-eyed Vireo (*Vireo olivaceus*), Swainson's Thrush (*Catharus ustulatus*), Tennessee Warbler (*Oreothlypis peregrina*), Winter Wren (*Troglodytes hiemalis*), White-throated Sparrow (*Zonotrichia albicollis*), Yellow Warbler (*Setophaga petechia*), and Yellow-rumped Warbler (*Setophaga coronata*). Vocalizations were localized using the workflow outlined below under 'Data Processing'. Variations of this experiment were performed to account for slight differences in array design used throughout this thesis (Table A1.1).

Table A1.1. Error in localization associated with different study designs for events within microphone arrays. ‘Survey’ under Microphone Positions Estimates indicates the Hemisphere S320 survey GPS, and ‘Mounted’ indicates mounted Garmin 16x GPS attached to the recording unit. ‘All’ under Species indicates a subset (14-21 species) of the species listed in text.

Microphone Spacing (m)	Microphone Position Estimates	Species	Mean Error (m)	95% Confidence Interval (m)
35	Survey	All	2.97	±0.37
35	Survey	Ovenbird	1.88	±0.41
37.5	Mounted	All	7.05	±0.84
37.5	Mounted	Ovenbird	6.06	±2.21
50	Mounted	All	11.53	±1.78
50	Mounted	Ovenbird	11.28	±3.80

Data Processing

Generally, multichannel recordings are assembled and scanned (manually, or using automated species recognition) to locate vocalizations which meet predetermined quality criteria. These criteria must be developed on a case by case basis in error experiments, but possible considerations include relative amplitude of signal, minimum number of channels signal must be detected on, and amount of masking by biotic and abiotic noise that is acceptable. Next, the time of arrival differences of vocalizations to each channel in the array are determined. Cross correlations are verified, and spurious correlations where signals on selected channels are misaligned, due to low quality signals or masking may be removed. Finally, the time of arrival differences are used to calculate position estimates under a known speed of sound. Publicly available software to perform localization includes SoundFinder and XBAT (Cortopassi 2006, Wilson et al. 2013). These programs provide similar levels of accuracy, however XBAT is more time efficient. SoundFinder is an open source program that can be used in the program R, or spreadsheet software. Before using SoundFinder, time of arrival differences must be determined in external software, such as Raven Pro (Bioacoustics Research Program 2014). This involves clipping individual signals from longer recordings prior to localization. Similar calculations to those used by GPS technology are then used to estimate positions based on time of arrival differences under a known speed of sound and microphone positions (Wilson et al. 2013). An alternative approach is the CSE

location algorithm (version 2.3) in XBAT, which runs in the Matlab environment (Cortopassi 2006, Figueroa and Robbins 2007, MathWorks Inc. 2014). This program automates estimation of time of arrival differences through cross correlation, and only requires selection of vocalizations to be localized on a reference channel (Cortopassi 2006, Campbell & Francis 2012). The time of arrival differences of a signal to different channels in the ALS are determined using pairwise cross correlations between channels. These time of arrival differences are used to calculate the location of the signal under a known speed of sound and microphone locations (Cortopassi 2006). Each annotated vocalization was localized using a minimum of four channels to estimate positions, and a search radius of 100 m (Campbell and Francis 2012).

For the purposes of this thesis, recordings that did not maintain synchronization, or failed due to wildlife damage were first removed from processing. Arrays were not processed at a given time if there were issues with four or more channels. Three hours of dawn chorus (05:30-08:30 AM), when songbirds are mostly likely to perform territorial vocalizations, were selected for processing at each site. Recording files were converted to wav format and spectrograms were visualized using a 512 FFT hamming window in the program Audacity 2.1.3 (Audacity Team 2017). All files were grouped into four channel tracks based on spatial proximity, and scanned visually to locate songbirds performing territorial vocalizations within the microphone array. This was done for several reasons. First, it is impractical to scan 25 channels simultaneously on a single computer monitor. Further, songs were often only detected with sufficient amplitude for analysis on ~4 recordings. Given that dawn chorus is acoustically complex at my study sites, multiple individuals would sing simultaneously. If all channels are included, some of which contain concurrent sounds other than the signal of interest, they may be mistaken as the target signal during cross correlation, resulting in incorrect estimates of time of arrival differences (Fig. A1.2). It was helpful to sketch estimated positions of birds within the ALS to avoid double counting birds across multiple four channel segments.

Vocalizations were included in further analyses if the entire song was detected clearly on four microphones, and did not coincide with other songs of greater amplitude, or overlap with any fainter singing events for 25% of the duration of the target vocalization on any channel. The multichannel track which contained the strongest signal for each

identified bird was assembled in Audacity and used in subsequent analyses. The proper multitrack to use for localization can generally be estimated based on relative amplitude between channels (Fig. A1.2). As not all recordings will be utilized, it is recommended only to assemble recordings that will be utilized in further analyses.

Temperature data from the nearest Environment and Climate Change Canada weather station were summarized for each research site, and used for estimation of speed of sound (Wilson et al. 2013, Environment and Climate Change Canada 2017). The multichannel tracks, microphone positions, and speed of sound were imported into XBAT for analysis. Each vocalization that met the criteria mentioned earlier was annotated. The CSE location algorithm (version 2.3) was used for acoustic localization (Cortopassi 2006). The following is an outline of the workflow used for the CSE location algorithm (version 2.3) in XBAT:

1. Import multichannel recordings for analysis into XBAT.
2. Add attributes (speed of sound and sensor geometry) for each multichannel recording.
3. Apply the selected spectrogram window settings (i.e. Hamming 512 window).
4. Create logs for signals of interest.
5. Annotate each vocalization on single reference channel (the channel with the strongest signal). Draw the smallest annotation that can contain the vocalization as possible, and log the event. Quality scores and tags can be added to each vocalization.
6. Localize the individuals using the CSE location algorithm, and selected settings for correlation peak threshold (0), minimum and maximum channels (4), search radius (100m), and termination criterion (500m; Campbell and Francis 2012).
7. Validate cross correlations for each event to ensure algorithm has identified the correct signal on each channel (Fig. A1.2)
8. Export a CSV file of the log containing coordinates of the selected vocalizations.

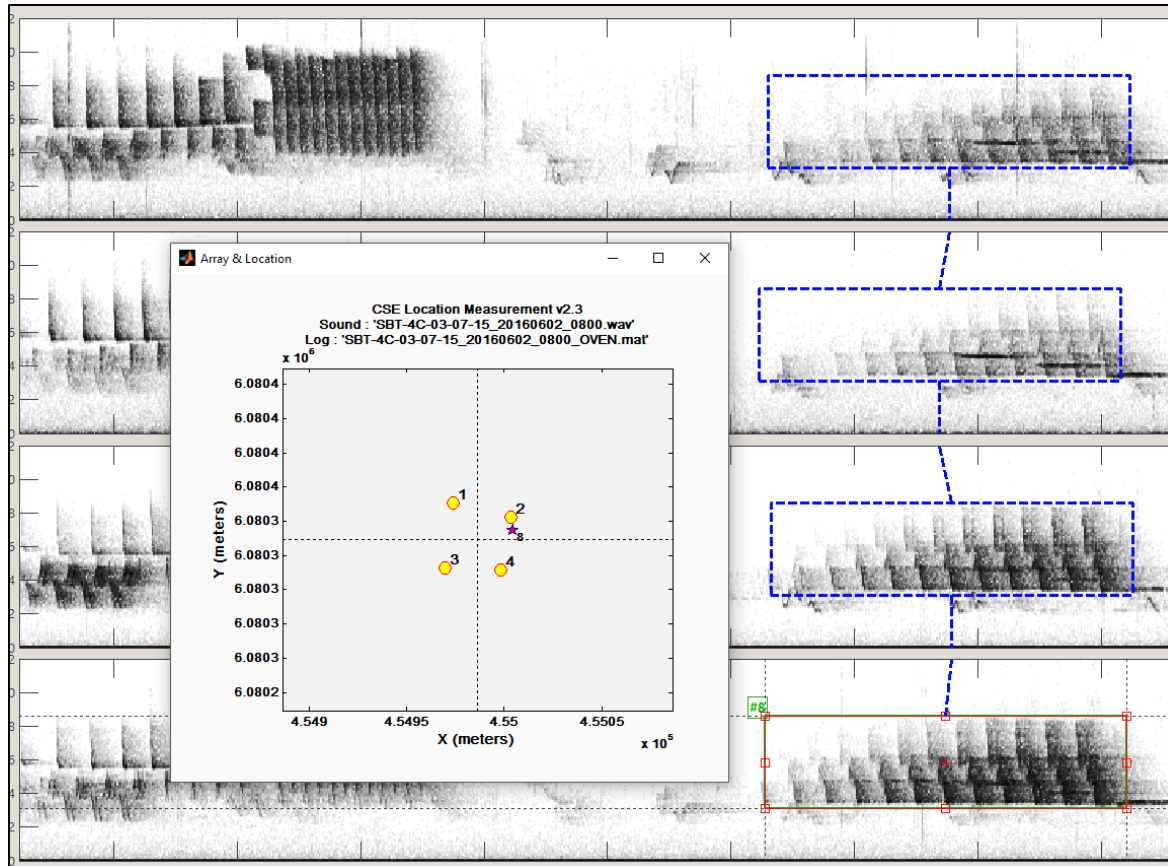


Figure A1.2. Example of spurious cross correlation due to masking. Here the Ovenbird appears closest to the fourth, followed by third channel. However, the estimated singing location is closest to channel two due to masking by a White-throated Sparrow.

Spatial locations were validated to determine if they were closer to the channel with the greatest amplitude than to other channels used in localization. Observations were discarded if not closest to the channel with the greatest amplitude, however this occurred for only a few events, and mainly when obstructed by another vocalization, resulting in misalignment of correlation peaks. The proportion of vocalizations which cannot be localized due to masking should be documented for each study. If singing locations did not occur within the multichannel track (resulting in positions outside the set of four microphones) but were still within the microphone array, they were rerun in the correct multichannel track based on the estimated locations to limit error associated with distance from the centre of the array. Finally, I recommend storing spatial

locations associated with vocalizations in a database with hierarchical structure, where singing events are nested under individual birds.

Conclusion

Localization provides high quality data to answer questions on bird behavior and habitat use (Taylor et al. 2016). Major considerations when using an ALS include inter-microphone distances, size of array/number of channels, and ability to obtain accurate microphone positions. Feasibility of an ALS should be determined prior to its use which can vary based on habitat, and vocal behavior of the species of interest. This technology is only expected to improve with development of sensor arrays, and improved automated species recognition algorithms (Taylor et al. 2016). Pairing these data with high resolution remote sensing data, behavioural observations, and conventional estimates of bird space use (e.g. spot mapping, telemetry) will increasingly allow us to answer questions on fine scale habitat use in birds more efficiently and accurately than ever before.

Appendix 2. Wellsite Metadata

I collected data on wellsites from the Alberta Energy Regulator database of Alberta wellsites (Table A2.1; Alberta Energy Regulator 2017). Survey diagrams provided by the program Abadata were used to determine size, orientation, and centre of wellsite footprints (Abacus Datagraphics Limited 2015).

Table A2.1. Wellsite metadata for sites used throughout thesis. Of these sites, 19 were used in Chapter 2, and 13 in Chapter 3.

Wellsite License	Latitude	Longitude	Reclamation Date	Development Date
39993	54.868	-111.702	1972	1971
40956	54.826	-111.695	1972	1971
245451	55.119	-111.961	2006	2000
85030	54.992	-111.745	1999	1980
90079	55.017	-111.750	2006	1981
250726	54.958	-111.852	2011	2001
48830	55.058	-111.626	1998	1974
79384	55.001	-111.458	1999	1979
89742	55.013	-111.462	2002	1981
169517	54.825	-111.670	1999	1994
245270	55.120	-111.950	2005	2000
31619	55.059	-111.719	1967	1967
251242	54.980	-111.850	2006	2001
174962	54.929	-111.579	1998	1995
53015	55.059	-111.768	2002	1975
119447	54.949	-111.597	1989	1985
264868	55.057	-112.060	2008	2002
31953	55.238	-114.447	1968	1967
84884	55.421	-114.626	1985	1980
148736	55.181	-114.007	1996	1991