

**The habitat association of bats in the South
Okanagan Valley, British Columbia, Canada:
Radar-acoustic surveys to assess the use of
vineyards by insectivorous bats
(*Vespertilionidae*)**

by

Marie Madeleine Edna Danielle Dagenais

B.Sc., University of Northern British Columbia, 2004

Thesis Submitted in Partial Fulfillment of the
Requirements for the Degree of
Master of Science

in the
Department of Biological Sciences
Faculty of Science

© **Danielle Dagenais 2016**

SIMON FRASER UNIVERSITY

Spring 2016

All rights reserved.

However, in accordance with the *Copyright Act of Canada*, this work may be reproduced, without authorization, under the conditions for "Fair Dealing." Therefore, limited reproduction of this work for the purposes of private study, research, criticism, review and news reporting is likely to be in accordance with the law, particularly if cited appropriately.

Approval

Name: Marie Madeleine Edna Danielle Dagenais

Degree: Master of Science (Biology)

Title of Thesis: *The habitat association of bats in the South Okanagan Valley, British Columbia, Canada: Radar-acoustic surveys to assess the use of vineyards by insectivorous bats (Vespertilionidae)*

Examining Committee: Chair: Lance Lesack
Professor

Ronald Ydenberg
Senior Supervisor
Professor

Rhonda Millikin
Supervisor
Adjunct Professor

David Green
Supervisor
Professor

Ken Otter
External Examiner
Professor
Ecosystem Science & Management Program
Natural Resources and Environmental Studies
University of Northern British Columbia

Date Defended/Approved: April 15, 2016

Ethics Statement

The author, whose name appears on the title page of this work, has obtained, for the research described in this work, either:

- a. human research ethics approval from the Simon Fraser University Office of Research Ethics

or

- b. advance approval of the animal care protocol from the University Animal Care Committee of Simon Fraser University

or has conducted the research

- c. as a co-investigator, collaborator, or research assistant in a research project approved in advance.

A copy of the approval letter has been filed with the Theses Office of the University Library at the time of submission of this thesis or project.

The original application for approval and letter of approval are filed with the relevant offices. Inquiries may be directed to those authorities.

Simon Fraser University Library
Burnaby, British Columbia, Canada

Update Spring 2016

Abstract

British Columbia's South Okanagan has an expanding wine industry and supports the greatest diversity of bats in Canada. I surveyed bat activity in six matched pairs of vineyards and adjacent natural sagebrush habitats during the summer of 2013 using a unique radar-acoustic system, which I described and evaluated. By evaluating the characteristics of radar tracks and combining radar and acoustic data, I was able to compare bat activity over the habitats. Target parameters (height, speed, and relative size measured as Signal-to-Noise Ratio) had similar distributions in both habitats. There was no statistical difference between habitats in mean target track length per unit area or in the mean number of acoustic 'individual bat passes', nor did these measures differ between surveys in early (bat pregnancy and parturition), middle (lactation) and late summer (pup fledging). My results suggest that the amount of bat activity over vineyards and natural habitats is similar; however the use of habitat by bat species differs.

Keywords: insectivorous bats; mobile surveillance radar; vineyards; shrub-steppe and sagebrush habitat; acoustic monitoring; fragmented landscape

To my husband and son, Corey
and Isaac, thank you for all of
your patience, understanding, help,
motivation and love along the way.

Acknowledgements

I would like start by thanking Rhonda Millikin, CEO and President of EchoTrack Inc., who made this study possible with funding and equipment. Rhonda was not only my corporate sponsor but also an extraordinary supervisor. She provided with me the essential training, education, and guidance needed to understand radar use for biological studies. Thank you for taking me under your wing and teaching me all that you know. She also went out of her way, using her contacts, to ensure I had training in bat acoustic analysis and Python Coding. Through Rhonda I was introduced to Doug Burles.

Doug is an exceptional biologist with a passion for bats. Over the years Doug became my mentor and good friend. He has been there for me since the beginning and provided me with a great amount of training, support, and guidance. Doug introduced me to the beautiful creatures of the night that I will forever hold dear in my heart. Thank you Doug for everything, I could not have done this without you. I would also like to thank Doug for introducing me to Dr. Mark Brigham. Mark thank you so much for helping me with my thesis and your advice along the way.

Dr Ron Ydenberg, my senior supervisor, thank you for your academic and personal support, as well as financial support during my masters. Your guidance and support was greatly appreciated in my weakened and stressful moments. Thank you for not given up on me and for helping me stay focused to the end. And Dr. David Green, my third committee member, thank you for your thorough review of my chapters, and guidance along the way. CWE staff and personnel, especially Philina English, thank you for your help and support. Connie Smith a big thank you for helping me navigate through the administrative components and permitting, as well as for acting as my safety coordinator during my field season. Marlene Nguyen, you are an incredible Graduate Program Assistant. Thanks for keeping me organized and always making my smile.

To the Nk'Mip (Osoyoos) Indian Band, private landowners, wineries, viticulturists, Nature Trust BC, BC Ministry of Environment, and BC Ministry of Forests, Lands and Natural Resources, I could not have done this work without your approval. Thank you for

allowing me to conduct my research on your property and within your vineyards. Thank you for also providing me with weather data from any onsite weather stations, answering all of my questions regarding operations and for letting me use your facilities. This project would also not have been possible without financial support from National Sciences and Engineering Council of Canada, the Centre for Wildlife Ecology, and Simon Fraser University.

A huge thank you to Carl Schwarz, Jack Davis, and Shivanand Balram for helping with statistics and GIS. It seemed like I bombarded you all with so many questions during my analysis, but you always found time for me and sat there with great patience with a smile on your faces; you all saved me much frustration and grey hairs. I would also like to thank Jess Holla and Christopher Scarp for introducing me to the basics of GIS. And Andre Iwanchuk and BC Ministry of Agriculture and Lands for providing me with the cadastre data required for my project.

A special thanks to all my volunteers, friends and family that came out to help me trap bats during my field season and to those who also providing me with photos: Christianne Aikins, Mike Baxter, Sara Bunge, Tim Forrester, Catherine Grima, Dan Grima, Faith Henrichsen, James Henrichsen, Joe Lariviere, Natasha Lukey, Megan McAndrew, Adam Patterson, Roxanne Snook, Colin Starkevich, and Amanda Turner. These trapping events would not have been possible without the help, equipment, training, experience, and generous time commitments of Mike Sarell, Doug Burles, and Allison Haney.

I would also like thank EchoTrack staff, Allan, Tom, and Dick, for their patience in answering all of my questions, and providing the changes and software updates needed for my analysis. Hugh Stimson and Ryan Daw thank you for introducing me and helping me with Python Coding and kml files. Thomas Lowery and Dr. Gerhard Gries thank you for your knowledge regarding nocturnal insects. The Oliver Fire Department and Tourism Centre you will not be forgotten. Thank you so much for making my field season more enjoyable and refreshing by letting me use your facilities, as well as letting me plug in and use your power to compress my acoustic data in the field.

Lastly, but most importantly, to my family, in-laws and close friends, thank you all for your love and support. To my mother-in-law, Helene, I am forever grateful for your all of your help and care for Isaac. The time you guys spent together is so precious and priceless. Thank you, Nannie, for going out of your way to help out. Corey, my love and best friend, you helped me physically and emotionally in and out of the field and provided me with technical assistance along the way. You stood beside me at every hurdle and helped me persevere. Thanks for putting up with me and my masters for the last four years. We have been through a lot, but this has only made our love stronger. Isaac thank you for being such a fun distraction, giving me breaks when needed. I first introduced you to bats while in my tummy, and brought you trapping before your first birthday. I hope your passion for bats and the outdoors will continue for a lifetime.

Table of Contents

Approval.....	ii
Ethics Statement.....	iii
Abstract.....	iv
Dedication.....	v
Acknowledgements.....	vi
Table of Contents.....	ix
List of Tables.....	xi
List of Figures.....	xii
List of Acronyms.....	xv
Glossary.....	xvi

Chapter 1. Introduction: Agriculture and bats.....	1
1.1. Background information.....	5
1.1.1. Study species.....	5
1.1.1.1. South Okanagan bat species.....	7
1.1.2. Study area.....	8
1.1.3. The Bunchgrass Biogeoclimatic Zone.....	8
1.1.4. Okanagan vineyards.....	9
1.1.5. Study sites.....	12
1.2. Thesis outline.....	13

Chapter 2. A review of radar and the EchoTrack Radar-Acoustic Airborne Wildlife Surveillance System for the study of bats in vineyards.....	15
2.1. Radar use for biological studies.....	15
2.2. The EchoTrack Radar-Acoustic Airborne Wildlife Surveillance System.....	17
2.2.1. Operation of the EchoTrack System.....	20
2.3. Radar basics.....	24
2.4. Target detection.....	25
2.5. Radar challenges and limitations.....	28
2.5.1. Radar location: Clutter and noise.....	30
2.5.2. Radar location: Undulating terrain and zero-detection zones.....	31
2.5.3. Target range.....	33
2.5.4. Target reflection and species identification.....	37
2.5.4.1. Study specifics: Species identification.....	38
2.5.5. Interference.....	42
2.5.6. Weather.....	43
2.6. Study challenges associated with the acoustic array.....	45
2.6.1. Undulating terrain.....	46
2.6.2. Vegetative growth and saturated bat calls.....	47
2.7. Recommendations for future studies and system improvements.....	50
2.7.1. Site reconnaissance.....	51
2.7.2. Acoustic arrays.....	51
2.7.3. Additional sampling.....	52
2.7.4. Radar-acoustic fusion.....	52
2.7.5. Onboard weather station.....	52

2.7.6. Quality of the bat calls.....	53
2.7.7. EchoTrack omni-directional bat sensor testing and validation	53
2.8. Conclusion	54

Chapter 3. Comparing bat activity over vineyards and natural habitat in the South Okanagan Valley, British Columbia 55

3.1. Methods	59
3.1.1. Study design and sampling regime	59
3.1.2. Radar track analysis.....	60
3.1.3. Acoustic analysis	63
3.1.4. Bat trapping	66
3.1.5. Statistical analysis.....	67
3.2. Results.....	68
3.2.1. Radar tracks	68
3.2.2. Acoustic analysis	75
3.2.2.1. Species richness: Bat frequency groups.....	76
3.2.3. A comparison of radar and acoustic data	79
3.2.4. Habitat features and bat use	82
3.2.5. Inclement weather.....	83
3.3. Discussion.....	85
3.4. Further research and recommendations	92
3.5. Conclusion	93

References 95

Peer Reviewed Journals, Books, and Book Chapters.....	95
Theses	104
Documents, Technical Reports, and Websites	104
Personal Communications and BC Bat Biologists	108
Appendix A. South Okanagan bat species	109
Appendix B. Vineyard insects associated with crop damage	111
Appendix C. Commonly used radar	114
Appendix D. Sample of EchoTrack’s file outlining the radar-defined tracks and their parameters	115
Appendix E. Site locations and project data.....	116
Appendix F. Echolocation calls of the South Okanagan bat species	117

List of Tables

Table 2.1.	A comparison of the EchoTrack’s radar parameters to other surveillance radar used for biological studies (Richardson 1976; Gudmundsson 1993; Mabee et al. 2006).	26
Table 2.2.	Resolution cell dimensions for the EchoTrack System.	35
Table 2.3.	Radar-cross section values defined for birds and insects taken from Riley 1985, Vaughn 1985, and Martin and Shapiro 2006.....	37
Table 3.1.	A list of bat species associated with the four frequency groups identified by minimum frequency of the bat’s call. These categories are based on unpublished data obtained from BC bat biologists (D. Burles and C. Lausen) and a BC bat study (Sarell et al. 2011).	65
Table 3.2.	Summary of radar analysis showing the amount of habitat surveyed, number and length of tracks analyzed and summary statistics of mean track parameters.	69
Table 3.3.	Summary of the acoustic analysis showing the number of Individual Bat Passes recorded and the number of buzzes detected within the vineyard and natural plots.	76
Table 3.4.	Number of Individual Bat Passes recorded in vineyard and natural plots based on the call’s minimum frequency.	78
Table 3.5.	Number of species groups recorded in each of the frequency groups during each sampling interval.	79
Table 3.6.	Data collected during thunderstorms.	83

List of Figures

Figure 1.1.	Map of the South Okanagan Valley showing my study area that extends from Okanagan Falls, BC to Osoyoos, BC. My study sites are indicated by the red dots.....	14
Figure 2.1.	Screen capture of the radar imagery video displayed through EchoTrack's processing phase showing all targets, including terrain and vegetation (white dots) detected within the first few minutes of sampling at one of my sites. The crosshair shows the location of the radar and the circle denotes a 2 km radius.....	19
Figure 2.2.	Screen capture of the radar imagery video displayed through EchoTrack's processing phase showing radar-defined tracks (white lines) detected during one sampling interval (14 minutes) at one of my sites. The crosshair shows the location of the radar and the circle denotes a 2 km radius.....	20
Figure 2.3.	Photo showing the setup of the EchoTrack System with the use of both acoustic arrays positioned ~90 m perpendicular to the trailer. The bird microphones are shown by red circles and the EchoTrack omni-directional bat sensors are shown with the blue circles.....	21
Figure 2.4.	Overview of the bat acoustic array setup in one of my natural plots. The image shows the unique design of the EchoTrack omni-directional bat sensors and the configuration of acoustic array used for bat sampling.....	22
Figure 2.5.	The EchoTrack radar beams and side lobes for a 2 km sampling radius shown for the radar's location at Site 1; image provided by EchoTrack Inc. Blue indicates the location of the main beam, whereas yellow shows the top and bottom sidelobes.	28
Figure 2.6.	An example of the zero-detection zones (red hatched areas) that were not surveyed for bats at one of my sites due to obstructions from the landscape and buildings. The position of the radar is shown by the star and the circle denotes the 1 km sampling radius.	33
Figure 2.7.	Image showing the vertical separation of multiple airborne animals within the same resolution cell that were identified as separate targets dues to their height. This image is from another EchoTrack project and shows three sets of overlapping flights (red arrows).....	36

Figure 2.8.	Interference seen along the frost tower cut line causing a break in the radar tracks (no track trajectories seen within burgundy rectangle); note no interference occurred at the frost tower north of the radar. Imagery was created by importing kml files into GoogleEarth and shows the location of the radar (red circle), microphone array (V), radar tracks (yellow lines), and frost towers (blue rectangles).	43
Figure 2.9.	An example of poor placement of the microphone array imposed by site topography on trailer placement (red circles) resulting in very few tracks and bat calls detected above the acoustic array (V) compared with the adjacent areas having higher track density.	47
Figure 2.10.	Spectrogram showing saturated calls recorded from multiple 25-35 kHz bats and an associated buzz (black circle).	49
Figure 2.11.	Spectrogram showing saturated calls (within the black circles) recorded from a 25-35 kHz bat during a thunderstorm.	50
Figure 3.1.	All radar tracks detected during one night of sampling at Site 1 projected in two-dimension over landuse classes.	62
Figure 3.2.	The intersected segments of radar tracks detected over vineyard habitat during one night of sampling at Site 1.	63
Figure 3.3.	The distribution of mean wind adjusted target speed for vineyard and natural tracks.	70
Figure 3.4.	The height distribution for vineyard and natural tracks, where height corresponds with the target height assigned to the first track point. Height is relative to the antenna, which sits 2.43 m above the ground.	71
Figure 3.5.	The distribution of target SNR values for vineyard and natural tracks.	72
Figure 3.6.	(Preceding pages) Rose graphs for each site showing the proportion of mean track direction for all tracks detected (irrespective of habitat) 45 minutes after sunset and 60 minutes prior to sunrise.	75
Figure 3.7.	Mean natural log (tracks/min+1) calculated for each sampling interval showing nocturnal activity detected throughout the night. Error bars represent 95% confidence intervals. The x-axis corresponds with my sampling intervals and represents minutes after sunset or minutes prior to sunrise.	81

Figure 3.8. Mean natural log (IBP/min+1) calculated for each sampling interval showing nocturnal activity detected throughout the night. Error bars represent 95% confidence intervals. The x-axis corresponds with my sampling intervals and represents minutes after sunset or minutes prior to sunrise. 82

Figure 3.9. Proportion of Individual Bat Passes (squares) and radar tracks (triangles) detected during each night sampled at Sites 3, 4, and 5 that sampled bat activity during thunderstorms. Nights with thunderstorms are denoted by the larger data points. 84

List of Acronyms

EC	Environment Canada
GIS	Geographic Information System, such as ArcMap.
IBP	Individual Bat Pass
IPM	Integrated Pest Management
NEXRAD	NEXt Generation RADar
RCS	Radar-cross Section
SI	Sampling Interval
SNR	Signal-to-Noise Ratio
wrt	with regards to

Glossary

Arthropod	Arthropods are animals having an exoskeleton, segmented bodies and jointed appendages, and include insects, spiders, centipedes, and millipedes. For this thesis insects and arthropods are used interchangeably to represent prey eaten by bats.
Bat call / Call	A bat call is one sonogram in a series that shows the frequencies that a bat uses to echolocate.
Biogeoclimatic Zone	A classification system designed by the BC Ministry of Forests that delineates the landscape into 14 areas with similar climate and dominant vegetation types.
Bioscatter	Radar echoes created from radio wave scatter from a biological aerial organism such as birds, arthropods, and bats.
Bunchgrass Biogeoclimatic Zone	Regions in British Columbia that have a dry, hot climate, limited precipitation, and are predominantly vegetated with grasses, shrub-steppe species, Ponderosa pine and/or Douglas fir.
Cane	Vertically growing woody shoots of the grape vine that extends up from the cordon.
Clutter	Clutter consists of any radar echo that interferes with the detection and observation of the desired target and includes echoes from the landscape elements, vegetation, anthropogenic features, and bioscatter. It is generally associated with objects near the ground surface, where a large amount of reflection persists and masks target detection.
Cordon	The horizontal extensions of the grape vine that run along a wire that support the canes.
Crepuscular period	The crepuscular period is associated with twilight and is defined as the sun's position relative to the horizon; however for this thesis, the Crepuscular Period is defined as a time period and represents the 45 minute period following sunset and the 45 minute period prior to sunrise. The terms dusk and dawn are used to represent these periods.
Day roost	An area where bats rest during day light hours. Bats are generally inactive in their day roosts; however female bats may tend to their pups during this time.
Direction (wrt radar tracks)	The mean relative direction of the track, in relation to where it originated from and ended.
Echo	The energy returned from a target to the receiver that identifies and displays the target on the radar screen.
Feeding roost	An area where bats consume their prey.

Generalist bat species	Bat species that prey on various types and sizes of arthropods. Generalists are often associated with various habitat types.
Granite gneiss	A common form of metamorphic rock originating from igneous rock.
Hybrid grapes	The crossing of two or more grape varieties of different species (<i>Vitis</i> spp).
Integrated Pest Management	An environmentally sensitive practice used to manage insects that feed on and cause damage to crops. The practice focuses on natural controls and aims to reduce chemical use.
Interference	The suppression of target detection from any object that emits a signal and interferes with the operation of the radar. This includes the operational noise generated by the radar itself that results in minimal interference.
kml	A kml (keyhole markup language) file contains a set of data specification for displaying geographical information. It was created for use in GoogleEarth, but can be incorporated into 2-dimensional or 3-dimensional mapping programs.
Maternity colony roost	The day roost where female bats congregate to bear and raise their pups. Maternity colony roosts may be located in a cliff, under rocks, tress, buildings, or bat houses. In Canada, maternity colonies may consist of a few bats to thousands of bats.
Mobile radar	A portable radar system consisting of an antenna, generator, computer and software. The antenna acts as both the transmitter and receiver.
Natural plot	An area within my site that represents naturally occurring vegetation of the Bunchgrass Biogeoclimatic Zone such as grasses and/or shrub-steppe species where an acoustic array was positioned. This area may have been unaltered from its original state or rehabilitated to a natural state.
Night roost	A feature, such as a tree or building, located within or near a bat's foraging area that it uses to rest on between feeding bouts.
Opportunistic bat species	Bat species that takes advantage of new opportunities and new resources available to them.
Parturition	Giving birth of live young.
Pass / Individual Bat Pass	A series of sequential bat calls having similar parameters and characteristics. An Individual Bat Pass is a series of bat calls separated by a gap of two or more seconds.
Phloem	The phloem of a grape vine is found within the outside bark. It transports nutrients and sugars from the leaves to the rest of the vine.

Plot	One of two habitats (natural or vineyard) where the microphone array was positioned.
Pulse length	A measurement in microseconds given the duration of the transmitted radar pulse.
Radar sampling volume	The volume of air sampled by the radar. The EchoTrack radar is capable of sampling a volume of air equivalent to 31.62km ³ given no obstructions from the terrain, buildings, or vegetation.
Range	The horizontal distance of the target from the radar, determined by measuring the time between the transmission of the signal and reception of the echo.
Resolution cell	Individual volumes of airspace defined by the radar pulse duration and beam width that is scanned for targets. Each sweep of the antenna surveys numerous resolution cells for targets as the beam moves along its horizontal plane.
Riparian corridor	The vegetated area adjacent to a watercourse or waterbody.
Sampling interval	A 14 minute sampling period during which radar and acoustic data were recorded simultaneously.
Shrub-steppe	A vegetative community with low precipitation that supports grasses and shrubs. Common shrub species include sagebrush, antelope-brush and rabbitbrush.
Spectrogram	The frequency-time structure of a bat pass.
Speed / Target speed	Airspeed of a target calculated through EchoTrack's program by incorporating the animal's movement and the wind vector.
Spillover	Interference caused by the radar itself when part of the emitting signal feeds directly into the receiver causing noise.
Study site	The vineyard location where my radar was positioned that encompasses a 1 km radius from the radar's location.
Target	One or more individual objects flying in the same resolution cell that was detected and displayed by the radar as ONE echo.
Taxa	For this thesis, taxa is defined as birds, insects, and bats.
Torpor	A state of inactivity. Bats are capable of lowering their heart rate, metabolism, respiration, and body temperature to conserve energy during short periods of inclement weather and/or low prey availability.
Track	A representation of an organism (s) movement over the landscape while in continuous view of the radar. The EchoTrack System creates a track when it identifies three or more sequential points as the same target based on their parameters (range, location, size, and speed). These points are connected to display the target's trajectory.
Tuff	Rock deposits consisting of volcanic ash.

Vegetative canopy	The upper leaves and branches of grape vines, shrubs, or trees.
Vegetative fragmentation	The modification of the landscape that results in the change and discontinuity of the natural vegetative structure. It is caused by urbanization, agriculture, or commercial activities and is only one component of habitat fragmentation.
Vineyard block	A block is defined by repeating rows of grapes having the same orientation, canopy structure, and often grape variety. Blocks are delineated by vineyard roads, natural patches, vineyard infrastructure, and/or the landscape relief.
Vineyard plot	The vineyard within my site where the radar and an acoustic array were located.
Viticulture	The study and practice of grape cultivation.
<i>Vitis vinefera</i>	The common grape vine native to the Mediterranean Region used for high quality wine.
Wind data	The average wind speed and wind direction calculated for each sampling interval based on the data collected at a nearby weather station. Wind data are necessary to calculate target speed.

Chapter 1.

Introduction: Agriculture and bats

One of the greatest threats to bat populations worldwide is anthropogenic habitat alteration, especially the alteration of natural habitats to agricultural lands (Fenton 1983; Nagorsen and Brigham 1993; Fenton 1997; Bernard and Fenton 2007; Henderson and Broders 2008; Kunz and Parsons 2009; Kunz et al. 2011). This modification of the landscape results in a reduction in native habitat, introduces pesticides to the area, causes disturbances, and may result in animal displacement. Agricultural monocultures may further impact bat population as these areas are often associated with lower biodiversity, including arthropod¹ diversity and abundance, than un-modified landscapes (Fenton 1997; Wickramasinghe et al. 2003; Bernard and Fenton 2007; DiSalvo et al. 2009). Bats can be affected by shifts in arthropod diversity, as their foraging habitats are limited by prey selection and availability, as well as access to water, and for some, proximity to their day roost (Furlonger et al. 1986; Holroyd et al. 1994; Agosta et al. 2003; Henderson and Broders 2008; Rambaldini and Brigham 2011). Monocultures can also lead to habitat fragmentation. However, habitat fragmentation must be defined at the species level and is more than simply a change in vegetative structure (Franklin et al. 2002). Habitat fragmentation includes shifts in vegetation, but also considers the suitability of the surrounding habitats, as well as a species' access to resources needed for their survival and reproduction (Andrén 1994; Franklin et al. 2002). Numerous studies worldwide have studied bat responses to anthropogenic habitat alteration, including agricultural intensification, but the results show negative, positive, or neutral effects depending on location and bat species (Fenton 1997; Law et al. 1999; Estrada and Coates-Estrada 2002; Wickramasinghe et al. 2004; Bernard and Fenton 2007; Henderson and Broders 2008; DiSalvo et al. 2009; Williams-Guillén et al. 2015).

¹ This thesis contains a glossary of terms commonly used in biology, the wine industry, and radar studies to aid readers who are not experts in these fields.

Quantifying the impacts of fragmentation and habitat alteration on bat populations is difficult as flight allows bats to move across the landscape to locate resources and find new feeding opportunities (Fenton 1997; Law et al. 1999; Estrada and Coates-Estrada 2002; Wickramasinghe et al. 2003; Bernard and Fenton 2007).

When comparing agricultural lands to un-modified landscapes, most research indicates that bats prefer native vegetation compared to agricultural lands; however bat responses vary (Fenton 1997; Jaberg and Guisan 2001; Wickramasinghe et al. 2003; Henderson and Broders 2008; DiSalvo et al. 2009; Boyle et al. 2011; Stahlschmidt 2012). For example, agricultural intensification and habitat loss has resulted in the decline of six European bat species and is responsible for species listing in North America (Dyer and Lea 2003; Wickramasinghe et al. 2003, COSEWIC 2010). Yet, in the United Kingdom all bat species have been observed feeding over agricultural crops (Wickramasinghe et al. 2003). Many bat species worldwide will forage over agricultural areas and these insectivorous bats can provide important biological pest control for these crops (Kunz et al. 2011; Zukal and Gajdošík 2012; Wanger et al. 2014; Brown et al. 2015; Maine and Boyles 2015). Studies in Britain and the United States (US) have also shown that bats foraging over agricultural fields may be specializing in insect families dominating those habitats (Whitaker 1995; Wickramasinghe et al. 2004). For example, big brown bats (*Eptesicus fuscus*) have been identified as an important biological control agent for the corn industry in the US (Whitaker 1995). Big brown bats are typically known as generalists, but have adapted to the monoculture corn habitat of Indiana and are now specializing on the beetles which damage corn crops during beetle populations spikes (Whitaker 1995). Boyles et al. (2011) estimated that the amount of agricultural pests consumed by bats in the US represents an economic saving of \$22.9 billion per year. Due to the perceived economic value of bats in the US, integrated pest management (IPM) programs are beginning to incorporate bats into their programs (Whitaker 1995; Heaton et al. 2008; Boyles et al. 2011). Generalist and opportunistic bat species both contribute to this economic saving as these species are more adaptive to change. They may use a wide variety of habitats throughout the season and may even switch habitats while foraging throughout the night (Nagorsen and Brigham 1993; Holroyd et al. 1994; Whitaker 1995; Bartonička and Zukal 2003 unpublished cited in Zukal and Gajdošík 2012; Boyles et al. 2011; Zukal and Gajdošík 2012).

The Okanagan Valley of British Columbia (BC), Canada has been anthropogenically altered for the past 150 years, with the landscape vegetation changing from its native bunchgrass and shrub-steppe species to farmlands, orchards and most recently vineyards (Lea 2008; Senese et al. 2012). The Okanagan also has the greatest diversity of bats in Canada (Nagorsen and Brigham 1993) and is home to many generalist and opportunistic species (Appendix A). The agricultural industry continues to expand, however despite its growth and the high diversity of bats in the region, little research has been conducted on the use of agricultural lands by bats (Leonard and Fenton 1983; Rambaldini and Brigham 2011). Research in the region has focused in the naturally-vegetated Bunchgrass Biogeoclimatic Zone (Bunchgrass Zone) or within the riparian corridors (Fenton et al. 1980; Holroyd et al. 1994; Sarell and Haney 2000). The habitat use and bat species distribution in the Okanagan Valley is poorly understood as many information gaps still exist. The agricultural landscape of the South Okanagan may be creating opportunities for bats (Holroyd et al. 1994; Garcia et al. 1995; COSEWIC 2004a, b; Sarell et al. 2011). With better understanding, the quality of habitats can be improved.

Most bat species in the Okanagan have the potential to use vineyards as foraging habitat given the diverse insect community associated with vineyards. The insectivorous bats of the South Okanagan have a voracious appetite. Males consume 30 % – 50 % of their body mass in insects per night, while lactating females consume 50 % – 100 % of their body mass per night (Fenton 1983; Nagorsen and Brigham 1993; Altringham 1996; Kunz et al. 2011). The high energy demand of lactating females requires them to forage throughout the night (Aldridge and Brigham 1991; Altringham 1996). In the Okanagan, lactating big brown bats have been observed foraging 136 % longer than pregnant bats (Aldridge and Brigham 1991). To minimize energy requirements and decrease their commute time, lactating females will search for foraging habitat closer to their day roost (Racey and Swift 1985). Due to the proximity of day roosts to vineyard habitat in the South Okanagan, vineyards may be creating a niche for lactating females.

The purpose of my study was to assess the spatial distribution of bats to compare habitat use in a modified landscape where vineyards dominate. My primary objective was to determine the extent to which bats use vineyard habitat in the South

Okanagan compared to their use of nearby natural habitats. I wanted to understand the role that vineyards play in the ecology of the South Okanagan bat community and specifically, if vineyards function as foraging habitat or just commuting corridors. To accomplish this, I used mobile radar in conjunction with acoustic monitoring to document the movements of bats in both vineyards and adjacent natural habitats at six locations in the South Okanagan.

Radar technology was crucial to fully understand bats' use of the landscape. Bats are difficult to study and habitat association studies are complicated by their nocturnal habits, their ability to fly, their use of multiple roost sites, and large home range. Their nocturnal habits also complicate survey methods, as it is difficult to observe their behaviour throughout the night. The use of spotlights or beams can alter the behaviour being studied and their speed and agility makes them difficult to follow with night vision equipment (Bruderer et al. 1999; Adams et al. 2009; Holdereid and Jones 2009; Sarell et al. 2011). Furthermore, radio-telemetry studies are limited to small sample sizes, species that are more easily captured, and species greater than 10 g that can carry the transmitter (Fenton 1997; Hayes et al. 2009). Mine is the first study to use a mobile radar unit to assess the habitat associations of bats. Radar has been used since World War II to study migratory birds on a large scale and to study the movement of large bat colonies following their emergence (Parslow 1969; Williams et al. 1973; Gudmundsson 1993; Gauthreaux 1996; Horn and Kunz 2008; Chilson et al. 2012b). However, it has not been used on a smaller scale to track individuals and determine habitat preferences.

I wished to understand the role that vineyards play in bat ecology. My study objectives aimed to:

1. Evaluate the use of a unique radar-acoustic surveillance system to assess the habitat association of bats in the South Okanagan.
2. Assess if bats are using vineyards for more than just commuting between their day roosts and foraging areas. If bats are solely using vineyards as commuting corridors, activity within the vineyard would only be seen at dusk and dawn.
3. Assess if vineyards provide a foraging niche for lactating females due to their proximity to maternity colony roost and the high energy requirements of lactating bats.

4. Identify the bat species using vineyards.
5. Assess whether the presence of trees, buildings, and/or lights within vineyards have an effect on bat activity.

1.1. Background information

1.1.1. Study species

Bats are a unique group of mammals. They are the only mammal capable of flight and despite the relatively small size of many species they are long lived (10-30 yrs) (Nagorsen and Brigham 1993; Kerth and Dechmann 2009). They have few natural predators. The greatest impacts to their populations worldwide are from anthropogenic activities, especially land-use changes and disturbances to roosts (Fenton 1983; Nagorsen and Brigham 1993; Kunz and Parsons 2009; Harvey et al. 2011). Bats occupy a vast array of ecosystems from deserts to rainforests and are only absent from Polar Regions (McNab 1982; Harvey et al. 2011).

There are more than 1300 bat species worldwide (Harvey et al. 2011). Seventy percent of all bats, including all Canadian species, are insectivores² (Nagorsen and Brigham 1993; Harvey et al. 2011). Insectivores capture prey in flight (aerial hawkers) or seek prey resting on vegetation or the ground (gleaners). Some species, much as long-eared myotis (*Myotis evotis*) and fringed myotis (*Myotis thysanodes*), are not restricted to one foraging strategy and can hunt aerial and stationary prey (Barclay 1991). All insectivorous bats are capable of using echolocation to detect prey. However, unlike aerial hawkers that rely on their echolocation calls to locate prey, some gleaners such as the pallid bat (*Antrozous pallidus*) produce few calls while hunting and instead rely on prey generated sounds (Rambaldini and Brigham 2011). Insectivorous bats may also use echolocation for navigation, which allows them to hunt while commuting (Verboom and Huitema 1997; Sarell and Haney 2000).

² The Pallid bat predominantly feeds on large arthropods; however it will occasionally consume small reptiles or mammals.

Echolocation allows bats to predict the horizontal and vertical components of their prey to within 2° – 5° up to 60 m away (Neuweiler 2000). Echolocation calls are associated with foraging strategies, habitat preferences, and prey selection (Fenton 1982a; Adam et al. 2009) and provide biologists with a measure of habitat use (Fenton 1982a, b; Leonard and Fenton 1983; Hayes et al 2009). Bat calls produce sonograms that are generally frequency modulated, sweeping from a maximum frequency to a minimum frequency; however some bat species produce sonograms with a constant frequency over time, or show constant frequency at the end of their calls. Bat species present in the Canada have calls that range from a minimum frequency of 6 kHz to 50 kHz to a maximum frequency of 15 kHz and 110 kHz (Fenton and Bell 1981; Sarell et al. 2011).

Bats are the only mammals capable of powered flight (Nagorsen and Brigham 1993; Kerth and Dechmann 2009). The flight speed of bats has been studied in the tropics, neotropics, and temperate regions (Hayward and Davis 1964; Patterson and Hardin 1969; Findley et al. 1972; Morrison 1980; Jones and Rayner 1988; Sahley et al. 1993; Winter 1999; Sánchez-Hernández et al. 2006; Grodzinski et al. 2009). These studies found that bat flight speeds in natural setting and enclosures are between 1.8 m/s and 13.9 m/s. Based on literature and personal communication with bat biologists, bat species have average foraging speeds between 1.8 m/s and 7 m/s (Schnitzler et al. 1987; Jones and Rayner 1988 and 1991; Britton et al 1997; Winter 1999; Grodzinski et al 2009; M. Sarell, personal communications January 3, 2013; D. Burles, personal communications January 7, 2013). Holdereid and Jones (2009) estimated the flight speed of 13 aerial hawk insectivores to be between 2.5 m/s and 12 m/s using Pennycuick's formula, which is based on minimum power speed and maximum speed range (Pennycuick 1989 cited in Holdereid and Jones 2009). In trial surveys, variation in flight speed was observed within and among individuals of the same species, with flight speeds varying by as much as a factor of three (Hayward and Davis 1964; Sahley et al. 1993; Winter 1999). In addition, Patterson and Hardin (1969) observed flight speeds increase by as much as 4.7 m/s in natural settings compared to enclosures. For many species, flight speeds have been correlated with forearm length indicating that larger bats have faster flight speeds (Hayward and Davis 1964; Morrison 1980).

1.1.1.1. South Okanagan bat species

All bats in the South Okanagan are nocturnal and insectivorous. They will use a variety of habitats for roosting and foraging including: shrub-steppe, rocky cliffs, talus slopes, riparian corridors, Ponderosa pine forests, Douglas fir forests, as well as anthropogenic features such as attics, barns, abandoned mines, and cultivated fields (Nicholson et al. 1991; Nagorsen and Brigham 1993, Holroyd et al. 1994). Of the fifteen species inhabiting the South Okanagan, seven are listed as species at risk either provincially and/or federally (Appendix A) (Fenton et al. 1980; Nagorsen and Brigham 1993; Holroyd et al. 1994; Sarell and Haney 2000; Harvey et al. 2011). Okanagan bat species eat a wide variety of arthropods and forage from ground level to heights well into the troposphere (Nagorsen and Brigham 1993; Holroyd et al. 1994; Harvey et al. 2011; Sarell et al. 2011). Preferred prey species varies with bat species; however common prey includes beetles, moths, and true flies (Barclay 1986; Nagorsen and Brigham 1993; Holroyd et al. 1994; Whitaker 2004; Harvey et al. 2011).

Okanagan bats are active from dusk to dawn between March and November. Parturition occurs between mid-June and mid-July, with young becoming independent at the beginning of August or into September (Nagorsen and Brigham 1993; Holroyd et al. 1994; Sarell and Haney 2011). Prior to parturition, females form maternity colonies ranging in size from a few individuals to 1000s of individuals (Nagorsen and Brigham 1993; Altringham 2011). Maternity colony roosts are located in gneiss cliffs, attics, trees, or within bat boxes (Nagorsen and Brigham 1993; Holroyd et al. 1994). Most species have one pup per year that weigh approximately 25 % of the female's mass at birth (1 g to 7.5 g). These altricial young reach adult size within three to six weeks (Nagorsen and Brigham 1993). In the summer, males of most species roost separately from the females, either solitary or in small colonies, and will often forage in different locations (Fenton et al. 1980; Kerth and Dechmann 2009; Altringham 2011).

Bats emerge from their day roosts near sunset to search for water and food. Bats are most active throughout the first half of the night with peak foraging times in BC identified between 0.5 hrs to 1.5 hrs after sunset, between midnight and 01:00 hrs, and prior to dawn; however some species are active throughout the night (Nagorsen and Brigham 1993; Holroyd et al. 1994; BC Ministry of Environment 1998; Rambaldini and

Brigham 2011). Species foraging times vary throughout the night and many species will use feeding roosts and/or night roosts between foraging bouts (Fenton et al. 1980). Bats return to their day roost between midnight and sunrise roosting for 16 hrs to 20hrs before emerging the following night (Racey 1982).

1.1.2. Study area

BC's Okanagan Valley is situated in south-central British Columbia and stretches for 250 km from Vernon (50.2695 N -119.2734 W) to the US border (48.9997 N - 119.4435 W) (Senese et al. 2012). The district of the South Okanagan extends for approximately 80 km south of Peachland (49.7711 N -119.7410 W). The region contains numerous large lakes that are connected via the Okanagan River, which runs down the centre of the valley. The regions' climate is hot and dry. The South Okanagan valley orients north-south and is approximately 2.5 km wide. It consists of plateaus and rolling hillsides and is bordered by granite gneiss cliff to the east and predominantly tuff cliffs with sandstone and limestone to the west (Senese et al. 2012). The bluffs and mountain peaks range in elevation from 790 m to 1772 m. Agricultural lands extend from the base of the cliffs in many areas to the valley bottom resulting in remnant naturally vegetated areas scattered throughout the valley. These areas consist of grasses, shrub-steppe species, open Ponderosa pine forests, and/or Douglas fir forests (Nicholson et al. 1991).

1.1.3. The Bunchgrass Biogeoclimatic Zone

The low elevation grasslands (275 m – 700 m ASL) found along the Okanagan consists of the Bunchgrass Zone (Holroyd et al. 1994; BC Ministry of Environment 1998). This zone covers less than 1 % of BC's land base and is unique to Canada (BC Ministry of Forests 1998). Despite its size, it is one of the most populated and agriculturally developed Biogeoclimatic Zones in BC (Insight Environmental Consulting 2010). The Bunchgrass Zone consists of three ecosystems: (1) bunchgrass, (2) sagebrush steppe, and (3) antelope-brush steppe (Holroyd et al. 1994; BC Ministry of Forests 1998). These ecosystems support a large diversity of plants and wildlife, including more than 100 species provincially and/or federally-listed for conservation due to agricultural intensification and urbanization in the area (Nicholson et al. 1991; Dyer and Lea 2003; Insight Environmental Consulting 2010; BC Ministry of Environment

2012). Many of the floral and fauna are also endemic to this region in Canada, which includes one species of bat, the pallid bat (Nicholson et al. 1991; Nagorsen and Brigham 1993).

The Bunchgrass Zone has been subjected to extensive land use; patches of native vegetation are rare (Redpath 1990; Dyer and Lea 2003). Agricultural expansion, livestock grazing, and urban development have resulted in the Bunchgrass ecosystems being endangered in Canada (Dyer and Lea 2003, Lea 2008; Knight 2013). From the late 1800s to 2003, 90 % of the valley bottom land, and 60.7 % of gentle-sloped grasslands and shrub-steppe areas have been transformed for urbanization and agricultural use (Redpath 1990; Lea 2008). Years of fire suppression has also resulted in the encroachment of trees into the remaining shrub-steppe plant communities changing the vegetative structure of the area (Turner and Krannitz 2001; Welstead 2002). Habitat conversion continues to change the landscape of the South Okanagan. Due to the rapid alterations of land uses since the 1920s, it is difficult to determine which areas have not been historically modified (Redpath 1990; Garcia et al. 1995, Lea 2008).

1.1.4. Okanagan vineyards

The Okanagan Valley is presently the second largest wine producing region in Canada and has the title of the “*Best Wine Growing Terroir in Canada*” (Schreiner 2009). Although grapes were first planted in 1859, these were only used for making sacramental wine (Lea 2008; Insight Environmental Consulting Ltd. 2010; Senese et al. 2012). The first commercial grape winery opened its doors in the late 1920s (Senese et al. 2012; L. Corbeil, personal communication, February 13, 2012). This winery and the few that followed depended on hybrid grapes (*Vitis* spp) or other fruit that produced mediocre wines (Schreiner 2009; Senese et al. 2012). In 1988, the winery industry underwent a transformation when two thirds of previous 1418 ha of hybrid grapes were removed from the region and replaced with varieties of *Vitis vinifera* to produce high quality wines (Schreiner 2009; Senese et al. 2012).

The Okanagan grape wine industry grew rapidly after 1992 once the region’s potential was seen (Schreiner 2009; BC Ministry of Agriculture and Lands 2010; Senese et al. 2012). Many orchards were also replaced with vineyards in the early 2000s due to

better crop yields, (Chapman et al. 1994; Senese et al. 2012; L. Corbeil, personal communication, February 13, 2012). From 1988 to 2012 vineyard land area increased from 566 ha to more than 5000 ha (Schreiner 2009), with vineyards planted on private lands, and crown land including the Osoyoos Indian Reserve (Senese et al. 2012). At the start of my study in 2012, there were 320 independent wine growers and 144 wineries contributing to sales over 200 million dollars per year (Schreiner 2009, L. Corbeil, personal communication, February 13, 2012). Today vineyards cover a significant proportion of the South Okanagan with more than 2045 ha planted around Oliver, BC (BC Ministry of Agriculture and Lands 2010; Oliver Osoyoos Winery Association 2014).

South Okanagan vineyards are located along both sides of the valley from the valley bottom (~280 m) to 565 m in elevation. They are situated along plateaus and steep hillsides. The vineyard rows generally follow a north-south orientation; however, at undulating sites, rows generally run parallel to the slope. Vineyards contain multiple roads that run throughout them to access the area. Frost towers are also placed throughout the vineyards at even intervals to minimize climate damage to the grapes. The vineyard canopy to row width ratio is 1:1 (generally between 2.3 m – 2.5 m), with the cordons commonly placed 0.8 m to 0.9 m above the ground, thus producing a relatively open canopy (BC Ministry of Agriculture and Lands 2010). Many bats inhabiting this region use a variety of foraging habitats and would be adapted to feeding in the sparse vegetation and low canopy cover of vineyards should prey be available to them (Nagorsen and Brigham 1993; Holroyd et al. 1994; Sarell et al. 2011).

Native grasses, herbs and forbs are planted below the vines and between the rows to encourage the presence of beneficial native insects (Statistics Canada 2005; Insight Environmental Consulting Ltd. 2010). The vineyard operators alternate mowing between rows to maintain the presence of these beneficial insects (BC Ministry of Agriculture and Lands 2010). The vineyards are also irrigated, trimmed, and pruned regularly to maximize growth of the vines and maintain the canopy composition (BC Ministry of Agriculture and Lands 2010). In 2010, the BC Wine Grape Council developed a Sustainable Winegrowing Program in addition to their Best Practices Guide for Grapes to incorporate all aspects of environmental management into the industry practices. These guidelines include sections on assessing impacts to wildlife and using

IPM with a focus on beneficial insects and birds (BC Ministry of Agriculture and Lands 2010). The IPM program promotes a reduction in chemical use in the area, by incorporating biological, cultural, physical, and behavioural methods prior to using chemicals to control pests in the vineyards.

The primary threats to BC crops include two grape diseases caused by fungi, *Uncinula necator* (Powdery Mildew) and *Botrytis cinerea* (Botrytis bunch rot), and three main insect groups; however, 30 groups/species of insects have been identified to cause damage to crops (Appendix B) (BC Ministry of Agriculture and Lands 2010; Insight Environmental Consulting Ltd. 2010). All three of the main insect groups have been identified as prey for bats (Nagorsen and Brigham 1993; Garcia et al. 1995; Agosta et al. 2003; Harvey et al. 2011; Rambaldini and Brigham 2011; Williams-Guillén et al. 2015). The first group includes cutworm larvae (*Abagrotis* spp), which cause considerable damage in the spring. Caterpillars are nocturnal and feed on the buds and shoots (Ministry of Agriculture and Lands 2010; University of California 2012). There are approximately 25 species of cutworms in the Okanagan Valley, 18 species have larvae that will feed on the vines; however three species appear to cause the most damage (BC Ministry of Agriculture and Lands 2010; Lowery and Mostafa 2010; T. Lowery, personal communication, November 5, 2014). The second insect group includes two species of leafhoppers (*Erythroneura ziczac* and *E. elegantula*). Leafhopper nymphs and adults damage crops in the spring and summer by feeding on leaves and removing phloem and its components (BC Ministry of Agriculture and Lands 2010). The third major insect group includes wasps (Hymenoptera: Vespidae) which feed on the grapes and are a potential vector for other diseases (BC Ministry of Agriculture and Lands 2010). There are several species of wasps that damage crops in the fall; many are also a nuisance for the vineyard workers throughout the wine growing season. Although leafhoppers and wasps are diurnal insects, they have been identified as bat prey (Nagorsen and Brigham 1993; Harvey et al. 2011). Gleaning bats are able to consume these insects as they remain on the plant part they feed upon throughout the night (G. Gries, personal communication, November 27, 2014).

Despite the diversity of arthropods feeding on grapevines, Okanagan grape growers use fewer pesticides than other grape growing regions in Canada, as well as the orchard industry that previously dominated the area (Chapman et al. 1994, Statistics

Canada 2005; BC Ministry of Agriculture and Lands 2010). The Okanagan wine industry has a lower incident rate of pesticide use as the arid climate and frequent winds that blow down the valley through the vineyard rows minimize the incidence of fungi (Chapman et al. 1994, BC Ministry of Agriculture and Lands 2010; C. Withler, personal communication, September 10, 2014). In addition, the South Okanagan is isolated from other grape growing regions reducing the number of insects causing damage to the crops (C. Withler, personal communication, September 10, 2014). The region's sustainable wine growing program and vineyard management techniques allow for predator species such as parasitic insects, and spiders to feed on problem insects. Furthermore, bluebird nest boxes placed along the vineyard periphery have proven successful (Heaton et al. 2008; Jedlicka et al. 2011; Willis 2013). Bluebirds will feed on leafhoppers and aid with natural predator control. Other bird species and bats may also be providing natural predator control.

1.1.5. Study sites

My study sites were located throughout the southern half of the South Okanagan extending from Okanagan Falls (49.3389 N -119.5703 W) to the north end of Osoyoos Lake (49.0530 N -119.4795) (Figure 1.1). I selected six vineyards that bordered gneiss cliffs in and around Oliver, BC (49.1828° N, 119.5514° W), which all had a potential to support maternity colony roosts. Five sites were located on the eastern side of the valley, with Site 2 located on the western side just north of Oliver, BC. All sites were located in the low elevation Bunchgrass Zone with elevations ranging from 290 m to 440 m. All sites contained both vineyard and natural patches, although some natural sites were re-established in the area. Due to the extensive land modification that occurred in the South Okanagan Valley, it is unknown whether all of my natural plots have been re-established (Redpath 1990).

The vineyard plots contained uniform rows of vines and consisted of varying sized blocks spread across the landscape. The vineyard canopies were relatively open and all measured less than 2.5 m high. Five sites followed the structure outlined in Section 1.1.4, with Site 1 having a shorter canopy with heights between 1.5 m and 2 m. All vineyard sites were adjacent to natural habitat, with some vineyards also containing small patches of shrub-steppe, as well as small numbers of Ponderosa pine (*Pinus*

ponderosa), within the vineyard. Water was limited at the majority of the sites. The main water source available to bats was the Okanagan River, Vaseux Lake, and Osoyoos Lake. All sites had buildings and infrastructure in place for vineyard maintenance and/or tourism.

1.2. Thesis outline

This thesis consists of three chapters including this general introduction. In Chapter 2, I explain the history of radar, radar basics, factors affecting target detection, and common radar challenges faced with any biological radar study. Chapter 2 also describes the use of the EchoTrack's Radar-Acoustic Airborne Wildlife Surveillance System for my study, discusses how the EchoTrack system deals with common radar challenges, and makes recommendations for future use. Chapter 3 presents data I collected on the use of space and time by airborne targets identified by the EchoTrack System to compare the use of vineyards and natural habitat by bats in the South Okanagan Valley. I used ArcGIS to determine the amount of bat activity associated with both habitats by comparing track length per unit area. I also assess the use of habitat by comparing bat passes and foraging rates recorded in my acoustic plots. In addition, I assess mean radar-defined tracks parameters (speed, height, and relative size) obtained for tracks over each habitat, identify bat species groups using both habitats, and compare the nightly temporal variation of tracks and bat passes throughout the night. I conclude Chapter 3 with suggestions for future research needed in the area to understand the role that vineyards play in the ecology of bats inhabiting the South Okanagan.

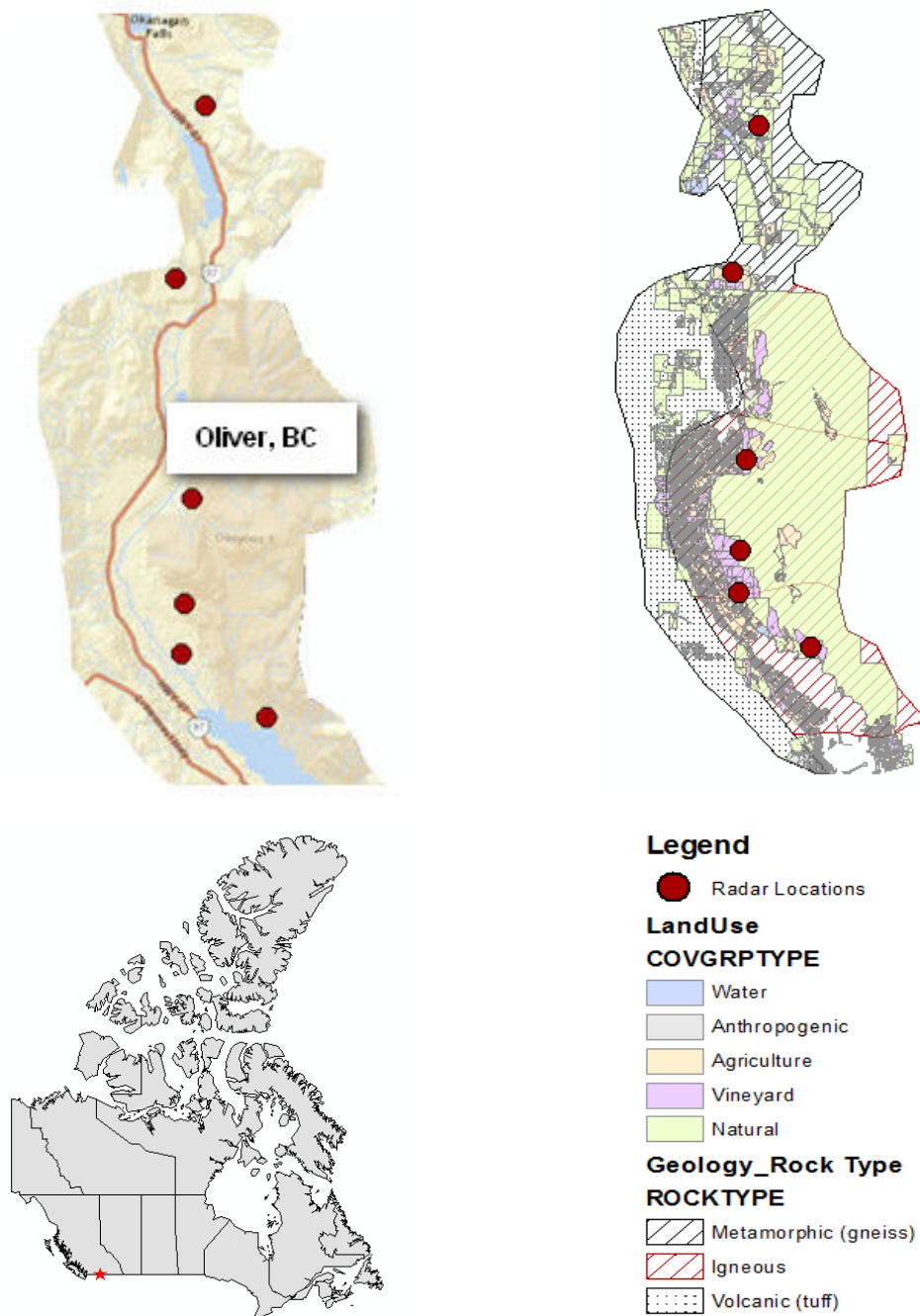


Figure 1.1. Map of the South Okanagan Valley showing my study area that extends from Okanagan Falls, BC to Osoyoos, BC. My study sites are indicated by the red dots.

Chapter 2.

A review of radar and the EchoTrack Radar-Acoustic Airborne Wildlife Surveillance System for the study of bats in vineyards

2.1. Radar use for biological studies

Since World War II and the discovery of the unidentified echoes, referred to as “angels” that are produced from radar energy reflected from bioscatter, biologists around the world have used stationary radar to study animals (Lack and Varley 1945; Hajovsky et al. 1966; Eastwood 1967; Vaughn 1985). Radar can be used day or night. It can passively sample a large volume of airspace and is capable of scanning the horizontal (360 degrees) and/or vertical plane in seconds to provide an overall picture of the activity occurring in the area (Millikin and Buckley 2001; Gauthreaux and Belser 2003; Millikin 2005; Mabee et al. 2006). Radar provides large data sets and allows for the continuous monitoring of multiple animals at greater distances and altitudes than conventional sampling methods (Parslow 1969; Gauthreaux and Belser 2003; Millikin 2005). Furthermore, marine and military radars can detect targets in inclement weather when other surveys are often abandoned (Bruderer 1997; Millikin 2005). Using radar, ornithological studies have detected two to ten times more activity than bird-banding stations and audiovisual surveys (Parslow 1969; Gauthreaux and Belser 2003). Radar has been used to detect, monitor, and track the spatial and temporal patterns of bird flocks and insect swarms over large geographical areas to understand and quantify their movements (Hajovsky et al. 1966; Parslow 1969; Gudmundsson 1993; Smith et al 1993; Gauthreaux and Belser 2003; Dean and Drake 2005; Diehl and Larkin 2005; Millikin 2005). These biological radar studies have provided biologists with knowledge about animal migration, animal distributions, flight characteristics, and habitat preferences (Eastwood 1967; Parslow 1969; Gudmundsson 1993; Dean and Drake 2005; Diehl and Larkin 2005; Millikin 2005). Radar provides a unique opportunity to study animals with

minor to no effects on the organisms or the behaviour being observed (Richardson 1976; Bruderer et al. 1999). Its use for biological studies continue to increase and has played an important role in the conservation of birds since the 1980s and bats post 2005 (Gauthreaux and Belser 2003; Ruth et al. 2005). Most recently, radar is being used to track insects and agricultural pests across the US to understand their movements and to aid with their management (McCracken et al. 2008; Chapman et al. 2011).

Mobile radar have been used for biological studies since 1979 (Gauthreaux and Belser 2003). These systems are mounted on vehicles and are capable of tracking aerial animals within a few kilometres of the unit (Cryan and Diehl 2009). These radar systems are designed to acquire detailed data acquisition from small targets allowing biologists to track the movements of individual biological organisms (Millikin 2001; Gauthreaux and Belser 2003; Mabee et al. 2006; Van Gasteren et al. 2008; Cryan and Diehl 2009; Frick et al. 2013). Mobile radar can be used to assess the habitat associations of species due to their relatively small size and mobility. They are commonly used to study the effects of transmission lines and wind farms on migratory and resident bird and bat populations, as well as for flight safety with regards to bird strikes (Gauthreaux and Belser 2003; Mabee et al. 2006; Millikin 2006).

Radar has been more commonly used to study birds and insects; however radar studies of bats have occurred since the 1960s (Williams et al. 1973). Using radar, bat biologists have studied the high altitude flights of bats and their pursuit of high altitude insects, as well as roost emergence, nightly dispersal, bat flight characteristics, and bat migration (McCracken 1996; Bruderer and Popa-Lisseanu 2005; Mabee et al. 2006; McCracken et al. 2008; Horn and Kunz 2008; Frick et al. 2012). Bat radar studies grew considerably in the US in the 1990s with the application of the Next Generation Radar (NEXRAD). The NEXRAD system is a national network of 159 weather-surveillance radar built across the country to monitor meteorological events (Kelly et al. 2012; Frick et al. 2013). Biologists can use the reflectivity values obtained from the NEXRAD system to study the movements of large congregation of bats (thousands/millions of individuals), as well as birds, at day roosts (Horn and Kunz 2008; Chilson et al. 2012a, b; Frick et al. 2012, Kelly et al. 2012). The NEXRAD system records data every five to ten minutes and has been archived since 1990, allowing biologists to study present and past movements (Frick et al. 2013).

Given the increased use of radar, it is important to evaluate the strengths and weaknesses associated with radar studies. In this chapter, I describe the EchoTrack Radar-Acoustic Wildlife Surveillance System (the EchoTrack System) used for my research. I provide a brief overview of radar and radar challenges associated with any biological study. I assess how the EchoTrack System deals with these challenges and evaluate the performance of the system. I also assess the quality of the radar data collected for the analysis of bat activity over my study sites. Although the main focus of this chapter is on radar use; the EchoTrack System consists of acoustic arrays that work in conjunction with the radar. I therefore conclude by identifying study challenges associated with these arrays and provide recommendations for future habitat association studies using the EchoTrack System.

2.2. The EchoTrack Radar-Acoustic Airborne Wildlife Surveillance System³

Surveillance radars are commonly used for biological studies (Appendix C) (Gudmundsson 1993; Gauthreaux 1996; Gauthreaux and Belser 2003; Mabee et al. 2006; Chilson et al. 2012b). They are capable of observing flights close to the ground and can be compact enough to be mounted on a vehicle for easy access to study sites. I used the radar-acoustic system automated by EchoTrack Inc. to assess the use of vineyards by bats (Millikin 2001). It consists of an X-band radar that was modified from a Racal Decca BridgeMaster E marine surveillance radar. It has a frequency of 9.1 GHz corresponding to a wavelength of 3.2 cm (Table 2.1). The EchoTrack System is capable of surveying a large volume of air (31.62 km³) with high spatial resolution to determine targets and their flight trajectories. It can detect small individual organisms (such as passerines and large bats) to a range of 2 Km and a height of 1668 m above the ground. This system was designed in 1999-2001 to study the dispersal and migration patterns of passerines (average size 7 g) during spring and fall migration, from sunset to sunrise. Its application was intended to be used during clear nights or during nights with light to medium precipitation events; however it can be used day or night in all visibility

³ The information outlined in this section is based on Millikin 2001, Millikin and Buckley 2001, and The EchoTrack Operations Guide (Millikin 2011).

conditions. All components can be used in inclement weather, including storms, which can provide valuable data when most biological studies are abandoned. The system was launched by EchoTrack in 2003. It has been used in Canada, the US, and Africa to study both migratory birds and bats to identify important migratory corridors and recommend setback zones for proposed wind farms.

EchoTrack's radar is mounted on a cargo trailer and works in conjunction with one or more acoustic arrays (Millikin 2001). It passively tracks organisms, while the acoustic arrays identify organisms flying through the area. The cargo trailer associated with the unit is fully equipped as a mobile field station. It consists of the control system with independent power source and operator accommodations. The control system contains all hardware and software needed for data collection and analysis. It operates with Sigma Engineering RSi 3000 radar digitising and recording system and Sigma S6 Seaview processing system. The radar's processing software allows for echo recognition, and comparison of target location and velocity to plot individual targets and their trajectories over the landscape (Figures 2.1 and 2.2). This processing software filters out stationary targets, as well as non-biological moving targets such as vehicles and aircraft based on the radar-defined target parameters. To reduce false target trajectory allocation, the radar assigns a trajectory only when three or more echoes are detected from a target with subsequent rotations of the antenna. The coordinates associated with the radar-defined targets and their trajectories (aka tracks) are in decimal degrees true. The geographic coordinate system used is GCS_WGS_1984.

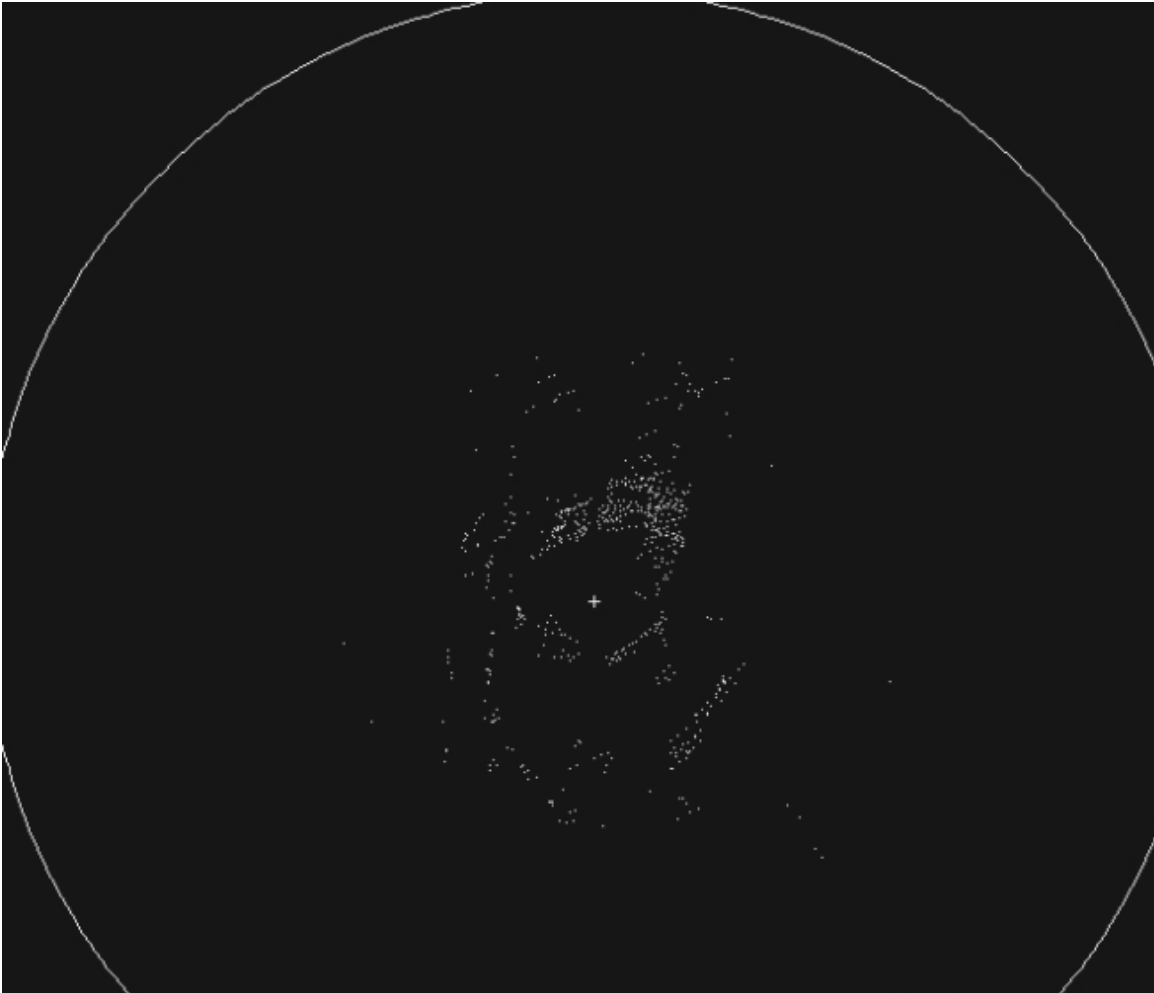


Figure 2.1. Screen capture of the radar imagery video displayed through EchoTrack's processing phase showing all targets, including terrain and vegetation (white dots) detected within the first few minutes of sampling at one of my sites. The crosshair shows the location of the radar and the circle denotes a 2 km radius.



Figure 2.2. Screen capture of the radar imagery video displayed through EchoTrack's processing phase showing radar-defined tracks (white lines) detected during one sampling interval (14 minutes) at one of my sites. The crosshair shows the location of the radar and the circle denotes a 2 km radius.

2.2.1. Operation of the EchoTrack System

The EchoTrack System was designed to operate with two acoustic arrays; one set of four Sennheiser ME66 microphones with a windsock to record bird calls and one set of four EchoTrack omni-directional bat sensors to record bat calls (Figure 2.3). The microphone arrays are typically situated 90 m perpendicular to the trailer to collect and store data directly onto the trailer's computer for compression and analysis. The array configuration consists of a central microphone and three peripheral microphones placed 120° apart from each other (Figures 2.3 and 2.4). The peripheral bird microphones are

placed 20 m from the central microphone with the omni-directional bat sensors situated 10 m from the central microphones. For proper operation of EchoTrack's radar, the trailer-mounted antenna must be levelled. To ensure antenna levelling, the trailer must be positioned over an area that does not exceed a change in ground height of 30 cm over the width of the trailer or 45 cm along the length of the trailer. The trailer's location is critical at the start of any project, as the operator must accommodate for the antenna and the microphone arrays while striving to maximize target detection and minimize clutter (See Sections 2.5.1 and 2.5.2).



Figure 2.3. Photo showing the setup of the EchoTrack System with the use of both acoustic arrays positioned ~90 m perpendicular to the trailer. The bird microphones are shown by red circles and the EchoTrack omni-directional bat sensors are shown with the blue circles.

EchoTrack omni-directional bat sensors are very different from conventional bat detectors. They are anchored to survey tripods and must be surveyed, levelled, and placed at the same elevation (Figure 2.4). These sensors were designed by EchoTrack and Vandervalk Neeson Instruments Ltd. and consist of a parabolic reflector that records omni-directional sound in full spectrum in both audio and ultra-sonic range up to 140 kHz (Figure 2.4) (Neeson 2006). EchoTrack tested their omni-directional bat sensors using

calls from eastern Canadian bat species recorded by Dr. Brock Fenton (Neeson 2006). This testing confirmed that they are capable of detecting calls originating from any direction. These sensors are unique to bat research. Other bat detectors/microphones, with the exception of the Song Meter SM2⁴, are directional and could easily miss bat calls originating outside of their narrow cone of reception. EchoTrack's omni-directional bat sensors can record 30 kHz sounds from a distance of 50 m and 50 kHz calls at a distance of 22 m (Neeson 2006). Higher frequency calls attenuate faster in air, therefore reducing their range (Verboom and Huitema 1997; Adams et al. 2009).



Figure 2.4. Overview of the bat acoustic array setup in one of my natural plots. The image shows the unique design of the EchoTrack omni-directional bat sensors and the configuration of acoustic array used for bat sampling.

All of the equipment is tested nightly prior to operation using EchoTrack software to minimize data loss. After testing, the operator uses the system software to setup the nightly sampling regime. The sampling regime automates the recording of radar and

⁴ The Song Meter SM2 is an omni-directional detector that was designed and launched by Wildlife Acoustics in 2009.

acoustic data simultaneously. It consists of a number of sampling intervals (SI) that varies with the change in day length. To accommodate for both the sampling of bird and bat calls, the acoustic arrays are automatically turned on and off at 15 minute intervals, recording 14 minutes of acoustic data each every half-hour following sunset. The location and orientation of the trailer, as well as, the location and heights of the microphones are inputted in the software program nightly as their positions are considered during the processing phase.

Following data collection, the raw radar files are processed using EchoTrack software. Data processing is critical to filter out undesired targets and to incorporate weather (See Sections 2.5.4 and 2.5.6). The data processing generates 10 text files per SI that outline the specifics of the project, and identifies the radar-defined targets, tracks and their parameters. Targets and tracks are outlined in separate text files and can be imported into a statistical program for analysis. Appendix D shows a sample of the track data text file that was collected during my study. Two of the text files generated can also be used to convert the radar-defined tracks into kml files using Python script for use in Google Earth or a Geographic Information System (GIS) (See Chapter 3 Section 3.1.2). In addition to the text files, a video can be viewed during the radar processing phase, which shows the detection of targets throughout each SI and outlines the location of the tracks (Figure 2.2). Further to the processing of radar data, the raw acoustic files are compressed using EchoTrack software to generate waveform audio files. These wave files are then imported into bird and bat acoustic analysis programs for identification. The simultaneous sampling of radar and acoustic data equates to a substantial amount of data that are stored on external 2TB hard drives. One hard drive is capable of storing two to four nights of continuous sampling depending on the time of year and length of darkness.

The radar and acoustic systems are independent of each other but are used simultaneously. The acoustic arrays provide an independent observation of bird and bat activity to complement the radar. Used together, the EchoTrack System indicates areas used by organisms, identifies travel corridors, and identifies species present in the survey area.

2.3. Radar basics⁵

All radars consist of three main components: (1) a transmitter, (2) an antenna, and (3) the receiver. The transmitter emits a radio wave (aka a signal) to send out electromagnetic energy in pulses that radiates out of the antenna in a relatively straight line and constant speed (Wolff 2009). The antenna collects the reradiated electromagnetic energy from the target (aka the echo), and sends it to the receiver (Wolff 2009). The receiver amplifies the echo and filters it from clutter to detect the target. The signal emitted, the echo, and the time elapse of the echo allows the radar to detect targets and determine their range, speed, direction of travel, change in direction over time, altitude, levelness of flight, and/or their relative size. The constant rotation of the antenna allows the radar to scan the sky every couple of seconds to determine target trajectories (tracks).

The signal emitted by the transmitter is set to a radar frequency band. This frequency band is associated with a range of wavelengths, which is set to match the desired target the radar was designed to track. For example, X-band radar has a frequency band of 8 GHz – 12 GHz producing wavelengths between 2.5cm to 3.75cm (Appendix C). This type of radar, as well as S-band, and C-band radar are commonly used in biological studies to gain knowledge on birds, insects, and bats (Appendix C) (Williams et al. 1973; Vaughn 1985; Gudmundsson 1993; Bruderer and Popa-Lisseanu 2005; Van Gasteren et al. 2008; Westbrook 2008; Frick et al. 2012). The frequencies associated with these three types of radar produce short wavelengths (2.5 cm to 15 cm), which are ideal for providing accurate data to track small individual targets. A short wavelength is required to image small targets as wavelengths longer than the desired target result in poor reflection causing the target to be invisible to the radar.

⁵Much of the radar information contained in this section and Section 2.4 is based on a radar course taken during my graduate studies. The course textbook was Skolnik 1990; references listed in both sections support Skolnik's book.

2.4. Target detection

Radar's ability to detect a target is not simply a function of target size. Target detection relies on multiple factors and is enhanced with proper radar design. Radar components such as the power transmitted by the radar, the gain of the antenna, the number of radiating elements in the antenna, the radar pulse length, beam width, wavelength, and radar processing software are chosen to optimize the detection of the desired target. The detection of small organisms, such as bats, is made possible with a short wavelength, enhanced target imaging, and greater resolution. Target detection can be further improved by the design of mobile X-band radar such as the EchoTrack System. Mobile radars with short wavelengths above 1.5 cm and with ranges less than 10 km have negligible absorption and scattering of energy along the observation path, which produce stronger echoes for enhanced detection (Vaughn 1985).

Enhanced target imaging and greater resolution is achieved through the design of the antenna. The antenna determines the type and shape of beam that is produced by the transmitted energy (Bruderer 1997). The longer the antenna, the narrower the beam width, which yields greater detailed target data (Bruderer 1997). Narrower beams are ideal for detecting small targets as it divides the sweep area along its horizontal plane into smaller sections. This allows for the detection and tracking of small individual movements. The pulse length further enhances target imaging, as shorter, more frequent pulses in conjunction with narrower beam widths provide greater resolution (Bruderer 1997). Greater resolution reduces the size of the resolution cells. The beam is divided into many resolution cells along its radius as it rotates 360°. These individual pockets of airspace are surveyed for targets. Smaller cells allow targets to be separated into individual organisms when applicable (Bruderer 1997; Van Gasteren et al. 2008); however, target height, range, or angle may still restrict the detection of individual organisms (Wolff 2009). Height acquisition allows targets at different altitudes within the same resolution cell to be separated out into individuals (See Section 2.5.3. and Figure 2.7). The radar's angular resolution and range resolution also helps to enhance individual detection. These system parameters outline the minimum angle and minimum distance necessary for the radar to distinguish targets at the same range or along the same bearing respectively (Wolff 2009). A smaller angular resolution and/or range

resolution provide more opportunity to separate individual organisms. The radar parameters shown in Table 2.1 compares the EchoTrack System with other radar surveillance systems used for biological studies and outlines how the EchoTrack radar was designed to detect individual targets.

Table 2.1. A comparison of the EchoTrack’s radar parameters to other surveillance radar used for biological studies (Richardson 1976; Gudmundsson 1993; Mabee et al. 2006).

Radar parameter	The EchoTrack radar parameters	Other surveillance radar
Transmitter frequency ^a	9148 MHz	9410 MHz
Peak power ^b	25 kW	10-15 kW; 150kW
Band of frequencies	X-band	X-band; C-band; S-band
Wavelength ^a	3.2 cm	3.3-10 cm
Antenna	1.8m, slotted waveguide	2m slotted waveguide
Antenna rotation ^{ab}	48 rpm	12.5, 25 rpm
Antenna sweep ^{ab}	1.33 sec	2.5-3sec
Antenna polarization ^b	Elevated from horizontal	horizontal
Horizontal beam width ^{ab}	0.5°	1.2°; 2.2°
Vertical beam width ^a	24°	22°-25°
Sidelobe	±10° of main beam	±10-20° of main beam
Pulse length ^b	0.05 μsec	0.07 μsec; 0.3 μsec
Pulses ^{ab}	3000/sec	
Range	2 km	1.5 km; 10 km; 75 km
Range accuracy ^b	7.5 m	10-30 m
Range resolution ^b	2.498 m	
Angular resolution ^b	0.158°	

^aParameters that have changed from Millikin 2001 due to operational changes and modification of the radar hardware and software since its initiation

^bParameters that provide the EchoTrack System with higher and greater resolution for data acquisition

The EchoTrack radar is a transceiver, both transmitting and receiving signals. It was designed to maximize individual organism detection and operates with a peak power of 25 kW. This power is greater than most surveillance radars used for biological studies (Table 2.1). It produces a shorter pulse length (0.05 μsec) that generates 3000

pulses per second. This short pulse length increases the accuracy of the target parameters, such as target location, range, and speed to aid with target identification (Millikin 2001; Mabee et al. 2006). The radar's antenna consists of a 1.8 m tilted, slotted antenna with a horizontal beam width of 0.5° (Millikin 2001). The antenna is similar to a fan beam radar and transmits energy in a combined waveform as it sweeps across the sky every 1.33 seconds. The tilted antenna reduces ground clutter; while side lobes allow targets to be detected near the ground (Figure 2.5). The tilt of the antenna and the radar's large vertical beam width in combination with a neutral regression algorithm and/or azimuthal bins allows for the acquisition of altitudinal data simultaneously with horizontal data (Millikin and Buckley 2001). Most surveillance radars are incapable of determining target height as they only operate along a horizontal plane (Gudmundsson 1993; Mabee et al. 2006). The modification of the EchoTrack antenna surveys both the horizontal and vertical plane simultaneously to provide four-dimensional flight path information (X, Y, Z coordinates over time). This is exclusive to other biological radar studies. The antenna's faster rotation speed in combination with the antenna length and narrower horizontal beam width is optimal for tracking small individual organisms and their small movements across the sky. This system is similar to other surveillance radars used for biological studies; however, it provides higher resolution for individual target detection and greater accuracy for target parameters acquisition (Table 2.1). The integration of radar and acoustic data allows for the passive monitoring of small organisms and provides high spatial accuracy for target detection and the identification of free-flying organisms.

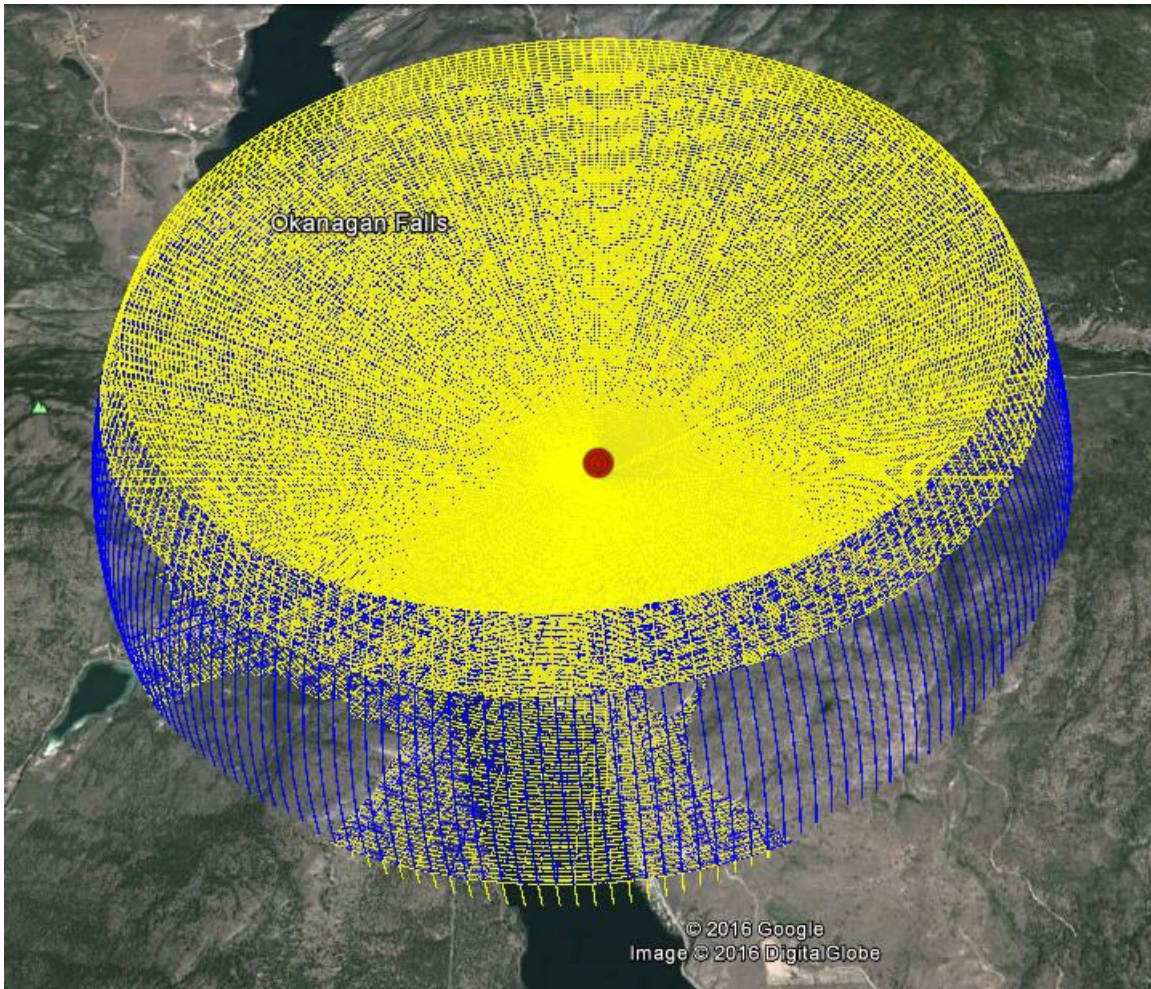


Figure 2.5. The EchoTrack radar beams and side lobes for a 2 km sampling radius shown for the radar’s location at Site 1; image provided by EchoTrack Inc. Blue indicates the location of the main beam, whereas yellow shows the top and bottom sidelobes.

2.5. Radar challenges and limitations

Biological radar studies provide an overview of the activity occurring in the area but only represent relative values. It is important to note that no absolute number of organisms can be obtained. The number of targets or tracks detected is a function of target detectability. Radar signals can be impeded by site conditions resulting in a single organism being responsible for multiple targets or tracks as it flies in and out of the radar’s field of view. Conversely, multiple organisms could be classified as a single target when they occupy the same resolution cell (see Section 2.5.4). Radar studies

assume that the radar samples all taxa equally, including all organism size classes, and that these are all equally abundant at each range surveyed by the radar (Van Gasteren et al. 2008). Radar use for biological studies has many advantages that have been previously discussed; however, radar also has many challenges that are associated with any biological study. These challenges include:

1. Identifying individual targets from each other, and from the background clutter (Sections 2.5.1, 2.5.3, and 2.5.4).
2. Identify the study species (Section 2.5.4). Target identification cannot be achieved with radar alone but must be supported with another sampling technique. Target identification and classification is also supported with inference based on a general understanding of the organism's habitat preferences and ecology.
3. Obtaining relevant target parameters with enough detail for the identification of individual target trajectories (Sections 2.5.3 and 2.5.4). Target parameters (relative size, speed, flight characteristics, etc...) recorded are estimates of the true value for all targets detected; radar studies assume these to be accurate and representative.
4. Dealing with the circumstances pertaining to the operation of radar at sites with undulating terrain (Sections 2.5.1 and 2.5.2). For example, mobile radar systems must be placed in a suitable location for the correct operation of the radar as this will limit the survey area and affect target detectability.
5. Incorporating weather data for the acquisition of target parameters (Section 2.5.6). Target parameters rely on the incorporation of accurate weather data that should be obtained from a reliable source and should be representative of the study area and sampling times.

The identification of biological organisms is the most challenging aspect of any biological radar study (Hajovsky et al. 1966; Vaughn 1985; Larkin 1991; Gudmundsson 1993; Mabee et al. 2006; Martin and Shapiro 2006; Chilson et al. 2012b). Separating biological targets from non-biological targets is accomplished in the processing phase and is based on the movement, speed, and size of the targets. Very few misclassifications of biological and non-biological targets result (Richardson 1976; Cryan and Diehl 2009); although in rare incidences birds have been mistaken for aircraft or ships (Lack and Varley 1945). Separating out biological targets is feasible for taxa with considerable size differences or with different flight patterns (i.e. soaring raptor vs. seabird vs. passerine). However, it is especially difficult to separate taxa and species of similar size (i.e. small birds vs. bats vs. large insects) (Richardson 1976; Vaughn 1985;

Larkin 1991; Millikin 2001; Martin and Shapiro 2006; Cryan and Diehl 2009). For radar studies assessing bat activity, songbirds and large insects are of greatest concern as their size and speeds overlap (Cryan and Diehl 2009).

The radar, study design, and analyzing criteria used should aim to minimize radar challenges. However, in addition to the radar challenges outlined, external factors also act on every radar study. These external factors affect both target detection and target identification and must be considered with every project. These include: (1) clutter and noise, (2) radar location, (3) target range, (4) target reflection, (5) radar interference, and (6) the weather during operation. The common radar challenges seen with any biological study are reviewed in the following sections and are associated to the external factors affecting target detection and identification. These sections also include a discussion of how the EchoTrack System deals with the challenges and external factors when its approach is unique to other radar. In addition, I discuss how my study and methods aimed to minimize their effects and evaluate the performance of the EchoTrack system for my study.

2.5.1. Radar location: Clutter and noise

Unwanted echoes (noise) from any landscape features results in a large amount of clutter that must be filtered out. In addition, any target flying adjacent to landscape features are missed when the clutter mutes their reflectivity. To increase target detectability with mobile radar, the radar should be positioned to maximize the landscape surveyed while minimizing obstacles and clutter. To enhance target detection in high clutter areas, the operator must use a radar system with sufficient power to detect and continually monitor an organism's flight path. The EchoTrack radar has a threshold for detecting targets within or adjacent to clutter and only detects targets that have a reflective strength above this threshold. The tilt of EchoTrack's antenna also helps to reduce ground clutter.

In addition to ground clutter, atmospheric components such as insects, pollen, spores, dust, and smoke are detected with radar and will account for atmospheric clutter (Horn and Kunz 2008; Westbrook 2008). These undesired targets generate unwanted noise that must be filtered out as they will affect the detection of the desired target.

Atmospheric clutter generated by particles and organisms without powered flight is of little concern. These atmospheric components will drift with the wind and can be easily removed by incorporating wind data into the processing phase. In biological radar studies assessing bird and bat movements, noise generated from insects with powered flights pose many challenges for target identification as these cannot be easily separated out from the desired targets. Most small insects and migrating insects can be removed with wind data as their speed and direction often correspond with the wind (Vaughn 1985; Verboom and Huitema 1997; Millikin 2001; Diehl and Larkin 2005). However, insects that fly upwind and have flight speeds that overlap those of birds and bats will contaminate the data (Riley 1975; Larkin 1991; Smith et al 1993; Mabee et al. 2006; Martin and Shapiro 2006). In my study, I only assessed targets with powered flight having speeds greater than 4 m/s. This excluded small insects and insects with slow flight speeds from my analysis (See Section 2.5.4.1).

2.5.2. Radar location: Undulating terrain and zero-detection zones

In most biological radar studies, the radar often misses low-flying targets as they fly under the horizontal beam due to the earth's curvature (Diehl and Larkin 2005). The effects of topography at sites with undulating terrain therefore provide a large challenge for biological studies. The topographic relief at these sites have vertical barriers where targets are missed. These areas are known as zero-detection zones. Zero-detection zones further reduce the radar sampling volume and its range (Figure 2.6). In addition to terrain, zero-detection zones are also created by buildings, other manmade structure, trees, or dense vegetation through which radar signals cannot penetrate. Zero-detection zones and targets flying above or below the radar beams create breaks in radar tracks, giving the impression that flights start or stop suddenly. All of my study sites were located within undulating terrain. This restricted the trailer's location within my vineyard plots as the levelling of the equipment required that I situate the trailer in a relatively flat area (See Section 2.2.1). This was not optimal for reducing clutter or minimizing obstructions from the surrounding terrain, vegetation, and infrastructure. The creation of kml files and the use of GIS with EchoTrack's data provided me with an overview of zero-detection zones within each of my study sites (Figure 2.6). This allowed me to

calculate the area of land that was surveyed for bats within my 1 km sampling radius. On average 58.2 % of my sampling radii were surveyed for bat activity.

The relief within my 1 km sampling radii resulted in ground elevations differences of 95 m to 266 m. The elevation differences over vineyards were 20 m to 90 m from the radar elevation; whereas elevation differences over natural habitat had a greater variation (15 m to 200 m). The undulating terrain at my sites made it difficult to assess the target height parameter. The output files I used for analysis provided only the height at the start of the track. By using the first height, important information may have been missed, as bats will change their altitude when searching for prey. I positioned the radar within my vineyard plots, which were at lower elevation than the surrounding gneiss cliffs that contained potential maternity colony roosts. If the radar's first detection of a bat trajectory occurred after emergence and the radar's view was uninterrupted by the terrain or clutter, the target height would be overestimated if the bat descended from the cliff to fly along or among the vegetation. Any habitat surveyed upslope of the radar would have ground heights less than the start height assigned to the track and therefore targets would be more associated with the habitat than any areas surveyed downslope of the radar. In addition, the GIS mapping program I used was incapable of extrapolating track position over ground elevations to give a track start height relative to the ground, as such all start track heights are heights relative to the radar antenna. Mapping programs such as MapInfo is capable of providing this detail; however I did not have access to this program. Any habitat association project using radar should invest in such a program to provide more accurate detail of flight trajectories across the habitat surveyed.

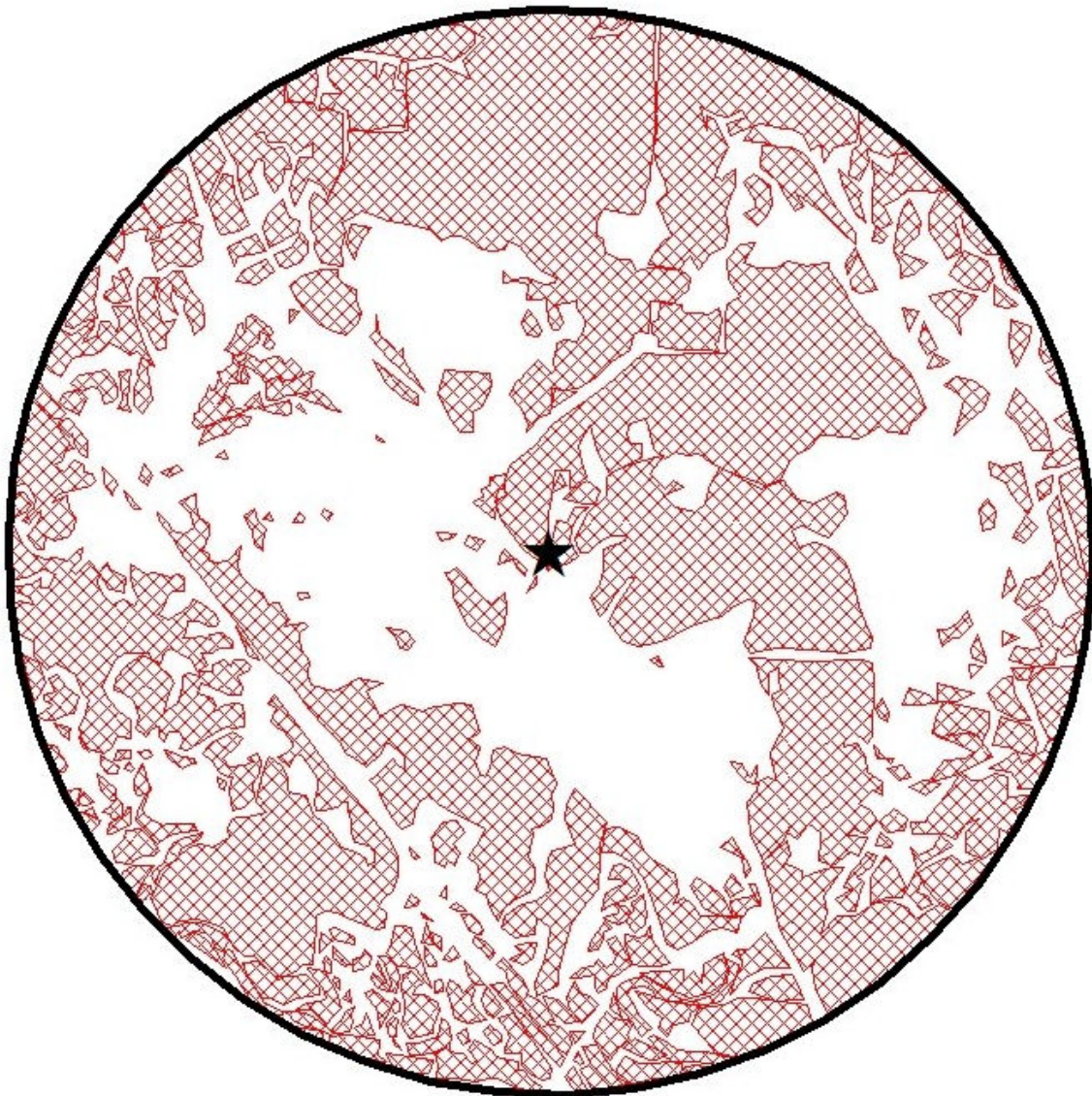


Figure 2.6. An example of the zero-detection zones (red hatched areas) that were not surveyed for bats at one of my sites due to obstructions from the landscape and buildings. The position of the radar is shown by the star and the circle denotes the 1 km sampling radius.

2.5.3. Target range

Radar can detect targets out to many kilometres; however, target detection decreases by the 4th power based on the radar's beam width and the target's range (Gauthreaux and Belser 2003; Van Gasteren et al. 2008; Wolff 2009; Chilson et al. 2012a). Furthermore, individual organisms cannot be detected beyond a few kilometres

of the radar as the size of the resolution cell increases exponentially with distance. Beyond a few kilometres, multiple organisms occupying a single resolution cell would account for a single target. Van Gasteren et al. (2008) reported that the detection of individual large birds using a C-band Doppler weather radar is best within 4.5 km of the radar. To increase target detection, the radar sampling volume must be set to a radius or range that optimizes the detection of the desired target. Biological radar studies assessing the behaviour and flight characteristics of large individual organisms should not exceed 4.5 km, and this distance would need to be less for smaller organisms. EchoTrack's operation manual suggests that the sampling radius be no greater than 2 km for small passerine birds and 4 km for large birds. This range corresponds with Van Gasteren et al. (2008) findings, and therefore optimizes the detection of individual targets.

The size of the resolution cells and EchoTrack's height parameter further help to differentiate individual targets across the sampling radius (Table 2.2 and Figure 2.7). The EchoTrack beam contains 266 resolution cells at a given point as it sweeps across the sky. These cells have a narrow cell width and a wide cell height, which accommodate for the detection and movement of individuals across the sky. The cell width associated with EchoTrack's radar beam increases from less than 1 m at 100 m from the radar to approximately 18 m at 2 km. These small widths allow the radar to sweep numerous cells along the horizontal beam with every rotation. EchoTrack's large cell height increases to 1668 m at 2 km. This allows for a large volume of air to be sampled within each cell to ensure that the trajectories of individual organisms flying through different altitudes will not be lost. EchoTrack's height parameter also permits individuals within the same resolution cells to be separated and detected individually when flying at different altitudes (Figure 2.7). EchoTrack's resolution cell depth of 7.5 m is consistent across all ranges as it is a function of the pulse length and not beam width (Weik 1989).

Table 2.2. Resolution cell dimensions for the EchoTrack System.

Distance from radar (m)	Cell depth (m)	Cell width (m)	Cell height (m)
10	7.5	0.09	8.34
50	7.5	0.44	41.72
100	7.5	0.88	83.44
200	7.5	1.75	166.88
300	7.5	2.63	250.32
400	7.5	3.51	333.75
500	7.5	4.39	417.19
600	7.5	5.26	500.63
700	7.5	6.14	584.07
800	7.5	7.02	667.51
900	7.5	7.89	750.95
1000 ^a	7.5	8.77	834.38
1500	7.5	13.16	1251.58
2000	7.5	17.54	1668.77

^aSampling radius used in my study

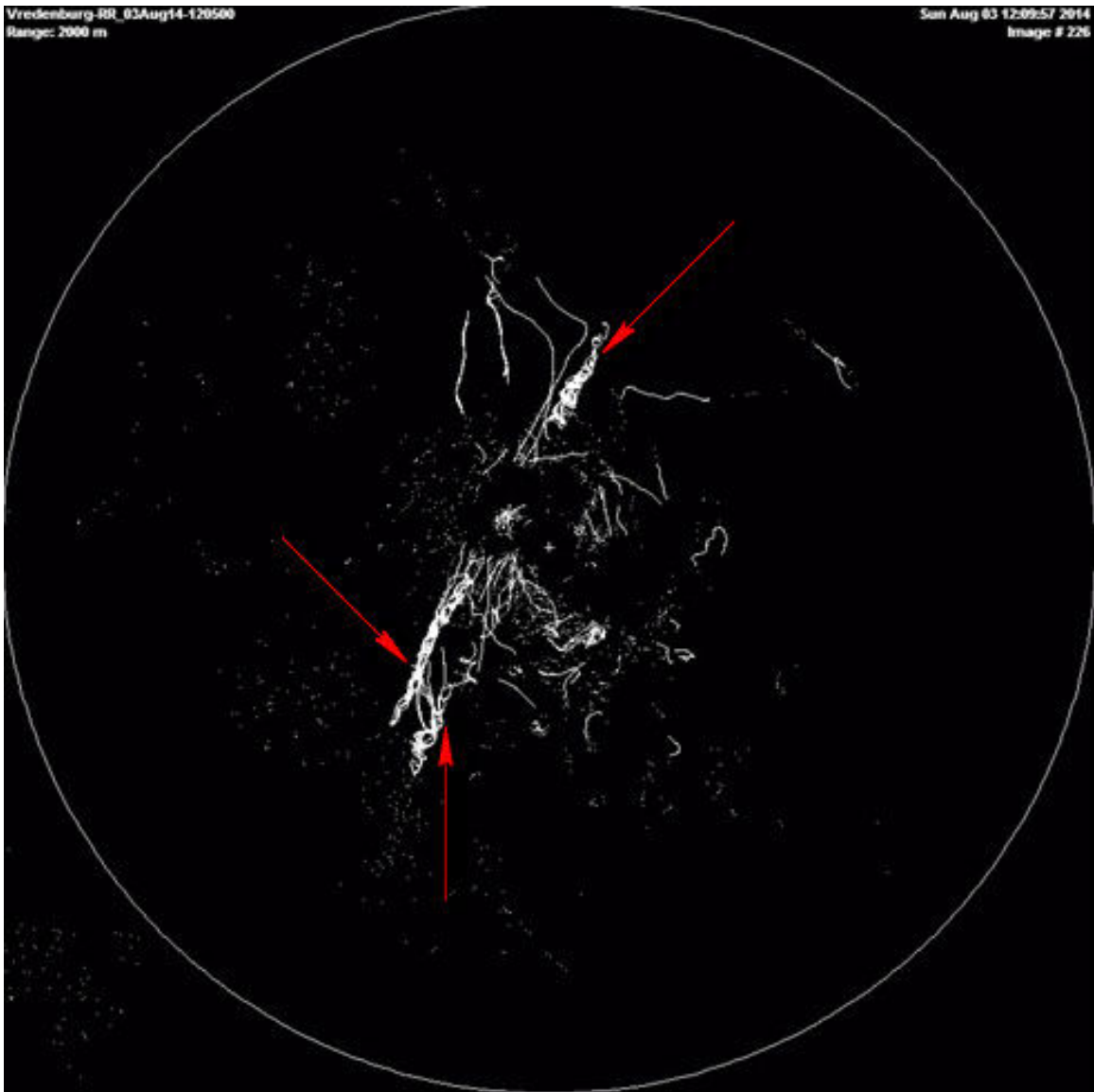


Figure 2.7. Image showing the vertical separation of multiple airborne animals within the same resolution cell that were identified as separate targets due to their height. This image is from another EchoTrack project and shows three sets of overlapping flights (red arrows).

In addition to the size of the radar sampling radius, target detectability is also reduced within close proximity to any radar. Targets within the operator safety buffer (generally 10 m – 15 m from the unit) cannot be detected. The main effect of the safety buffer would be a break in target trajectories as targets move towards and away from the radar.

2.5.4. Target reflection and species identification

The reflective property of a target allows the radar signal to perceive a target and produce an echo. The reflective strength or intensity of the echo provides a relative measure of target size. In most biological radar studies, this is described as the target's radar cross-section (RCS). For biological targets, it is measured in squared centimetres and is based on a spherical water droplet of similar mass. The RCS of mammals and birds is a function of the amount of water in their blood and tissues; whereas the RCS of insects is proportional to the amount of chitin in their exoskeletons. A range of RCS values have been determined for many organisms for reference in biological radar studies and are shown in Table 2.3 (Riley 1985; Vaughn 1985; Martin and Shapiro 2006).

Table 2.3. Radar-cross section values defined for birds and insects taken from Riley 1985, Vaughn 1985, and Martin and Shapiro 2006.

Biological organism	Radar-cross section
All birds	0.1 cm ² - 1000 cm ²
Most bird species	1 cm ² – 100 cm ²
Most passerines	10 cm ² - 31 cm ²
Swallows ^a	2.47 cm ²
Insects	0.000001 cm ² - 10 cm ²
Moth / butterflies	0.01 cm ² - 10 cm ²

^aRCS values could not be found for bats; however given the size of North American bats and their flight characteristics, RCS values are expected to be similar to that given for swallows, and would therefore overlap with birds and insects.

The EchoTrack System uses Signal-to-Noise Ratio (SNR) to provide a size estimate for targets. As with RCS, this value is also a measure of reflected energy; however the two values cannot be compared directly. SNR values result from the intensity of reflected energy off the target above the background reflection from the vegetation or terrain (noise). It is calculated using the sum of intensity values of the pixels in the target echo. Targets are detected irrelevant of their orientation; however, they are best detected broadside to the radar's antenna as this increases the surface area of the target's reflective properties. Broadside targets have greater RCS/SNR values than the same targets detected head-on or end-on to the radar. For optimal

detection of targets, the EchoTrack System is positioned to maximize the detection of echoes from broadsided targets where possible by considering expected flight paths. The RCS values listed in Table 2.3 show a wide range of values for the organisms listed, as well as overlaps between birds and insects. These overlaps would be also seen with SNR values as SNR would also vary with target orientation, distance, and behaviour (Riley 1985; Vaughn 1985; Larkin 1991). Taxa cannot be classified simply from their RCS/SNR values. In order to correctly identify biological targets, biologists must have a general understanding of the organism's behaviour, flight characteristics, habitat preferences, and ecology (Vaughn 1985; Larkin 1991; Millikin 2001; Diehl and Larkin 2005; Horn and Kunz 2008; Cryan and Diehl 2009; Chilson et al. 2012b). In addition, radar data must be supported with visual/audio ground-truthing techniques, such as visual observations, photography, and/or acoustic arrays (Parslow 1969; Williams et al. 1973; Larkin 1991; Gudmundsson 1993; Gauthreaux 1996; Millikin 2001; Diehl and Larkin 2005; Horn and Kunz 2008; Cryan and Diehl 2009; Chilson et al. 2012b). The EchoTrack System provides simultaneous sampling of acoustic data with the radar operation to help identify airborne organisms.

To assess the quality of the SNR values obtained at my sites, height, speed and range were plotted against SNR to understand how the distribution of SNR values varied with each of these track parameters. No relationships were seen between height or speed and SNR; however one was seen with range. A range bias with respect to SNR values was expected as target detection decreases with range due to a decrease in radar sensitivity (Gauthreaux and Belser 2003; Horn and Kunz 2008; Van Gasteren et al. 2008; Wolff 2009; Chilson et al. 2012a). Small targets are not detectable beyond a certain distance from the radar. I used a radius of 1 km to ensure that the radar sampled all bat species equally at my sites.

2.5.4.1. Study specifics: Species identification

Tracks detected with any radar would include any nocturnal animal using the airspace as it is difficult to differentiate bats from small birds or large insects (Richardson 1976; Vaughn 1985; Larkin 1991; Millikin 2001; Mabee et al. 2006; Martin and Shapiro 2006; Cryan and Diehl 2009). I used the EchoTrack system to collect and process data on the use of vineyard and natural habitat by bats in the South Okanagan. I used

EchoTrack software to process the raw radar data and used JMP 11.2.0 to filter through the data to exclude tracks that represented non-biological targets, and to reduce noise from birds and insects. I used the following criteria to determine if a track would be included in my analysis and to help identify the targets as bats. To discriminate between biological taxa, I used speed and size thresholds from the literature. These criteria provided the basis for identifying tracks as bat activity, which was further validated by comparing radar data with the acoustic data collected.

1. I excluded any track having an average target speed, adjusted for wind, greater than 15 m/s. These speeds exceed the maximum recorded flight speeds determined for bat species residing in the South Okanagan and would also exclude fast flying birds (See Chapter 1 Section 1.1.1).
2. I excluded any track having an average target speed, adjusted for wind, less than 4 m/s to reduce insect noise.
3. I excluded any track that was assigned a SNR value less than 0.01, as many of these tracks would represent small targets such as insects.
4. I excluded any track that was not assigned a height, as the echo at the start of these tracks would have had reduced resolution.
5. I excluded any track with its entire length outside of the 1 km sampling radius to reduce noise from non-biological targets and biological targets larger than bats. This also ensured that all insectivorous bat species in the area were equally sampled, as species such as the western small-footed myotis (*Myotis ciliolabrum melanorhinus*) would not be detected out to 2 km due to their small size (weigh of 3 g – 6 g).
6. If tracks contained segments both within and beyond the 1 km sampling radius; I included the track segment if it had a minimum of 3 sequential track points that were within the 1 km radius, as this criterion defines a track.

With respect to speed threshold, I used wind-adjusted speeds to ensure I only included organisms with powered flight. To reduce tracks created by birds, I chose a maximum speed filter of 15 m/s based on literature. The maximum speed of bats in Canada has not been studied; however the study of bat flight speeds worldwide suggest that exclusion of tracks greater than 15 m/s would not exclude any bats (Patterson and Hardin 1969; Findley et al. 1972; Morrison 1980; Nagorsen and Brigham 1993; Grodzinski et al. 2009), but would exclude fast flying birds. The maximum speed filter

would also account for the variation of flight speeds recorded for bat species observed in an enclosure in the United States that are found in the South Okanagan (See Chapter 1 Section 1.1.1) (Patterson and Hardin 1969).

I also minimized the challenge of separating birds from bats by timing my study at night and not during migration but within the bird breeding season (nights sampled: June 28th – August 12th), which would correspond to a period of minimal bird activity. Early passerine migration may have been detected in early August; however migrating birds would likely be restricted to flight paths along the side of the valley and altitudes above the bluffs and mountain tops. A small percentage of tracks over vineyard and natural habitat had heights within the elevation range of the rock bluffs (See Chapter 3, Section 3.2.1 and Figure 3.4). Little information is available for flight speeds of birds during their breeding season; however radar studies during spring and fall migration when birds are commuting and not interacting with ground vegetation, recorded average flight speeds between 9 m/s and 14 m/s (Parslow 1969; Bruderer and Boldt 2001; Nilsson et al. 2014). Bruderer and Boldt (2001) observed multiple bird species and guilds and reported warblers and robins as the slowest flyers, with flight speeds as low as 6 m/s. Although these two species are present in the South Okanagan, they are not nocturnal insectivores and would not be active during the night. Hedenström and Ålerstam (1995) indicated that migration speeds average around maximum range speed (V_{mr}) and predicted that birds flying between food patches or transporting food to young would fly at greater speeds than V_{mr} . This suggests that any nocturnal bird activity recorded at my sites would have speeds averaging greater than 9 m/s. Of the bird species potentially active at night at my sites, two goatsucker (*Caprimulgidae*) species, nighthawks and poorwills, were of greatest concern. Nighthawks have been seen foraging alongside big brown bats in the South Okanagan (Fenton et al. 1980; Aldridge and Brigham 1991) and may forage throughout the night under moonlit conditions (Mills 1986). Goatsuckers are lunarphilic and forage by visual cues seeking backlit insects in the moonlight (Mills 1986), whereas many insectivorous bats are lunar-indifferent (Leonard and Fenton 1983; Negraeff and Brigham 1995; Vaughan et al. 1997; DiSalvo et al. 2009). I did not have an effect of percent moon illuminated or the length of time the moon was above the horizon on the tracks detected ($m/m^2/min$), suggesting that most goatsuckers were removed with the filters used.

To reduce noise from insects I used a minimum speed filter. A minimum threshold of 6 m/s is commonly used to differentiate insects from birds (Larkin 1991; Mabee et al. 2006); however the separation of insects and bats is more challenging as bats fly at much slower speeds than birds and overlap a great deal with insects. For example, little brown myotis (*Myotis lucifugus*) has been recorded flying as slow as 2.2 m/s when foraging, whereas individual moths have been recorded flying at speeds averaging 3.1 m/s to 4.5 m/s (Hayward and Davis 1964, Drake et al. 1981 cited in Larkin 1991; Westbrook 2008). Some species of bats and moths have been detected beyond 1 km from the radar. To aid with the detection of bats in my study, I used a speed filter of 4 m/s. Although this speed threshold would have excluded potential foraging bats, it also removed many echoes generated by small and/or slow flying insects (Smith et al. 1993). Some overlap in bat and insects speeds would however still exist as insect flight speeds have been recorded up to 10 m/s (Larkin 1991).

With respect to size, a size filter of SNR less than 0.01 was used to remove small targets. This threshold would have removed noise from insects, as well as removed smaller bat species, especially those orientated head-on or end-on to the radar. Given the range of SNR values seen in my raw data prior to size thresholding (0 - 99941), the range of SNR values given for tracks analyzed over my study sites (0.01 – 40.7) would represent small biological organisms such as bats, birds, and insects. With respect to the size threshold, large insects and songbirds are within the size range of bats. I eliminated songbirds by selecting a season when these birds are not active at night. Furthermore, any songbird movements would have been constrained to short-distance flights within the vegetative canopy, where the radar would not be able to detect them due to clutter. The radar data may include insects, however as the bats in the South Okanagan are insectivores and many species are generalists, bat activity would be directed towards the areas with insect activity.

To further assess the proportion of radar tracks associated with bat activity, I used three methods to compare the density of tracks detected at my sites with the number of Individual Bat Passes (IBPs) recorded. Method 1 calculated the percentage of IBPs recorded (1817) to total number of tracks (78633) analyzed over the habitats (2.3 %) and compared this with the percentage of area sampled by the microphones (94250 m²) versus the area sampled by the radar (8470000m²) (1.1%), which both

accounted for zero-detection zones. Method 2 compared the number of IBPs recorded in the plots (1817) with the number of tracks detected within my acoustic plots (2287). Finally, Method 3 compared the proportion of total detection (IBPs + tracks) to determine if each track was associated with an IBP, which would be indicated by a ratio of 50 %. The results of the last method was variable but indicated that tracks were underrepresented as more calls were detected than tracks within my sampling plots (ratio of 63 %; SD 34 %). All three methods of comparing radar and acoustic data suggest that the majority of the tracks analyzed represented bat activity. The tracks analyzed had parameters representative of all bat species found in the South Okanagan based on literature and personal communication with biologists having worked with the bat species in my study area (See Chapter 3 Section 3.2.1). The timing of my study, filtering criteria used, and the speed and size thresholds applied were capable of discriminating bats and minimized noise from birds and insects.

2.5.5. Interference

There will always be some loss of target detection with interference as this includes the spillover from the radar transmitter itself and any thermal noise generated from electron agitation (Wolff 2009). Spillover cannot be avoided; however, the radar's sensitivity can be adjusted to minimize its effects. Electromagnetic interference from outside sources is also a concern. This includes electromagnetic radiation emitted by nearby radar systems, communication towers, power lines, jammers, electronics, thunderstorms, and solar flares. Electromagnetic interference generated by electronics includes bat detectors, generators, computers, and computer cables. Electromagnetic interference can create zero-detection zones where no targets or tracks are detected (See Section 2.5.2). To minimize electromagnetic interference, the radar should be situated away from other radar systems, power lines, and communication towers. Furthermore, the interference from any other electronic equipment required on site should be identified and minimized.

Interference was detected at one of my sites and is believed to have been caused by a frost tower. The ether cables and power cords running from the trailer to the microphone arrays did not cause interference at any other site; however, it is believed that the added electromagnetic interference generated along the cutline for the

frost tower caused the break in tracks seen over the acoustic arrays (Figure 2.8). This interference was not anticipated at the start of the study.

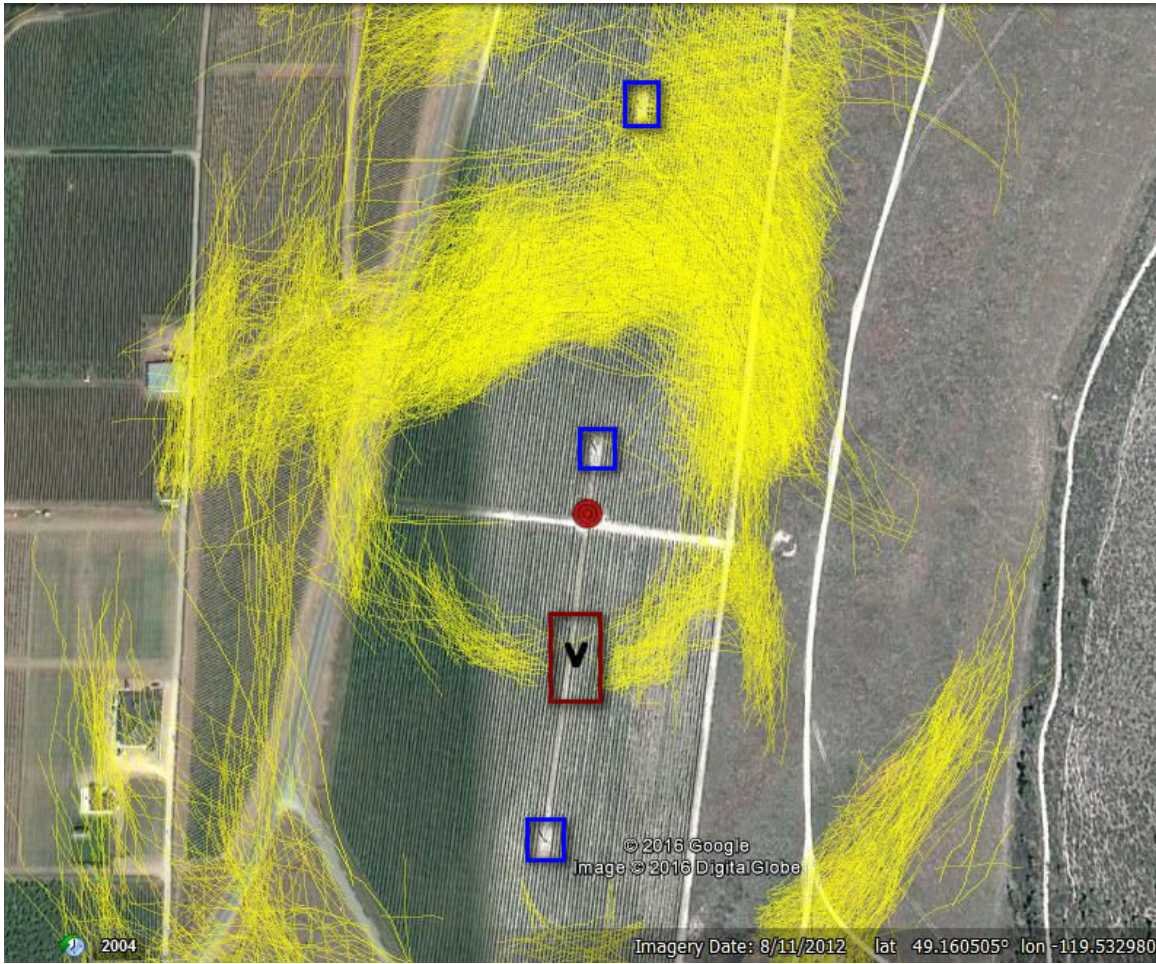


Figure 2.8. Interference seen along the frost tower cut line causing a break in the radar tracks (no track trajectories seen within burgundy rectangle); note no interference occurred at the frost tower north of the radar. Imagery was created by importing kml files into GoogleEarth and shows the location of the radar (red circle), microphone array (V), radar tracks (yellow lines), and frost towers (blue rectangles).

2.5.6. Weather

Radar can be used in inclement weather; however, target detection is only achieved when the target is flying in a different direction and at a different speed than the prevailing precipitation (aka noise). To obtain reliable target echoes and target parameters, weather parameters, especially wind, must be obtained during the study

and incorporated into the processing phase. The incorporation of weather data should be obtained from an accurate and reliable source and should be representative of the study area and sampling times. The radar's frequency and its associated wavelength can help to reduce the effects of precipitation; however, biological radar studies are most often conducted during clear-air conditions. Bat radar studies using NEXRAD and mobile radar in the US make inferences about bat activity using weather data from stations 25 km to 100 km away (Chilson et al. 2012a; Kelly et al. 2012). Weather stations used in my study were located 10 m to 17 km from the radar's location, and therefore, followed the same protocol of other bat studies. Most weather stations measure weather variables at one location and represent weather at the height of the recorder. This has minimal effects on target parameters as only temperature and humidity vary with altitude (H. Dagenais, personal communication, September 15, 2014). For my study, weather data were obtained from two local Environment Canada (EC) stations and from three vineyard weather stations. The EC weather stations in the South Okanagan represent weather for a 30 km – 50 km area as elevation grades are less than 610 m (H. Dagenais, personal communication, September 15, 2014). Two of the vineyard stations were located within my study plots, which would account for local weather effects and any effects from frontal passages at these sites.

Weather data at EC stations were averaged hourly as there is little change in weather parameters during this period outside of frontal passages (H. Dagenais, personal communication, September 15, 2014). Each reading given for a specific time does not give actual data for that time but infers an average from the previous time to the current time. For example, the averaged weather data given for 22:00hr would represent an hourly average of each weather parameter between 21:00 and 21:59hr. The vineyard weather stations recorded weather data every 10 minutes to 15 minutes and represented actual time data or the average data from the previous time interval. The incorporation of weather data into the EchoTrack software was challenging for my study as I used weather data from five different weather stations. These data came in different forms (15 min intervals versus hourly intervals), used different collection methods (real-time data versus average data), collected data at different times than my SIs, and collected different weather parameters. However, all the weather stations recorded wind speed and wind direction, which was crucial for my analysis. Despite

these challenges, the EchoTrack System was capable of using data from different weather stations for my project. Once the data were entered into EchoTrack's software, the software designers created algorithms for each weather station based on their form and collection method to average weather data for each of my SIs. The software program then used this average wind data in the processing phase to adjust target speed, velocity, direction, and change in direction. Following processing, weather text files were created, which allowed me to verify the weather data used for each of my SIs. Errors associated with weather data can be easily missed if the operator fails to acknowledge how weather data are collected. Any false representation of wind data would provide incorrect target parameters.

The EchoTrack System was capable of dealing with the radar challenges and most of the external factors affecting target detection. The five common radar challenges identified were overcome by the design of the EchoTrack System, as well as processing and analyzing criteria. Challenges 1, 2, and 3 pertaining to target classification and identification were aided by speed and size thresholds, as well as the acoustic arrays which recorded data simultaneously with the radar system. In addition, these challenges were handled by making inferences based on an understanding of the ecology of the organisms in the area. Challenge 4 created numerous zero-detection zones; however these zones were taken into account with regards to my analysis (See Chapter 3). Finally, Challenge 5 was not an issue as weather data from onsite and offsite weather stations were used and incorporated into the processing phase to refine target parameters. This ensured that the target parameters included wind-adjusted speed and that the tracks analyzed were only from targets having powered flight.

2.6. Study challenges associated with the acoustic array

The EchoTrack System was designed to work with two sets of acoustic arrays to record both bird and bat calls; however I only used the omni-directional bat sensors in my study. Two acoustic bat sensor arrays were setup in two different habitats (vineyard and natural). During my study, I faced three challenges using the EchoTrack omni-direction bat sensors. These challenges included:

1. Setting up the acoustic arrays at sites with undulating terrain.
2. Operating EchoTrack omni-direction bat sensors within the vegetative canopy.
3. Dealing with saturated bat calls.

2.6.1. Undulating terrain

The location of the EchoTrack omni-directional bat sensors were limited by the undulating terrain found at my study sites. In addition, vineyard arrays were restricted by the trailer placement as they had to be within 100 m of the trailer. The location of the acoustic arrays is important as they only sample a small subset of the radar sampling volume. For my study each acoustic array sampled 7854 m², based on a sampling radius of 50 m, vs. 3140000 m² that could potentially be surveyed by the radar. Poor placement of the arrays restricted the number of calls that could be recorded and could have also misrepresented or underestimated the species in the area. In addition, vertical barriers due to topographic relief caused portions of the airspace around the acoustic arrays to be within zero-detection zones. Any acoustic array within the zero-detection zone had no track detection and therefore radar tracks and calls could not be associated.

To alleviate this challenge with other project using the system in undulating terrain, EchoTrack has designed a portable acoustic unit that runs independently of the trailer's power source and computer. This portable unit can be setup anywhere within the radar sampling volume, as it does not require a direct connection into the trailer. The data are easily transferred onto the trailer's computer once sampling is complete. In my study, the portable acoustic unit was used in conjunction with the trailer acoustic unit to allow me to sample two habitat plots (vineyard and natural) simultaneously. The undulating terrain had little effect on the placement of the bat sensors situated in the natural plots, but greatly affected my vineyard arrays. The radar trailer was positioned within the vineyards, and therefore the levelling of the antenna, the levelling of the bat sensors, and height placement of each microphone restricted where the trailer could be positioned. As a result, poor placement of vineyard acoustic arrays was seen (Figure 2.9).



Figure 2.9. An example of poor placement of the microphone array imposed by site topography on trailer placement (red circles) resulting in very few tracks and bat calls detected above the acoustic array (V) compared with the adjacent areas having higher track density.

2.6.2. Vegetative growth and saturated bat calls

Unlike EchoTrack’s bird microphones that are mounted on EMT conduit allowing their height to be adjusted, the height of the EchoTrack’s omni-directional bat sensors cannot be adjusted. These microphones must be secured to the top of survey tripods, and must all be levelled and positioned at the same elevation. This, in addition to the undulating terrain, greatly restricted the position of the EchoTrack omni-directional bat sensors within both vegetative canopies (vineyard and natural) at my sites. Furthermore, the vineyard rows also restricted the location of vineyard acoustic arrays. To accommodate for the surveying and levelling of the microphones within the vineyards, the acoustic array location and configuration was determined one month prior

to the start of my study before any vegetative growth. Throughout my study, the vines grew from their cordons to reach heights above 2.5 m above the ground. The amount of vegetative growth seen in the vineyards was underestimated. The effects of the vegetation were minimized in the natural plots where possible. The positioning of the EchoTrack omni-directional bat sensors, well within the vegetative canopy, greatly reduced the quality of calls recorded during my study. EchoTrack's omni-directional bat sensors provide higher quality calls in areas with low vegetative canopy as poor quality calls or saturated calls result from echoes from any surrounding vegetation. Saturated calls can also be produced from noise generated from insects, precipitation, wind, or other external sources, such as rattling equipment. The saturation of call files masked any bat calls within the noise (Figures 2.10 and 2.11). The saturated calls collected during my study were not automatically recognized by any acoustic analysis program. Each acoustic file was manually analyzed to determine the call parameters; therefore the number IBPs assessed, as well as calls from low-intensity calling species or buzzes may have been underestimated. The manual assessment of each waveform audio files was very time consuming. To minimize the saturation of calls, the bat sensors should have been placed above the vegetative canopy.

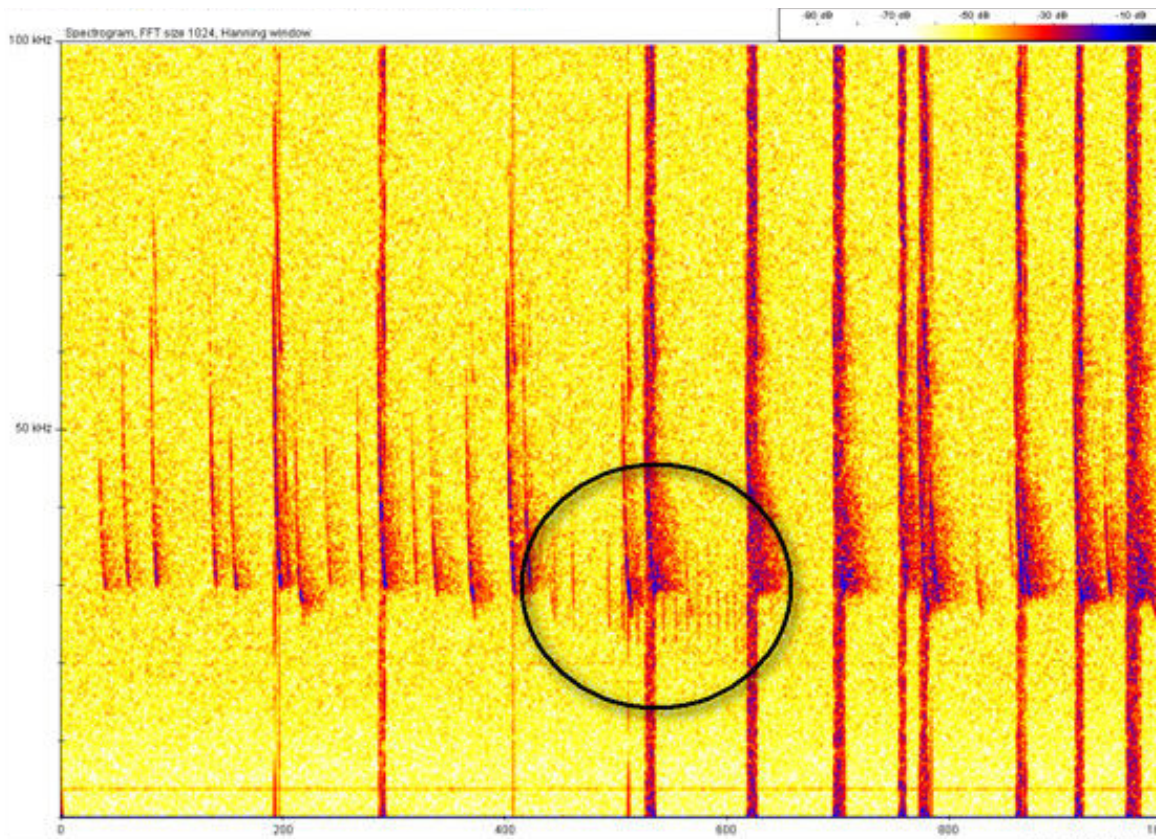


Figure 2.10. Spectrogram showing saturated calls recorded from multiple 25-35 kHz bats and an associated buzz (black circle).

Note: Frequency 0 – 100 kHz is on the y-axis, time in milliseconds in on the x-axis (0 – 1000 msec). The colour spectrum at the top right denotes call intensity and is measured in decibels (low-intensity (white) -70 dB to high-intensity (blue) -10 dB). BatSound's automatic parameter extraction feature could not detect any of these calls

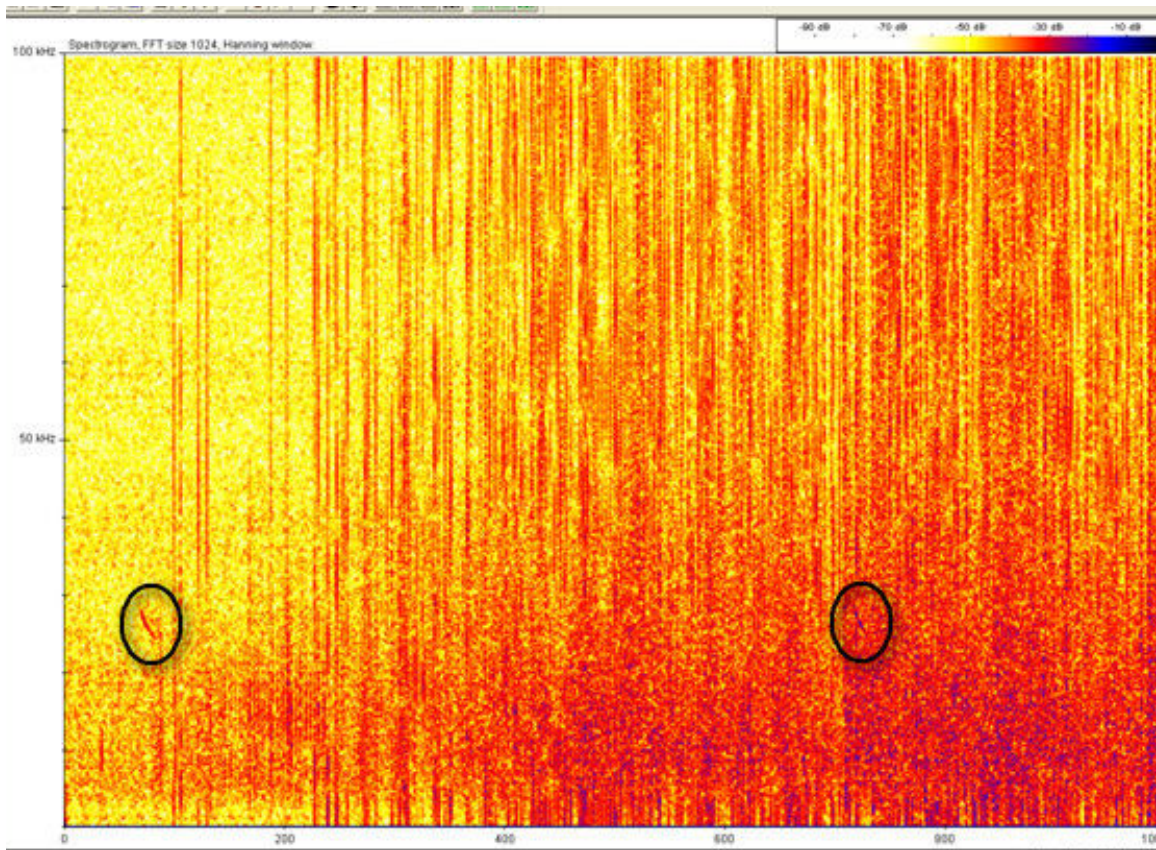


Figure 2.11. Spectrogram showing saturated calls (within the black circles) recorded from a 25-35 kHz bat during a thunderstorm.

Note: Frequency 0 – 100 kHz is on the y-axis, time in milliseconds in on the x-axis (0 – 1000 msec). The colour spectrum at the top right denotes call intensity and is measured in decibels (low-intensity (white) -70 dB to high-intensity (blue) -10 dB).

2.7. Recommendations for future studies and system improvements

EchoTrack's radar was in operation for nine years at the start of my master's. Many radar processing software upgrades and improvements have occurred and further upgrades will continue to improve the system and increase its efficiency and ease of use. The following outlines recommendations that should be considered based on the challenges faced during my study. These recommendations should be considered for any future project working in undulating terrain or assessing the habitat association of bats. These include:

1. Site reconnaissance to determine optimal location for both radar and acoustic arrays.
2. The use of both bird and bat acoustic arrays for target classification and identification.
3. Additional sampling to the radar-acoustic recording to aid with ground-truthing of target classification and identification.
4. Automated fusion of the radar and acoustic data.
5. The use of an onboard weather station for the direct association of weather and radar-defined track parameters.
6. Better quality bat calls with minimal saturation.

In addition to these specific study recommendations, I also recommend, the user of EchoTrack technology do additional in situ testing of the omni-directional bat sensors to determine the maximum detection distance for bat calls at different frequency and intensity in their environmental conditions.

2.7.1. Site reconnaissance

Due to the possible effect of vegetative growth on the trailer and microphone setup, a site reconnaissance should be done over all seasons. This pre-assessment should include one or two nights of radar-acoustic sampling and analysis to determine areas of high activity and travel corridors that could be sampled with the acoustic arrays. This would provide more detailed information and could maximize sampling efforts to identify species/species groups using the area. The pre-assessment would also ensure that the microphones are not placed within a zero-detection zone and would identify any areas producing electromagnetic interference.

2.7.2. Acoustic arrays

To validate target identification both bird and bat microphone arrays should be used with each project despite the desired target. The use of both microphone arrays would provide a better picture of the nightly activity and indicate whether the tracks detected originate from birds and/or bats.

2.7.3. Additional sampling

Although, I was capable of using the system without assistance during my study, an additional crewmember would have been beneficial to provide additional sampling and further ground-truthing. A second crewmember could be responsible for walking/driving transects to provide notes on any observed bird, bat, and insect activity. In addition, a second crewmember could conduct additional acoustic surveys throughout the radar sampling area with handheld units to support the species identified with the acoustic arrays and to aid with target identification. Any acoustic sampling conducted outside of the microphone sampling area could identify other species using the area that were not recorded by the acoustic arrays. This would be most valuable when the radar is sampling multiple habitats. In addition, an infrared camera could be used to further ground truth the radar data and would sample species not detected by the acoustic arrays.

2.7.4. Radar-acoustic fusion

The EchoTrack System is designed to simultaneously record radar and acoustic data (Millikin 2001). To further improve species identification and to reduce noise, the software updates should include a more user-friendly method to fuse the radar and acoustic data. From this, SNR values would provide better insight on how these changes with target orientation and range. Greater refinement and understanding of SNR is needed with any biological study. To refine the SNR criteria for future studies, the insect and bird communities active during each SI should be monitored and SNR values for those species should be calculated. This would provide accurate information for target size associated with bats, birds, and insects. If done for each project, radar-acoustic fusion would ensure target size is representative of the organisms being studied.

2.7.5. Onboard weather station

Although the EchoTrack System can be used with multiple weather stations and data collection techniques, an onboard weather station would standardize the methods for the collection of weather parameters and inputs into the processing software. An

onboard station would provide accurate weather at each sampling site and would account for local effects and any effects from frontal passages. Furthermore, an onboard weather station could be programmed to collect data in sync with the SIs, rather than relying on average data collected outside of the SIs. This would provide more accurate data during processing, which would output track parameters with better accuracy. The collection of weather parameters every 15 minutes at each sampling site would also provide higher granularity and enhanced analysis for target detection and identification.

2.7.6. Quality of the bat calls

The saturation of the bat calls recorded with the EchoTrack omni-directional bat sensors when placed within the vegetative canopy required manual assessment of each acoustic file. To minimize the effects of the vegetative canopy, the bat sensors should be situated in an area with low vegetative canopy to increase the quality of the recorded calls. This location must also be within the radar sampling area to aid with the identification of the targets detected with the radar. Furthermore, if the study commences prior to the growing season, changes in vegetative canopy height must be compensated for. If the microphones must be placed within the canopy, a reflective cone could be used to minimize the saturation of calls. Precautions should also be taken to reduce noise from precipitation, wind, and external sources to decrease the amount of saturation.

2.7.7. EchoTrack omni-directional bat sensor testing and validation

Further to the challenges I faced, I also recommend that the EchoTrack omni-directional bat sensors be tested in various field conditions by the user or an independent company. This testing should incorporate bat calls from species present in the area. It should also include procedures to indicate how the microphone detection differs for high-intensity and low-intensity calling bats. Additional testing by an independent company could follow methods similar to Downes 1982. This would provide information on the microphone's cone of reception, their angular range, and a maximum distance of detection for different frequencies and intensities.

2.8. Conclusion

Radar has been used for decades for biological studies and continues to advance. EchoTrack's Radar-Acoustic Wildlife Surveillance System is a unique modification of a marine surveillance radar. EchoTrack's radar has better detection of individual targets as targets can be separated by angle, range and altitude. It has higher and greater resolution for data acquisition than other surveillance radars used for biological studies. This higher resolution is a result of its short pulse length, high power, faster rotation and four-dimensional track trajectories.

The EchoTrack System provided a unique method to passively study the nocturnal behaviour and activity of bats in the South Okanagan. It was capable of detecting individual bats throughout the night, in all weather conditions, to provide an overview of activity over my study sites. My study, assessing the use of vineyards by bats in the South Okanagan, was the first study to use this system for habitat association. The design of the EchoTrack System overcame many of challenges faced with any biological radar study. The criteria I used and the comparison of radar and acoustic data minimized noise from birds and insects, enabling me to assess bat activity. In addition to the common radar challenges, my study faced additional challenges resulting from the undulating terrain and changes in the vegetative canopy. These additional challenges affected target detection and the quality of the recorded bat calls. These challenges, however, can be overcome in future projects with site reconnaissance that considers vegetative growth and a study design that keeps both bird and bat microphones.

Chapter 3.

Comparing bat activity over vineyards and natural habitat in the South Okanagan Valley, British Columbia

The South Okanagan Valley, British Columbia is an economically important area of Canada and has growing tourism and agriculture industries, which are both dominated by wine (Schreiner 2012). This region is also the most studied bat region in Canada, as it contains the highest diversity of bat species, and supports both local and migrant bats (Holroyd et al. 1994; Millikin unpublished). Half of these species are listed as species at risk provincially and/or federally (Appendix A), making it also an important conservation area for bats (Holroyd et al. 1994). The landscape in the South Okanagan has been modified various times due to agricultural demands over the last 150 yrs with little natural vegetation remaining (Dyer and Lea 2003; Lea 2008). Bat studies worldwide indicate the importance of natural habitat to bats (Estrada and Coates-Estrada 2002; Boyle et al. 2011; Rambaldini and Brigham 2011; Kalda et al. 2015). However, bats are more adaptable to changing landscape than other mammals due to their mobility (Fenton 1997; Law et al. 1999). In addition, bats worldwide have been observed foraging over agricultural areas and exploiting insects in these areas (Wickramasinghe et al. 2003; Kunz et al. 2011; Stahlschmidt et al. 2012; Wanger et al. 2014; Brown et al. 2015; Tietje et al. 2015). Despite numerous bat studies conducted in the South Okanagan, many information gaps remain, including details on the habitat use.

Few studies worldwide have focused on insectivorous bat activity over vineyards. These studies found that vineyards have bat species richness similar to that of the surrounding habitats, although bat activity was lower (Marques et al. 2004; DiSalvo et al. 2009; Boyle 2010; Stahlschmidt et al. 2012; Sirami et al. 2013). For example Stahlschmidt (2012) recorded 12 of 14 bat species in vineyards, yet only 0.1 % – 15 % of the bat passes were recorded over vineyards. He associated low bat activity with an

overall low insect abundance over vineyards. However, he also stated that the grey long-eared bat (*Plecotus austriacus*) had the greatest number of recorded calls over vineyards as its preferred prey, moths (*Lepidoptera*), had a higher diversity and abundance over vineyards than the surrounding agricultural areas (Stahlschmidt 2012). Most studies of bats over agricultural lands have focused on linear features, remnant tree patches, or retention ponds as these are important habitat features that would benefit bats (Verboom and Huitema 1997; Downs and Racey 2006; Lesiński et al. 2007; Henderson and Broders 2008; Stahlschmidt et al. 2012; Zukal and Gajdošík 2012; Sirami et al. 2013; Tietje et al. 2015). The South Okanagan Valley is unique as it has not been modified from a treed environment. The historic vegetation within the valley bottom was dominated by shrub-steppe species and grasses, with trees present only along riparian features. Although this landscape has been greatly modified, the valley bottom is still dominated by low-growing vegetation. Vineyards in this area have canopies less than 3 m and the bats inhabiting the region may be adapted to feeding in the low canopy cover of vineyards should prey be available to them (Nagorsen and Brigham 1993; Holroyd et al. 1994; Sarell et al. 2011). Furthermore, vineyard rows may act as linear landscape features that would provide commuting routes for bats. Small insects remain close to leeward edges of linear elements and could provide abundant foraging opportunities for bats (Verboom and Huitema 1997). If the insect community along vineyard rows are diverse enough for the energetic demands of bats, bats may remain in these areas to feed throughout the night.

To date no study has assessed vineyards as habitat available to the bat community in the South Okanagan. Rambaldini and Brigham's (2011) study focused on the pallid bat (*Antrozous pallidus*), a ground foraging bat. Their results indicated that pallid bat activity was greater in natural areas; however they also showed that vineyards in the South Okanagan can offer suitable prey for this species. Vineyards have the potential to support the bat community in the area, but the question remains if vineyards provide foraging opportunities for all bats inhabiting the South Okanagan. The insects associated with vineyard crop damage discussed in Chapter 1 Section 1.1.4, and any other insects associated with vineyards would provide prey to the bat community. In addition, buildings, artificial lights, and/or scattered trees found within or adjacent to these vineyards may provide roosting or foraging areas for bats, and provide

opportunities for bats to remain in vineyards throughout the night (Furlonger et al. 1986; Nagorsen and Brigham 1993; Fenton 1997; Agosta et al. 2003; Zupal and Gajdošik 2012).

To fill in information gaps about habitat use, biologists need to understand the behaviour of the animal and its spatial distribution, but for nocturnal animals gathering this information can be challenging. The agricultural studies reviewed relied on acoustic surveys to measure relative bat activity and determine species richness in vineyards, but acoustic surveys can not describe the spatial use and spatial distribution of bat activity. Spatial use is generally studied using radio-telemetry, however radio-telemetry surveys are limited by the sample size, the size of the bat, the transmitter, and is bias by the species captured (Fenton 1997; Hayes et al. 2009). Radar has been used since World War II to study birds, insects, and bats (Eastwood 1967; Vaughn 1985; Hayes et al. 2009). It can passively sample an area and provide an overall picture of activity throughout the night both in the horizontal and vertical plane. Mobile radars are designed with higher resolution than most stationary radar in order to track the movements of small individual targets.

My study was designed to assess the nocturnal movements of bats during their reproductive season (pregnancy and parturition, lactation, pup fledging). These periods corresponds with high energy demands for female bats (Neuweiler 2000). These periods are also associated with a time when females are unlikely to relocate from their maternity colonies, thus providing an ideal opportunity to observe foraging behaviour over vineyards. I used EchoTrack Inc. Radar-Acoustic Airborne Wildlife Surveillance System (The EchoTrack System) to determine if, when, where and how bats are using the landscape in the South Okanagan with a focus on vineyard and natural habitats. This system consists of a mobile modified marine radar capable of detecting small targets within a two kilometres radius. This study was designed to assess how bats are using the fragmented landscape of the South Okanagan and to determine if bats are merely using vineyards as commuting corridors or if they are remaining in these areas to forage. Understanding the role that vineyards play in the ecology of bats in the South Okanagan could be important for the management and conservation of bats in the area. My study objectives are outlined in Chapter 1; from these I had the following expectations:

1. If bats are simply commuting through vineyards I expected to detect bat activity over vineyards only within two hours following sunset and prior to dawn, which would correspond to the time following roost emergence and prior to their return.
2. If bats are remaining in vineyards to forage, I expected to detect activity throughout the night.
3. I expected to detect a lower amount of activity over vineyards compared with natural habitats.
4. I expected to detect more activity when female bats are lactating compare with pregnancy and partition or pup fledging due to the higher energy demands associated with this period.
5. I expected that bat species richness would be similar in vineyards to that found over natural habitat.
6. If bat activity was detected throughout the night in vineyards, I expected this activity to be concentrated near buildings, artificial lights, and/or remnant trees and tree patches.
7. I expected to detect little bat activity during windy, and/or rainy nights as bats minimize their foraging in adverse weather conditions.

In this chapter, I review the radar and acoustic data to determine if bats are using vineyards and assess the amount of activity detected over vineyards compared to the activity detected over natural habitats. I assess the data for a period effect to determine if more bat activity was detected during any period. I review radar track parameters (speed, height, and relative size) and explain how these differ between vineyard and natural habitats. I also assess the acoustic files for evidence of foraging activity with the presence of buzzes and identify species richness over both habitats. I compare the nightly trends observed with radar detections and acoustic recordings throughout my sampling intervals (SIs) to determine if bats are remaining within these habitats throughout the night. I assess bat activity detected during thunderstorms with heavy precipitation and high winds, and lastly, I discuss further research needed to understand the role that vineyards play in the ecology of bats.

3.1. Methods

3.1.1. Study design and sampling regime

I selected six vineyard sites in the South Okanagan with the aid of a local bat biologist (M. Sarell) to ensure that each site was located adjacent to a potential day roost. I positioned the radar in a vineyard plot and sampled the landscape within a 1 km radius. A 1 km radius allows the radar to have high resolution and reduces the chance of targets representing more than one individual. This sampling radius also ensured that small bat species such as the western small-footed myotis (*Myotis ciliolabrum melanorhinus*) would be detected, as due to their small size (weigh of 3 g – 6 g) they would not be detected out to 2 km. Site location was restricted by site topography and site distance. The location of the radar between sites was greater than 2 km, with distances ranging from 2.3 km to 9.8 km, to ensure no overlap in area sampled. A summary of the site locations, and the data collected is provided in Appendix E. Bat trajectories were not known, however I speculated that a proportion of the bats in the study area would commute from the rock faces and cross over the radar in search of food and water upon emergence. As such, I situated the radar perpendicular to gneiss rock faces, as these provide ideal roosting habitat for many bat species found in the region (Sarell and Haney 2000). This would allow the radar to detect the broadside of targets to increase target detection.

I used EchoTrack omni-directional bat sensors to collect radar and acoustic data simultaneously. Simultaneous sampling of the radar and acoustic data accounts for any temporal or climatic variation; therefore sampling occurred in all weather conditions, including storms. I surveyed each site over two consecutive nights during three replicates for a total of 36 nights. Each replicate corresponded with different life stages of the bats and corresponded with the following periods: (1) pregnancy and parturition (June 28th, 2012 to July 10th, 2012), (2) lactation (July 17th to July 29th), and (3) pup fledging (July 31st to August 13th 2012). I used two acoustic arrays to record bat calls simultaneously within a vineyard and natural plot. The vineyard acoustic arrays were positioned 58 m to 100 m from the radar and were connected to the trailer's system. The natural arrays were placed in an adjacent shrub-steppe area, were powered by a portable generator, and collected data on a toughbook. The natural arrays were located

134 m to 353 m from the radar. The EchoTrack System and setup are described in Chapter 2 Section 2.2, and in Table 2.1. I commenced recording 15 minutes after sunset and recorded data over 14-minute intervals every 30 minutes throughout the night. The number of SIs varied with the length of darkness (range 15 – 17 per night). My study design aimed to record data over 96 SIs per site and collect 1344 minutes each of radar, vineyard acoustic and natural acoustic data for each site. My sampling regime included SIs during the evening crepuscular period following sunset, but did not survey the dawn crepuscular period each night. Of my 36 sampling nights, 19 nights included a dawn crepuscular sampling block, 10 nights partially sampled into start of the dawn crepuscular period, and 7 nights did not include a sample during this period as my sampling ended prior to 45 minutes before sunrise. To account for the variation in number of SIs per night and the period of night sampled, I analyzed the data comparing time (minutes) relative to both sunset and sunrise. The SIs prior to dawn refers to when the sampling period ended, therefore “SI -30” indicates that period ended within 30 minutes of sunrise.

3.1.2. Radar track analysis

To ensure that the radar tracks represented bat activity I used speed and size thresholds to minimize noise from birds and insects (See Chapter 2 Section 2.5.4.1). Tracks outside these thresholds were excluded from the analysis. I also compared tracks with the acoustic data collected.

To analyze radar tracks, I used two EchoTrack track text files with Python 2.7 coding to create kml files for each of my SIs. I displayed these in two-dimensions using ArcGIS ArcMap 10.2 and 2006 – 2007 cadastre landuse data obtained from the BC Ministry of Agriculture and Lands (Figure 3.1). I projected all data layers imported into ArcMap in NAD 1983 UTM Zone 11N to ensure that my data displayed correctly and to minimize measurement distortion errors. I assessed the landuse class assigned to each land parcel within the cadastre layer and manually re-digitized and reclassified parcels with an incorrect landuse class based on my field reconnaissance. I also delineated primary and secondary roads that ran through natural habitat and excluded these from the analysis, but kept vineyard right-of-ways within the vineyard habitat as all vineyards include multiple right-of-ways for operations. This ensured that the land cover within

each sampling radius was accurate at the time of survey. To assess the habitat use by bats, I measured track length per unit area per minute ($m/m^2/min$) crossing vineyard and natural habitats. For this, I clipped all tracks to be within my 1 km radius and used ArcMap's intersection function. To determine the area of each landuse class surveyed by the radar, I used another radar text file that outlines the location of any target detected irrelevant of a trajectory, in conjunction with the kml track files. This visually displayed any area surveyed or not surveyed by the radar. Areas outside of the radar's field of view were identified to be within zero-detection zones (See Chapter 2 Section 2.5.2). I manually digitized any portion of a land use class found within each zero-detection zone to subtract this area from the total corresponding landuse area contained within my sampling radius.

To compare track parameters over habitats, I ensured that a single count for each parameter assigned to a track was not counted more than once. ArcMap's intersection function caused one or more breaks along a track's trajectory at each point where it crossed a separate land parcel. This resulted in one track being spliced multiple times or one track crossing both vineyard and natural habitats (Figure 3.2). I therefore combined the intersected segments for a single track by habitat to remove any duplicated parameter value for a given track. In addition, I maintained track length to obtain average speed and direction (relative to true north) along its trajectory, as these are averaged from each track point detected along its trajectory. Target height (relative to antenna height) and target size [as it relates to Signal-to-Noise Ratio (SNR)] were also compared. These parameters represent the value assigned to first track point detected, and were not averaged over the track trajectory.

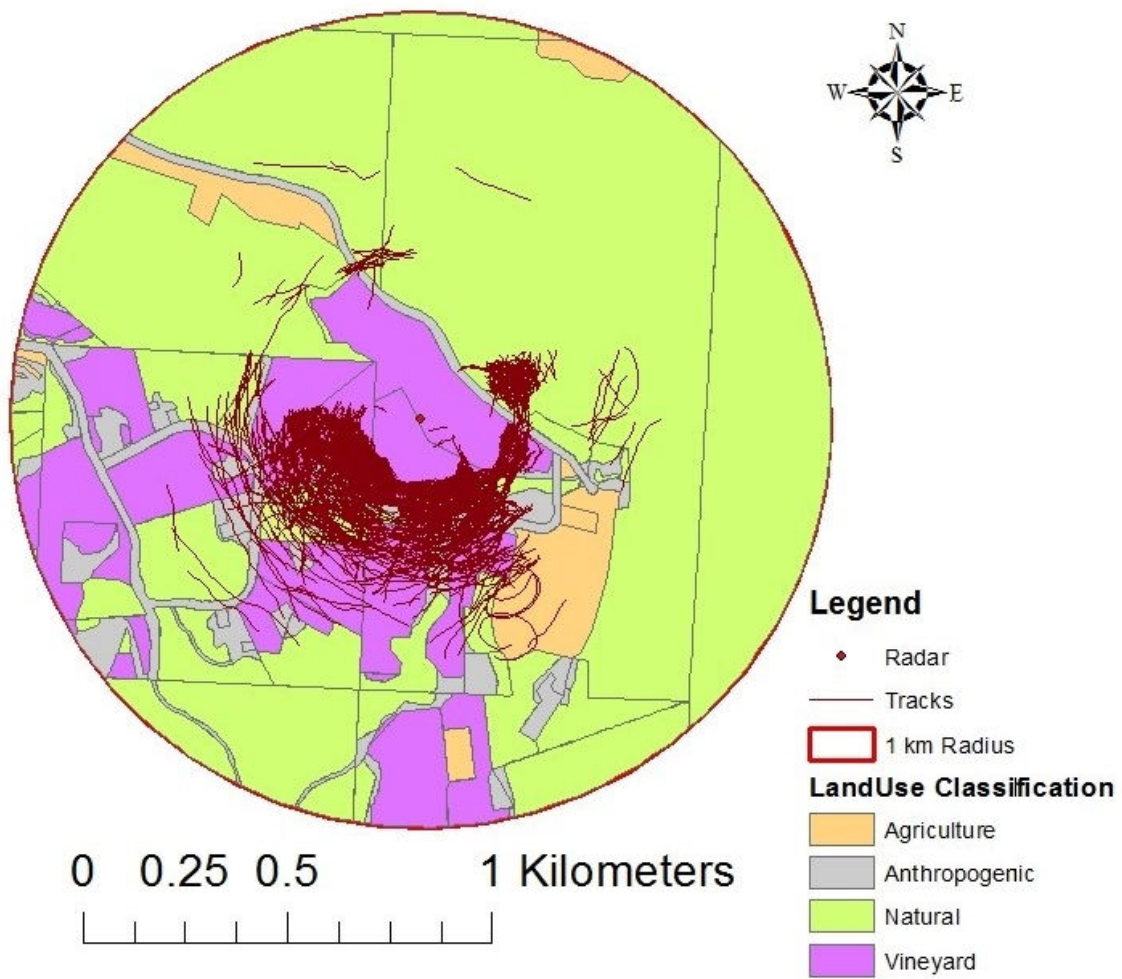


Figure 3.1. All radar tracks detected during one night of sampling at Site 1 projected in two-dimension over landuse classes.

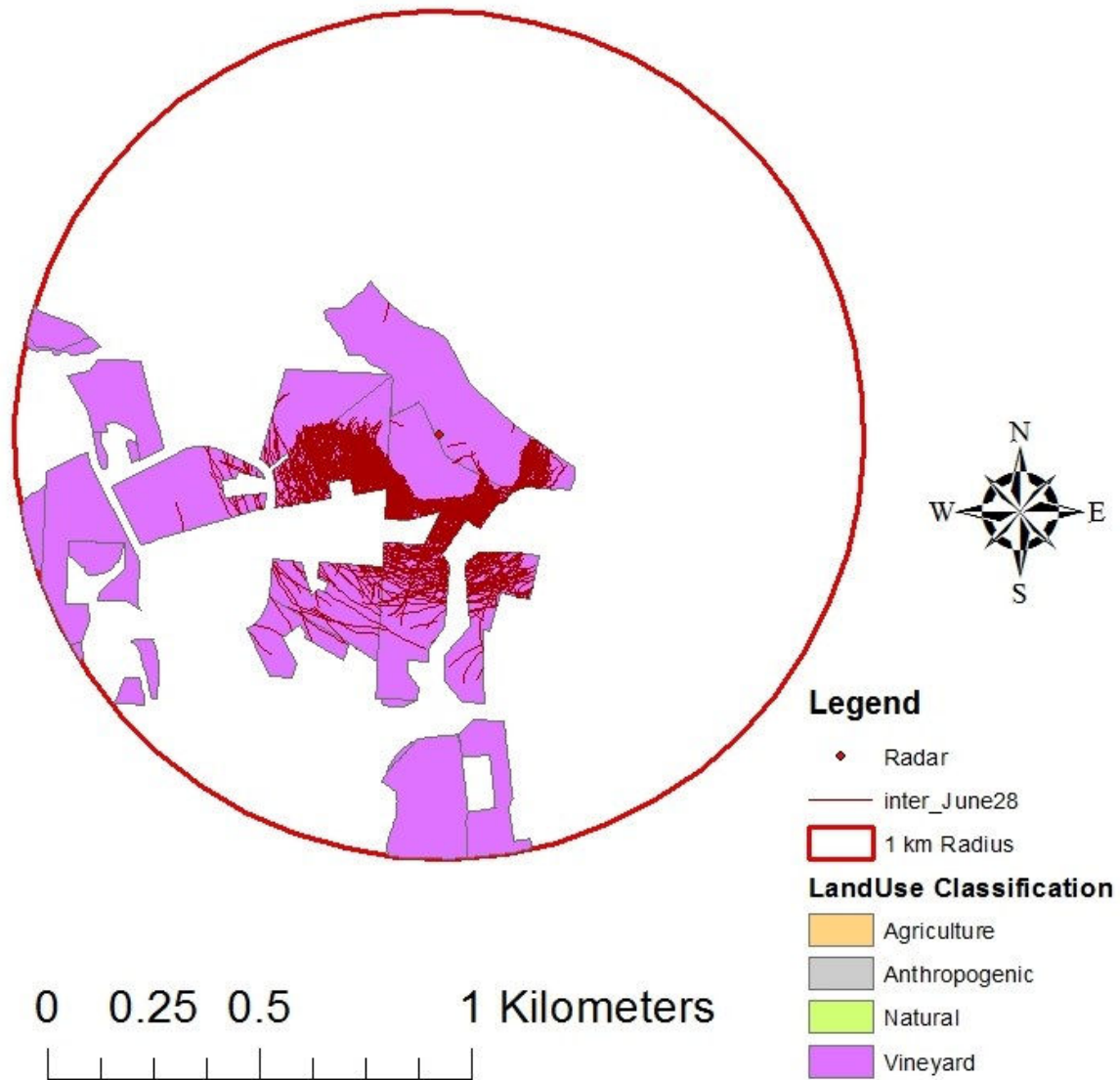


Figure 3.2. The intersected segments of radar tracks detected over vineyard habitat during one night of sampling at Site 1.

3.1.3. Acoustic analysis

EchoTrack's omni-directional bat sensors generated raw acoustic files each time a sound between 0 kHz and 140 kHz was detected. This included sounds generated by bats, as well as noise interference from insects, the equipment, and the weather. I compressed these files using EchoTrack software to generate waveform audio files (Millikin 2001). The majority of the wave files collected (83 %) were saturated requiring me to manually assessed each one. I imported these into BatSound Pro – Sound

Analysis Version 3.31a (BatSound) and looked for regularly spaced sonograms having a downward sweeping frequency-modulated or a constant-frequency component that identifies bat calls (Fenton and Bell 1979; Fenton and Bell 1981). I also assessed each acoustic file for the presence of a buzz, a series of rapid calls showing a slight increase in minimum call frequency, followed by a sudden drop in frequency, which usually indicates the detection of an insect (Griffin 1974) (See Chapter 2 Section 2.6.2 Figure 2.10). Buzzes have also been associated with drinking behaviour (Griffiths 2013), however given the range of the omni-directional bat sensors and the absence of water within 100 m of my acoustic arrays, recorded buzzes within my plots probably indicated foraging attempts. The average rate of buzzes detected per night was used to compare foraging rates (Stahlschmidt et al. 2012). The buzz rate was calculated each night by dividing the number of buzzes detected by the number of bat passes recorded.

Each acoustic bat file was assessed using the minimum frequency of the call, the characteristic frequency, call duration, and call profile. I calculated average call parameters using three characteristic calls observed in a pass with the spectrogram and the power spectrum in BatSound. Using call information I obtained from literature and two BC bat biologists⁶, I assigned each bat pass to a frequency group and species group based on its minimum frequency and call characteristics (Table 3.1; Appendix F). I compared frequency groups using categories rather than bat species in my analysis, as most bat species have intraspecies variation, and many species in the area have overlapping call characteristics (Nagorsen and Brigham 1993; Fenton 1997; Adam et al 2009; Parsons and Szewczak 2009; Sarell et al 2011). The species groups associated with each frequency group represent 13 of the 15 bat species present in the South Okanagan, with only Townsend's big-eared (*Corynorhinus townsendii*) and canyon bat (*Parastrellus hesperus*) being excluded. Although these bats may have been present at my sites, they were not included in the acoustic analysis as their distinctive call structures were not seen within my acoustic files. The minimum number of species detected with the acoustic arrays is represented by the species groups outlined in Appendix F. The bat frequency group categories and species groups were also used to

⁶ Bat call recordings were obtained from D. Burles and C. Lausen. These calls were obtained from known free-flying bats, ziplined bats, or kited bats.

assess the number of species active throughout my study and throughout the evenings, by determining the percentage active per night and across my SIs.

Each wave file created with the bat sensors was timed stamped. As my acoustic arrays consisted of four microphones, the timing of each wave file was evaluated to ensure that bat calls were not duplicated. I used the following criteria to determine the number of Individual Bat Passes (IBPs) recorded over each habitat.

1. Call files produced from different microphones having similar call parameters within 2 seconds of each other were assessed as the same individual.
2. Call files produced from the same microphone having similar call parameters within 2 seconds of each other were assessed as the same individual.
3. Any gap greater than 2 seconds between bat passes within a wave file was assessed to represent two passes.
4. Calls within the same wave file that represented different frequency groups were counted as two or more passes.
5. Calls within the same wave file that represented the same frequency groups were counted as two or more passes when the time between calls were shorter than that expected for search phase calls (See Chapter 2 Section 2.6.2 Figure 2.10).

I calculated the number of IBPs recorded per minute over each plot to compare habitat use. The total number of IBPs per minute gives a relative estimate of bat activity in the area but does not indicate the absolute abundance, as it is not possible to determine if one bat was recorded multiple times or if multiple bats were recorded.

Table 3.1. A list of bat species associated with the four frequency groups identified by minimum frequency of the bat’s call. These categories are based on unpublished data obtained from BC bat biologists (D. Burles and C. Lausen) and a BC bat study (Sarell et al. 2011).

Category	Frequency Group	Possible bat species identified by their species code
Category 1	≤ 22 kHz	Euma, Laci, Epfu, Myth
Category 2	25 kHz – 35 kHz	Anpa, Epfu, Labo, Laci, Lano, Myev, Myth
Category 3	40 kHz – 45 kHz	Myca, Myci, Mylu, Myvo, Myyu
Category 4	50 kHz	Myca, Myyu

3.1.4. Bat trapping

Bat echolocation calls vary considerably with region and vary slightly with the bat detector used; therefore to aid with bat species identification, I arranged bat trapping sessions with local bat biologists (M. Sarell and D. Burles) and volunteers within my study area. We trapped bats over two trapping sessions, for a total of five nights, two during my field season, and three the following spring. During these sessions, I setup the EchoTrack acoustic array to release capture bats over the microphones. This was done to create a reference library of calls with the EchoTrack bat sensors to allow me to compare my study calls with the call files obtained by others (D. Burles, unpublished files; C. Lausen, unpublished files). Unfortunately, our trapping efforts resulted in few captured bats and therefore a reference library was not created; however the calls collected were used to help sort the acoustic files collected during my study into species groups. The radar was not in operation during these trapping sessions.

All bat handlers followed the BC inventory methods for bats standards and the National white-nose syndrome decontamination protocols version 06.25.2012 (BC Ministry of Environment, Lands, and Parks 1998; WNS Decontamination Team 2012). We used standard bat mist nets (4 shelves, 38 mm mesh, and 2.6 m tall) measuring 2.6 m to 18 m in length. We set five to eight nets per night, away from the acoustic array within natural habitat adjacent to one of my vineyard plots. We monitored nets continuously and closed the nets when bat activity in the area decreased. Once captured, we immediately removed the bat from the mist net and placed it into a cloth bag. We took the following measurements to identify bat species: ear length (mm), tragus length (mm), forearm length (mm), hind foot length (mm), weight (g). In addition, we also noted the following characteristics for each bat: the presence of hair on the tail (fringed or not), the presence of a keeled calcar, the sex of the bat (if female whether she was lactating), the age of the bat (adult/juvenile) and looked for any signs of white-nose syndrome. Once processed, we placed the bat back into the cloth bag and walked over to the microphone array. We ensured it was recording before removing the bat from the cloth bag. Before releasing the bat, we warmed it up with our gloved hands, and hand released it over the array. We noted the time of release to assess the calls of the known species.

3.1.5. Statistical analysis

To assess habitat use of bats, I used a mixed model, split-plot design with habitat and replicate as the two factors. My three replicates represented three periods in the reproductive cycle of female bats: (1) pregnancy and parturition, (2) lactation, and (3) pup fledging, and therefore, allowed me to test for a period effect. The model was blocked using "Site" and my six nights of sampling at each site nested within "Site" as random effects. The model was first tested for an effect of factor interaction by assessing the profile interaction plot with habitat on the y-axis and period on the x-axis. The plot had relatively parallel lines showing signs of additivity. The F-statistics confirmed no evidence of an interaction between the two factors and are given in the results. The main effects of habitat and period were tested using the F-statistics and a multiple comparison procedure was used to compare the difference of means. The same statistical model was used for both my radar and acoustic analysis. The acoustic data were normalized using a natural log + 1 transformation. I did not include environmental variables in the model as preliminary analysis found no evidence that bat activity varied with any of the environmental variables recorded. Each variable was tested independently and together (all $p \geq 0.13$, range 0.13 – 0.96); these included moon phase (percent moon illuminated and time above the horizon were both considered), precipitation, cloud cover, average nightly wind speed, barometric pressure, temperature, and humidity.

Model: $Y = \text{Habitat} + \text{Replicate} + \text{Habitat} * \text{Replicate} + \text{Site (R)} + \text{Night}[\text{Site}] (\text{R})$

Where Y = length of track (m) over habitat area (m²) per minute or natural log (IBP/min +1)

Habitat = natural or vineyard

Replicate = period (bat pregnancy and parturition, lactation, pup fledging)

Night = the six days of sampling at each site

Site = one of my six sites

I examined the distribution of track parameters (wind adjusted speed, height at start of track, and SNR value at start of track) by plotting the proportion of vineyard and natural habitat tracks by parameter bins. The directionality of the tracks was assessed graphically using rose graphs. These graphs depict eight cardinal directions (N, NE, E, SE, S, SW, W, and NW) and are visual displays of average track direction (relative to true north) irrespective of habitat, 45 minutes past sunset and one hour prior to dawn.

These times were used as they corresponded with an increase amount of bat activity detected over my sites following roost emergence and prior to roost re-entry. Rose graphs are displayed for each site and displays track direction for each period, which is represented by replicate. Commuting bats emerging from their day roost would have been depicted by a large proportion of tracks crossing over the radar from gneiss cliffs. Bats returning to the roost prior to sunrise would have shown a reversal in direction. Therefore I expected to see a 180° difference in mean track direction from sunset to sunrise. No statistical analysis was conducted on the rose graphs.

The distribution of buzzes and species frequency groups within vineyard and natural plots were analyzed using chi-square tests. A 2 x 2 and 4 x 2 contingency tables were used to calculate the chi-square goodness of fit with observed and corresponding expected values.

Temporal variation in the number of tracks per minute and IBP/s per minute (\pm 95% CI) were examined graphically using a line element that connected the means calculated for each SI. The radar and acoustic data were normalized using a natural log + 1 transformation to allow for comparison.

3.2. Results

3.2.1. Radar tracks

I attempted to sample habitat use over six nights at each of my six sites; however I only collected six nights of data at four sites, and had five nights of sampling at two sites. Two nights of sampling were lost due to delays in equipment setup and damage to an external hard drive (Appendix E). I recorded a total of 7952 minutes of radar data. I assessed 78633 radar defined bat tracks and surveyed an average of 65.5 % of the available vineyard habitat per site (range 44 % – 83 %) and 46.9 % of natural habitat (range 22 % – 70 %). A total of 50480 tracks had trajectories over vineyards and 40561 tracks crossed natural habitat (Table 3.2). No interaction effect was detected between habitat and period ($F_{2, 33} = 0.36$, $p = 0.70$), and no difference in mean track length per area per minute was detected between the three periods sampled ($F_{2, 28} = 1.79$, $p = 0.19$). The total track length detected over vineyards was greater than natural areas,

however no statistical difference was detected for mean track length per area per minute per night over either habitat ($F_{1, 33} = 3.35$, $p = 0.08$). The difference in mean track length per area per minute was $0.0006 \text{ m/m}^2/\text{min} \pm 0.0003 \text{ m/m}^2/\text{min}$ (mean \pm SE). Track parameters are outlined in Table 3.2 and Figures 3.3 – 3.5.

Table 3.2. Summary of radar analysis showing the amount of habitat surveyed, number and length of tracks analyzed and summary statistics of mean track parameters.

	Vineyard	Natural
Total habitat area contained within my study sites	6.6 km ²	8.8 km ²
Habitat area surveyed with the radar	4.3 km ²	4.2 km ²
Percent of total area surveyed with the radar	65.1 %	47.7 %
Number of tracks analyzed over each habitat ^a	50480	40561
Total track length over each habitat	5509 km	4624 km
Mean track length per area per minute per night	0.0012 m/m ² /min	0.0007 m/m ² /min
95% confidence intervals for mean track length per area per night	0.0004 → 0.0021 m/m ² /min	-0.0002 → 0.0015 m/m ² /min
Mean target flight speed ^b per track \pm SD	7.3 m/s \pm 2.1 m/s	7.4 m/s \pm 2.2 m/s
Mean target size (SNR) ^c per track \pm SD	0.24 \pm 0.67	0.33 \pm 0.82

^aOne track may have crossed both natural and vineyard habitat along its trajectory

^bSpeed was adjusted for wind speed and direction

^cSize corresponds with the SNR value assigned to the first track point

As a result of speed thresholding and the application of speed filters, tracks had target speeds adjusted for wind between 4 m/s and 15 m/s (Figure 3.3). The distribution of target flight speeds over vineyard and natural habitat shows a similar pattern with a large proportion of speeds centering between 5 m/s and 7.5 m/s (47.2 % of tracks over vineyards and 46.5 % over natural; Figure 3.3). Forty-nine percent of all vineyard and natural habitat tracks had speeds greater than the foraging speeds identified for bats (>7 m/s; See Chapter 1 Section 1.1.1).

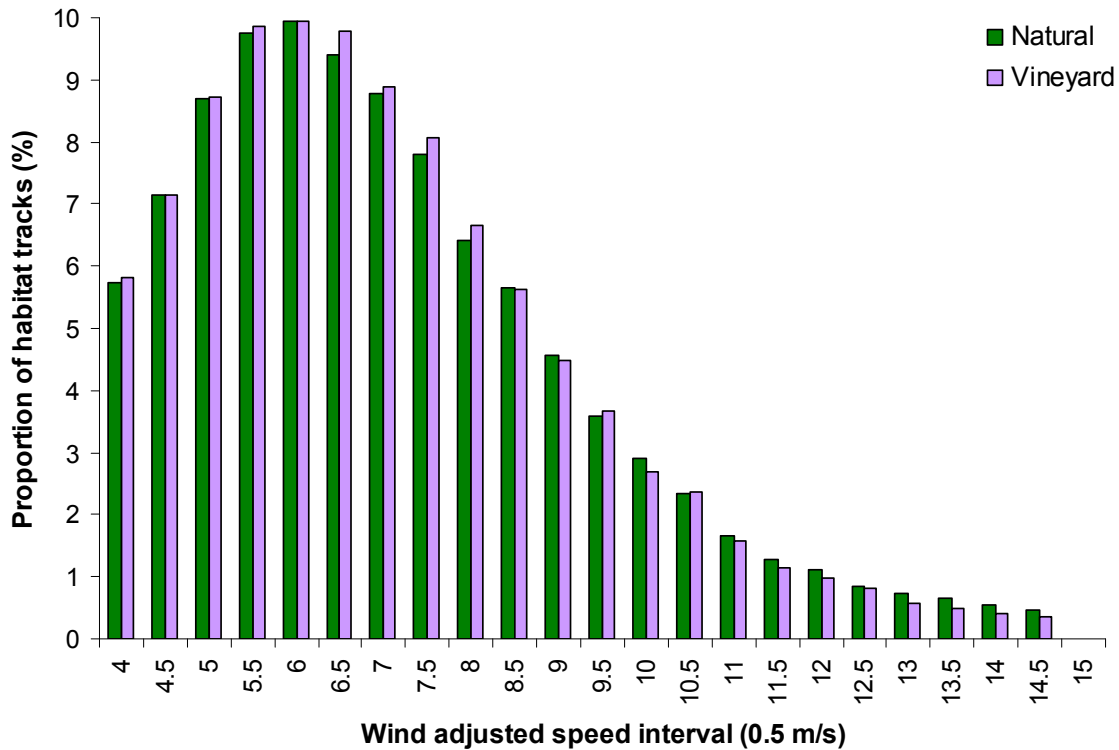


Figure 3.3. The distribution of mean wind adjusted target speed for vineyard and natural tracks.

The height distribution of tracks over vineyard (range 0.04 m – 555 m) and natural habitat (range 0.04 m – 497 m) is shown in Figure 3.4. This figure shows a bimodal distribution for both habitats with tracks low over the ground having start heights less than 20.1 m (Figure 3.4, $e^{1-2.5}$ – refer to legend in figure) and high above the ground with heights between 54.6 m to 244.6 m (Figure 3.4, $e^{4.5}$). Vineyards had a greater proportion of high tracks (55%) than low tracks (34%); whereas the distribution of low and high tracks over natural habitat was similar (42 %). Twenty-five percent and 31 % of the tracks over vineyards and natural areas respectively had track start heights between 4.5 m and 7.4 m (Figure 3.4, $e^{1.5}$). Few tracks had start heights below 2.7 m (Figure 3.4, $<e^1$). Vineyards and natural habitats had the greatest proportion of tracks between 90.0 m to 148.4 m (26 % and 23% respectively; Figure 3.4, $e^{4.5}$). Only 2.4% and 3.2% of tracks over vineyard and natural habitats had heights greater than 244.6 m above the antenna (Figure 3.4, $e^{5.5+6}$). These heights correspond to heights within the elevation range of the rock bluffs found within the region.

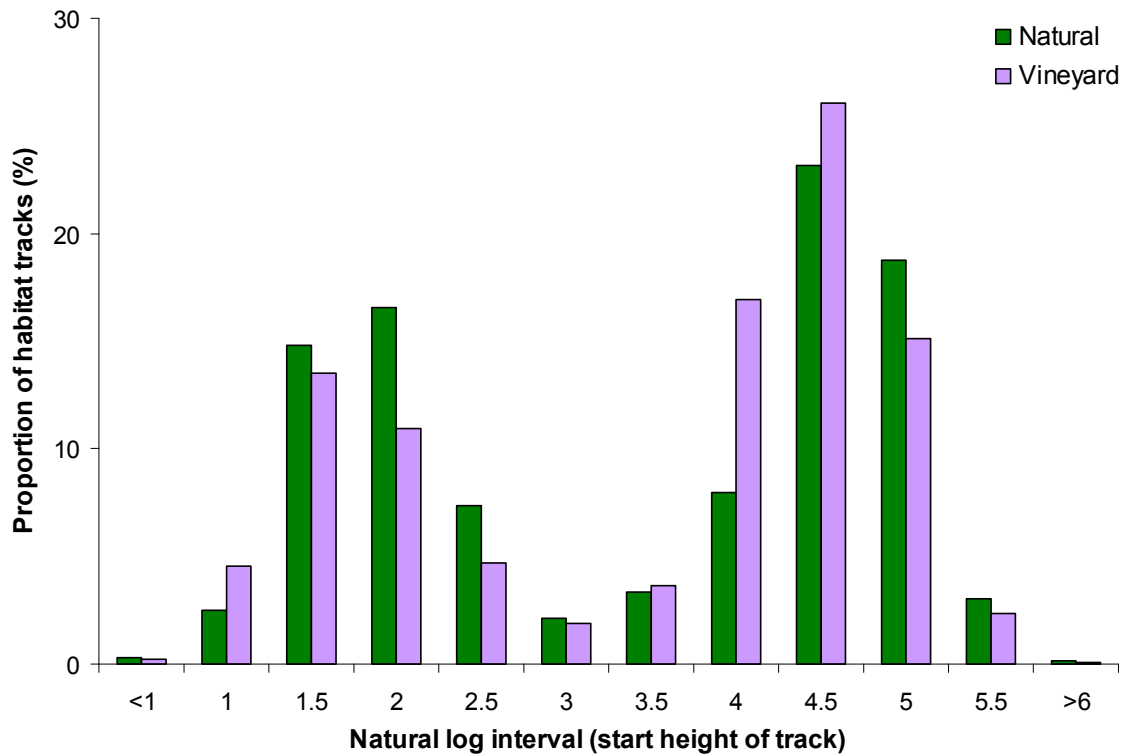


Figure 3.4. The height distribution for vineyard and natural tracks, where height corresponds with the target height assigned to the first track point. Height is relative to the antenna, which sits 2.43 m above the ground.

Where $e^1 = 2.7 \text{ m} - 4.5 \text{ m}$; $e^{1.5} = 4.5 \text{ m} - 7.4 \text{ m}$; $e^2 = 7.4 \text{ m} - 12.2 \text{ m}$; $e^{2.5} = 12.2 \text{ m} - 20.1 \text{ m}$; $e^3 = 20.1 \text{ m} - 33.1 \text{ m}$; $e^{3.5} = 33.1 \text{ m} - 54.6 \text{ m}$; $e^4 = 54.6 \text{ m} - 90.0 \text{ m}$; $e^{4.5} = 90.0 \text{ m} - 148.4 \text{ m}$; $e^5 = 148.4 \text{ m} - 244.6 \text{ m}$; $e^{5.5} = 244.6 \text{ m} - 403.4 \text{ m}$; $e^6 = 404 \text{ m} - 560 \text{ m}$

The distribution of SNR values for vineyard (range 0.01 – 29.7) and natural habitat (0.01 – 40.7) tracks are shown in Figure 3.5. This graph represents a measure of relative size for the targets detected over both habitats. Few tracks had SNR values greater than one (4.5 % and 6.2 %, over vineyard and natural habitats respectively). A large proportion of tracks detected had SNR values below 0.05 (56.9 % over vineyards and 43.9 % over natural; Figure 3.5). The mean difference in SNR values was greater in the natural areas than vineyard (0.08 ± 0.005 (mean \pm SE), $p < 0.0001$), suggesting that vineyards had a greater proportion of relatively smaller targets compared with the natural areas.

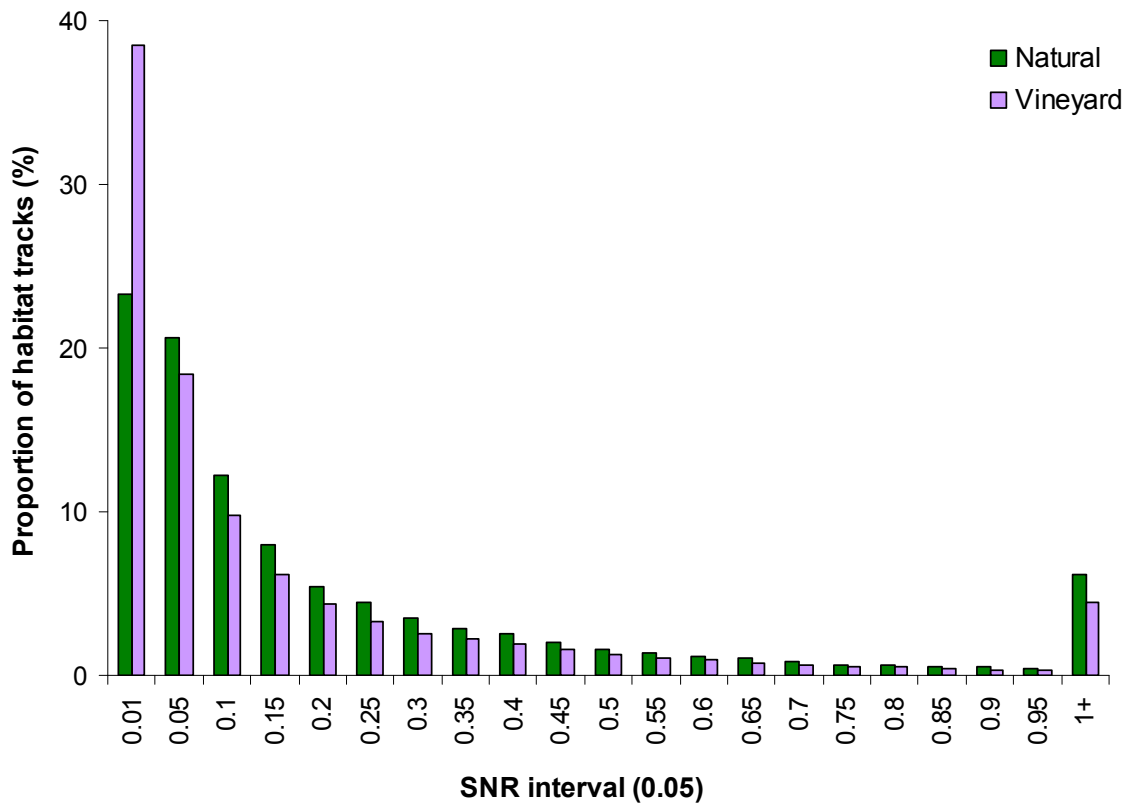
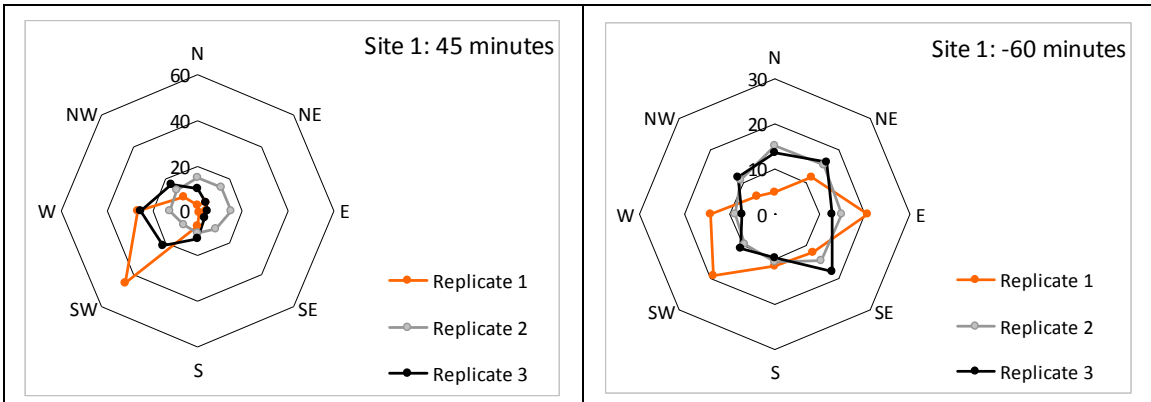
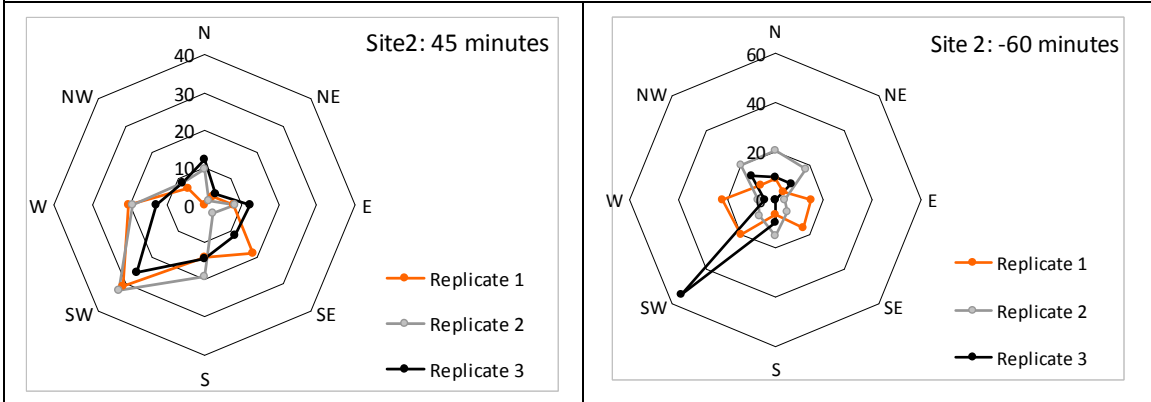


Figure 3.5. The distribution of target SNR values for vineyard and natural tracks.

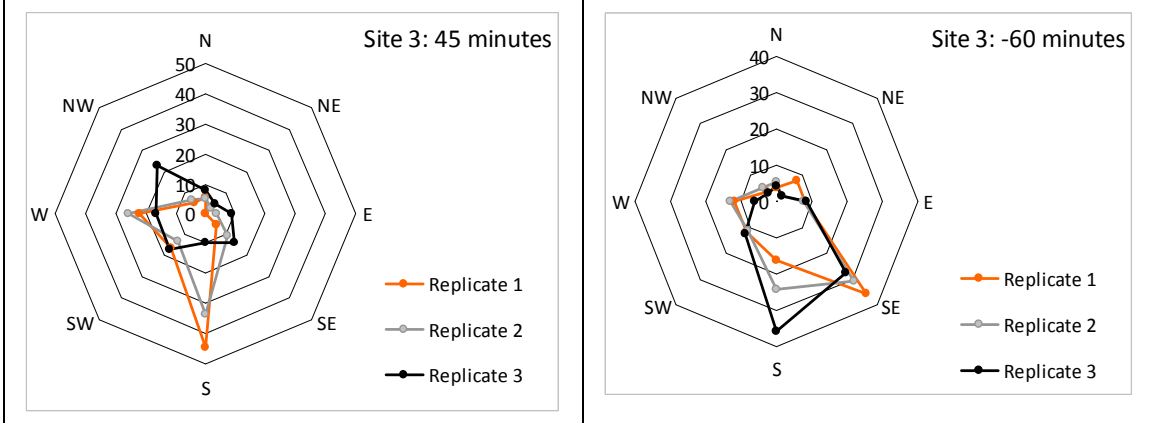
Rose graphs depicting the mean track direction of flight trajectories 45 minutes after sunset and one hour prior to sunrise are shown in Figure 3.6. No patterns of bats emerging or returning to day roosts after sunset and prior to sunrise were observed throughout the periods at any site (Figure 3.6). The general pattern displayed in the rose graphs show diverse track direction indicating that targets were randomly flying around at each site.



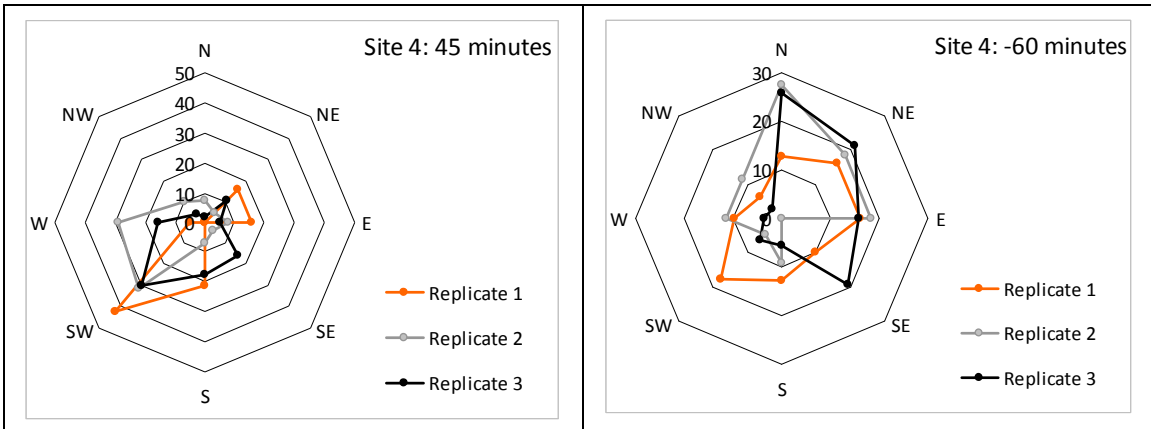
Site 1: a maternity colony roost was confirmed NE of the radar. Only Period 1 (pregnancy and parturition, orange line) showed a SW direction 45' after sunset (46 %); however a NE direction was not prominent during this period prior to sunrise.



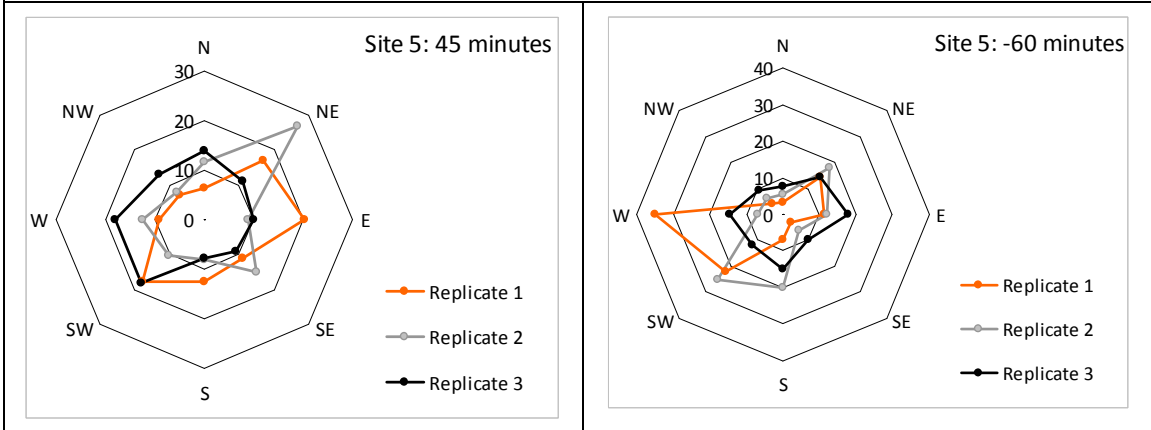
Site 2: gneiss cliffs were located north of the radar (NE – NW). All three periods show 26 % - 32 % of tracks travelling in a mean SW direction; however NE – NW directions were not seen prior to sunrise during any period.



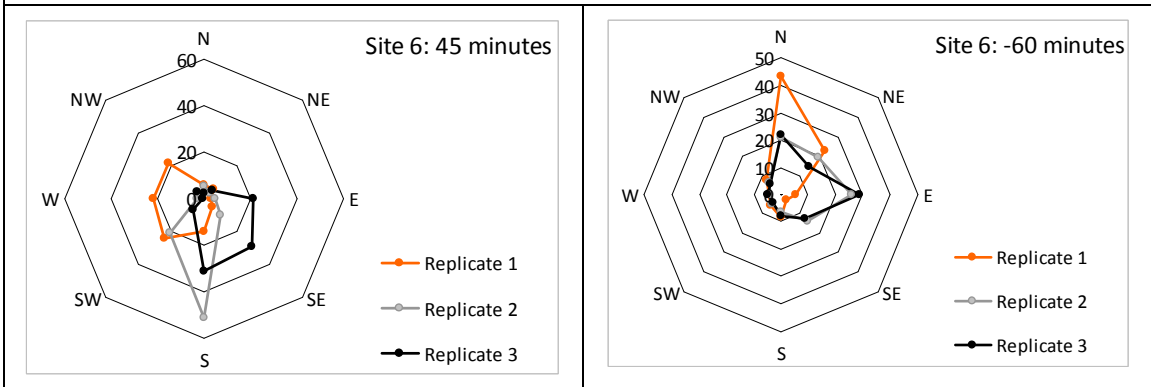
Site 3: gneiss cliffs were located south of the radar (S – SE). No pattern of roost emergence was seen after sunset; however 52 % - 63 % of tracks had S – SE directions prior to sunrise.



Site 4: the radar was surrounded by gneiss cliffs (N → S) with a potential day roost identified NE – E of the radar (M. Sarell, personal communication, April 23, 2012). A large proportion of tracks (46 % - 60%) had a mean direction of W – SW 45° after sunset during all three periods, with the majority of tracks directions travelling N – SE prior to sunrise.



Site 5: gneiss cliffs were located east of the radar. No pattern of roost emergence or bats returning to the roost was seen during any period.



Site 6: gneiss cliffs were located north of the radar (NW – NE). Only Period 2 (lactation, light grey line) showed a S direction towards Osoyoos Lake 45° after sunset (51 %); 43 % of tracks during Period 1 (pregnancy and parturition) showed a N direction prior to sunrise.

Figure 3.6. (Preceding pages) Rose graphs for each site showing the proportion of mean track direction for all tracks detected (irrespective of habitat) 45 minutes after sunset and 60 minutes prior to sunrise.

3.2.2. Acoustic analysis

The radar and vineyard acoustic arrays were synchronized through the trailer's computer to record data simultaneously; however, the damaged hard drive resulted in data from different SIs being recovered for data collected on July 17th (Appendix E). I collected 7952 minutes of acoustic data over vineyards and identified 852 IBPs (Table 3.3). I recorded 7490 minutes of acoustic data over natural habitats for a total of 965 IBPs (Table 3.3). I was only able to collect 1344 minutes of natural acoustic data (six full nights of sampling per site) at one of my six sites. The sampling regime was not attained during nine nights as a result of delays in equipment setup, equipment malfunction, and premature shutdown of the portable generator. Equipment malfunction resulted in no data collected on July 27th at Site 1 and only 28 minutes of data collection at the start of the night on July 20th at Site 4. No interaction effect was detected between habitat and period ($F_{2, 20.3} = 0.60$, $p = 0.56$), nor was a difference in IBPs per minute detected during the three periods sampled ($F_{2, 18.4} = 2.54$, $p = 0.11$). The total number of IBPs recorded over natural habitats was greater than that recorded over vineyards; however no statistical difference was detected for the mean IBPs per minute per night over either habitat ($F_{1, 20.3} = 1.04$, $p = 0.32$). The difference in mean IBPs recorded per minute was $0.03 \text{ IBP/min} \pm 0.03 \text{ IBP/min}$ (mean \pm SE). These results, in addition to the radar track analysis (Section 3.2.1) indicate that bats are not using vineyards less than natural area. Fewer tracks and IBPs were detected during Period 1; however the number of detections was highly variable from night to night thus resulting in no evidence of a period effect.

I recorded 75 buzzes during my study within my vineyard and natural plots with an average buzz rate per night of 2 % and 6 % respectively (Table 3.3). The vineyards had less buzzes detected than the natural habitats ($\chi^2 = 5.69$ $df = 1$, $p < 0.02$). Four of the six vineyard plots had evidence of foraging. The majority of all buzzes (89 %) were recorded within 2 hrs of sunset or within 1.5 hrs of sunrise (Table 3.3). Buzzes were produced by Category 2 and 3 bats (Table 3.1).

Table 3.3. Summary of the acoustic analysis showing the number of Individual Bat Passes recorded and the number of buzzes detected within the vineyard and natural plots.

	Vineyard	Natural
Total number of IBPs recorded per habitat	852	965
Average IBPs recorded per night (range per night)	24 (1 – 254)	28 (1 – 152)
Mean IBPs per minute per night	0.08 IBP/min	0.12 IBP/min
95% confidence intervals for mean IBP/min per night	0.02 → 0.14 IBP/min	0.06 → 0.18 IBP/min
Average rate of buzzes detected per IBP per habitat (range per night)	2 % (0 – 22 %)	6 % (0 – 30 %)
Percent of nights with buzzes recorded	27.8 %	55.9 %
Number of buzzes detected within 2hrs of sunset	7	49
Number of buzzes detected within 1.5hrs prior to sunrise	7	4
Frequency group of bats feeding in habitat	25-35 kHz, 40-45 kHz	25-35 kHz, 40-45 kHz

3.2.2.1. Species richness: Bat frequency groups

Both vineyard and natural plots recorded bats calls that represented all four category bats with regards to frequency groups (Table 3.1). The distribution of frequency groups over vineyard and natural habitats was different ($\chi^2 = 103.3$ df = 3, $p < 0.00001$); however this difference was affected by the over representation of Category 2 bats recorded over the vineyard plot at Site 1 (see below). Based on the calls recorded, heard, trapping efforts, and the differences in sonogram characteristics observed, six to nine bat species were detected within my vineyard plots and eight to twelve bat species were present within my natural plots. Category 1 bats were detected less than the other categories both in number recorded and number of nights recorded (Table 3.4). This category includes four bat species and the sonogram characteristics for these calls suggest that a minimum of three species were detected. Two Category 1 species were confirmed at my sites. Fringed myotis (*Myotis thysanodes*) calls were identified by a bat biologist in two of my natural plots and I heard a spotted bat (*Euderma maculatum*) within a vineyard plot and a natural plot at two different sites. A large proportion of the total IBPs recorded were from Category 2 bats [73 % of vineyard IBPs (N = 619) and 50 % of natural IBPs (N = 481)]. This category represents seven species, which includes

two species also represented by Category 1 bats due to intraspecies variation of call parameters (Table 3.1). The number of Category 2 bats recorded over vineyard plots was skewed by Site 1, with 511 IBPs recorded at this site (83 % of the total). During the spring trapping session, a maternity colony roost was discovered 200 m NE of the radar's location, placing the acoustic array 130 m from the roost. No bats were captured outside of the roost; however the Category 2 calls recorded at Site 1 indicate that the day roost was likely occupied by big brown bats (*Eptesicus fuscus*). Sonogram characteristics for all Category 2 calls suggest a minimum of five species were detected. In addition, to big brown bats, this would also include pallid bats as a maternity colony roost is known to exist within Site 6 (Rambaldini and Brigham 2011). Category 3 bats represent 24 % of vineyard IBPs and 47 % of natural IBPs. This frequency group was recorded during most nights and throughout 15 of 16 SIs in both plots (Tables 3.4 and 3.5). This category represents five species with two species also represented by Category 4 bats (Table 3.1). Sonogram characteristics for these calls suggest a minimum of three species were detected. Three Category 3 bats were confirmed present within my sites from trapping efforts, and included Yuma myotis (*Myotis yumanensis*), long-legged myotis (*Myotis volans*), and the western small-footed myotis. Category 4 bats represent 2 % of the total IBPs recorded and were detected the least throughout the SIs surveyed. This category represents two species (Table 3.1), with Yuma myotis confirmed as being present at two sites.

Table 3.4. Number of Individual Bat Passes recorded in vineyard and natural plots based on the call's minimum frequency.

	Category 1 ≤ 22 kHz	Category 2 25 kHz – 35 kHz	Category 3 40 kHz – 45 kHz	Category 4 50 kHz
Vineyard plot				
Total IBPs detected (mean/night ± SD)	12 (0.3 ± 0.9)	619 (17.2 ± 56.6)	207 (5.8 ± 5.1)	14 (0.4 ± 0.7)
Percent of nights with frequency group detected	13.9 %	83.3 %	91.7 %	30.6 %
Percent of SI with frequency group detected	50 %	87.5 %	93.8 %	43.8 %
Natural plot				
Total IBPs detected (mean/night ± SD)	13 (0.4 ± 0.8)	481 (14.1 ± 26.5)	454 (13.3 ± 10.7)	17 (0.5 ± 0.7)
Percent of nights with frequency group detected	20.6 %	91.2 %	97.1 %	44.1 %
Percent of SI with frequency group detected	62.5 %	93.8 %	93.8 %	56.3 %

Table 3.5 lists the number of species groups associated with each category of frequency group based on number of different sonograms seen with my acoustic analysis. These species groups are given for each SIs and show how the number of potential species differs throughout the night between vineyards and natural habitats. Table 3.5 indicates that only one species was detected in vineyards and three species recorded over natural habitat 15 minutes after sunset in contrast to, eight species groups and 10 species groups recorded within vineyard and natural plots respectively during the second SI, 45 minutes after sunset. This increase in species richness corresponds with the rise in bat activity seen in Figures 3.7 and 3.8 below. Table 3.5 also shows one species detected 30 minutes prior to dawn, versus nine species groups and six species groups recorded in the vineyard and natural plots respectively one hour prior to dawn. In addition, SI -60 corresponds with an increase of species richness from the previous SI (-

90). This increase in species richness can also be associated with the slight rise in bat activity seen in Figures 3.7 and 3.8.

Table 3.5. Number of species groups recorded in each of the frequency groups during each sampling interval.

	Vineyard				Natural			
	≤ 22 kHz	25 kHz – 35 kHz	40 kHz – 45 kHz	50 kHz	≤ 22 kHz	25 kHz – 35 kHz	40 kHz – 45 kHz	50 kHz
15	0	1	0	0	1	1	1	0
45	0	3	4	1	1	5	3	1
75	2	4	2	1	2	2	3	1
105	1	3	3	1	1	2	3	1
135	0	3	1	0	1	2	3	0
165	1	2	2	0	1	3	2	1
195	0	2	3	1	1	3	3	1
225	0	2	3	0	0	2	3	0
255	1	3	3	0	1	2	3	1
≥285	0	1	3	0	1	3	2	1
-180	0	0	3	1	0	1	3	1
-150	0	1	3	0	0	2	1	0
-120	1	1	2	1	0	2	1	1
-90	1	2	2	0	1	2	2	0
-60	1	3	4	1	0	2	4	0
-30	0	0	1	0	0	0	0	0

Note: Species groups within a category or across categories may represent the same species due to intraspecies variation of call parameters (See Table 3.1 and Appendix F).

3.2.3. A comparison of radar and acoustic data

The mean natural log + 1 for number of radar tracks detected per minute and IBPs per minute detected across the SIs for both habitats are shown in Figures 3.7 and 3.8. Figures 3.7 and 3.8 both show a rapid rise of activity following sunset. In Figure 3.7 this rise is followed by a slight overall decrease in activity throughout the night, with two additional peaks in activity detected within the middle of the night (SI ≥285) and at 1 hr to 2 hrs prior to dawn (-120 to -60). In Figure 3.8, the rapid rise of activity following sunset

is followed by a rapid decrease in activity. A small amount of activity was detected throughout the rest of the night, with a rise in activity seen prior to dawn (SI -90) (Figure 3.8). Similar to Figure 3.7, the IBPs per minute recorded over natural plots has a small peak in activity at $SI \geq 285$. The $SI \geq 285$ peak represents bat activity between 01:00hrs and 03:00hrs. The vineyard IBPs per minute graph shows an earlier peak middle of the night with a rise in activity detected between SI 165 and 195 (Figure 3.8). This latter peak corresponds with activity detected between 22:15hrs and 01:35hrs. Unlike the peaks observed following sunset and prior to sunrise, the peaks observed in the middle of the night in both figures for either plots do not correspond with an increase in species richness (Table 3.5).

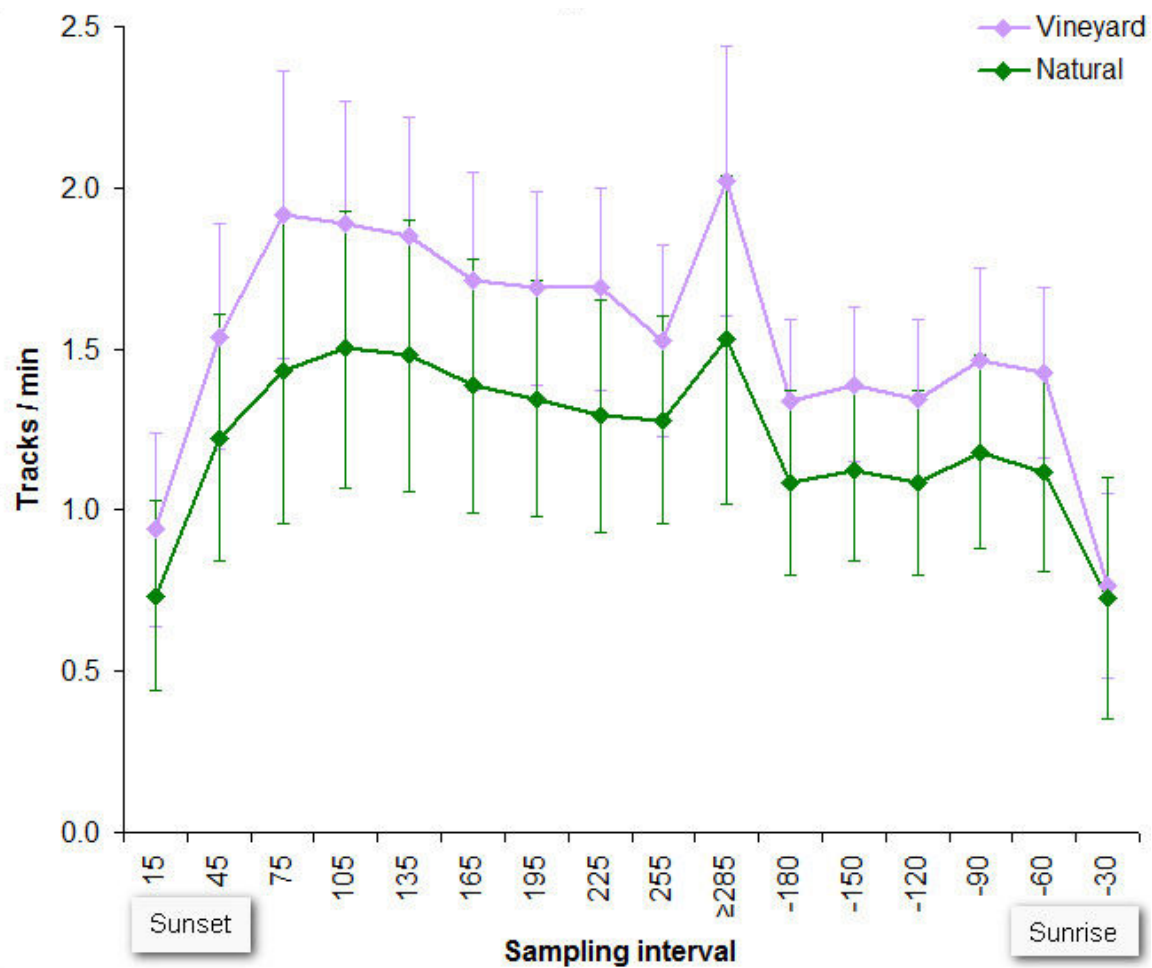


Figure 3.7. Mean natural log (tracks/min+1) calculated for each sampling interval showing nocturnal activity detected throughout the night. Error bars represent 95% confidence intervals. The x-axis corresponds with my sampling intervals and represents minutes after sunset or minutes prior to sunrise.

Note: Due to the change in length of darkness during the study, only 19 of 36 nights surveyed sampling interval of -30.

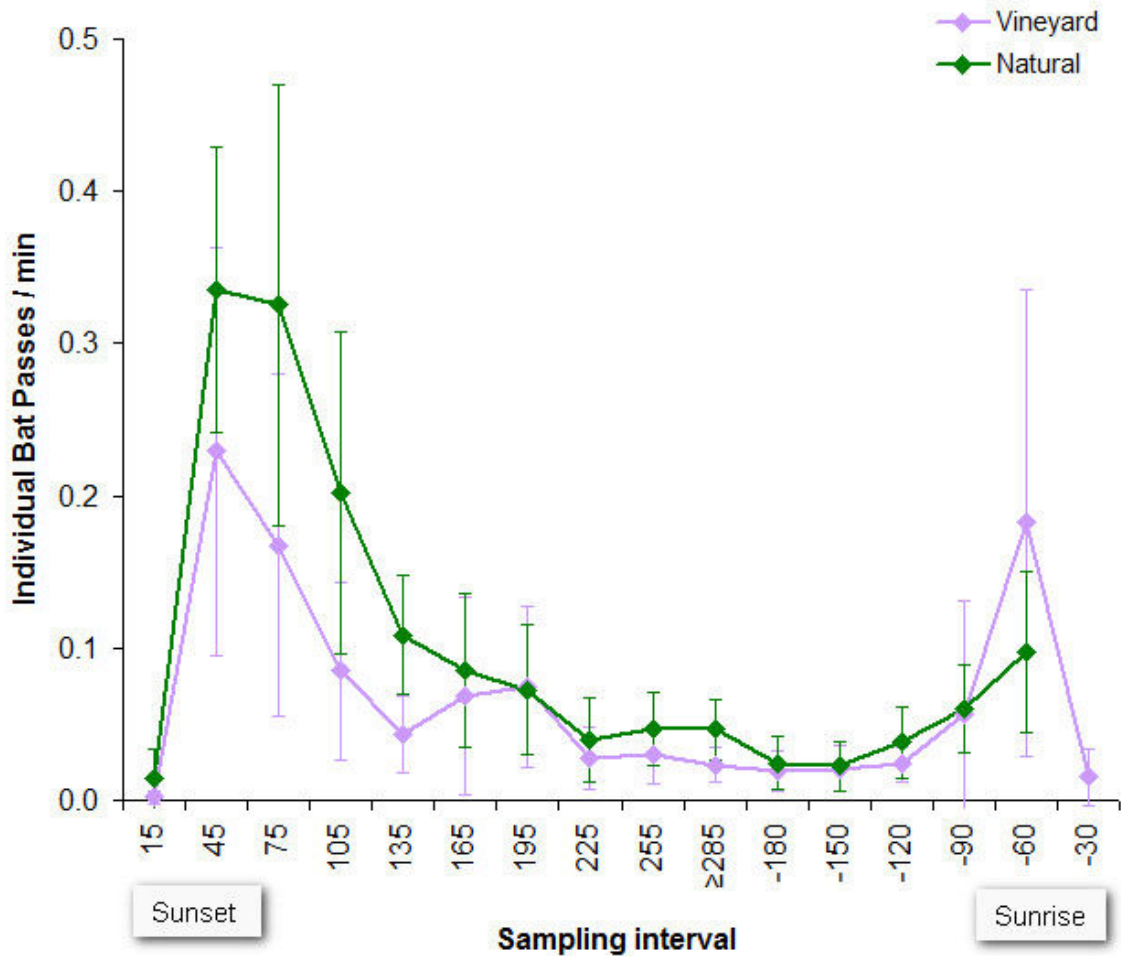


Figure 3.8. Mean natural log (IBP/min+1) calculated for each sampling interval showing nocturnal activity detected throughout the night. Error bars represent 95% confidence intervals. The x-axis corresponds with my sampling intervals and represents minutes after sunset or minutes prior to sunrise.

Note: Due to the change in length of darkness during the study, only 19 of 36 nights surveyed sampling interval of -30.

3.2.4. Habitat features and bat use

I was unable to evaluate if bat use within vineyards was concentrated around habitat features such as remnant tree patches, buildings, and areas with artificial lighting, as many of these features were situated within zero-detection zones. Only two sites with remnant tree patches could be visually assessed, and no conclusions could be made due to small sample size and variable response. Three sites had buildings; however a high density of tracks was only seen at one site. This site contained a

maintenance shop which kept its lights on throughout the night. Further work is needed to conclude if these features affect bat use within the habitat.

3.2.5. Inclement weather

The EchoTrack System allowed me to survey bat activity over eight nights during inclement weather. This included evenings with rain, high wind, and storms. These events reduced the quality of acoustic files and produced saturated wave files (See Chapter 2 Section 2.6.2 Figure 2.11). Four of my evenings surveyed included storms. One was a lightning storm that lasted past midnight and centred over land west of my site. Three nights included thunderstorms that started prior to my sampling times and centered over my sites. These storms had heavy precipitation, high winds, and included thunder and lightning. Two of these storms occurred at two sites during Period 1 (pregnancy and parturition) and one night at a different site during Period 2 (lactation). During Period 1, both thunderstorms lasted past midnight, whereas in Period 2 the thunderstorm lasted until early morning with heavy precipitation not ceasing until the end of the storm. During each thunderstorm, bat activity was recorded within the SIs that corresponded with heavy precipitation. In addition, I observed beetles and moths flying within the storms over my plots when backlit insects could be observed. The number of IBPs recorded and tracks detected during the three thunderstorms are included in Table 3.6.

Table 3.6. Data collected during thunderstorms.

	Nights surveyed	Total IBPs recorded in vineyard plots	Total IBPs recorded in natural plots	Total tracks detected
Period 1	2	6	22	994
Period 2	1	17	85	740

The number of tracks and IBPs detected during the six nights of sampling at each site was highly variable between the sampling nights and periods sampled throughout my study (Figure 3.9). Radar tracks and bat calls were both detected during all three thunderstorm events and did not always correspond with the least amount of activity

detected at any of the sites (Figure 3.9). Only the tracks at Site 4 and IBPs recorded at Site 5 during the Period 1 thunderstorms corresponded with the lowest number of detections for those sites respectively (Figure 3.9). No buzzes were detected during any of these evenings; however they may have been hidden in the saturated calls.

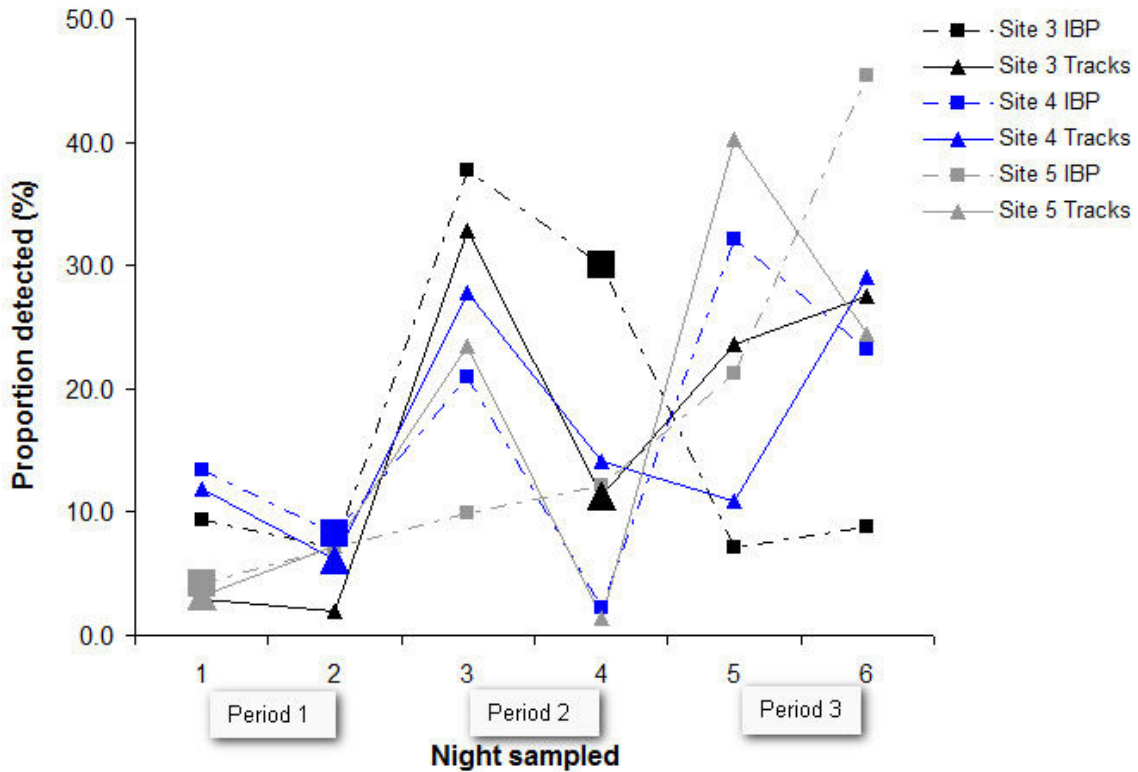


Figure 3.9. Proportion of Individual Bat Passes (squares) and radar tracks (triangles) detected during each night sampled at Sites 3, 4, and 5 that sampled bat activity during thunderstorms. Nights with thunderstorms are denoted by the larger data points.

Note: Other inclement weather events occurred during two additional nights at Site 3. These include precipitation at sunset during Night 1, and a lightning storm west of my study site during Night 3. No precipitation or high winds occurred during any of the other sampling nights at Site 4 or 5.

A greater amount of activity was detected during Period 2 (74 % of vineyard IBPs, 79 % of the natural IBPs, and 43 % of the tracks) than the nights surveyed during Period 1 (Table 3.6). During the Period 2 storm at Site 3 radar tracks were detected throughout all SIs, with acoustic data recorded within 13 of the 16 SIs. No bat calls were detected between 02:00hrs – 02:30hrs (SI ≥ 285 and SI -180) or within one hour prior to sunrise (SI -60); however the tracks activity indicated that bats were still active at these

times. The IBPs recorded during this event were also the second greatest number of IBPs recorded at Site 3 throughout the study (Figure 3.9). Species recorded during this storm were represented by all but Category 1 bats.

3.3. Discussion

EchoTrack's Radar-Acoustic Airborne Wildlife Surveillance System provided a unique opportunity to compare the use of vineyards and natural habitat in the South Okanagan. My study shows that bats are using vineyards in the regions and are not using vineyards less than natural habitat. This differs from other studies where activity was greater in natural areas compared with vineyards (DiSalvo et al. 2009; Boyle 2010; Stahlschmidt et al. 2012; Sirami et al. 2013). This difference may be attributed to the proximity of vineyards to potential day roosts as vineyards extend from the base of the cliffs in many areas to the valley bottom. Female bats will seek foraging areas near roost sites to reduce energy expenditure (Downs and Racey 2006). During lactation (Period 2) females return to the roost throughout the night to tend to their pup; therefore I expected to detect an increase in activity during this period. The total number of tracks detected and IBPs recorded during lactation increased from the pregnancy and parturition period. During lactation at two sites, I detected 5 – 25 times more IBPs than the other periods. One of these sites had a confirmed maternity colony roost located within 130 m of my vineyard array. However, overall, no period effect was observed as the data varied considerably from night to night. Vineyards and natural habitats were equally used by bats throughout their reproductive season.

The radar data showed a bimodal distribution in flight altitude over both vineyards and natural habitats (Figure 3.4). The detection of low and high flying bats could be attributed to bats using different foraging strategies. Bats will forage along the ground to heights well above treetops (Holroyd et al. 1994; Harvey et al. 2011; Sarell et al. 2011). Fast flying bat species and aerial hawkers forage in open areas or above the vegetative canopy, while slow flying bats have greater maneuverability and forage in cluttered environments, close to or within the vegetation. Some species will also forage at different altitudes throughout the night (Fenton et al. 1980; Barclay 1991). Foraging heights for the South Okanagan bat species have not been well documented; however

eastern red bats (*Lasiurus borealis*) and spotted bats are known to forage above the tree canopy (Sarell and Haney 2000; Harvey et al. 2011). The insectivorous Brazilian free-tailed bats (*Tadarida brasiliensis*) inhabiting southern North America have been observed foraging at heights up to 800 m above the ground (Fenton and Griffin 1997; McCracken 1996). The heights recorded over both plots between 54.6 m and 244.6 m may be attributed to high foraging bats. Further research should focus on foraging heights of bats in the area. Alternatively, the bimodal distribution of track heights may be attributed to commuting versus foraging bats. The distribution of speeds shows a large percentage of commuting bats with speeds over 7 m/s in both habitats (49%; Figure 3.3). The vineyards and natural habitats also had 55 % and 42 % of tracks above 54.6 m respectively. Although bats could forage at these heights, these heights would also represent commuting bats as commuting bats generally fly at higher altitudes than foraging bats. Furthermore, as mentioned above, Period 2 would have seen a large amount of commuting activity from lactating bats, with females commuting back and forth from their foraging grounds. The difference in height distribution over vineyards indicates that fast flying bat species, aerial hawkers, and species that forage at higher altitude use vineyards more than gleaners and slow flying bats. In addition, more bats were likely detected commuting through these areas. The similar proportion of low and high flying bats over natural habitats suggests that commuting and foraging bats were equally detected over this habitat. Few tracks had start heights below 2.7 m, which was a result of the vegetative canopy and terrain (Figure 3.4, $<e^1$). The average vineyard canopy height of 2.5 m would have restricted target detection within the vines. The location of the radar relative to natural habitat, as well as the vegetation, clutter, and relief over natural habitat, would have impeded the detection of targets below 2.7 m in these areas. Little detection within the canopy would have underestimated activity from gleaning species. Gleaners feed within the vegetative canopy, therefore their detection, within either habitat, while foraging would have been minimized due to clutter. The bimodal distribution suggests that the bats are using the two habitats differently in the South Okanagan. The wind adjusted target speed was plotted against my SIs for each habitat to assess the temporal variation of speed throughout the night and height was also plotted against speed. Although these graphs were not included, no correlations were identified and did not further explain the bimodal distribution.

The distribution of relative target size showed very few targets with a SNR value greater than 1 (Figure 3.5). This implies that the bat species present at my site may be associated with SNR values less than or equal to 1. Although my filtering criteria minimized noise from insects (Chapter 2 Section 2.5.4.1), large insects were likely detected by the radar. During my study at three sites, I observed high activity of dragon flies and nighthawks feeding over vineyards compared with the adjacent natural habitat prior to equipment setup. Insect abundance was not visually assessed during my sampling times. The distribution of SNR values suggests that vineyards had higher insect abundance throughout the night; however the large proportion of targets with a SNR value of 0.01 may have also resulted from bats being detected head on or end on from the radar. Further research is needed to assign taxa and species to SNR values and to understand how SNR values vary with each taxa.

The acoustic data showed evidence of foraging within vineyards and natural habitat with buzzes detected across multiple SIs in both plots. My data suggest that bats are remaining in both habitats throughout the night to forage, and that natural habitat provides better foraging opportunities for bats. However, a greater number of buzzes were detected prior to sunrise (SI -90 – SI -60) over my vineyard plots (Table 3.3). Overall, I recorded a low number of buzzes in both plots (Table 3.3). The buzz rates were lower than those seen with other studies (Furlonger et al. 1986; Stahlschmidt et al. 2012; D. Burles, personal communications, March 7, 2016). The low buzz rates may have been affected by the saturated files (Chapter 2 Section 2.6.2). Buzzes have a lower-intensity than search phase calls and could have been underestimated. Furthermore, the low buzz rates may have been a factor of foraging strategies. Buzzes from gleaners and bats that forage at high altitudes would not have been detected by the acoustic arrays. As discussed previously, a large percentage of tracks were detected above 54.6 m. Further research is needed to compare the foraging rates of bats over vineyards and natural habitats throughout the night. Bats have preferred foraging areas (Woodsworth et al. 1981; Racey and Swift 1985; Fenton 1997; Verboom and Huitema 1997; Zukal and Gajdošík 2012), and by chance the majority of my acoustic arrays did not sample the high track density areas seen within my sites. My radar data provide insight to where activity was concentrated over both habitats; this could be used to properly assess foraging activity between vineyard and natural habitats. Sampling

should take place throughout the night or at a minimum during the peak activity times identify by Figures 3.7 and 3.8. This would assess whether natural habitats overall provide better foraging opportunities for bats and if vineyards provide better foraging opportunities for bats prior to sunrise. In addition to acoustic monitoring, visual observations using night vision or infrared cameras should be considered as this would provide better insight into foraging activities by accounting for species and buzzes not detected by the bat detectors.

In addition to buzz rate, foraging activity can also be related to the detection of bat passes over an area (Fenton 1982a; Vaughan et al. 1997). Echolocation by insectivorous bats is used to search for prey and is generally associated with a bat's attempt to feed (Norberg 1994; Fenton 1997; Sarell et al. 2011). Due to the short range of echolocation calls from attenuation, the detection of any bat call would imply foraging activity in the surrounding area and provides information on habitat use (Fenton 1982a). My results did not detect any evidence that bats were spending more time searching for prey in natural habitats compared to vineyards.

All four category bats were recorded within vineyard and natural plots, with low detections of Category 1 and Category 4 bats (Table 3.4). The low minimum frequency for calls generated by Category 1 bats has a greater range of detection than the other frequency groups. Their low occurrence indicates a low relative abundance of Category 1 species within my study sites (Table 3.1). The high minimum frequency for calls generated by Category 4 bats attenuate quickly through air resulting in a shorter range of detection, and therefore calls from these species may have been missed. My acoustic analysis identified multiple species using both vineyards (six to nine) and natural habitats (eight to twelve) throughout the night, with seven species confirmed within my study sites. Although Townsend's big-eared bat and canyon bat were excluded from my acoustic analysis, they may have been present at my sites and detected with the radar. Townsend's big-eared bats were likely present as these bats produce low-intensity calls, which are hard to detect with microphones (Appendix F). In addition, one was captured at Site 1 in 1997 (D. Burles, personal communications, March 7, 2016). Bat activity and species richness detected over the vineyard and natural plots showed different results than other agricultural studies (Marques et al. 2004; DiSalvo et al. 2009; Boyle 2010; Stahlschmidt et al. 2012; Sirami et al. 2013). I

expected to detect less activity over vineyards, but have similar species richness between the habitats. My results show no difference in activity, with fewer species detected over vineyards. This difference may have been attributed to high foraging bats. Calls generated by bats flying high above the microphone array would have been harder to detect due to attenuation. In addition, there may have been some loss in detection with low intensity echolocating bats and gleaners. Low intensity bats produce soft calls described as whispers and are often underestimated due to their shorter range of detection (0.5 m – 5 m) (Downes 1982; Fenton 1982b; Barclay 1991; Verboom and Huitema 1997; Down and Racey 2006; Adams et al. 2009). Gleaners, such as long-eared myotis (*Myotis evotis*) and pallid bats, rely on prey generated sounds rather than echolocation when foraging, thus limiting their detection with the acoustic arrays (Norberg 1994; Rambaldini and Brigham 2011).

The temporal variation in the natural log number of tracks per minute and IBP per minute for both habitats shows evidence that bats were remaining in these areas throughout the night. Activity was detected during each SI implying that bats are not simply commuting through vineyards on their way to natural habitats after roost emergence and returning from these areas prior to roost re-entry (Figures 3.7 and 3.8). This conclusion is further supported by the rose graphs which display a range of track directions following sunset and prior to sunrise (Figure 3.6). Figures 3.7 and 3.8 both show peaks in activity that correspond with the peak foraging times identified for bats in the area with a peak following sunset, a peak in the middle of the night, and a peak prior to dawn (Nagorsen and Brigham 1993; Holroyd et al. 1994; Rambaldini and Brigham 2011). The peaks following sunset and prior to dawn seen in both plots in both graphs correspond with the energy demands of bats (Racey 1982). During my study, bats roosted for a minimum of 15 hrs during the day before emerging from their roost after sunset. Upon emergence bats seek food and water to replenish their small fat reserves and support their high energy demands (McNab 1982). Before returning to their roosts bats will build up fat reserves at the end of the night (McNab 1982, Racey 1982). The peaks following sunset and prior to dawn also corresponded with increases in species richness (Table 3.5). This table shows few bat species emerging from their day roost immediately after sunset, with multiple species active towards the end of the dusk crepuscular period (SI 45). Similar to roost emergence, bats return to their day roost

before the dawn crepuscular period (SI -60). The temporal variation in the number of IBPs per minute is different between vineyard and natural habitats with respect to the peak identified in the middle of the night. The later peak observed in the natural plots may be related to a shift in prey species over vineyard to natural habitats. Habitat use and bats foraging activity is often related to prey selection rather than insect abundance and diversity (Furlonger et al. 1986; Whitaker 1995; Agosta et al. 2003; Rambaldini and Brigham 2011; Stahlschmidt 2012).

Three separate comparisons of the track density with the number of Individual Bat Passes (IBPs) recorded suggested that the majority of the tracks were generated from bats (Chapter 2 Section 2.5.4.1). The overall patterns seen with the temporal variation graphs for both habitats are different (Figures 3.7 and 3.8). Figure 3.7 shows a slight decrease in bat activity across the night, while Figure 3.8 shows a rapid decrease in activity after SI 75. This difference suggests that the majority of the bat species active between SI 75 and SI -90 were not picked up by the acoustic arrays. The small number of IBP/min detected during these latter intervals could be a result of multiple factors. These include (1) bat activity concentrated in areas outside of the range of the acoustic detectors, both laterally and vertically, (2) bat species active at these times had calls that attenuated quickly, reducing their range of detection, (3) gleaning bat species, active during these times, produced few echolocation calls and were not detected by the acoustic arrays. With regards to bat species, Category 2 and 3 bats were active throughout the night (Table 3.5). However, calls from Category 2 bats were recorded from species groups having high-intensity calls (Appendix F). Three Category 2 bat species have low intensity calls; very few IBPs (N = 6) were associated with their species groups (0.3%; Appendix F). Although Category 3 bats were detected throughout the night, the bats associated with this category would have a lower range of detection due to their higher minimum frequency (Table 3.1 and Appendix F). Therefore high foraging Category 3 bats would have been missed by the acoustic arrays. Category 1 and 4 bats had gaps of detection throughout the SIs (Table 3.5). The species associated with these latter categories may not have been detected throughout each SI as they may use feeding or night roost more often than the species associated with Category 2 and 3 bats. In addition, as previously mentioned, the Category 1 bats

had low relative abundance within my sites and calls from Category 4 bats may have been missed.

Habitat features such as buildings, trees, and lights can enhance bat habitat and increase foraging opportunities (Furlonger et al. 1986; Saunders and Barclay 1992; Fenton 1997; Sarell and Haney 2000; Agosta et al. 2003). Habitat assessment of these features was not accomplished due to zero-detection zones. Despite this complication, a visual assessment of the tracks over Site 6 showed a high density of tracks concentrated over the maintenance shop. The lighting at this shop was very bright and left on throughout the night. This would have attracted bat species such as long-legged myotis, big brown bat, hoary bat (*Lasiurus cinereus*), and eastern red bat that will forage around lights (Furlonger et al. 1986; Saunders and Barclay 1992; Fenton 1997; Sarell and Haney 2000; Agosta et al. 2003). The resort within Site 5 is also known to be a night roost for bats, as bats have been seen hanging on side of the building (personal communication with the vineyard owner during my field season). Buildings within vineyards may be important to bats in the South Okanagan; however further research is needed.

Using radar to assess the habitat association of bats provided a unique opportunity to monitor bat activity during thunderstorms. Bat activity is not typically surveyed in inclement weather as insect activity is reduced and bats have difficulty detecting prey during storms. Visual observations and radar-acoustic data indicated that despite the high winds and heavy precipitation associated with three thunderstorms both bats and insects were active. Furthermore, preliminary analysis found no evidence that bat activity varied with any of the environmental variables recorded, which included precipitation, cloud cover, and average nightly wind speed. An assessment of the storm data showed a greater amount of bat activity during the worst storm, which also corresponded with lactation (Figure 3.9). These data show the energy constraints put on lactating bats. During pregnancy bats can enter torpor; however the use of torpor will delay foetal development. Torpor is not normally used during lactation. The high energy demand of lactating females requires them to forage throughout the night and forage longer than pregnant bats (Aldridge and Brigham 1991; Altringham 1996). Females must find food to support their own energy demands, as well as those of their growing pups (Norberg 1994). Lactating bats actively seeking prey during the worst storm

encountered in my study put in a greater amount of effort to detect prey. An overall greater amount of activity was detected during that night, as well as activity was detected throughout the night (Figure 3.9). This activity could not have been assessed if the radar only operated during clear-air operations.

When comparing agricultural lands to un-modified landscapes, most research indicates that bats prefer native vegetation compared to agricultural lands; however bat responses vary (Fenton 1997; Jaberg and Guisan 2001; Wickramasinghe et al. 2003; Henderson and Broders 2008; DiSalvo et al. 2009; Boyle et al. 2011). In the South Okanagan no difference in bat activity was detected over vineyards and natural habitats. My results show that vineyards provide habitat and foraging opportunities for bats in the region. Bats use vineyards as equally as natural habitats throughout their reproductive season, and multiple species were detected using both habitats throughout the night. Greater species richness was detected over natural habitats; however six to nine species are using vineyards. A different diversity of bat species or a difference in habitat use is suggested through the assessment of radar track parameters over both habitats and likely attributed to foraging strategies and flight modes. My results suggest that the prey diversity over vineyards is sufficient enough to attract bats to these areas. The integrated pest management control used by viticulturists favours beneficial insects and would increase insect diversity and abundance over and within the crops (BC Ministry of Agriculture and Lands 2010). All bat species in the South Okanagan have the potential to forage within vineyards given the diverse insect community associated with them. Beneficial insects, in addition to crop pests would provide prey for the bat community in the region.

3.4. Further research and recommendations

My results demonstrate that bats are using vineyards in the South Okanagan, however many information gaps remain. Bat research in the area should be ongoing to understand the role that vineyards play in the ecology of bats and to determine if and how bat activity over vineyard and natural habitats change with the growing wine industry. Bats may be feeding on the insects damaging vineyard crops and could be providing ecosystem services for the wine industry, as seen with the agricultural industry

in the US (Whitaker 1995; Boyles et al. 2011; Brown et al. 2015; Maine and Boyle 2015). In addition, bat species may indirectly reduce the number of larvae damaging crops by affecting the oviposition of moth species that are sensitive to their echolocation calls (Maine and Boyle 2015). To understand the relationship of bats and vineyards, the insect community throughout the night, relative to bat prey, should be studied. Research should assess for any temporal and seasonal differences (as it relates to the bats' reproductive periods). Any insect study should also include methods to assess the quantity of prey consumed by bats, as bats must consume enough adults to have a direct effect on the reproductive success of the insects and therefore provide an ecosystem service to the South Okanagan winery industry (Maine and Boyle 2015).

In addition to insect studies, other bat research in the region could focus on habitat features within vineyards that would support and enhance bat activity. Better study design and methods could assess buildings, trees, and lights. An assessment of habitat features could enhance the foraging opportunities for bats and increase the habitat quality within vineyards. Another important habitat feature identified for bats is water. Water is very important to bats, especially in dry regions (Adams and Thibault 2006; DiSalvo et al. 2009). The South Okanagan is a desert and has limited water resources for bats. These are mostly confined to the major water bodies in the valley bottom. Bats have evaporative water loss within their day roost and seek water upon emergence (Neuweiler 2000; Adams and Thibault 2006). A retention pond or water trough could be constructed within vineyards, close to potential day roosts to determine if and when bats would use these resources. This type of study could assess if the addition of water affects bat activity, species richness and diversity over vineyards as seen with other studies (Stahlschmidt et al. 2012; Sirami et al. 2013). The addition of retention ponds or water troughs in vineyards could benefit bats, as well as viticulturists if the design allowed for irrigation purposes.

3.5. Conclusion

Agricultural areas and monocultures are often associated with habitat fragmentation and habitat loss; however species access to resources within the landscape must be considered (Franklin et al. 2002). Agricultural areas, including

vineyards, can provide opportunities for bats as flight allows them to move across the landscape to locate resources (Fenton 1997; Law et al. 1999; Estrada and Coates-Estrada 2002). Bats will feed on crop pests and are contributing to billions of dollars in economic savings for the US agricultural industry (Whitaker 1995; Boyles et al. 2011). I used EchoTrack's Radar-Acoustic Airborne Wildlife Surveillance System to assess the spatial distribution of bats over vineyard and natural habitat in the South Okanagan Valley. This is the first study of its scale to address habitat association of bats using a mobile surveillance radar. No difference in the amount of habitat use was observed between vineyards and natural habitats; however bat species in the area are likely using the two habitats differently. Peak activity times were observed in both habitats; however bats were active throughout the night. Vineyards provide both commuting and foraging habitat for multiple bat species in the region throughout their reproductive cycle. It is important to recognize the use of vineyards by bats in the South Okanagan as their natural habitat is diminishing and human-modified habitats can help with management efforts. The BC Wine Grape Council should incorporate bats into their Sustainable Winegrowing Program and Best Practices Guide for Grapes as this would support the bat community in the South Okanagan, and would likely benefit the wine industry.

I show that vineyards provide resources to bats and play a role in the ecology of the South Okanagan bat community; however this role is not yet understood. Future research is needed to understand how bats use vineyards, what prey bats are targeting, and how prey activity varies temporally and seasonally with regards to the bat's reproductive cycle. An understanding of vineyard use is important for the management and conservation of bat species in the region. Further research would also provide an understanding of the ecosystem services provided by bats to the growing wine industry in the region.

References

Peer Reviewed Journals, Books, and Book Chapters

- Adams, M.D., B.S. Law, and K.O. French. 2009. Vegetation structure influences the vertical stratification of open-and edge-space aerial-foraging bats in harvested forests. *Forest Ecology and Management* 258:2090-2100.
- Adams, R.A. and K.M. Thibault. 2006. Temporal resource partitioning by bats at water holes. *Journal of Zoology* 270:466-472.
- Agosta, S.J., D. Morton, and K.M. Kuhn. 2003. Feeding ecology of the bat *Eptesicus fuscus*: 'preferred' prey abundance as one factor influencing prey selection and diet breadth. *Journal of Zoology, London* 260:169-177.
- Aldridge, H.D.J.N., and R.M. Brigham. 1991. Factors influencing foraging time in two aerial insectivores: the bird *Chordeiles minor* and the bat *Eptesicus fuscus*. *Canadian Journal of Zoology* 69:62-69.
- Altringham, J.D. 1996. *Bats: biology and behaviour*. Oxford University Press, Oxford, England. Pp. 262.
- Altringham, J.D. 2011. *Bats: from evolution to conservation*, 2nd Edition. Oxford University Press, Oxford, England. Pp. 324.
- Andrén, H. 1994. Effects of habitat fragmentation on birds and mammals in landscapes with different proportions of suitable habitat: a review. *Oikos* 71:355-366.
- Barclay, R.M.R. 1986. The echolocation calls of hoary (*Lasiurus cinereus*) and silver-haired (*Lasionycteris noctivagans*) bats as adaptations for long- versus short-range foraging strategies and the consequences for prey selection. *Canadian Journal of Zoology* 64: 2700-2705.
- Barclay, R.M.R. 1991. Population structure of temperate zone insectivorous bats in relation to foraging behaviour and energy demand. *Journal of Animal Ecology* 60:165-178.
- Bernard, E., and M.B. Fenton. 2007. Bats in a fragmented landscape: species composition, diversity and habitat interactions in savannas of Santarém, Central Amazonia, Brazil. *Biological Conservation* 134:332-343.
- Boyles, J.G., P.M. Cryan, G.F. McCracken, and T.H. Kunz. 2011. Economic importance of bats in agriculture. *Science* 332:41-42.

- Britton, A.R.C., G. Jones, J.M.V. Rayner, A.M. Boonman, and B. Verboom. 1997. Flight performance, echolocation and foraging behaviour in pond bats, *Myotis dasycneme* (Chiroptera: Vespertilionidae). *Journal of Zoology, London* 241:503-522.
- Brown, V.A., E. Braun de Torrez, and G. McCracken. 2015. Crop pests eaten by bats in organic pecan orchards. *Crop Protection* 67:66-71.
- Bruderer, B. 1997. The study of bird migration by radar. *Naturwissenschaften* 84:1-8.
- Bruderer, B., D. Peter, and T. Steuri. 1999. Behaviour of migrating birds exposed to x-band and a bright light beam. *The Journal of Experimental Biology* 202:1015-1022.
- Bruderer, B., and A. Boldt. 2001. Flight characteristics of birds: I. radar measurements of speeds. *Ibis* 143:178-204.
- Bruderer, B., and A.G. Popa-Lisseanu. 2005. Radar data on wing-beat frequencies and flight speeds of two bat species. *Acta Chiropterologica* 7:73-82.
- Chapman, J.W., V.A. Drake, and D.R. Reynolds. 2011. Recent insights from the radar studies of insect flight. *Annual Review of Entomology* 56:337-356.
- Chilson, P.B., W.F. Frick, P.M. Stepanian, J.R. Shipley, T.H. Kunz, and J.F. Kelly. 2012a. Estimating animal densities in the aerosphere using weather radar: to Z or not to Z? *Ecosphere* 3:1-18.
- Chilson, P.B., W.F. Frick, J.F. Kelly, K.W. Howard, R.P. Larkin, R.H. Diehl, J.K. Westbrook, T.A. Kelly, and T.H. Kunz. 2012b. Partly cloudy with a chance of migration: weather, radars, and aeroecology. *Bulletin of the American Meteorological Society* 93:669-686.
- Cryan, P.M., and R.H. Diehl. 2009. Chapter 22: Analyzing bat migration. Pp. 476-481, In: *Ecological and behavioural methods for the study of bats 2nd Edition* (T.H. Kunz and S. Parsons, eds.). The Johns Hopkins University Press, Baltimore, Maryland.
- Dean, T.J., and V.A. Drake. 2005. Monitoring insect migration with radar: the ventral-aspect polarization pattern and its potential for target identification. *International Journal of Remote Sensing* 26:3957-3974.
- DiSalvo, I., D. Russo, and M. Sarà. 2009. Habitat preferences of bats in a rural area of Sicily determined by acoustic surveys. *Hystrix, the Italian Journal of Mammalogy* 20:137-146.
- Downes, C.M. 1982. A comparison of sensitivities of three bat detectors. *Journal of Mammalogy* 63:343-345.
- Downs, N.C., and P.A. Racey. 2006. The use by bats of habitat features in mixed farmland in Scotland. *Acta Chiropterologica* 8:169-185.

- Eastwood, E. 1967. Radar ornithology. Methuen and Co Ltd, London, England. Pp 290.
- Estrada, A., and R. Coates-Estrada. 2002. Bats in a continuous forest, forest fragments, and in an agricultural mosaic habitat-island at Los Tuxtlas, Mexico. *Biological Conservation* 103:237-345.
- Fenton, M.B. 1982a. Echolocation calls and patterns of hunting and habitat use of bats (*Microchiroptera*) from Chillagoe, North Queensland. *Australian Journal of Zoology* 30:417-425.
- Fenton, M.B. 1982b. Chapter 7: Echolocation, insect hearing, and feeding ecology of insectivorous bats. Pp. 261-285, In: *Ecology of bats* (T. H. Kunz, ed.). Plenum Press, New York, New York.
- Fenton, M.B. 1983. *Just bats*. University of Toronto Press, Toronto, Ontario. Pp 165.
- Fenton, M.B. 1997. Science and the conservation of bats. *Journal of Mammalogy* 78:1-14.
- Fenton, M.B., and G.P. Bell. 1979. Echolocation and feeding behaviour in four species of *Myotis* (Chiroptera). *Canadian Journal of Zoology* 57:1271-1277.
- Fenton, M.B., C.G. vanZyll de Jong, G.P. Bell, D.B. Campbell, and M Laplante. 1980. Distribution, parturition dates, and feeding of bats in south-central British Columbia. *Canadian Field-Naturalist* 94:416-420.
- Fenton, M.B., and G.P. Bell. 1981. Recognition of species of insectivorous bats and their echolocation calls. *Journal of Mammalogy* 62:233-243.
- Fenton, M.B., and D.R. Griffin. 1997. High-altitude pursuit of insects by echolocating bats. *Journal of Mammalogy* 78:247-250.
- Findley, J.S., E.H. Studier, and D.E. Wilson. 1972. Morphologic properties of bat wings. *Journal of Mammalogy* 53:429-444.
- Franklin, A.B., B.R. Noon, and T.L. George. 2002. What is habitat fragmentation? *Studies in Avian Biology* 25:20-29.
- Frick, W.F., P.M. Stepanian, J.F. Kelly, K.W. Howard, C.M. Kuster, T.H Kunz, and P.B. Chilson. 2012. Climate and weather impact timing of emergence of bats. *Plos One* 7:1-8.
- Frick, W.F., P.B. Chilson, N.W. Fuller, E.S. Bridge, and T.H. Kunz. 2013. Chapter 8: Aeroecology. Pp. 149-167, In: *Bat evolution, ecology, and conservation* (R.A. Adams and S.C. Pedersen, eds). Springer Science+Business Media, New York, New York.
- Furlonger, C.L., H.J. Dewar, and M.B. Fenton. 1986. Habitat use by foraging insectivorous bats. *Canadian Journal of Zoology* 65:284-288.

- Gauthreaux, SA Jr. 1996. Historical perspectives, Bird migration: methodologies and major research trajectories (1945-1995). *The Condor* 98:442-453.
- Gauthreaux, S.A. Jr., and C.G. Belser. 2003. Radar ornithology and biological conservation. *The Auk* 120:266-277.
- Griffin, D.R. 1974. *Listening in the dark: the acoustic orientation of bats and men* (first published in 1958). Dover Publications Inc. New York, New York. Pp 413.
- Griffiths, S.R. 2013. Echolocating bats emit terminal phase buzz calls while drinking on the wing. *Behavioural Processes* 98:58-60.
- Grodzinski, U., O. Spiegel, C. Korine, and M.W. Holderied. 2009. Context-dependent flight speed: evidence for energetically optimal flight speed in the bat *Pipistrellus kuhlii*? *Journal of Animal Ecology* 78:540-548.
- Gudmundsson, G.A. 1993. The spring migration pattern of arctic birds in southwest Iceland, as recorded by radar. *Ibis* 135:166-176.
- Hajovsky, R.G., A.P. Deam, and A.H. LaGrone. 1966. Radar reflections from insects in the lower atmosphere. *IEEE Transactions on Antennas and Propagation* AP-14:224-227.
- Harvey, M.J., J.S. Altenbach, and T.L. Best. 2011. *Bats of the United States and Canada*. John Hopkins University Press, Baltimore, Maryland. Pp. 202.
- Hayes, J.P., H.K. Ober, and R.E. Sherwin. 2009. Chapter 6: Survey and monitoring of bats. Pp. 112-129, In: *Ecological and behavioural methods for the study of bats 2nd Edition* (T.H. Kunz and S. Parsons, eds.). The Johns Hopkins University Press, Baltimore, Maryland.
- Hayward, B., and R. Davis. 1964. Flight speeds in western bats. *Journal of Mammalogy* 45:236-242.
- Hedenström, A., and T. Alerstam. 1995. Optimal flight speed of birds. *Philosophical Transactions of the Royal Society of London B* 348:471-487.
- Henderson, L.E., and H.G. Broders. 2008. Movements and resource selection of the northern long-eared myotis (*Myotis septentrionalis*) in a forest-agriculture landscape. *Journal of Mammalogy* 89:952-963.
- Holdereid, M.W., and G. Jones. 2009. Chapter 21: Flight dynamics of bats. Pp. 459-475, In: *Ecological and behavioural methods for the study of bats 2nd Edition* (T.H. Kunz and S. Parsons, eds.). The Johns Hopkins University Press, Baltimore, Maryland.
- Horn, J.W., and T.H. Kunz. 2008. Analyzing NEXRAD Doppler radar images to assess nightly dispersal patterns and population trends in Brazilian free-tailed bats (*Tadarida brasiliensis*). *Integrative and Comparative Biology* 48:24-39.

- Jaberg, C. and A. Guisan. 2001. Modelling the distribution of bats in relation to landscape structure in a temperate mountain environment. *Journal of Applied Ecology* 38:1169-1181.
- Jedlicka, J.A., R. Greenberg, and D.K. Letourneau. 2011. Avian conservation practices strengthen ecosystem services in California vineyards. *Plos One* 6 (e27347):1-8.
- Jones, G., and J.M.V. Rayner. 1988. Flight performance, foraging tactics and echolocation in free-living Daubenton's bats *Myotis daubentoni* (Chiroptera: Vespertilionidae). *Journal of Zoology, London* 215:113-132.
- Kalda, O., R. Kalda, and J. Liira. 2015. Multi-scale ecology of insectivorous bats in agricultural landscapes. *Agriculture, Ecosystems and Environment* 199:105-113.
- Kelly, J.F., J.R. Shipley, P.B. Chilson, K.W. Howard, W.F. Frick, and T.H. Kunz. 2012. Quantifying animal phenology in the aerosphere at a continental scale using NEXRAD weather radars. *Ecosphere* 3:1-8.
- Kerth, G., and D.K.N. Dechmann. 2009. Chapter 18: Field-based observations and experimental studies of bat behaviour. Pp. 393-406, In: *Ecological and behavioural methods for the study of bats 2nd Edition* (T.H. Kunz and S. Parsons, eds.). The Johns Hopkins University Press, Baltimore, Maryland.
- Kunz, T.H., and S. Parsons (Ed). 2009. Preface: Ecological and behavioural methods for the study of bats, 2nd Edition. The Johns Hopkins University Press. Baltimore, Maryland.
- Kunz, T., E. Braun de Torrez, D. Bauer, T. Lobo, and T.H. Fleming. 2011. Ecosystem services provided by bats. *Annals of the New York Academy of Sciences* 1223:1-38.
- Lack, D., and G.C. Varley. 1945. Detection of birds by radar. *Nature* 156:446.
- Larkin, R.P. 1991. Flight speeds observed with radar, a correction: slow "birds" are insects. *Behavioral Ecology and Sociobiology* 29:221-224.
- Law, B.S., J. Anderson, and M. Chidel. 1999. Bat communities in a fragmented forest landscape on the south-west slopes of New South Wales, Australia. *Biological Conservation* 88:333-345.
- Lea, T. 2008. Historical (pre-settlement) ecosystems of the Okanagan Valley and Lower Similkameen Valley of British Columbia – pre-European contact to the present. *Davidsonia* 19:3-36.
- Leonard, M.L., and M.B. Fenton. 1983. Habitat use by spotted bats (*Euderma maculatum*, Chiroptera: Vespertilionidae): roosting and foraging behaviour. *Canadian Journal of Zoology* 61:1487-1491.

- Lesiński, G., M. Kowalski, B. Wojtowicz, J. Gulatowska, and A. Lisowska. 2007. Bats on forest islands of different size in an agricultural landscape. *Folia Zoologica* 56:153-161.
- Lowery, D.T., and A.M. Mostafa. 2010. Cutworm species (Lepidoptera: Noctuidae) feeding on grapevines in the Okanagan Valley, British Columbia, with notes on rearing. *The Canadian Entomologist* 142:173-180.
- Maine, J.J, and J.G. Boyles. 2015. Bats initiate vital agroecological interactions in corn. *Proceedings of the National Academy of Sciences* 112:12438-12443.
- Marques, J.T., A. Rainho, M. Carapuço, P. Oliveira, and J.M. Palmeirim. 2004. Foraging behaviour and habitat use by the European free-tailed bat *Tadarida teniotis*. *Acta Chiropterologica* 6:99-110.
- Martin, W.J., and A. Shapiro. 2006. Discrimination of bird and insect radar echoes in clear-air using high-resolution radars. *Journal of Atmospheric and Oceanic Technology* 24:1215-1230.
- McCracken, G.F. 1996. Bats aloft: a study of high-altitude feeding. *Bats* 14: 7-10.
- McCracken, G.F., E.H. Gillam, J.K. Westbrook, Y. Lee, M.L. Jensen, B.B. Balsley. 2008. Brazilian free-tailed bats (*Tadarida brasiliensis*: Molossidae, Chiroptera) at high altitude: links to migratory insect populations. *Integrative and Comparative Biology* 48:107–118.
- McNab, B.K. 1982. Chapter 4: Evolutionary alternatives in the physiological ecology of bats. Pp. 151-200, In: *Ecology of bats* (T. H. Kunz, ed.). Plenum Press, New York, New York.
- Millikin, R.L, and J.R Buckley. 2001. Use of an adapted marine radar for the short-range detection and tracking of small birds in flight. *Geoscience and Remote Sensing Symposium IGARSS'01 IEEE International* 5:2010-2012.
- Mills, A.M. 1986. The influence of moonlight on the behavior of goatsuckers (*Caprimulgidae*). *The Auk* 103:370-378.
- Morrison, D.W. 1980. Flight speed of some tropical forest bats. *American Midland Naturalist* 140:189-192.
- Nagorsen, D.W., and R.M. Brigham. 1993. *Bats of British Columbia (Vol 1)*. UBC Press and Royal British Columbia Museum. Vancouver, BC. Pp164.
- Negraeff, O.E., and R.M. Brigham. 1995. The influence of moonlight on the activity of little brown bats (*Myotis lucifugus*). *Zeitschrift für Säugetierkunde (International Journal of Mammalian Biology)* 60:330-336.
- Neuweiler, G. 2000. *The biology of bats*. Oxford University Press Inc. New York, New York. Pp 310.

- Nicholson, A., E. Hamilton, W.L. Harper, and B.M. Wikeem. 1991. Chapter 8: Bunchgrass Zone. BC Special Report Series 6:125-137, In: Ecosystems of British Columbia, (D. Meidinger and J. Pojar, eds.). Research Branch, British Columbia Ministry of Forests, Victoria, BC. Available from <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.396.8205&rep=rep1&type=pdf#page=138>
- Nilsson, C., J. Bäckman, and T. Alerstam. 2014. Seasonal modulation of flight speed among nocturnal passerine migrants: differences between short- and long-distance migrants. *Behavioral Ecology and Sociobiology* 68:1799-1807.
- Norberg, U.M. 1994. Chapter 9: Wing design, flight performance, and habitat use in bats. Pp. 205-239, In: *Ecological morphology: Integrative organismal biology*, (P.C. Wainwright and S.M. Reilly, eds). The University of Chicago Press, Chicago, Illinois.
- Parslow, J.L.F. 1969. The migration of passerine night migrants across the English Channel studied by radar. *Ibis* 111:48-79.
- Parsons, S. and J.M. Szewczak. 2009. Chapter 5: Detecting, recording, and analyzing the vocalizations of bats. Pp. 91-111, In: *Ecological and behavioural methods for the study of bats 2nd Edition* (T.H. Kunz and S. Parsons, eds.). The Johns Hopkins University Press, Baltimore, Maryland.
- Patterson, A.P., and J.W. Hardin. 1969. Flight speeds of five species of vespertilionid bats. *Journal of Mammalogy* 50:152-153.
- Racey, P.A. 1982. Chapter 2: Ecology of bat reproduction. Pp. 57-104, In: *Ecology of bats* (T. H. Kunz, ed.). Plenum Press, New York, New York.
- Racey, P.A., and S.M. Swift. 1985. Feeding ecology of *Pipistrellus pipistrellus* (Chiroptera: Vespertilionidae) during pregnancy and lactation I. Foraging Behaviour. *Journal of Animal Ecology* 54:205-205.
- Rambaldini, D.A, and R.M. Brigham. 2011. Pallid bat (*Antrozous pallidus*) foraging over native and vineyard habitats in British Columbia, Canada. *Canadian Journal of Zoology* 89:816-822.
- Riley, J.R. 1975. Collective orientation in night-flying insects. *Nature* 253:113-114.
- Riley, J.R. 1985. Radar cross section of insects. *Proceedings of the IEEE* 73:228-232.
- Sahley, C.T., M.A. Horner, and T.H. Fleming. 1993. Flight speeds and mechanical power outputs of the nectar-feeding bat, *Leptonycteris curasoae* (Phyllostomidae: Glossophaginae). *Journal of Mammalogy* 74: 594-599.
- Sánchez-Hernández, C., M. de Lourdes Romero-Almaraz, M.C. Wooten, G.D. Schnell, and M. Kennedy. 2006. Speed in flight of common vampire bats (*Desmodus rotundus*). *The Southwestern Naturalist* 51:422-425.

- Saunders, M.B., and R.M.R. Barclay. 1992. Ecomorphology of insectivorous bats: a test of predictions using two morphologically similar species. *Ecology* 73:1335-1345.
- Schnitzler, H., E. Kalko, L. Miller, and A. Surlykke. 1987. The echolocation and hunting behaviour of the bat, *Pipistrellus kuhli*. *Journal of Comparative Physiology A* 161:267-274.
- Schreiner, J. 2009. The wineries of British Columbia. Whitecap Books, North Vancouver, BC. Pp 479.
- Schreiner, J. 2012. John Schreiner's Okanagan wine tour guide 4th edition. Whitecap Books, North Vancouver, BC. Pp 368.
- Senese, D.M., W. Wilson, and B. Momer. 2012. Chapter 5: The Okanagan wine region of British Columbia, Canada. Pp. 81-91, In: *The geography of wine: regions, terroir and techniques* (P.H. Dougherty, ed.). Springer Dordrecht Heidelberg, New York, New York.
- Sirami, C., D.S. Jacobs, and G.S. Cumming. 2013. Artificial wetlands and surrounding habitats provide important foraging habitat for bats in agricultural landscapes in the Western Cape, South Africa. *Biological Conservation* 164:30-38.
- Skolnik, M.I. 1990. Radar handbook 2nd edition. McGraw-Hill, New York, New York. Pp .1165.
- Smith, A.D., J.R. Riley, and R.D. Gregory. 1993. A method for routine monitoring of the aerial migration of insects by using a vertical-looking radar. *Philosophical Transactions of the Royal Society of London B* 340:393-404.
- Stahlschmidt, P., A. Pätzold, L. Ressler, R. Schulz, and C.A. Brühl. 2012. Constructed wetlands support bats in agricultural landscapes. *Basic and Applied Ecology* 13:196-203.
- Turner, J.S., and P.G. Krannitz. 2001. Conifer density increases in semi-desert habitats of British Columbia in the absence of fire. *Northwest Science* 75:176-182.
- Van Gasteren, H., I. Holleman, W. Bouten, E. Van Loon, and J. Shamoun-Baranes. 2008. Extracting bird migration information from C-band Doppler weather radars. *Ibis* 150:674-686.
- Vaughan, N., G. Jones, and S. Harris. 1997. Habitat use by bats (Chiroptera) assessed by means of a broad-band acoustic method. *Journal of Applied Ecology* 34:716-730.
- Vaughn, C.R. 1985. Birds and insects as radar targets: a review. *Proceedings of the IEEE* 73:205-227.

- Verboom, B., and H. Huitema. 1997. The importance of linear landscape elements for pipistrelle *Pipistrellus pipistrellus* and the serotine bat *Eptesicus serotinus*. *Landscape Ecology* 12:117-125.
- Wanger, T.C., K. Darras, S. Bumrungsri, T. Tschardtke, and A. Kelin. 2014. Bat pest control contributes to food security in Thailand. *Biological Conservation* 171:220-223.
- Westbrook, J.K. 2008. Noctuid migration in Texas within the nocturnal aeroecological boundary layer. *Integrative and Comparative Biology* 48:99-106.
- Whitaker, J. 1995. Food of the big brown bat *Eptesicus fuscus* from maternity colonies in Indiana and Illinois. *American Midland Naturalist* 134:346-360.
- Whitaker, J. 2004. Prey selection in a temperate zone insectivorous bat community. *Journal of Mammalogy* 85:460-469.
- Wickramasinghe, L.P., S. Harris, G. Jones, and N. Vaughan. 2003. Bat activity and species richness on organic and conventional farms: impacts of agricultural intensification. *Journal of Applied Ecology* 40:984-993.
- Wickramasinghe, L.P., S. Harris, G. Jones, and N. Vaughan Jennings. 2004. Abundance and species richness of nocturnal insects on organic and conventional farms: effects of agricultural intensification on bat foraging. *Conservation Biology* 18:1283-1292.
- Williams, T.C., L.C. Ireland, and J.M. Williams. 1973. High altitude flights of the free-tailed bat, *Tadarida brasiliensis*, observed with radar. *Journal of Mammalogy* 54:807-820.
- Williams-Guillén, E. Olimpi, B. Mass, P.J. Taylor, and R. Arlettaz. 2015. Chapter 6: Bats in the anthropogenic matrix: challenges and opportunities for the conservation of Chiroptera and their ecosystem services in agricultural landscapes. Pp. 151-186, In: *Bats in the Anthropocene: conservation of bats in a changing world* (C.C. Voight and T. Kingston, eds.). Springer International Publishing.
- Winter, Y. 1999. Flight speed and body mass of nectar-feeding bats (*Glossophaginae*) during foraging. *The Journal of Experimental Biology* 202:1917-1930.
- Woodsworth, G.C., G.P. Bell, and M.B. Fenton. 1981. Observations of the echolocation, feeding behaviour, and habitat use of *Euderma maculatum* (Chiroptera: Vespertilionidae) in southcentral British Columbia. *Canadian Journal of Zoology* 59:1099-1102.
- Zukal, J., and M. Gajdošík. 2012. Diet of *Eptesicus serotinus* in an agricultural landscape. *Vespertilio* 16:357-363.

Theses

- Boyle, S.E. 2010. A comparison of bat activity in vineyards and adjoining native scrub in the Adelaide Hills. Honours Thesis, Flinders University of South Australia. Pp 44. Available from the Australasian Bat Society ausbats.org.au.
- Knight, E.C. 2013. Impacts of habitat fragmentation by agriculture on breeding songbirds in the Okanagan sagebrush shrubsteppe. M.Sc. thesis, Simon Fraser University, Department of Biological Sciences, Burnaby BC. Pp 95.
- Millikin, R.L. 2001. Sensor fusion for the localization of birds in flight. Ph.D. thesis, Royal Military College of Canada, Kingston, Ontario. Pp 240.
- Richardson, W.J. 1976. Bird migration over southeastern Canada, the western Atlantic and Puerto Rico: a radar study. Volumes 1, 2, and 3. Ph.D. thesis, Cornell University, Ithaca, New York. Pp 1074.
- Stahlschmidt, P. 2012. Assessment of bat activity in agricultural environments and the evaluation of the risk of pesticides. Thesis, Institute for Environmental Sciences, University of Koblenz-Landau. Landau, Germany. Pp 110.
- Welstead, K. 2002. Factors affecting nest predation of artificial and real sagebrush Brewer's sparrow (*Spizella breweri breweri*) nests in the South Okanagan and Similkameen Valleys, British Columbia. M.Sc. thesis, University of British Columbia, Faculty of Forestry, Vancouver BC. Pp 94.
- Willis, C. 2013. Are changes in climate and land-use associated with changes in migration strategies of western bluebirds (*Sialia mexicana*) in southern British Columbia? M.Sc. thesis, Queen's University, Department of Biology, Kingston, Ontario. Pp 48.

Documents, Technical Reports, and Websites

- Boyle, S., S. Delaney, S. Delaney, and K. Sanderson. 2011. Anabat surveys at Sinclair Gully Vineyard and adjacent woodland. School of Biological Sciences Research. Flinders University of South Australia. Pp 3. Available from: <http://www.sinclairsgully.com/Article%20-%20May2010%20Anabat%20Survey%20at%20Sinclair%20Gully%20Vineyard%20and%20Adjacent%20Woodland.PDF>.
- British Columbia Ministry of Agriculture and Lands. 2010. Best practices guide for grapes for British Columbia growers. Prepared for the British Columbia Wine Grape Council, Victoria, BC. Pp 230. Available from the BC Wine Grape Council at bcwgc@telus.net.
- British Columbia Ministry of Environment. 1998. Habitat atlas for wildlife at risk; species profiles for fringed myotis, western red bat, spotted bat, Townsend's big-eared bat, and the pallid bat. Available from: <http://www.env.gov.bc.ca/okanagan/esd/atlas/profiles.html>

- British Columbia Ministry of Environment. 2012. Continually updated. BC Conservation Data Center's BC species and ecosystem explorer website. URL: <http://a100.gov.bc.ca/pub/eswp/search.do?method=reset>.
- British Columbia Ministry of Environment, Lands, and Parks. 1998. Inventory methods for bats: standards for components of British Columbia's biodiversity No. 20 – Version 2.0. Resources Inventory Branch for the Terrestrial Ecosystem Task Force, Resources Inventory Committee, Victoria, BC. Pp. 58. Available from: <https://www.for.gov.bc.ca/hts/risc/pubs/tebiodiv/bats/assets/bats.pdf>.
- British Columbia Ministry of Forests. 1998. The ecology of the Bunchgrass Zone. Research Branch, Victoria BC. Pp 6. Available from: <https://www.for.gov.bc.ca/hfd/pubs/docs/bro/bro54.pdf>.
- Chapman, K., K. McGuiness, and R.M. Brigham. 1994. Status of the pallid bat in British Columbia. BC Ministry of Environment, Lands, and Parks, Wildlife Branch. Wildlife Working Report No. WR-61. Victoria, BC. Pp 35. Available from: <http://www.env.gov.bc.ca/wld/documents/statusrpts/wr61.pdf>.
- COSEWIC. 2004a. COSEWIC assessment and status report on the spotted bat *Euderma maculatum* in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa. Pp 34. Available from: http://www.registrelep-sararegistry.gc.ca/document/default_e.cfm?documentID=441
- COSEWIC. 2004b. COSEWIC assessment and update status report on the fringed bat *Myotis thysanodes* in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa. Pp 33. Available from: http://www.sararegistry.gc.ca/document/default_e.cfm?documentID=471
- COSEWIC. 2010. COSEWIC status appraisal summary on the pallid bat *Antrozous pallidus* in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa. Pp 12. Available from: https://www.registrelep-sararegistry.gc.ca/virtual_sara/files/cosewic/pallid_bat_sse_0911_eng.pdf
- Diehl, R.H., and R.P. Larkin. 2005. Introduction to the WSR-88D (NEXRAD) for ornithological research. USDA Forest Service Gen. Tech. Rep. PSW-GTR-191: 876-887. Available from: http://www.fs.fed.us/psw/publications/documents/psw_gtr191/psw_gtr191_0876-0888_diehl.pdf.
- Dyer, O., and E.C. Lea. 2003. Status and Importance of the Antelope-Brush-Needle-and-Thread Grass plant community in the South Okanagan Valley, British Columbia. Pp. 13-18, In: Proceedings ecosystems at risk: antelope brush restoration (R. Seaton, ed.). March 28-30, 2003, Osoyoos British Columbia, Canada. Ministry of Water, Land, and Air Protection. Technical Report. Pp 8. Available from: <http://chapter.ser.org/westerncanada/files/2012/08/2003-Proceedings-v3web.pdf>.
- Entomological Society of America website: <http://www.entsoc.org/home>.

Environment Canada historical weather available from:
http://climate.weather.gc.ca/index_e.html

Garcia, P.F.J., S.A. Rasheed, and S.L. Holroyd. 1995. Status of the western small-footed myotis in British Columbia. BC Ministry of Environment, Lands, and Parks, Wildlife Branch. Wildlife Working Report No. WR-74. Victoria, BC. Pp 25. Available from: <http://www.env.gov.bc.ca/wld/documents/statusrpts/wr74.pdf>

Heaton, E., R. Long, C. Ingels, and T. Hoffman. 2008. Songbird, bat and owl boxes: vineyard management with an eye towards wildlife. The Regents of the University of California, Division of Agriculture and Natural Resources, Publication 21636, Oakland, California. Pp 51. Available from: <http://anrcatalog.ucdavis.edu>.

Holroyd, S.L., R.M.R. Barclay, L.M. Merk, and R.M. Brigham. 1994. A survey of bat fauna of the dry interior of British Columbia. Ministry of Environment, Land, and Parks, Wildlife Branch, Wildlife Working Report No. WR-63. Victoria, BC. Pp. 84. Available from: http://www.env.gov.bc.ca/wld/documents/techpub/wr63/wr63_1.pdf.

Insight Environmental Consulting Ltd. 2010. British Columbia sustainable winegrowing program: sustainable practices for BC vineyards self-assessment and guidebook Version 1.0. Prepared for the BC Wine Grape Council. Pp 205. Available from: <http://www.bcwgc.org/bc-sustainable-winegrowing-program>.

Mabee, T.J., J.H. Plissner, and B.A. Cooper. 2006. A radar and visual study of nocturnal bird and bat migration at the proposed Centreville and Wethersfield windparks, New York, Spring 2006. ABR, Inc. Environmental Research and Services Report. Prepared for Ecology and Environment Inc. and Noble Environment Power, LLC. Pp 46. Available upon request at <http://www.noblepower.com/>.

McCracken, G.F. 1996. Bats aloft: a study of high-altitude feeding. *Bats* 14:7-10.

Millikin, R. 2005. Migration monitoring with automated technology. USDA Forest Service Gen. Tech. Rep. PSW-GTR-191:860-869. Available from: http://www.fs.fed.us/psw/publications/documents/psw_gtr191/psw_gtr191_0860-0870_millikin.pdf

Millikin, R. 2006. Réaction des oiseaux et des chauves-souris face éoliennes. Bulletin d'information du GTSHOC 3:1 and 5. Available from: http://www.bape.gouv.qc.ca/sections/mandats/eole_matane/documents/DB32-1.pdf.

Millikin, R. 2011. EchoTrack radar-acoustic airborne wildlife surveillance system operations guide. EchoTrack Inc, Ottawa, ON. Pp 18.

Millikin unpublished. Migration corridor study in southern British Columbia looking at flight paths of birds and bats during the fall of 2012.

- Neeson, I. 2006. Confidential report of EchoTrack: sensor head comparison. Vandervalk Neeson Instruments Report No. RE061001. Available upon request at <http://echotrack.com/>.
- Oliver Osoyoos Winery Association. Continually updated. URL: <http://www.oliverosoyoos.com/>.
- Redpath, K. 1990. Identification of relatively undisturbed areas in the south Okanagan and Similkameen valleys, British Columbia. Canadian Wildlife Service, Pacific and Yukon Region. Delta, BC. Pp 15. Available from the Ministry of Environment's Ecological Reports catalogue at <http://www.env.gov.bc.ca/clir/>.
- Ruth, J.M., W.C. Brown, R.S. Sojda, D.K. Dawson, R.H. Diehl, A. Manville, M.T. Green, D.J. Krueper, and S. Johnston. 2005. Advancing migratory bird conservation and management by using radar: an interagency collaboration. Open-File Report 2005-1173. Fort Collins, Co: US Geological Survey. Pp 12. Available from: www.fort.usgs.gov/publication/21469
- Sarell, M.J., and A. Haney. 2000. South Okanagan rare bat inventory 2000: spotted bat, pallid bat and western red bat. Unpublished report prepared for BC Environment, Penticton and the Habitat Conservation Trust Fund, Victoria, BC. Pp 86.
- Sarell, M., T. Hill, J. Hobbs, and F. Iredale. 2011. Bridge River bat assessment 2010. Prepared for the British Columbia Hydro Bridge Coastal Fish and Wildlife Restoration Program and Matt-Manuel Lillooet Tribal Council. Draft of Technical Report, Lillooet. Pp 53. Available from: http://www.lillooetnaturalistsociety.org/documents/Public_Bat%20report%202011%20FWCP.pdf.
- Statistics Canada. 2005. Pesticide Use and Pest Management Practice of Canadian Grape Growers. Available from : <http://www.agr.gc.ca/eng/about-us/offices-and-locations/pest-management-centre/publications-and-newsletter/results-of-the-canadian-crop-protection-survey/pesticide-use-and-pest-management-practices-of-canadian-grape-growers-2005-1-of-6/pesticide-use-and-pest-management-practices-of-canadian-grape-growers-2005-2-of-6/?id=1313590560120>
- Tietje, W.D., T.J. Weller, and C.C. Yim. 2015. Bat activity at remnant oak trees in California central coast vineyards. Proceedings of the 7th California Oak Symposium: managing Oak Woodlands in a dynamic world. General Technical Report PSW-GTR-251. Pp 10. Available from: <http://www.treearch.fs.fed.us/pubs/49974>
- University of California. Continually updated. UC IPM online: statewide integrated pest management program. URL: <http://www.ipm.ucdavis.edu/PMG/r302300111.html>. Division of Agriculture and Natural Resources. Accessed May 2012.

Weik, M. 1989. Communication standard dictionary 2nd edition. Van Nostrand Reinhold Co., New York, New York. Resolution cell information available from:
http://www.its.bldrdoc.gov/fs-1037/dir-029/_4335.htm and
http://www.its.bldrdoc.gov/fs-1037/dir-001/_0063.htm#WEIK

Wolff, C. Radartutorial: Book 1 radar basics. Revised December 20, 2009. Available from: www.radartutorial.eu. Pp 18.

WNS Decontamination Team. 2012. National white-nose syndrome decontamination protocols - Version 06.25.2012. Pp 5. Available from:
https://www.whitenosesyndrome.org/sites/default/files/resource/national_wns_revise_final_6.25.12.pdf.

Personal Communications and BC Bat Biologists

Brigham, Mark. Professor specializing in roosting and feeding ecology of insectivorous bats and nocturnal birds, University of Regina.

Burles, Doug. BC bat biologist, Kaisun Ecological Consulting, Kamloops, BC.

Corbeil, Louise. Administrator, BC Wine Grape Council

Dagenais, Henri. Meteorologist/Forecaster, Wildlife Management Branch, Ministry of Environment, Saskatchewan and the Jim Patterson broadcasting group ckbi 900.

Gries, Gerhard. Professor specializing in animal communication ecology and entomology, Simon Fraser University

Lausen, Cori. BC bat biologist, Birchdale Ecological, Kaslo, BC.

Lowery, Tom. Research Scientist, Agriculture and Agri-Food Canada, Pacific Agri-Food Research Centre

Sarell, Mike. Local biologist specializing in bats and reptiles, Ophiuchus Consulting, Oliver BC.

Withler, Carl. Regional Agrologist, Sustainable Agriculture Management, BC Ministry of Environment

Appendix A.

South Okanagan bat species

Table A1. A list of the 15 bat species found in the South Okanagan indicating their conservation status and foraging methods.

Common name	Latin name	Provincial listing	Federal listing	Foraging behaviour	Foraging style and habitat
Big brown bat	<i>Eptesicus fuscus</i>	Yellow (S5)	NA	Aerial hawker	G, V, AC, L, W
California myotis	<i>Myotis californicus</i>	Yellow (S4S5)	NA	Aerial hawker	G, V, W
Canyon bat ^a	<i>Parastrellus hesperus</i>	Pending	NA	Aerial hawker	G, V
Eastern red bat	<i>Lasiurus borealis</i>	Red (S1)	NA	Aerial hawker	O, V, AC, L, W
Fringed myotis	<i>Myotis thysanodes</i>	Blue (S3)	Data deficient	Aerial hawker / Gleaner	G, CF, V, W
Hoary bat	<i>Lasiurus cinereus</i>	Yellow (S4)	NA	Aerial hawker	V, AC, L
Little brown myotis	<i>Myotis lucifugus</i>	Yellow (S4)	Endangered	Aerial hawker	G, O, V, W, C
Long-eared myotis	<i>Myotis evotis</i>	Yellow (S4S5)	NA	Aerial hawker / Gleaner	C, CF, W
Long-legged myotis	<i>Myotis volans</i>	Yellow (S4S5)	NA	Aerial hawker	G, O, V, R
Pallid bat	<i>Antrozous pallidus</i>	Red (S2)	Threatened	Gleaner	G, O, Un, CF
Silver-haired bat	<i>Lasionycteris noctivagans</i>	Yellow (S4S5)	NA	Aerial hawker	AC, CF, W
Spotted bat	<i>Euderma maculatum</i>	Blue (S3S4)	Special concern	Aerial hawker	V, CF, W
Townsend's big-eared bat	<i>Corynorhinus townsendii</i>	Blue (S3)	NA	Gleaner	W , Un
Western small-footed myotis	<i>Myotis ciliolabrum melanorhinus</i>	Blue (S2S3)	NA	Aerial hawker	R, CF, W
Yuma myotis	<i>Myotis yumanensis</i>	Yellow (S5)	NA	Aerial hawker	W

^aAcoustic recordings of a canyon bat were captured by a local bat biologist near Osoyoos, BC in the spring of 2014.

Foraging Style and Habitat Abbreviations

G – generalist species; O – opportunistic species; V – feeds in a variety of habitats; CF – observed feeding over cultivated fields; AC – feeds well above forest canopy or high above the ground; C – feeds in cluttered habitats; L – feeds around lights; Un – feeds in uncluttered habitats; R – associated with rocky outcroppings and cliffs; W – feeds over water and along the riparian corridor, **W** – most often associated with riparian habitat

References for foraging styles included: Woodsworth et al. 1981; Barclay 1986; Nagorsen and Brigham 1993; Chapman et al. 1994; Holroyd et al. 1994; Garcia et al. 1995; Sarell et al. 2011.

Provincial Listings: Species inhabiting BC that are listed based on their Provincial Conservation Status

Red listed species – flagged species considered at risk in BC. Species may be extirpated, endangered or threatened. S1 = critically imperil; S2 = imperil

Blue listed species – flagged species considered special concern in BC as they are sensitive to natural disturbances and human activity. S2 = imperil; S3 = special concern, vulnerable to extirpation or extinction; S4 = apparently secure.

Yellow listed species – species with secure populations and therefore not at risk. S4 = apparently secure, S5 = demonstrably widespread, abundant and secure.

Pending – species under review, more information is needed before assigning a listing.

Federal Listings: Species listed on the Species at Risk Act Schedule that are reviewed by the Committee on the Status of Endangered Wildlife in Canada

Data deficient – species under review, more information is needed before assigning a listing.

Endangered – species that will become extirpated or extinct if their population is not monitored and protected.

Special concern – species that are at risk due to their sensitivity to natural disturbances and human activities.

Threatened – species that will become endangered if their population is not monitored and protected.

Appendix B.

Vineyard insects associated with crop damage

Table B1. A list of insects that feed on grapevines identified in North America, showing the ones that are of major concern to BC grape growers (highlighted cells) and ones that are potential prey for BC bats.

Common name	Latin name	Potential prey spp	Size (mm)	Damage
Hornets ^a	Numerous genera and species	Yes	15-20	Major pest to workers but will also feed on fruit and can spread diseases.
Paper wasps	Polistes spp	Yes	15	Major pest to workers but will also feed on fruit and can spread diseases.
Yellowjacket wasps	Vespa pennsylvanica	Yes	15	Major pest to workers but will also feed on fruit and can spread diseases.
Snailcase bagworm	Apterona helix	No	4	Feeds on leaves.
Cutworm ^a	3 main species include: Abagrotis orbis, A. reedi, A. nefascia	Yes	15-50	Larvae feed on buds and new shoots.
Click beetle ^a	Limonium canus	Yes	10-15	Feeds on roots of plants, may feed on grape buds.
Western grape rootworm beetle	Bromius obscurus	Yes	4-7	Larvae feed on roots; adults feed on leaves.
Wood-boring beetles	Numerous genera and species	No	5-10	Infest canes and vines causing shoots to break, often associated with older plants.
Minor cicada	Platypedia minor	No	20-40	Females deposit eggs into canes which weakens shoot and causes it to break.
Spotted wing drosophila	Drosophila suzukii	No	2-3	Females deposit eggs into fruit and larvae feed on ripening fruit.
European earwig ^a	Forficula auricularia	Yes	15	Minor pests of leaves.
Grasshoppers	Numerous genera and species	Yes	19-38	Feeds on lower leaves.
Virginia creeper leafhopper	Erythroneura ziczac	Yes	3-5	Damage by adults and nymphs in spring, cut leaves and suck out juices, excessive feeding delays maturity, reduces yields and fruit quality. Associated with early leafout.

Common name	Latin name	Potential prey spp	Size (mm)	Damage
Western grape leafhopper	<i>Erythroneura elegantula</i>	Yes	3-5	Damage by adults and nymphs in spring, cut leaves and suck out juices, excessive feeding delays maturity, reduces yields and fruit quality. Associated most in areas with early leafout.
Grape mealybug	<i>Pseudococcus maritimus</i>	Yes	1-5	Minor pest of BC wine grapes, will damage fruit and promotes growth of fungus and can spread virus.
Whitefly	Numerous genera and species	Yes	2	Suck juices out of leaves.
Cottony maple scale	<i>Pulvinaria vitis</i>	Yes	5-8	Minor pest of BC vineyards, will feed on phloem.
European fruit lecanium scale	<i>Parthenolecanium corni</i>	Yes	1-8	Minor pest of BC vineyards, will feed on phloem and cause black spots on leaves. May also stunt leaf growth.
Black vine weevil ^a	<i>Otiorhynchus sulcatus</i>	Yes	15	Feeds on grape clusters and leaves.
European red mite	<i>Panonychus ulmi</i>	No	0.5	Feeds on young foliage.
Grape erineum mite	<i>Colomerus vitis</i>	No	0.2	Creates galls around fruiting zones.
Grape leaf rust mite	<i>Calepitrimerus vitis</i>	No	0.2	Affects leaves and buds.
Two-spotted spider mite	<i>Tetranychus urticae</i>	No	0.5	Feeds on young foliage.
Grape phylloxera	<i>Daktulosphaira vitifoliae</i>	No	<1	Currently low incident rate in BC, affects roots and kept at bay with resistant rootstocks
Flower thrips	<i>Frankliniella tritici</i>	No	1	Feeds on flower and fruit, but more of a pest on table grapes.
Grape thrips	<i>Drepanothrips reuteri</i>	No	1	Feeds on flower and fruit, but more of a pest on table grapes.
Western flower thrips	<i>Frankliniella occidentalis</i>	No	1-1.5	Feeds on flower and fruit, but more of a pest on table grapes.
Three-cornered Alfalfa treehopper	<i>Spissistilus festinus</i>	Yes	6	Nymphs feed on leaf petioles and damage xylem affecting water intake.
Buffalo treehopper	<i>Spissistilus bisonia</i>	Yes	6	Nymphs feed on leaf petioles and damage xylem affecting water intake.

^aNocturnal insects

Although many of these insects are diurnal, they could be potential prey for gleaning bats as many remain on the vine foliage throughout the evening (Personal communication with G. Gries); potential prey of bats is based on prey species found in bat guano from other studies, prey size (>2mm), and insect damage (i.e. diurnal species feeding on leaves, buds, or fruit)

References used to create this table included: Barclay 1991; Saunders and Barclay 1992; Nagorsen and Brigham 1993; Holroyd et al 1994; Agosta et al. 2003; Whitaker 2004; Wickramasinghe et al. 2004; Downs and Racey 2006; Henderson and Broders 2008; BC Ministry of Agriculture and Lands 2010; Insight Environmental Consulting Ltd. 2010; Harvey et al. 2011; Rambaldini and Brigham 2011; Personal communications with T. Lowery; COSEWIC status reports and BC Ministry of Environment Habitat Atlas for Wildlife at Risk reports for South Okanagan bat species; University of California Integrated Viticulture website, and Entomological Society of America website.

Appendix C.

Commonly used radar

Table C1. A list of commonly used radar, their parameters and application from Skolnik 1990.

Radar type	Band name	Antenna	Application
Continuous-wave (CW)	K-band	2 antennae required	Speed gauges
Moving Target Indication (MTI), doppler or pulse	L-band		Speed gauges
Over-the-horizon	HF	Very large, complex	Detect targets over the horizon at great distances
Phase-array	X, C, S, L, UHF, VHF, HF	Multiple joined antennae	Military, vessel seeking, broadcasting/communication
Surveillance	X, C, S, L-band	Fan beam	Aircraft control, airspace surveillance, biological studies
Tracking	X, C-band	Pencil beam	Missile tracking, weapons control, biological studies
Weather	K, X, S-band	Fan beam	Weather warnings, biological studies

Radio frequency range and wavelength of the radar frequency bands as defined by the Institute of Electrical and Electronics Engineers:

High Frequency (HF): radio frequency of 3 MHz – 30 MHz, wavelength of 10 m – 100 m

Very High Frequency (VHF): radio frequency of 30 MHz – 300 MHz, wavelength of 1 m – 10 m

Ultra High Frequency (UHF): radio frequency of 300 MHz and 1 GHz, wavelength of 0.3 m – 1m

L-band: radio frequency of 1 GHz – 2 GHz, wavelength of 15 cm – 30 cm

S-band: radio frequency of 2 GHz – 4 GHz, wavelength of 7.5 cm – 15 cm

C-band: radio frequency of 4 GHz – 8 GHz, wavelength of 3.75cm – 7.5 cm

X-band: radio frequency of 8 GHz – 12 GHz, wavelength of 2.5cm – 3.75 cm

K-band: radio frequency of 18 GHz – 27 GHz, wavelength of 1.11cm – 1.67 cm

Appendix D.

Sample of EchoTrack's file outlining the radar-defined tracks and their parameters

Supplementary Data File

Description:

The accompanying Excel spreadsheet is a subset of an EchoTrack's trackpar file that outlines the radar-defined tracks and their parameters. The data were collected on July 25th at 22:02hrs.

Filename:

DanielleDagenais_Appendix D-EchoTrack_RawTrackFile.xls

Appendix E.

Site locations and project data

Supplementary Data File

Description:

The accompanying document identifies the radar locations and lists the radar and acoustic data collected and used for my analysis.

Filename:

DanielleDagenais_Appendix E-RadarLocation&Data.xls

Appendix F.

Echolocation calls of the South Okanagan bat species

Table F1. The frequency range, call intensity and frequency group identified for the South Okanagan bat species.

Common name	Latin name	Species code	Frequency range	Call intensity	Minimum call frequency
Big brown bat	<i>Eptesicus fuscus</i>	Epfu	Low	High	≤22 kHz; 25-35 kHz
California myotis	<i>Myotis californicus</i>	Myca	High	High	40-45 kHz, 50 kHz
Canyon bat	<i>Parastrellus hesperus</i>	Pahe	High	High	40-45 kHz
Eastern red bat	<i>Lasiurus borealis</i>	Labo	Middle	High	25-35 kHz
Fringed myotis	<i>Myotis thysanodes</i>	Myth	Low	Low	≤22 kHz; 25-35 kHz
Hoary bat	<i>Lasiurus cinereus</i>	Laci	Low	High	≤22 kHz; 25-35 kHz
Little brown myotis	<i>Myotis lucifugus</i>	Mylu	Middle	High	40-45 kHz
Long-eared myotis	<i>Myotis evotis</i>	Myev	Low	Low	25-35 kHz
Long-legged myotis	<i>Myotis volans</i>	Myvo	Middle	High	40-45 kHz
Pallid bat	<i>Antrozous pallidus</i>	Anpa	Low	Low	25-35 kHz
Silver-haired bat	<i>Lasionycteris noctivagans</i>	Lano	Low	High	25-35 kHz
Spotted bat	<i>Euderma maculatum</i>	Euma	Low	High	≤22 kHz
Townsend's big-eared bat	<i>Corynorhinus townsendii</i>	Coto	Low	Low	25-35 kHz
Western small-footed myotis	<i>Myotis ciliolabrum melanorhinus</i>	Myci	High	High	40-45 kHz
Yuma myotis	<i>Myotis yumanensis</i>	Myyu	High	High	40-45 kHz, 50 kHz

The **frequency of a call** is measured in kilohertz and is related foraging habitat. High frequency calls attenuates quickly and are used over shorted ranges such as within the canopy. Low frequency calls have a greater range and are used in more open habitats. Calls that sweep over a larger range of frequencies (Broadband) provide more information and are used to hunt smaller insects, and/or used in more cluttered environments. Calls that span few frequencies (Narrowband) are used to hunt larger prey and/or used in more open habitats.

The **call intensity** is measured in decibels and affects the detectability of the call. Call intensity is also related to the foraging habitats preferred by the bats. Low intensity calls (~60db) are soft calls often referred to as whispers and are hard to detect; these are most often associated with cluttered environments. High intensity (~110db) are loud calls and are easy to detect, these are most often associated with open environment.

References used to create this table included: Downes 1982; Barclay 1991; Nagorsen and Brigham 1993; Holroyd et al 1994; Sarell et al. 2011; C. Lausen, unpublished files; D. Burles, unpublished files and personal communications, November 6, 2014; M. Brigham, personal communication, February 2, 2016.

Table F2. A list of the species groups associated with the four frequency groups identified for my study.

Frequency group	Species groups	Total	Vineyard	Natural
≤ 22 kHz	Euma	2	0	2
	Laci	11	5	6
	Laci / Epfu	11	7	4
	Myth	1	0	1
		25	12	13
25 kHz – 35 kHz	Lano	1	1	0
	Laci / Epfu	3	3	0
	Epfu / Lano	404	269 ^a	135
	Epfu / Lano / Laci	10	6	4
	Anpa	1	0	1
	Anpa / Epfu / Lano / Myth	676	340 ^a	336
	Myth	2	0	2
	Myev / Labo	3	0	3
		1100	619	481
40 kHz – 45 kHz	Mylu / Myvo / Myci	475	142	333
	Myvo / Myci	66	19	47
	Myyu / Myca / Myvo / Myci	108	35	73
	Myyu / Myca	12	11	1
		661	207	454
50 kHz	Myyu / Myca	31	14	17

^aThe majority of these calls (189 and 316 respectively) were detected within the vineyard plot at Site 1. I believe that these calls are from big brown bats (*Eptesicus fuscus*) as a potential Epfu maternity colony roost was found within 130 m of the vineyard acoustic array.

Table F3. Species groups identified for each of the frequency groups during each nightly sampling interval.

Sampling interval	≤ 22 kHz	25 kHz – 35 kHz	40 kHz – 45 kHz	50 kHz
15	Laci ^N	Epfu/Lano ^{N,V}	Mylu/Myvo/Myci ^N	na
45	Laci/Epfu ^N	Anpa/Epfu/Lano/Myth ^{N,V} Myev/Labo ^N Epfu/Lano ^{N,V} Epfu/Lano/Laci ^N Laci/Epfu ^V Anpa ^N	Myyu/Myca/Myvo/Myci ^{N,V} Mylu/Myvo/Myci ^{N,V} Myvo/Myci ^{N,V} Myyu/Myca ^V	Myyu/Myca ^{N,V}
75	Laci ^{N,V} Laci/Epfu ^{N,V}	Anpa/Epfu/Lano/Myth ^{N,V} Epfu/Lano ^{N,V} Epfu/Lano/Laci ^V Lano ^V	Myyu/Myca/Myvo/Myci ^N Mylu/Myvo/Myci ^{N,V} Myvo/Myci ^{N,V}	Myyu/Myca ^{N,V}
105	Laci/Epfu ^V Myth ^N	Anpa/Epfu/Lano/Myth ^{N,V} Epfu/Lano ^{N,V} Epfu/Lano/Laci ^V	Myyu/Myca/Myvo/Myci ^N Mylu/Myvo/Myci ^{N,V} Myvo/Myci ^{N,V} Myyu/Myca ^V	Myyu/Myca ^{N,V}
135	Euma ^N	Anpa/Epfu/Lano/Myth ^{N,V} Epfu/Lano ^{N,V} Epfu/Lano/Laci ^V	Myyu/Myca/Myvo/Myci ^N Mylu/Myvo/Myci ^{N,V} Myvo/Myci ^N	na
165	Laci ^{N,V}	Anpa/Epfu/Lano/Myth ^{N,V} Myev/Labo ^N Epfu/Lano ^{N,V}	Myyu/Myca/Myvo/Myci ^N Mylu/Myvo/Myci ^{N,V} Myvo/Myci ^V	Myyu/Myca ^N
195	Laci/Epfu ^N	Anpa/Epfu/Lano/Myth ^{N,V} Myev/Labo ^N Epfu/Lano ^{N,V}	Myyu/Myca/Myvo/Myci ^N Mylu/Myvo/Myci ^{N,V} Myvo/Myci ^{N,V} Myyu/Myca ^V	Myyu/Myca ^{N,V}
225	na	Anpa/Epfu/Lano/Myth ^{N,V} Epfu/Lano ^{N,V}	Myyu/Myca/Myvo/Myci ^{N,V} Mylu/Myvo/Myci ^{N,V} Myvo/Myci ^{N,V}	na
255	Laci ^V Laci/Epfu ^N	Anpa/Epfu/Lano/Myth ^{N,V} Epfu/Lano ^{N,V} Laci/Epfu ^V	Myyu/Myca/Myvo/Myci ^{N,V} Mylu/Myvo/Myci ^{N,V} Myvo/Myci ^N Myyu/Myca ^V	Myyu/Myca ^N
≥285	Laci ^N	Anpa/Epfu/Lano/Myth ^N Epfu/Lano ^{N,V} Myth ^N	Myyu/Myca/Myvo/Myci ^{N,V} Mylu/Myvo/Myci ^{N,V} Myvo/Myci ^V	Myyu/Myca ^N
-180	na	Epfu/Lano ^N	Myyu/Myca/Myvo/Myci ^{N,V} Mylu/Myvo/Myci ^{N,V} Myvo/Myci ^{N,V}	Myyu/Myca ^{N,V}
-150	na	Anpa/Epfu/Lano/Myth ^N Epfu/Lano ^{N,V}	Mylu/Myvo/Myci ^{N,V} Myvo/Myci ^V Myyu/Myca ^V	na
-120	Laci ^V	Anpa/Epfu/Lano/Myth ^N Epfu/Lano ^{N,V}	Mylu/Myvo/Myci ^{N,V} Myvo/Myci ^V	Myyu/Myca ^{N,V}

Sampling interval	≤ 22 kHz	25 kHz – 35 kHz	40 kHz – 45 kHz	50 kHz
-90	Laci ^N Laci/Epfu ^V	Anpa/Epfu/Lano/Myth ^{N,V} Epfu/Lano ^{N,V}	Myyu/Myca/Myvo/Myci ^{N,V} Myly/Myvo/Myci ^{N,V}	na
-60	Laci/Epfu ^V	Anpa/Epfu/Lano/Myth ^{N,V} Epfu/Lano ^{N,V} Epfu/Lano/Laci ^V	Myyu/Myca/Myvo/Myci ^{N,V} Myly/Myvo/Myci ^{N,V} Myvo/Myci ^{N,V} Myyu/Myca ^{N,V}	Myyu/Myca ^V
-30	na	na	Myyu/Myca/Myvo/Myci ^V	na

^VSpecies group detected in the vineyard plots

^NSpecies group detected in the natural plots