

**SOUNDSCAPE DYNAMICS
IN THE SOCIAL-ECOLOGICAL SYSTEMS
OF TIERRA DEL FUEGO**

by

Dante Francomano

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STATEMENT OF COMMITTEE APPROVAL

Dr. Bryan C. Pijanowski, Chair

Department of Forestry and Natural Resources

Dr. Brady S. Hardiman

Department of Forestry and Natural Resources

Dr. Zhao Ma

Department of Forestry and Natural Resources

Dr. Andrea N. Raya Rey

Universidad Nacional de Tierra del Fuego

Dr. Alejandro E. J. Valenzuela

Universidad Nacional de Tierra del Fuego

Approved by:

Dr. Linda S. Lee

Dr. Robert G. Wagner

For the natural world that sustains and enriches our existence

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ABSTRACT

Human society is presently beset by an array of anthropogenic social-ecological crises that threaten the sustainability of the social-ecological systems that sustain our livelihoods. While research alone will not rectify these issues, it can help to answer key questions that must be addressed to develop effective solutions. To address such questions in a cohesive, compelling manner, social-ecological research can be bounded, structured, and distilled through innumerable organizing principles or theoretical frameworks. For this dissertation, I focused on the geographic region of Tierra del Fuego and sought to draw from the array of disciplines and methods that use sound as a lens for biological, ecological, and/or social inquiry. I also endeavored to consider various temporal, spatial, and organizational scales while investigating a selection of topics with a) specific importance in the social-ecological systems of Tierra del Fuego and b) general relevance to global social-ecological challenges. Chapter 1 provides an introduction to the dissertation, and Chapter 6 serves as a conclusion.

The objective of Chapter 2, “Biogeographical and analytical implications of temporal variability in geographically diverse soundscapes”, was to provide some guidance to passive acoustic monitoring (PAM) practitioners on how to design appropriate temporal sampling schemes based on the temporal variability of the sounds one wishes to measure and the power and storage limitations of acoustic recorders. We first quantified the temporal variability of several soundscape measurements and compared that variability across sites and times of day. We also simulated a wide range of temporal sampling schemes in order to model their representativeness relative to continuous sampling.

For Chapter 3, “Sentinels for sentinels: passive acoustic and camera trap monitoring of sensitive penguin populations”, we tested the utility of PAM to monitor behavior and abundance of Magellanic (*Spheniscus magellanicus*) and southern rockhopper penguins (*Eudyptes chrysocome*) at different spatial and temporal scales. We conducted *in situ* observations of the acoustic behavior of each species, and we compared acoustic metrics with penguin counts from narrowly focused camera traps and larger-extent observations of colony density.

Chapter 4, “Acoustic monitoring shows invasive beavers (*Castor canadensis*) increase avian diversity in Tierra del Fuego”, is focused on impacts of the invasive North American beaver (*Castor canadensis*) on Fuegian bird communities. We sought to determine how bird communities might differ between intact riparian forests, beaver ponds, and beaver meadows created by pond drainage. We conducted PAM and classic avian point counts under each of these conditions across seasons to test for differences between impact conditions and to compare the two methodologies.

For Chapter 5, “Human-nature connection and soundscape perception: insights from Tierra del Fuego, Argentina”, we evaluated the relationship between soundscape perception and nature relatedness by conducting surveys and soliciting responses to soundscape audio prompts. We also examined the potential for any demographic influences on nature relatedness or soundscape perception in the context of local social tensions.

CHAPTER 1—INTRODUCTION

1.1 Sound as a lens for social-ecological research

Although humanity has cultivated remarkable sociocultural achievements, many of our greatest “successes” have come to threaten the very ecosystem services (*sensu* Millennium Ecosystem Assessment 2003) that nurtured our development. Biodiversity loss, climate change, resource consumption, land use conversion, and various forms of pollution are all pushing Earth’s systems toward or beyond the boundaries of sustainability (Rockström et al. 2009; Sala et al. 2000; Loarie et al. 2009; Foley et al. 2005; Steffen et al. 2007; Scheffer et al. 2001). Given human dependence on ecosystem services, our inadequate responses to these problems are especially troubling (Caldwell 1970; Nilhlén Fahlquist 2009; Howlett and Kemmerling 2017), and they highlight the need for adaptive management and governance from social-ecological perspectives (Ostrom 2009; Folke 2019).

While research alone will not rectify these social-ecological crises, it can help to answer three central questions that must be addressed to develop effective solutions: 1) What is the nature and scope of the problem? 2) How and why did the problem arise? and 3) What are possible approaches to address the problem, and what are their respective merits and drawbacks? Depending on the scale of the considered problem, answering each of these questions may be fairly simple or incredibly complex, requiring diverse methods and interdisciplinary perspectives. Beyond answering each question in isolation, however, there is a need to generate comprehensive, integrated accounts that provide appropriate social-ecological contextualization (Ostrom 2009). Moreover, these narratives must be distilled to enable resource managers, governments, and the general public to make socially and ecologically responsible decisions (Kerner and Thomas 2014).

For the sake of practicality and thematic cohesion, social-ecological research can be bounded, structured, and distilled through innumerable organizing principles or theoretical frameworks. Spatial limitations based on political or ecological geography can provide useful boundaries, and focus on certain taxa can also help to limit scope. From a more methodological or theoretical

perspective, some example unifying themes could include capital (Bourdieu 1986; Stokols et al. 2013), networks (Bodin et al. 2016), spatial mapping (Alessa et al. 2008), or—as used in this dissertation—sound (Schafer 1993; Pijanowski et al. 2011a).

Sound is studied in social, ecological, and biological contexts by an array of often overlapping disciplines that employ diverse quantitative and qualitative methods. These disciplines and methods can be considered in a three-dimensional social-ecological-biological space to better understand their relationships to one another (Figure 1.1). Taken collectively, their diverse perspectives form a unique lens through which a number of social-ecological questions can be addressed from diverse perspectives (Table 1.1). One of the broadest goals of this dissertation was to use this lens of sound to answer a selection of questions from a social-ecological perspective. Figure 1.1 and Table 1.1 hint at the vast array of questions and approaches one could consider; given this preponderance of options, I sought to sample several approaches spanning some of the disciplines along the social-ecological continuum.

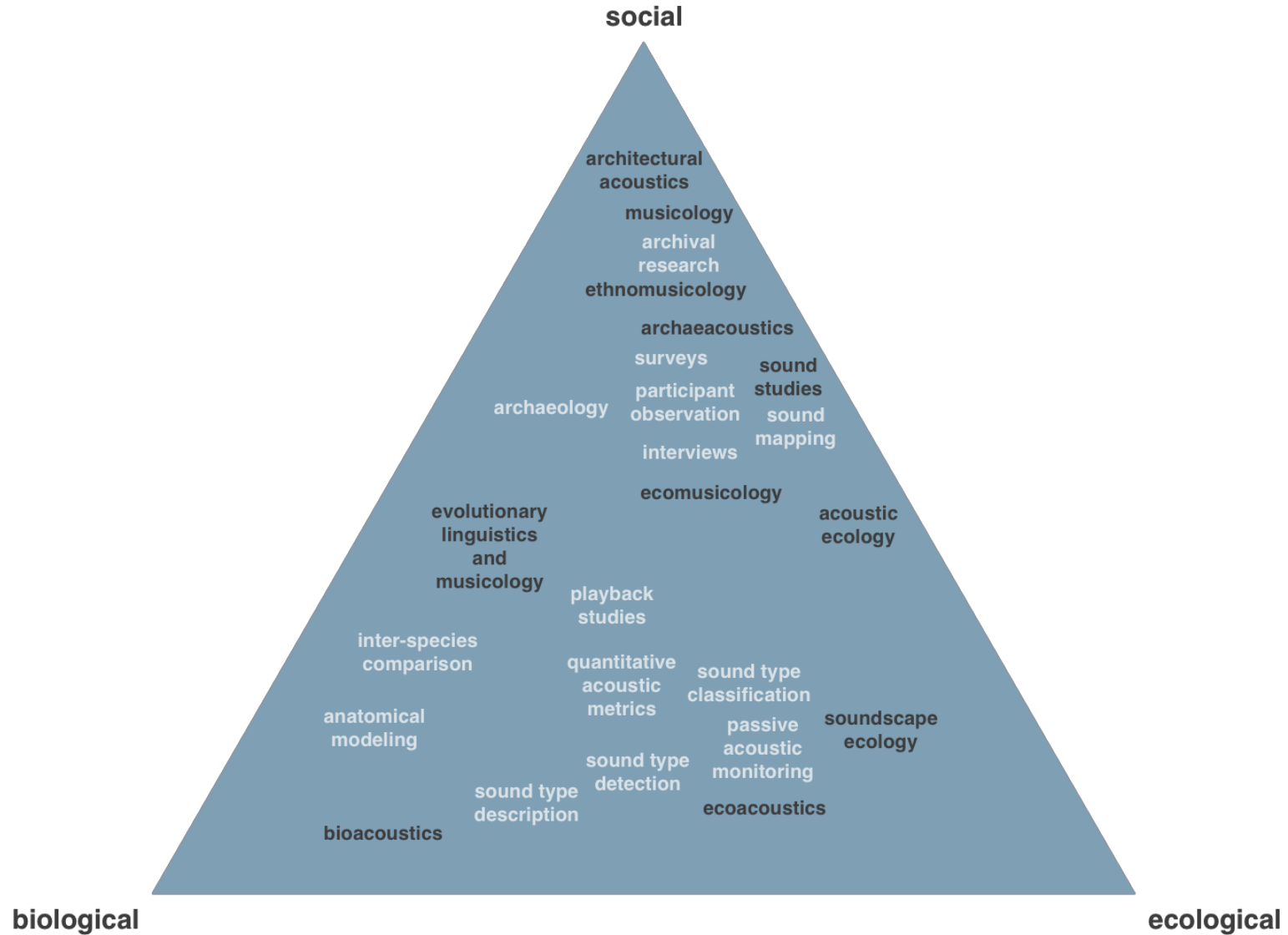


Figure 1.1. Heuristic illustration of disciplines that study sound in social, ecological, and/or biological contexts, along with their associated methods. Disciplines (dark text) are ordinated relative to maximum social, ecological, and biological relevance at the labeled triangle vertices. Methods (light text) are ordinated relative to the disciplines that might use them. Emphasis is on relative positions as opposed to distances.

Table 1.1. Overview of disciplines that focus on sound in a social, ecological, and/or biological context. Descriptions are not intended to be comprehensive, and disciplines are not necessarily mutually exclusive.

discipline	topics, themes, and characteristics	example social-ecological questions	methods	canonical or review reference(s)
architectural acoustics	<ul style="list-style-type: none"> • acoustical properties of the contemporary built environment • acoustic design • physics of sound • human sound perception • noise 	<ul style="list-style-type: none"> • How do human constructions alter the propagation of natural sounds? • Do green roofs increase biophonic contributions to soundscapes? 	<ul style="list-style-type: none"> • passive acoustic monitoring • quantitative acoustic metrics • surveys • interviews 	<ul style="list-style-type: none"> • Long 2006
archaeacoustics	<ul style="list-style-type: none"> • acoustical properties of prehistoric and historic natural and built environments and their cultural significance 	<ul style="list-style-type: none"> • How did natural landscape features with unique acoustic properties influence prehistoric human connection with nature? 	<ul style="list-style-type: none"> • archaeology • archival research 	<ul style="list-style-type: none"> • Scarre and Lawson 2006
musicology	<ul style="list-style-type: none"> • Western music history • music in and as culture 	<ul style="list-style-type: none"> • How did birdsong influence classical composers? 	<ul style="list-style-type: none"> • archival research 	<ul style="list-style-type: none"> • Beard and Gloag 2016
ethnomusicology	<ul style="list-style-type: none"> • Non-western music • music in and as culture • intercultural comparisons • origins of music 	<ul style="list-style-type: none"> • How has the availability of various natural resources influenced the construction of musical instruments around the world? 	<ul style="list-style-type: none"> • participant-observation • interviews • archival research 	<ul style="list-style-type: none"> • Nettl 2005
ecomusicology	<ul style="list-style-type: none"> • interplay between music, nature, and culture 	<ul style="list-style-type: none"> • What factors inspire punk rock lyricists to include themes of pollution in their songs? 	<ul style="list-style-type: none"> • participant-observation • interviews • archival research 	<ul style="list-style-type: none"> • Allen and Dawe 2015
sound studies	<ul style="list-style-type: none"> • sound in and as culture • critical perspective 	<ul style="list-style-type: none"> • What factors influence the choice of whether or not to listen to music while recreating in natural settings? 	<ul style="list-style-type: none"> • various 	<ul style="list-style-type: none"> • Sterne 2012
acoustic ecology	<ul style="list-style-type: none"> • effects of soundscapes on humans • normative perspective 	<ul style="list-style-type: none"> • How can we bring more natural sounds into urban environments? 	<ul style="list-style-type: none"> • sound mapping • various 	<ul style="list-style-type: none"> • Truax 1978 • Schafer 1993

Table 1.1. (continued).

discipline or field	topics, themes, and characteristics	example social-ecological questions	methods	canonical or review reference(s)
soundscape ecology	<ul style="list-style-type: none"> • sounds as a collective soundscape • sound as indicative of ecological pattern and process • the influence of sound on animals • landscape context • social-ecological context • acoustic niches • acoustic adaptation • geophony/biophony/anthrophony classification • multiple scales 	<ul style="list-style-type: none"> • Does acoustic diversity correlate positively with taxonomic and functional diversity across anthropogenic disturbance gradients? • How do geophonic, biophonic, and anthrophonic contributions to soundscapes vary across space and time? • How do land cover and landscape configuration affect the spatial distribution of biophony? 	<ul style="list-style-type: none"> • passive acoustic monitoring • sound type classification, description, and detection • quantitative acoustic metrics 	<ul style="list-style-type: none"> • Pijanowski et al. 2011a • Pijanowski et al. 2011b
ecoacoustics	<ul style="list-style-type: none"> • sound as indicative of ecological pattern and process • the influence of sound on animals • acoustic niches • acoustic adaptation • multiple scales 	<ul style="list-style-type: none"> • How does animal acoustic activity change in the presence of recreating humans? • Can climate-change-induced changes in insect abundance be detected acoustically? • How do geophonic and anthropic noise levels influence anuran habitat selection 	<ul style="list-style-type: none"> • passive acoustic monitoring • sound type classification, description, and detection • quantitative acoustic metrics 	<ul style="list-style-type: none"> • Sueur and Farina 2015
bioacoustics (here including auditory science and psychoacoustics)	<ul style="list-style-type: none"> • animal production, reception, and perception of sound • sound-behavior relationships 	<ul style="list-style-type: none"> • How do animals change their acoustic behavior in the presence of anthropogenic noise? • Which bird species are most capable of altering their vocalizations to avoid the masking effects of anthropogenic noise? 	<ul style="list-style-type: none"> • sound type description • quantitative acoustic metrics • playback studies • anatomical modeling • inter-species comparison 	<ul style="list-style-type: none"> • Bradbury and Vehrencamp 2011 • Penar et al. 2020
evolutionary linguistics and musicology	<ul style="list-style-type: none"> • origins of language and music • selective pressures influencing language and music 	<ul style="list-style-type: none"> • Did language and music develop differently in different ecological contexts? 	<ul style="list-style-type: none"> • archaeology • inter-species comparison • anatomical modeling 	<ul style="list-style-type: none"> • McMahon and McMahon 2012 • Wallin et al. 2001

1.2 Tierra del Fuego as the focal place for this dissertation

The choice of Tierra del Fuego as the focal place for this dissertation initially stemmed from a goal of the Center for Global Soundscapes: the collection and eventual comparative analysis of acoustic data from all of Earth's ecoregions (Magellanic Subpolar Forests in the case of southern Tierra del Fuego). I will later discuss some additional motivating factors, but an initial overview of the region's social-ecological systems will provide some preliminary context.

Isla Grande de Tierra del Fuego (hereafter Tierra del Fuego) is separated from mainland South America by the Strait of Magellan. The Atlantic Ocean lies to its east, the Beagle Channel to its south, and a series of fjords, smaller islands, and the Pacific Ocean to the west. The Andes Mountains run from west to east along the southern portion of the island, and they give way to flatter land to the north and northeast. Summers are cool and short, and winters are long and snowy. The flatter northeast portion of the island is warmer and drier than the more mountainous southwest, and this topographical and climatological gradient is reflected in the vegetation: from the southwest to the northeast, glaciers and tundra transition to forest, ecotone, and then steppe vegetation (Herrera et al. 2020). In the forested areas of the island, which are dominated by three *Nothofagus* species (*N. antarctica*, *N. betuloides*, and *N. pumilio*), windthrow is the primary mechanism of natural disturbance (Rebertus et al. 1997).

Herpetofauna are largely absent from the island, and species richness of exotic freshwater fish (four) and mammals (sixteen) equals or exceeds that of their native counterparts (Ceï 1979; Valenzuela et al. 2014). Avian species richness is higher than that of other taxa, but overall terrestrial animal species richness is still low in a global context (Valenzuela et al. 2014). Seabirds and marine mammals also rest and/or breed on the coasts of Tierra del Fuego and on neighboring islands in the archipelago (Schiavini and Raya Rey 2001; Raya Rey et al. 2014), augmenting the region's diversity, at least in the terrestrial-marine interfaces they occupy.

Humans have inhabited Tierra del Fuego since around 10,500 years ago (Morello et al. 2012). Four sociocultural groups of terrestrial or maritime hunter-gatherers, the Selk'nam (Ona), Haush (Manekennk), Yámana (Yagan), and Kawéskar (Alakaluf) are considered to have been present at the time of early European contact with the region beginning in the 1500s (Lanata 2002; Morello

et al. 2012). Increasing colonization and contact with European missionaries, miners, ranchers, sailors, whalers, and sealers in the late 1800s introduced diseases that devastated indigenous populations, and colonizers also murdered indigenous people (Marangoni et al. 2011), resulting in the fact that few descendants of these groups remain today (Guichón et al. 2006; Crespo et al. 2020).

In an effort to reinforce claims of sovereignty over their respective territories in the Fuegian Archipelago, Argentina and Chile encouraged settlement and development through a penal colony, military installations, and tax incentives (van Aert 2013). These initiatives had moderate success in increasing the regional population, but over the past few decades, increasing tourism has spurred further population growth and infrastructural development. In Argentina, the urban population of Tierra del Fuego, Antártida e Islas del Atlántico Sur Province increased by 419% between 1980 and 2010 compared to a national urban increase of 57% (Instituto Nacional de Estadística y Censos 2017; Herbert 2014). Around 400,000 tourists per year now visit the Argentine city of Ushuaia (or at least they did before the present COVID-19 pandemic), and many of Ushuaia's 70,000 residents are employed directly or indirectly by tourism (Instituto Fueguino de Turismo 2017; Secretaria de Turismo de Ushuaia, Departamento Estadísticas y Econometría 2011). The vast majority of Antarctic cruise passengers pass through Ushuaia, and they often spend at least some time ashore on Tierra del Fuego (Vereda 2010). This rapid change has created some social tensions: population growth in Ushuaia has outpaced infrastructural development, there is a perception of inequitably distributed tourism benefits, and attitudes vary concerning the natural environments that sustain local tourism (Herbert 2014).

Human impacts on Fuegian ecosystems have changed dramatically since colonization. Subsistence hunting and gathering by small indigenous populations likely had few major impacts on local ecology (Marangoni et al. 2011), although these groups may have influenced fire dynamics on the island (Markgraf and Huber 2010). Colonization introduced large scale ranching and forestry (Marangoni et al. 2011; Lencinas et al. 2018) as well as pollution (Raya Rey et al. 2017) and the large number of exotic species mentioned above (Valenzuela et al. 2014).

The social-ecological systems of Tierra del Fuego have clearly exhibited intensifying dynamism and complexity over the past centuries, and especially the past few decades. While certain changes and characteristics mentioned above occupy particular local contexts, they also share commonalities with global social-ecological trends. The proportion of exotic animal species in Tierra del Fuego is exceptionally high, but biotic exchange is globally ubiquitous. Most parts of the world do not offer cruises to Antarctica, but distribution of benefits from nature-based tourism is a common concern. Even though Tierra del Fuego may seem a remote place and is considered one of the world's remaining wilderness areas (Mittermeier et al. 2003), it is in fact highly connected to the rest of the world by flows of people, information, and capital (Raya Rey et al. 2017). Studying this dynamism and complexity with local nuance but global perspectives represented another key motivator for focusing this dissertation on Tierra del Fuego.

As we further explored potential research topics in this region from an acoustic perspective, the composition and spatial distribution of sounds in Tierra del Fuego stood out as features that make the area well suited for: a) studying social-ecological systems through the lens of sound and b) further developing the necessary methods to do so.

Throughout much of the terrestrial world, soundscapes (the collections of sounds occurring in given places over given timeframes) often contain a mix of geophony (sounds of geophysical processes), biophony (sounds of animals) from diverse taxa, and technophony (sounds from mechanical devices). These sound categories all occur in Tierra del Fuego, but with several distinctive characteristics that facilitate acoustic studies involving passive acoustic monitoring (PAM):

1. Inland from the coasts, biophony is sparse due to largely non-soniferous insects and a nearly complete lack of amphibians and reptiles (Cei 1979). As mammals are less diverse than birds in this region (Valenzuela et al. 2014) and are generally less soniferous than birds, avifauna are the dominant inland contributors to biophony. Such taxonomic simplicity in biophonic contributions is rare at lower latitudes, and it allows for easier testing and use of quantitative acoustic metrics with few potentially confounding sounds.
2. Along the coasts, the generally sparse biophony occasionally gives way to dense pockets of intense acoustic activity where seabirds and marine mammals congregate. These

congregations present opportunities to conduct fairly comprehensive monitoring of single species with minimal spatial sampling effort.

3. Technophony is largely restricted to three compact urban centers, the roads connecting them, the shipping channel in the Beagle Channel, and an air traffic corridor. This limited spatial coverage means that substantial areas are generally free of potentially confounding technophony.

1.3 Dissertation structure: focal problems and principal questions

In developing the sound-focused studies contained in this dissertation, I sought to investigate a selection of topics with a) specific importance in the social-ecological systems of Tierra del Fuego and b) general relevance to global social-ecological challenges. This dissertation is certainly not a comprehensive documentation of Tierra del Fuego's social-ecological systems, nor is it an exhaustive use of the sound-related disciplines or methods that could be applied to social-ecological systems. Rather, I have tried to address a selection of key local topics across several organizational scales using a range of sound-based methods. I hope this dissertation serves as a demonstration of the potential for such methods and applications.

Chapter 2, "Biogeographical and analytical implications of temporal variability in geographically diverse soundscapes", covers the broadest spatial extent, incorporating two sites from Tierra del Fuego and six others from three additional continents. In PAM studies, it is important to design an appropriate temporal sampling scheme based on the temporal variability of the sounds one wishes to measure and the power and storage limitations of acoustic recorders. The objective of this chapter was to provide some guidance to PAM practitioners on how to do so. We first quantified the temporal variability of several acoustic metrics and compared measurements of variability across sites and times of day. We also simulated a wide range of temporal sampling schemes in order to model their representativeness relative to continuous sampling. In this chapter we focused on an acoustic community level of organization (i.e. the collection of soniferous animals that could be recorded at each site).

For Chapter 3, "Sentinels for sentinels: passive acoustic and camera trap monitoring of sensitive penguin populations", we tested the utility of PAM to monitor behavior and abundance of

Magellanic (*Spheniscus magellanicus*) and southern rockhopper penguins (*Eudyptes chrysocome*) at different spatial and temporal scales. The study was conducted on Martillo Island in the Beagle Channel (Magellanic penguins) and on Staten Island off the east coast of Tierra del Fuego (both species). We conducted *in situ* observations of the acoustic behavior of each species, and we compared acoustic metrics with penguin counts from narrowly focused camera traps and larger-extent observations of colony density. Penguins (Sphenisciformes spp.) are sensitive to an array of marine and terrestrial ecological disturbances and thus serve as useful indicators of ecosystem function (they are “marine sentinels” in the terms of Boersma (2008)). As archetypical charismatic megafauna, they are also a primary attraction of nature-based tourism in Tierra del Fuego and elsewhere in the world (Raya Rey et al. 2017).

Chapter 4, “Acoustic monitoring shows invasive beavers (*Castor canadensis*) promote avian diversity in Tierra del Fuego”, is focused on impacts of North American beaver (*Castor canadensis*)—the most iconic of Tierra del Fuego’s invasive species due to a) its deliberate introduction by humans and b) its rapid spread and drastic alteration of landscapes by building dams and flooding low-lying areas (Anderson et al. 2009). Many of its impacts have been well documented, but avian responses to its landscape modification have received surprisingly little attention (Jiménez and Rozzi 2014), especially considering the ongoing consideration of beaver eradication (Schiavini et al. 2016). We sought to determine how bird communities might differ between intact riparian forests, ponds created by beaver dams, and meadows that are created when beaver ponds drain after dam breaches. We conducted PAM and classic avian point counts under each of these conditions across seasons to test for differences between impact conditions and to compare the two methodologies.

Chapter 5, “Human-nature connection and soundscape perception: insights from Tierra del Fuego, Argentina”, is the most explicitly social chapter, in that it actually involved human-subjects research as opposed to just social contextualization. A lack of human connection with nature is often highlighted as a cause or perpetuating factor for the environmental crises we face (Ives et al. 2018; Whitburn et al. 2020). A hypothesis motivating much of the outreach work conducted by the Center for Global Soundscapes, the United States National Park Service, and other organizations is that developing cognitive and affective connections between humans and

natural soundscapes will in turn promote connection with nature and responsible environmental stewardship (Ghadiri Khanaposhtani et al. 2018a, 2018b; US National Park Service 2018b). We sought to test the relationship between soundscape perception and nature relatedness by conducting surveys and soliciting responses to soundscape audio prompts. We also evaluated the potential for any demographic influences on nature relatedness or soundscape perception that might be related to the Ushuaian social tensions highlighted above.

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CHAPTER 2—BIOGEOGRAPHICAL AND ANALYTICAL IMPLICATIONS OF TEMPORAL VARIABILITY IN GEOGRAPHICALLY DIVERSE SOUNDSCAPES

Dante Francomano, Benjamin L. Gottesman, and Bryan C. Pijanowski
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Abstract

Unprecedented rates of biodiversity loss and intensifying human attempts to rectify the biodiversity crisis have heightened the need for standardized, large-scale, long-duration biodiversity monitoring at fine temporal resolution. While some innovative technologies such as passive acoustic monitoring are well suited for such monitoring challenges, many questions remain as to how they should be scaled out and optimally implemented across ecosystems.

Our research questions center on temporal sampling regimes—how frequently and how long one should collect data to represent biodiversity conditions over a given timeframe. Addressing this concern in the context of passive acoustic monitoring, we investigated whether temporal soundscape variability—the characteristic short-term acoustic change in an environment—is consistent across ecosystems and times of day, and we considered how various temporal subsampling schemes affect the representativeness of resultant acoustic index values, relative to continuous sampling. We quantified soundscape variability at eight sites across four continents based on temporal autocorrelation ranges and standard deviations of acoustic index values, and we created a heuristic model to classify types of soundscape variability based on those two variables.

Drawing on values derived from three distinct acoustic indices, we found that the characteristic temporal variability of soundscapes varied between sites and times of day (dawn, daytime, dusk, and nighttime). Some sites exhibited little difference in variability between times of day whereas other sites exhibited greater within-site differences between times of day than many inter-site differences. Daytime soundscapes generally tended to exhibit more temporal variability than nighttime soundscapes.

We also compared potential subsampling schemes that could be advantageous in terms of power, data storage, and data analysis costs by modeling subsample error as a function of total analysis time and number of subsamples within a larger block of time. Greater numbers of evenly distributed subdivisions drastically increased the representativeness of a sampling scheme, while increases in subsample duration yielded fairly minimal gains in representativeness between 33 and 67% of the full time one wishes to represent. Generally, our results show that for a long-term, fine temporal resolution monitoring program, one should record in evenly distributed durations at least as short as 1 minute while only recording up to a third of the time one wishes to represent. While more continuous monitoring can be advantageous and necessary in many cases, current economic and logistical limitations in power, data storage, and analysis capabilities will often warrant optimized subsampling designs.

2.1 Introduction

Animal biodiversity is in global decline, and some have stated that Earth's sixth mass extinction event is in progress (Barnosky et al. 2011; Ceballos et al. 2015; Kolbert 2014). As we try to monitor and address such significant global environmental changes, governments, nongovernmental organizations, and private landowners need to better understand how and why ecosystems change over time in response to management initiatives and ecological disturbances (Block et al. 2001; Fancy et al. 2009; Spellerberg 2005). For each monitoring effort, those conducting the monitoring must determine the overall duration of the monitoring program and the manner in which sampling will be scheduled within that overall duration. At the heart of these decisions is the concept of temporal variability. Ecosystems change over time in response to a vast array of interdependent ecological variables, and those changes occur at varying rates (Landres et al. 1999). Ecological monitoring must employ temporal sampling schemes designed to identify a signal (the change related to a driver of interest) amongst noise (change related to other inherent system variability) at the relevant temporal scale.

To maximize comprehensiveness and the chance of signal detection, monitoring would be continuous and of infinite duration. Unfortunately, such comprehensiveness is currently unattainable for most variables due to numerous constraints including funding, labor costs, fieldwork logistics, equipment, data storage resources, and data analysis resources (Caughlan and Oakley 2001). As a result of the inherent tradeoff between monitoring cost and comprehensiveness, many monitoring programs are conducted with wide temporal gaps between monitoring events (e.g., biennial or decennial measurements) and limited temporal extent of monitoring events (e.g., measurements only occurring during 1 week of summer mornings). Wide temporal gaps preclude gaining information at fine temporal resolution. For example, while the North American Breeding Bird Survey (USGS Patuxent Wildlife Research Center 2018) and Audubon Christmas Bird Count (National Audubon Society 2019) provide rich datasets on avian diversity and spatial distributions at two points in the year (and just one time of day for the Breeding Bird Survey), similar data are not available for the rest of the year or additional times of day. Moreover, such wide temporal gaps could misrepresent the system if monitoring events coincide with a series of highs or lows in a quickly fluctuating variable or are periodic with a different frequency than a periodic variable being measured. Mannocci et al.

(2017) highlight the importance of inter-annual variability in the California Current ecosystem due to the El Niño Southern Oscillation, and they emphasize the inadequacy of modeling based on low-resolution (e.g., decadal) measurements of variables in that system. Similarly, limited temporal extent only provides snapshots of variables that likely fluctuate outside of the temporal extent of the monitoring event. A 2-year study in the California Current would yield an incomplete picture of that system's states and dynamics.

Periodic monitoring events are not inherently problematic, particularly when there is preexisting knowledge of a system's temporal dynamics. For example, it is widely acknowledged that spring mornings are optimal times for assessing populations of most songbird species in temperate ecosystems (Ralph et al. 1995). That being said, continuous or near-continuous monitoring can be desirable for increased resolution when possible and can be necessary when little is known about the temporal variability of a system. Recent technological advances have facilitated the development of several methods of biodiversity or wildlife monitoring that generate continuous or near-continuous datasets. GPS tracking, camera trapping, and passive acoustic monitoring (PAM) are several examples of such promising emerging technologies that will be enhanced by refined analytical approaches with a greater focus on the temporal aspects of the data they produce (Cushman 2010; Frey et al. 2017; Gage and Axel 2014).

In the past decade, the emergence of soundscape ecology and/or ecoacoustics has taken PAM from its origins in bioacoustics and applied it to animal community biodiversity assessment and monitoring, based on the principle that aspects of biophony (sound from biological sources) are reflective of animal community biodiversity (Pijanowski et al. 2011b; Sueur et al. 2014; Sueur and Farina 2015). A number of studies have begun to test the relationship between acoustic indices (empirical soundscape measurements) and biodiversity, and while results have been inconsistent, some indices have shown promise in certain situations, with both simulated and field recordings. Various acoustic indices have been shown to be correlated with: the number of biological sounds in a recording, species richness (derived from a recording or observed *in situ*), species evenness, Shannon diversity of species, individual abundance, or measures of functional diversity (Boelman et al. 2007; Buxton et al. 2018; Eldridge et al. 2018; Elise et al. 2019; Fuller et al. 2015; Harris et al. 2016; Jorge et al. 2018; Machado et al. 2017; Mammides et al. 2017;

Pieretti et al. 2011; Sueur et al. 2008b; Zhao et al. 2019). The validation of acoustic indices is an ongoing process, but should not impede attempts to explore their PAM functions at this moment, as PAM has realized and potential applications for spatio-temporal monitoring of distribution patterns, phenology, and disturbance impacts from species to community levels (Sueur and Farina 2015).

PAM is a method for which continuous monitoring is possible, and such monitoring could be necessary in certain contexts, such as when one is interested in short-duration, infrequent sound events (Towsey et al. 2014a; Yoccoz et al. 2001). If triggered recording is impossible or impractical for example, continuous monitoring would be desirable to ensure that rare sounds of interest are captured. Technological advancements of the past 2 decades have reduced power consumption and increased capacity for storage and analysis of acoustic data from PAM, making continuous monitoring feasible in studies with limited overall duration and few spatial replicates (Hill et al. 2018; Merchant et al. 2015). Reduced size and cost of PAM units are also making spatial replication much easier (e.g., the Frontier Labs Bioacoustic Audio Recorder (Frontier Labs 2019), the Wildlife Acoustics Song Meter Mini (Wildlife Acoustics, Inc. 2019), and especially the Open Acoustic Devices AudioMoth (Open Acoustic Devices 2019)). Applications with increased duration and spatial coverage or resolution like the Australian Acoustic Observatory (Roe et al. 2018) are becoming increasingly realistic, and more such projects can be expected in the near future.

The potential continuous application of PAM is an asset when used to address certain questions (e.g., determining when rare sounds occur or considering how sounds may be triggered by the sounds preceding them), but continuous PAM is likely unnecessary and undesirable for the majority of applications in which researchers are interested in ecological change occurring over time scales of weeks to years. Continuous long-term PAM provides rich, potentially valuable data, but the preservation and use of that data requires technology that is often expensive to install and maintain, and those costs may outweigh the benefits of the additional data. Replacing power sources and data storage units in PAM units can be a time consuming and costly endeavor, particularly in multi-year studies and hard-to-access environments like marine systems, so such applications require well-informed decisions about sampling schedules. Less

comprehensive temporal sampling schemes would reduce the number of field excursions needed to change batteries and memory cards, potentially allowing time and money to be redirected towards increased spatial replication or the collection of additional relevant data about local flora and fauna. Limiting temporal sampling schemes would also reduce the logistical and financial challenges associated with data storage and processing.

The temporal variability of ecosystems is reflected in the variability of biophony emitted from them. Temporal variability in biophony stems from a variety of biological and ecological factors operating over a wide range of time scales that PAM practitioners must consider (Table 2.1). On the order of minutes, individual animals' patterns and characteristics of sound production are relevant. Over hours, weather events, changing light levels, tides, and animals' endogenous clocks may trigger changes in biophony like the widely recognized dawn and dusk choruses (Gottesman et al. 2018; Rodriguez et al. 2014). On longer scales, lunar cycles can affect biophony in marine systems (Staaterman et al. 2014) and for some terrestrial taxa like bats and katydids (Lang et al. 2006), and patterns of mating, reproduction, and migration can cause seasonal changes in biophony (Rice et al. 2017; Towsey et al. 2014b). Population dynamics, climate change, and certain disturbances can bring about even slower rates of change in biophony (Buxton et al. 2016; Campos-Cerqueira and Aide 2017; Krause and Farina 2016). Characterizing temporal soundscape variability across ecosystems and spatiotemporal scales would provide important biogeographical contextualization for the development of soundscape-based disturbance indicators—a primary research objective of soundscape ecology (Gasc et al. 2017; Lomolino et al. 2015). Of course, such indicators are dependent on baseline measurements that could simply represent average index values or even typical diel dynamics. Those baseline measurements must be grounded in a thorough understanding of the temporal variability that could bias them and must be obtained with an appropriate sampling schedule according to that potential bias (Almeira and Guecha 2019). This study represents an attempt to characterize within-day temporal variability of acoustic indices and determine how the nature of that variability can influence the representativeness of various subsampling schedules. The acoustic indices we employed do not necessarily correlate with any specific measure of biodiversity in every environment, but they can still provide meaningful information about the temporal variability of soundscapes more broadly.

Table 2.1. Drivers of temporal variability across scales.

temporal scale	drivers	consequences
seconds – hours	<ul style="list-style-type: none"> • individual repertoire size • sound characteristics (amplitude envelope and frequency modulation) • sound production patterns (continuous, repetitive, or sporadic) • acoustic community abundance and diversity 	<ul style="list-style-type: none"> • individuals emit more or less types of sounds • single sounds contain more or less variability • individuals produce a consistent or highly variable composition of biophony • higher-diversity assemblages likely produce higher-variability biophony
hours – days	<ul style="list-style-type: none"> • animal movement causing short-term changes to acoustic community abundance and diversity • endogenous clocks regulating acoustic activity • changing light levels • changing temperature 	<ul style="list-style-type: none"> • higher-diversity assemblages likely produce higher-variability biophony • the acoustically active community changes over time • individuals produce more or less sound • individuals produce more or less sound, sometimes at different frequencies • individuals produce more or less sound
days – seasons	<ul style="list-style-type: none"> • changing precipitation • animal movement causing short-term changes to acoustic community abundance and diversity • weather system movement • lunar cycles affecting light levels • lunar cycles directly affecting sound production • pulse disturbances (disturbing influences of short duration that begin and end rapidly) 	<ul style="list-style-type: none"> • higher-diversity assemblages likely produce higher-variability biophony • individuals produce more or less sound • individuals produce more or less sound • individuals produce more or less sound • individuals produce more or less sound
seasons – years	<ul style="list-style-type: none"> • emergence and breeding phenology of soniferous species • animal movement and migration causing seasonal changes to acoustic community abundance and diversity • changes in repertoires and sound production patterns • press and ramp disturbances (disturbing influences that are continuous and of long duration (press) or slowly increase in intensity (ramp)) • phenological changes in habitat structure 	<ul style="list-style-type: none"> • composition of acoustic communities changes and higher-diversity assemblages likely produce higher-variability biophony • higher-diversity assemblages likely produce higher-variability biophony • individuals produce a more consistent or variable composition of biophony • composition of acoustic communities changes or individuals produce more or less sound • biophony propagates differently, with individuals potentially changing their sound production in response
inter-annual	<ul style="list-style-type: none"> • population changes • press and ramp disturbances (disturbing influences that are continuous and of long duration (press) or slowly increase in intensity (ramp)) 	<ul style="list-style-type: none"> • individual species account for more or less of the contributions to overall biophony • composition of acoustic communities changes or individuals produce more or less sound

In this study we analyzed acoustic recordings from eight sites across four continents to characterize short-term (within-2-hour) and diel (within-24-hour) soundscape variability and to provide sampling schedule guidance to PAM practitioners. Using a set of three complementary acoustic indices, we addressed two principal questions: 1) is temporal soundscape variability consistent across ecosystems and times of day? and 2) considering any spatiotemporal differences in temporal variability, how do various temporal subsampling schemes affect the representativeness of resultant acoustic index values, relative to continuous sampling?

Regarding the first question, we hypothesized that temporal soundscape variability would be inconsistent across ecosystems because different ecosystems host characteristic animal assemblages that exhibit characteristic temporal patterns of sound production. Additionally, we hypothesized that temporal soundscape variability would be higher during daytime relative to nighttime, as nocturnally acoustically active taxa like insects and amphibians tend to produce sound repetitively and consistently, whereas diurnal taxa like birds tend to produce sound more sporadically. In terms of our second question, we expected that more subdivisions within sampling schedules would reduce “subsample error” (deviation from a “true” full-duration value caused by subsampling) by maximizing the chance of capturing rare sound events, while minimizing their influence (Cook and Hartley 2018). Despite the inherent loss of precision due to subsampling, we also hypothesized that subsampling would yield acceptably small subsample errors and that subsampling could efficiently and adequately represent values derived from continuous recording.

2.2 Methods

2.2.1 Goals

Our goals related to each question were as follows: For Question 1 (variability characterization), we sought to a) measure soundscape variability at diverse sites based on temporal autocorrelation ranges and standard deviations of acoustic index values and b) compare soundscape variability between sites and times of day. For Question 2 (subsampling implications), we sought to model subsample error as a function of total analysis time and number of subdivisions.

2.2.2 Site selection

For each question, we employed acoustic data from eight sites in diverse ecosystems on four continents. A site was included in this study if: 1) there were acoustic recordings from that site in the archives of the Center for Global Soundscapes (CGS) at Purdue University, 2) the recordings spanned at least 5 complete, consecutive days, 3) each recording was at least 59 minutes in length, and 4) aural assessment of sample recordings did not reveal predominance of geophony or technophony. Biophony-dominated sites were chosen in order to predominantly measure the temporal variability of biophony. Locations and details for the eight sites meeting the above conditions are presented in Table 2.2 and Figure 2.1. All sites were terrestrial with the exception of Coral Reef, which was located underwater near a coral reef off the coast of Puerto Rico. While these sites do not represent random locations, they are stratified across an assortment of biomes and a range of latitudes and longitudes.

Table 2.2. Site information, recording parameters, and data coverage. Under “recorder model”, “WA” indicates “Wildlife Acoustics”. Ecoregions are classified as by Olson et al. (2001) and Spalding et al. (2007).

site name	state/province, country	ecoregion	coordinates	recorder model	sample rate	user-defined gain	preamplifier gain	analog to digital converter gain	filtering	frequency analysis range
Penguin Colony	Tierra del Fuego, Argentina	Magellanic Subpolar Forests	54.9075° S, 67.3756° W	WA SM4	48 kilohertz	+12 decibels	+26 decibels	+3 decibels	none	0.15 – 24 kilohertz
Tropical Rainforest	Heredia, Costa Rica	Isthmian-Atlantic Moist Forests	10.4237° N, 84.0144° W	WA SM4	44.1 kilohertz	+20 decibels	+26 decibels	+3 decibels	none	1 – 22.05 kilohertz
Mongolian Grassland	Tšv, Mongolia	Mongolian-Manchurian Grassland	47.6917° N, 105.8835° E	WA SM3	48 kilohertz	0 decibels	+24 decibels	+3 decibels	none	0 – 24 kilohertz
Coral Reef	Puerto Rico, United States of America	Greater Antilles	17.9349° N, 67.0485° W	WA SM3M	48 kilohertz	0 decibels	+24 decibels	+3 decibels	none	0 – 24 kilohertz
Miombo Swamp	Rukwa, Tanzania	Central Zambebian Miombo Woodlands	5.4312° S, 30.5775° E	WA SM4	48 kilohertz	+18 decibels	+26 decibels	+3 decibels	high-pass at 220 Hertz	0.15 – 24 kilohertz
Nebraska Prairie	Nebraska, United States of America	Central and Southern Mixed Grasslands	40.7292° N, 98.5856° W	WA SM4	48 kilohertz	+12 decibels	+26 decibels	+3 decibels	high-pass at 220 Hertz	0.15 – 24 kilohertz
California Woodland	California, United States of America	California Interior Chaparral and Woodlands	38.42° N, 122.592° W	WA SM4	44.1 kilohertz	+18 decibels	+26 decibels	+3 decibels	high-pass at 220 Hertz	0.3 – 22.05 kilohertz
Magellanic Forest	Tierra del Fuego, Argentina	Magellanic Subpolar Forests	54.8473° S, 68.5442° W	WA SM4	48 kilohertz	+12 decibels	+26 decibels	+3 decibels	none	0.4 – 24 kilohertz

Table 2.2. (continued).

site name	start date	end date	number of complete days	percent missing files
Penguin Colony	2016/02/24	2016/03/19	15	18
Tropical Rainforest	2016/07/27	2016/08/02	5	0
Mongolian Grassland	2015/06/01	2015/07/06	22	9
Coral Reef	2017/07/03	2017/08/11	37	0
Miombo Swamp	2017/03/25	2017/04/08	14	0
Nebraska Prairie	2017/08/17	2017/08/27	9	0
California Woodland	2017/08/18	2017/08/25	7	0
Magellanic Forest	2016/02/17	2016/03/15	19	15

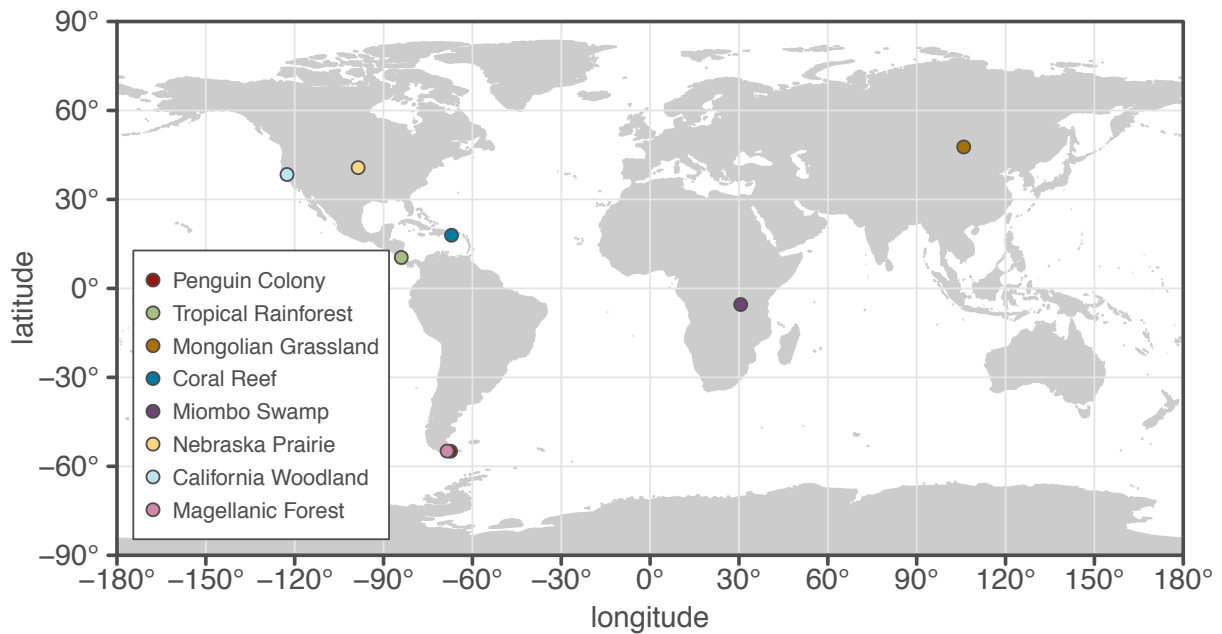
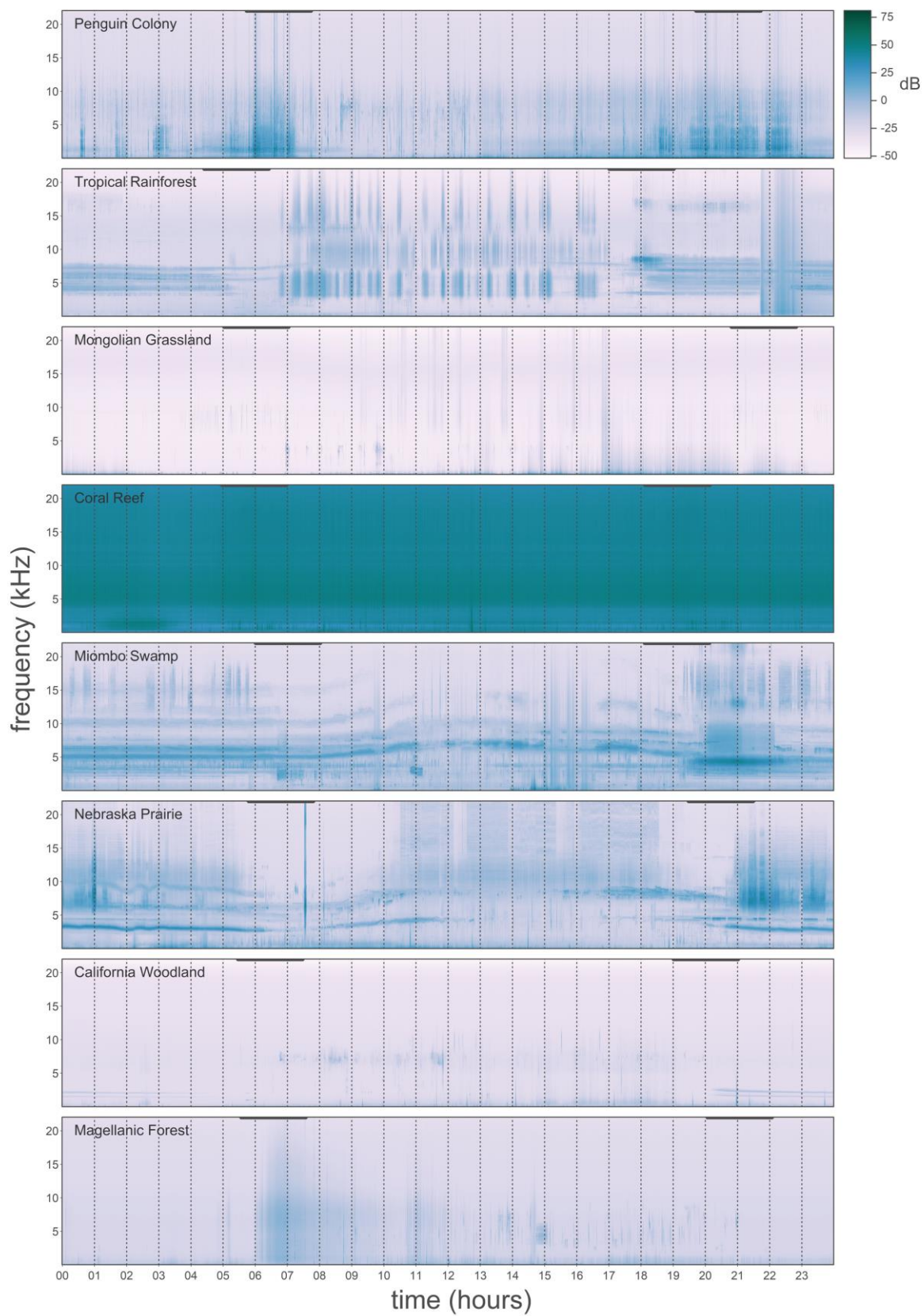


Figure 2.1. Site locations. Penguin Colony and Magellanic Forest overlap substantially on this map, as they are in close proximity relative to a global scale.

2.2.3 Data preparation

We first converted any recordings that existed as .flac files in the CGS archives to .wav format using R (R Core Team 2018) and the R packages “tuneR” and “seewave” (Ligges et al. 2016; Sueur et al. 2008a). All code associated with this study is available on GitHub at https://github.itap.purdue.edu/PijanowskiGroup/Francomano_et_al_2020_Temporal_Variability. We then removed corrupted files and files with durations below 59 minutes. Files from the Nebraska Prairie site did not begin at the start of each hour, so consecutive files for that site were combined and cut to a duration of 59 minutes with a top-of-the-hour start time. Other files that did not begin precisely at the top of the hour had their start times rounded (by up to 2 minutes and 18 seconds) to consider them as beginning precisely at the top of the hour. An evident DC-offset was removed from files from Mongolian Grassland and Coral Reef. The left channel was used for all analysis (aside from Coral Reef, which was recorded in mono). Data coverage over time is shown in Figures 2A.1 – 2A.8. 24-hour spectrograms for each site are presented in Figure 2.2, and 1-minute versions of the corresponding audio files are provided at the above GitHub link.

Figure 2.2. 24-hour power spectral density spectrograms. These spectrograms show the first complete day of recordings from each site. Power spectral density was calculated following the methods described by Merchant et al. (2015) using a 1-second window length, Hann window, and mean averaging to produce final spectrograms with 1-minute temporal resolution. Power is expressed as decibels re 20 micropascals squared per Hertz with the exception of the one marine site, Coral Reef, for which power is expressed as decibels re 1 micropascal squared per Hertz. All spectrograms have been cropped to a frequency range of 0 – 22.05 kilohertz, and the 60th minute of each hour is merely a duplication of the 59th minute. Horizontal lines at the top of each spectrogram represent the 2-hour dawn and dusk windows centered on sunrise and sunset for each day.



2.2.4 Acoustic index calculation

The acoustic complexity index (ACI; Pieretti et al. 2011), bioacoustic index (BI; Boelman et al. 2007), and spectral entropy (H_f ; Sueur et al. 2008b) were calculated in 59 consecutive 1-minute windows within each 59-plus-minute file, beginning at the beginning of the file. The 60th minute of each hour was assigned a value of N/A, and those values were ignored in subsequent analyses (the recorders wrote files to the memory cards during this minute, so a few seconds were typically lost). The R package “seewave” was used for the ACI and H_f , while “soundecology” (Villanueva-Rivera and Pijanowski 2016) was used for the BI. DF determined a separate frequency range for index calculation on files of each site by visualizing and listening to short sections of those files in Audacity (Audacity Team 2015). He examined 24 files—one from each hour of the day on days that were randomly selected from all the complete days present for each site. He noted the minimum and maximum frequencies of biophony in each file and decided on per-site frequency ranges that would include almost all biophony that might be present at each site. Those frequency ranges are presented in Table 2.2. Geophony and technophony were not considered in this frequency range determination, except to determine if a predominance of those sounds warranted excluding a site from further analysis. The above indices were selected due to their prominence in the soundscape ecology and/or ecoacoustics literature, their use in past considerations of study design (Pieretti et al. 2015; Quiroz et al. 2017), and their complementary nature. The BI provides a good measure of biophonic contributions to soundscape amplitude, H_f offers insight into the spectral composition of a soundscape, and the ACI incorporates information on changes in the spectral distribution of sound over millisecond-level time scales (using its default parameters).

2.2.5 Question 1 (variability characterization) analysis

We addressed Question 1 through two methods based on subsets of the same data. For both methods, we operationalized the concept of temporal variability by calculating standard deviations and autocorrelation ranges of acoustic index values. We calculated these for different “value lengths” (durations over which 1-minute index values were averaged) and “analysis windows” (temporal windows limiting the values included in each calculation). We employed value lengths of 1 minute, 5 minutes, 15 minutes, and 60 minutes, and we employed analysis

windows of 5 minutes, 15 minutes, 60 minutes, dawn (a 2-hour window centered on sunrise), daytime (the time from 1 hour after sunrise to 1 hour before sunset), dusk (a 2-hour window centered on sunset), and nighttime (the time from 1 hour after sunset to 1 hour before sunrise), and 24 hours (Figure 2.3). To make standard deviations and autocorrelation ranges from daytime and nighttime analysis windows comparable with those from dawn and dusk analysis windows, as many 2-hour segments as possible were selected within daytime and nighttime windows (centered between sunrise and sunset), and standard deviations and autocorrelation ranges were calculated on each segment and then averaged to produce single values that are representative of any 2-hour segment within each daytime or nighttime analysis window. Because autocorrelation ranges are not robust when calculated on short time-series, value length-analysis window combinations were not considered if the analysis window was less than four times the value length (e.g., 5-minute value length in 15-minute analysis window) or if the autocorrelation ranges for all acoustic indices were 0 for at least four sites. We calculated standard deviations using the “sd” function and autocorrelation range using the “acf” function, both from the “stats” package of R. We defined the significance threshold of the autocorrelation function as:

$$\frac{qnorm\left(\frac{1 + (1 - \alpha)}{2}\right)}{\sqrt{n}}$$

where *qnorm* is the quantile function of the normal distribution, α is the significance level (0.05 in this case), and *n* is the number of values in the time series. We defined the autocorrelation range (in minutes) as the product of the lag at which the autocorrelation function of the given time series first becomes less than the significance threshold and the value length (in minutes).

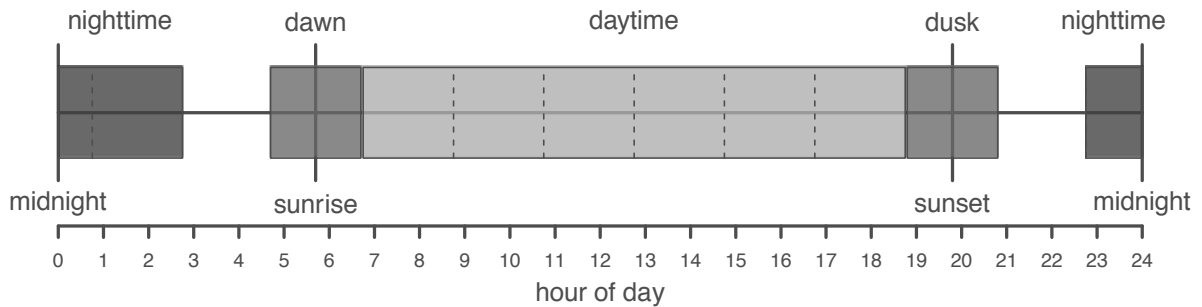


Figure 2.3. Illustration of analysis windows situated within times of day.

For the first method of addressing Question 1, we visualized within- and between-site differences by plotting standard deviations against autocorrelation ranges for each site (using inter-day averages). We constructed two plots for each index—one showing 1-minute value lengths within dawn, daytime, dusk, and nighttime analysis windows and another showing 1-hour value lengths in 24-hour analysis windows (Figure 2.6). This method allowed for visual comparison of a) sites and their values at different times of day over a relatively short timeframe (2 hours) and b) sites over a longer timeframe (24 hours). While one could consider any value length and analysis window, we believe that these combinations provided useful snapshots of temporal variability on various within-day scales.

For the second method, we conducted non-metric multidimensional scaling to plot sites in multidimensional space and check for any obvious clustering that would warrant use of adonis and discriminant analysis. We used the “metaMDS” function in the R package “vegan” (Oksanen et al. 2018) and the Euclidean dissimilarity index. As there was no evident clustering (Figure 2A.9) with a low stress level (0.063), we did not pursue this analysis further.

2.2.6 Question 2 (subsampling implications) analysis

For question 2, we separately determined subsample error for “full file lengths” of 12 and 60 minutes. We assigned 1-minute index values to dawn, daytime, dusk, and nighttime as described above, and subdivided the times of day for each site and day into as many 12- and 60-minute blocks as possible. For each block and each index, we calculated cumulative means of index values and then defined the subsample error as the absolute value of the difference between each cumulative mean and the 12- or 60-minute mean for that block. This process resulted in vectors of length 12 and 60 that were averaged within each site-time of day combination. Additionally, we calculated similar averages of differences for non-continuous subsampling—i.e. subsampling with multiple subdivisions. We calculated average differences for all possible evenly distributed subsampling schemes with subdivision durations of full minutes (integer values; Figure 2.4).

A. 12-minute full file length

TAT	NS	minute											
		1	2	3	4	5	6	7	8	9	10	11	12
1	1	1											
2	1	1	1										
2	2	1					1						
3	1	1	1	1									
3	3	1				1				1			
4	1	1	1	1	1								
4	2	1						1	1				
4	4	1			1						1		
5	1	1	1	1	1	1							
6	1	1	1	1		1							
6	2	1						1	1	1			
6	3	1				1	1				1		
6	6	1		1			1			1		1	
7	1	1	1	1	1	1	1						
8	1	1	1	1	1	1	1	1					
9	1	1	1	1	1	1	1	1	1				
10	1	1	1	1	1	1	1	1	1	1			
11	1	1	1	1	1	1	1	1	1	1	1		
12	1	1	1	1	1	1	1	1	1	1	1	1	

B. 60-minute full file length

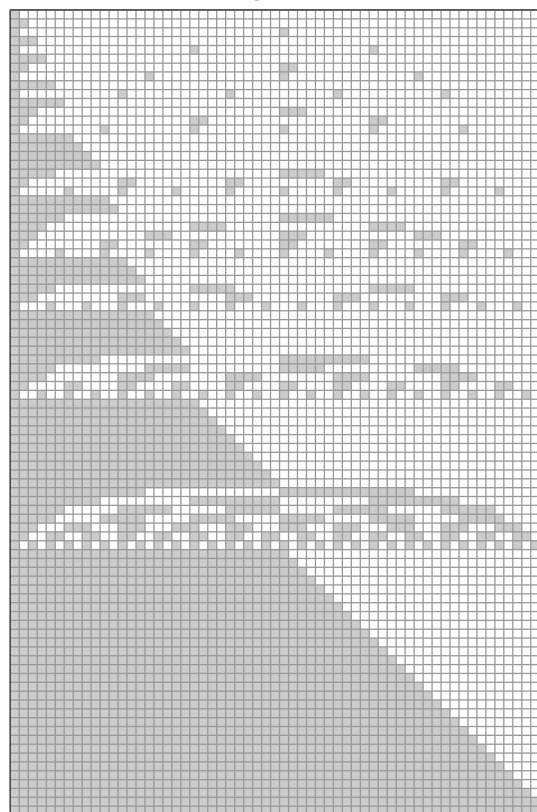


Figure 2.4. Illustration of all possible subsampling schemes for 12- (A) and 60-minute (B) full file lengths with a minimum recording duration of 1 minute and evenly distributed recording start times. “TAT” represents “total analysis time”, and “NS” represents number of subdivisions. Grey blocks represent recorded minutes and white blocks represent unrecorded minutes. B is unlabeled for legibility, but the format is the same as A: columns represent minutes 1 – 60 (left to right), and rows represent increasing TAT and NS (top to bottom).

We then computed separate linear mixed models for each index and each full file length. The last value of each continuous subsample error vector was not incorporated in the models, as it was necessarily 0. Global models including all potential independent variables were constructed with subsample error as the dependent variable, site as an independent random intercept, and time of day, total analysis time, total analysis time squared, total analysis time cubed, number of subdivisions, and the interaction between total analysis time and number of subdivisions as fixed effects. All non-categorical independent variables were scaled and polynomials were orthogonal. Site was incorporated as a random intercept to account for the non-independence of the subsample errors from each site. Models were computed using the R package “lme4” (Bates et al. 2015). All models failed visual tests for normality of residuals and homogeneity of variance, so we conducted a natural log transform on subsample error and recomputed the models.

Homogeneity of variance was then achieved for all models, and despite failing Shapiro-Wilk tests, qq-plots indicated that residuals were approximately normally distributed. Model selection was conducted using the “dredge” function of the R package “MuMIn” (Bartoń 2018) with AICc as the evaluation metric. The result of the selection procedure was that all independent variables were included in all models. Finally, we recomputed models with non-scaled independent variables and non-orthogonal polynomials to obtain meaningful coefficients for predictive purposes.

2.3 Results and discussion

2.3.1 Question 1 (variability characterization)

As presented in Figures 5 and 6, temporal variability as measured by standard deviation (SD) and autocorrelation range (AR) can be categorized in the four following non-discrete conceptual classes: I) high SD, high AR; II) low SD, high AR; III) low SD, low AR; and IV) high SD, low AR. Class I soundscapes vary substantially, but in a fairly predictable manner (e.g., the gradual emergence of an insect or amphibian chorus at dusk), whereas Class IV soundscapes vary substantially and unpredictably (e.g., sparse high-amplitude bird sounds). Class II soundscapes vary minimally and predictably (e.g., very quiet soundscapes or soundscapes with constant insect or amphibian choruses), while Class III soundscapes exhibit a small amount of fairly random variation (e.g., sparse low-amplitude bird sounds). While somewhat simplistic and based only on the means of standard deviations and autocorrelation ranges for the present data, this conceptual model is useful for interpretation of the following results.

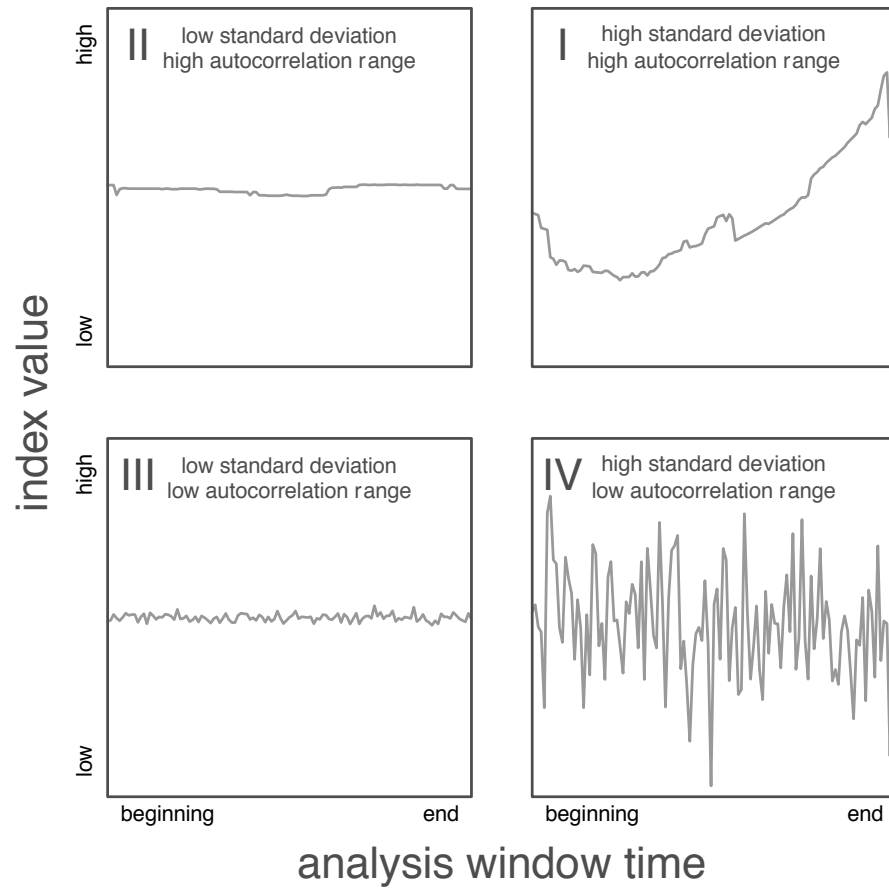


Figure 2.5. Soundscape classes based on their temporal variability characteristics.

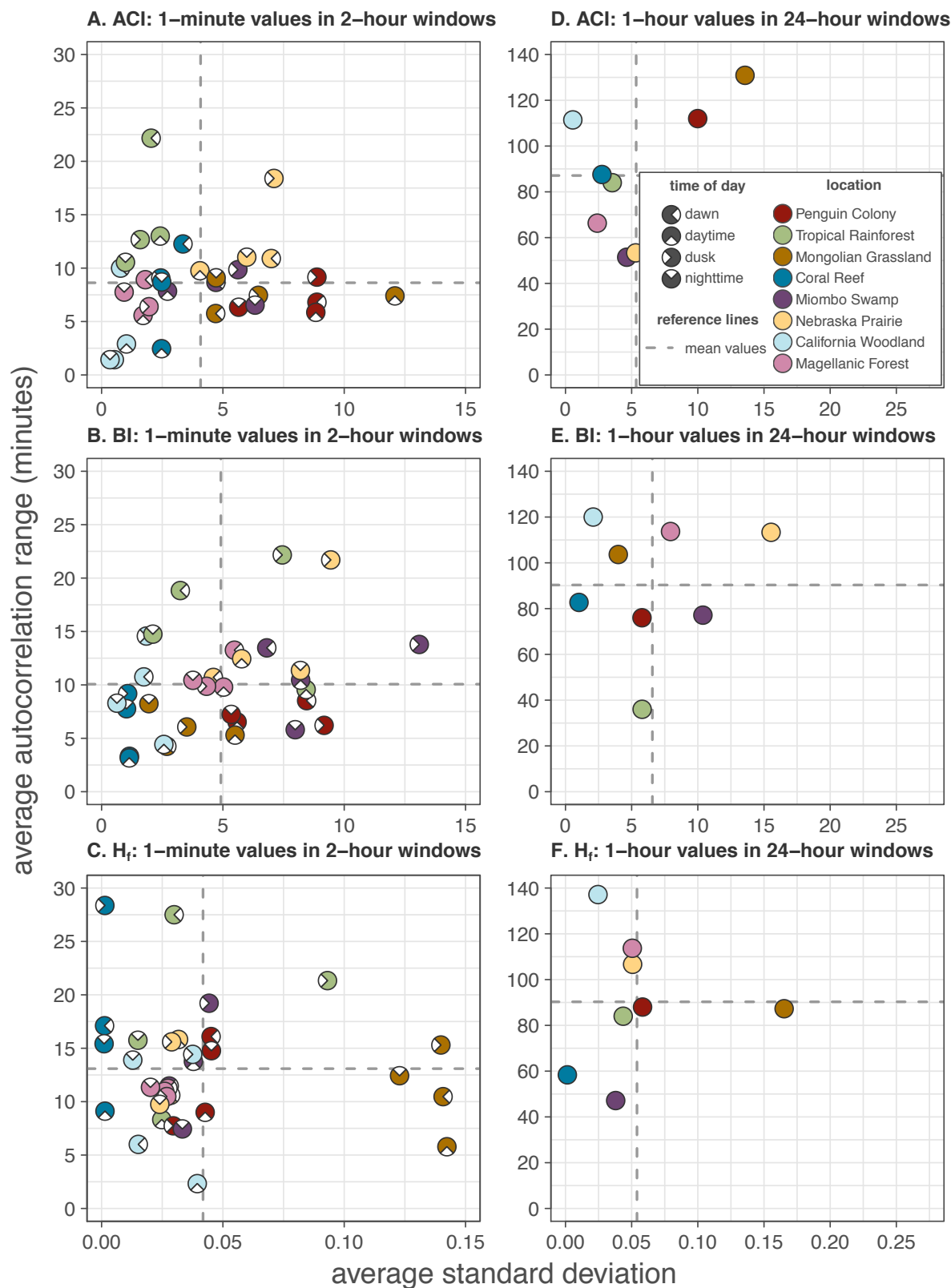


Figure 2.6. Temporal variability of sites plotted based on standard deviations and autocorrelation ranges. Plots feature different scales, but the y-axes are the same within each column of plots. Dotted lines indicate mean values within each plot.

One could define and measure temporal variability using a variety of metrics. We selected standard deviations to provide insight into the range and distribution of index values, and we chose autocorrelation ranges to highlight the consistency of index values between successive time windows. There are likely some aspects of temporal variability that are not captured in standard deviations and autocorrelation ranges (such as cyclicity), but the two concepts we employed proved useful in describing two distinct aspects of temporal variability. If standard deviations and autocorrelation ranges were measuring the same components of temporal variability, one would expect a predominance of points in Classes II and IV indicating a negative relationship between standard deviation and autocorrelation range. However, the fact that such a relationship is not apparent in any section of Figure 2.6 indicates that standard deviations and autocorrelation ranges in fact represent distinct components of the concept of temporal variability. This lack of correlation is promising for the future application of these metrics in characterizing the temporal variability of soundscapes.

1-minute values in 2-hour time of day windows

Cluster dispersion and the relative importance of sites and times of day

As assessed visually, the dispersion of each single-site cluster (i.e. the area of a convex polygon with the points for each time of day as vertices) was variable between sites. For example, Miombo Swamp values were much more dispersed than those of Magellanic Forest for the BI, and Tropical Rainforest values were much more dispersed than those of Nebraska Prairie for H_f. In one respect, it is unsurprising that dispersion would differ between sites: it has been widely documented that soundscapes exhibit diel dynamics and that the patterns and magnitudes of those dynamics differ between locations (Gasc et al. 2018; Gottesman et al. 2018; Lomolino et al. 2015; Towsey et al. 2014a). However, these dynamics have been demonstrated through counts of acoustic events and raw acoustic index values, and such diel dynamics would not preclude diel constancy for measures of temporal variability on shorter time scales. To illustrate, consider a site with dawn soundscapes dominated by near-constant birdsong and extremely quiet nighttime soundscapes. The magnitudes of the ACI for this site would be high at dawn and low during nighttime, but the standard deviations and autocorrelation ranges for the ACI within each time of day could be quite similar. The fact that single-site dispersions differed indicates that

some sites exhibited fairly constant temporal variability across times of day while others had more divergent variability for different times of day.

Single-site clusters almost always overlapped with each other, with the notable exceptions of Tropical Rainforest for the ACI (due to low standard deviations and high autocorrelation ranges) and Coral Reef and Mongolian Grassland for H_f (due to extremely low and high standard deviations, respectively). Given the fact that sites included in this study were widely distributed across continents and biomes it is perhaps surprising that single-site clusters were not more distinct. However, because the soundscapes of one site can be so variable between times of day, and acoustic indices provide quantitative as opposed to qualitative descriptions of soundscapes (e.g., spectral entropy as opposed to acoustic community composition), it is understandable that index-based measures of temporal variability would yield overlapping single-site clusters.

Within-site differences sometimes exceeded between-site differences. Considering H_f , the dispersion of Tropical Rainforest was greater than that of the combination of Penguin Colony, Miombo Swamp, Nebraska Prairie, and Magellanic Forest. For the BI, the dawn value of Miombo Swamp is closer to the dawn value of Magellanic Forest than any other Miombo Swamp values, and the daytime value of Tropical Rainforest is closer to the daytime values of Penguin Colony, Mongolian Grassland, Miombo Swamp, Nebraska Prairie, and Magellanic Forest (not to mention other times of day for those sites) than it is to other Tropical Rainforest values. The lack of spatial replicates in each location does not allow for statistical assessment of the relative importance of site- and time-of-day-based differences, but this initial graphical assessment with a single site for each general location suggests that both factors influence temporal soundscape variability. Some single site clusters are compact and/or distinct from those of other sites, but there is also substantial overlap between clusters with some clusters being relatively large. Generally, it can be assumed that there is greater change in the composition of the acoustically active animal community over the course of a 24-hour period in sites with large clusters than those with small clusters. One could argue that large clusters result from temporal acoustic niche partitioning (Krause 1993; Pijanowski et al. 2011a), but it is more likely that temporal partitioning of acoustic activity at such a coarse temporal scale is driven by non-acoustic factors (e.g., predator or prey activity patterns and light availability).

Trends based on time of day and sites

Within single-site clusters, dawn values exhibited no clear trends, but those for other times of day tended to exhibit consistent directionality within the clusters. Daytime values tended to have high standard deviations and low autocorrelation ranges, relative to the other times of day in the cluster, suggesting that daytime soundscapes are among the most highly variable within a given 2-hour window. Dusk autocorrelation ranges tended to be high, and nighttime standard deviations tended to be low, indicating that these soundscapes exhibit less short-term temporal variability. These results for daytime and nighttime soundscapes support our hypothesis that nighttime soundscapes would be less variable than daytime soundscapes due to the consistency of quiet or insect/amphibian-dominated nighttime soundscapes.

Standard deviation values were always below average for Coral Reef, California Woodland, nighttime and dawn for Tropical Rainforest, and dusk and nighttime for Magellanic Forest. Based on the authors' *in situ* and remote listening (both formal and informal), these sites—aside from Tropical Rainforest—all feature Class II and III soundscapes composed of little biophony and/or biophony from a small number of species.

The soundscapes of Coral Reef are dominated by broadband sounds from snapping shrimp and occasional low-frequency (< 2 kilohertz) fish choruses. This site is interesting in that its standard deviations were consistently low across indices and times of day whereas autocorrelation ranges were moderately to highly variable. Figure 2.6C provides a prime example of this unusual feature; a probable explanation is that some times of day are dominated by extremely gradual, locally monotonic changes in index values while others are characterized by more random short-term fluctuations. The relatively high dawn and dusk autocorrelation ranges could be due to increases in temporally consistent snapping shrimp activity during those times, whereas the lower nighttime values could be attributed to more variable fish choruses.

Autocorrelation ranges for Tropical Rainforest tended to be much higher than average (with the exceptions of daytime values for the BI and H_f). This indication of low short-term temporal variability could come as a surprise, considering the fact that the site is a local biodiversity hotspot within the global biodiversity hotspot of Mesoamerica (McDade et al. 1994; Myers et al.

2000) and contains a vast array of soniferous species. Moreover, those species' sounds span the frequency spectrum and are produced with a diversity of methods. Despite this diversity, the high autocorrelation ranges point to temporal consistency and categorization as Class I and II soundscapes. Despite the diversity of soniferous species at this site, its soundscapes are largely dominated by amphibian and insect sounds that are often consistent across any 2-hour analysis window, and this consistency likely explains the low standard deviations for this site.

The most distinctive site in terms of temporal variability for any one index is Mongolian Grassland for H_f . Its autocorrelation ranges hover around the global mean, but its standard deviations far exceed all values except that of Tropical Rainforest dusk. Recordings from this site featured a large amount of wind noise and occasional clipping, so that geophony could explain this outlying site. H_f represents the entropy of a mean spectrum, and clipping, or even just loud wind could drastically affect the shape of that spectrum. Because such gusts could either be absent from, or be predominant in, any given minute of a 2-hour period, wind could be responsible for the high standard deviations associated with H_f at this site.

1-hour values in 24-hour windows

On this longer time scale, several sites exhibit consistent relative temporal variability across indices. California Woodland is the most consistent, as it always displays low standard deviations and high autocorrelation ranges, indicating extremely low-variability Class II soundscapes. This result is unsurprising given the fact that the site featured very quiet soundscapes throughout the day. Tropical Rainforest and Coral Reef exhibited moderate to low standard deviations as well, but also exhibited moderate to low autocorrelation ranges, making their soundscapes Class III. Both sites featured some consistent biophony across a wide range of frequencies (e.g., birds, insects, and amphibians, at Tropical Rainforest and snapping shrimp at Coral Reef), but the soundscapes were also punctuated by less consistent biophonic and geophonic events like howler monkey sounds and rain at Tropical Rainforest and fish choruses at Coral Reef.

Other sites were far less consistent across indices. Soundscapes from Mongolian Grassland, Nebraska Prairie, and Magellanic Forest would be classed differently for each of the three

indices used in this study. This inter-index discrepancy highlights the fact that these indices measure different soundscape features (Sueur et al. 2014). This multifaceted information can be beneficial, but must be paired with supplemental soundscape analysis methods for well-informed interpretation (Gottesman et al. 2018).

Implications of autocorrelation ranges

Average autocorrelation ranges were highly variable between sites and times of day. 1-minute values in 2-hour windows ranged from less than 2 minutes (the ACI for California Woodland at dusk) to nearly 30 minutes (H_f for Coral Reef at dusk), and 1-hour values in 24-hour windows ranged from below 40 minutes (the BI for Tropical Rainforest) to nearly 140 minutes (H_f for California Woodland). In this study we used autocorrelation ranges to characterize temporal variability, but the concept of temporal autocorrelation can also be considered problematic if one were to treat two autocorrelated measurements as independent. Hopefully this study has provided a baseline that researchers can reference if they wish to assume that two temporally separated soundscape measurements are independent. We do however advise caution in this situation, as thresholds for temporal correlation are clearly dependent on the value length and the analysis window considered. To truly derive benefits from the temporal richness of a continuous or near-continuous dataset, we recommend further investigation and application of time-series analysis methods.

2.3.2 Question 2 (subsampling implications)

We constructed six models (one for each combination of the three indices and the two full file lengths (12 and 60 minutes) for predicting subsample error based on total analysis time, number of subdivisions, and time of day. Model coefficients are presented in Table 2.3, and predicted values for several subdivision scenarios are presented in Figure 2.7. While the subsample errors understandably differed between indices (mean raw 1-minute index values were 169.52 for the ACI, 53.20 for the BI, and 0.82 for H_f), the general shape of the predicted curves was similar across indices and 12-minute and 60-minute full file lengths. Initial increases in total analysis time yielded rapid decreases in subsample error that subsequently became more gradual. This finding corresponds with the conclusions of Pieretti et al. (2015), who found that sampling just 1

minute per 60 minutes yielded ACI values that were highly correlated with values from continuous recordings, and Bradfer-Lawrence et al. (2019), who found that the variance in the standard error of seven different acoustic indices initially declined rapidly with increased recording time. In our study, increasing the number of subdivisions substantially reduced subsample error, especially at low values of total analysis time. This finding reflects those of Cook and Hartley (2018), who applied similar analytical methods, but used aural species identification as opposed to acoustic indices. As a whole, our results suggest that to maximize representation with subsampling, 1) the number of subdivisions should be maximized and 2) extensions of total analysis time between approximately 33% and 67% of the full file length will yield relatively negligible decreases in subsample error, especially with greater subdivision.

Table 2.3. Model coefficients for non-orthogonal polynomials with a log-transformed dependent variable.

model identifiers		independent variable coefficients								
full file length (minutes)	index	total analysis time	total analysis time squared	total analysis time cubed	number of subdivisions	total analysis time * number of subdivisions interaction	time of day		location (intercept)	
12	ACI	-0.37766	0.04655	-0.00329	-0.27700	0.02025	dawn: daytime: dusk: nighttime:	0 0.12648 -0.00943 -0.27236	Penguin Colony: Tropical Rainforest: Mongolian Grassland: Coral Reef: Miombo Swamp: Nebraska Prairie: California Woodland: Magellanic Forest:	2.21545 0.50257 1.89240 1.09613 1.61909 1.78475 -0.38210 0.32862
12	BI	-0.37536	0.04747	-0.00337	-0.27373	0.01850	dawn: daytime: dusk: nighttime:	0 0.37637 0.20832 -0.19333	Penguin Colony: Tropical Rainforest: Mongolian Grassland: Coral Reef: Miombo Swamp: Nebraska Prairie: California Woodland: Magellanic Forest:	1.95067 1.23210 1.08886 0.10962 2.03693 1.73133 0.26729 1.35347
12	H _f	-0.36266	0.04742	-0.00350	-0.33975	0.02177	dawn: daytime: dusk: nighttime:	0 0.41328 0.27428 -0.06735	Penguin Colony: Tropical Rainforest: Mongolian Grassland: Coral Reef: Miombo Swamp: Nebraska Prairie: California Woodland: Magellanic Forest:	-3.34498 -3.98913 -2.06614 -7.06307 -3.49335 -3.73391 -4.06468 -3.98846

Table 2.3. (continued).

model identifiers		independent variable coefficients								
full file length (minutes)	index	total analysis time	total analysis time squared	total analysis time cubed	number of subdivisions	total analysis time * number of subdivisions interaction	time of day		location (intercept)	
60	ACI	-0.08883	0.00301	-0.00004	-0.13940	0.00240	dawn: daytime: dusk: nighttime:	0 0.07025 -0.07964 -0.38945	Penguin Colony: Tropical Rainforest: Mongolian Grassland: Coral Reef: Miombo Swamp: Nebraska Prairie: California Woodland: Magellanic Forest:	1.99019 0.53770 1.76442 0.89935 1.51449 1.85724 -0.72618 0.34437
60	BI	-0.09013	0.00314	-0.00004	-0.14886	0.00253	dawn: daytime: dusk: nighttime:	0 0.34626 0.34857 -0.21633	Penguin Colony: Tropical Rainforest: Mongolian Grassland: Coral Reef: Miombo Swamp: Nebraska Prairie: California Woodland: Magellanic Forest:	1.66119 1.25099 0.80856 -0.27410 1.93108 1.80276 0.11799 1.37731
60	H _f	-0.07845	0.00281	-0.00004	-0.17968	0.00308	dawn: daytime: dusk: nighttime:	0 0.17772 0.27893 -0.23105	Penguin Colony: Tropical Rainforest: Mongolian Grassland: Coral Reef: Miombo Swamp: Nebraska Prairie: California Woodland: Magellanic Forest:	-3.35637 -3.55620 -2.17019 -6.77298 -3.46006 -3.64096 -4.08940 -3.82858

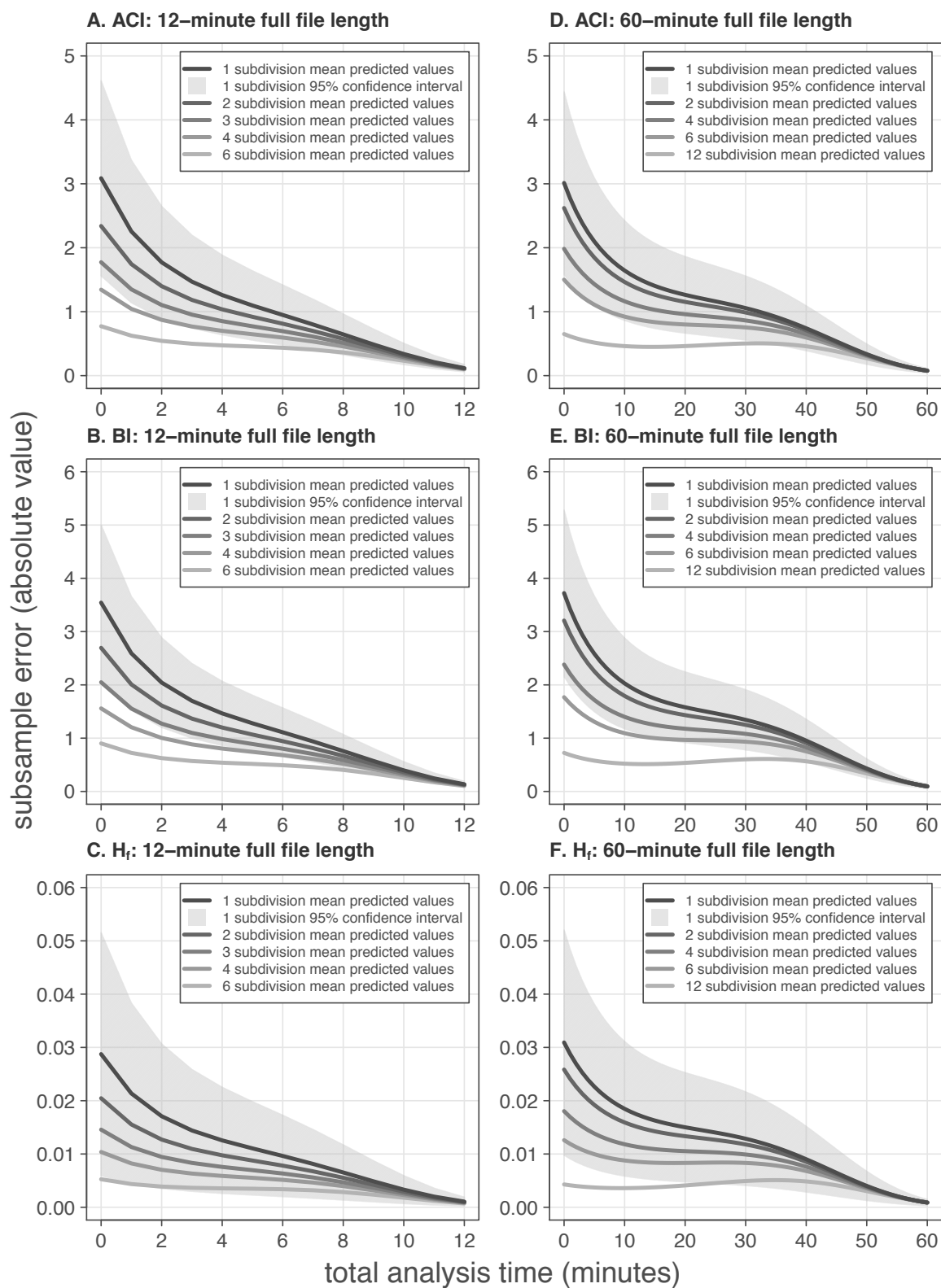


Figure 2.7. Predicted subsample error for different subsampling schedules. Values are based on inter-site and inter-time of day means, and the 95% confidence intervals for the 1-subdivision schedule are based on treating sites as replicates. For context, mean values for all 1-minute segments used in the calculation of these models were as follows: ACI—169.52; BI—53.20; Hf—0.82.

Relative magnitudes of subsample error

The magnitudes of subsample error differed across indices, relative to the global mean of raw 1-minute values for those indices. To illustrate, the approximate y-intercept for the ACI with one subdivision in 12- and 60-minute full file lengths is 3—less than 2% of its global mean; the approximate y-intercept for the BI with one subdivision in 12- and 60-minute full file lengths is 3.75—about 7% of its global mean; and the approximate y-intercept for H_f with one subdivision in 12- and 60-minute full file lengths is 0.03—about 4% of its global mean. While these values differed relative to means, they were fairly consistent with the mean standard deviations indicated in Figure 2.6. Across indices, the approximate y-intercept with one subdivision in 12- and 60-minute full file lengths represented about 75% of the mean standard deviation for 1-minute values in 2-hour analysis windows and about 55% of the mean standard deviation for 1-hour values in 24-hour analysis windows. This fact suggests that the magnitude of subsample error, as one might expect, is directly related to the variability of the raw index values. No index appeared to have such substantially greater subsample error that it would be problematic for representation through subsampling. Notably, we did not define an explicit threshold for acceptable error, as such a threshold would likely vary between studies. However, as stated above, the errors we documented are fairly small relative to the global means for each index.

Implications for sampling schedule design and limitations for application

We suggest that a “sweet spot” for maximizing soundscape representation and efficiency in terms of battery life and storage consumption would be a schedule in which one records for about a third of the time they wish to represent and in which they subsample as much as possible, at least until a minimum recording duration of 1 minute. As the Wildlife Acoustics SM4, one of the leading terrestrial automated field recording systems, does not allow scheduling for recording durations below 1 minute, we did not analyze such subsampling schemes in this study. There is reason to suspect that the relationships we found could be extrapolated for recording durations below 1 minute, especially for spectral indices that do not consider within-recording-duration temporal variability. However, for some indices like the ACI, one must set a minimum recording duration, if only to ensure that there are multiple temporal windows in a single file for appropriate calculation of the index.

Subdividing, and especially extreme subdividing (sub-minute), comes with several notable drawbacks. First, it means that certain sound events may extend beyond the recording duration. This is the case for any recording duration if one considers long enough sound events, but if one considers the recognized units of biophony emitted by most animals, one might not capture those full units when recording durations drop below several minutes (or longer for exceptional taxa like whales). At extreme values below around 10 seconds, some sounds may become unrecognizable for human listeners, potentially impeding any manual aural analysis. Additionally, the context of sounds is lost; extreme subdividing would obviously be inappropriate for studies considering the relationships between short-duration (approximately less than 10-second) sounds or acoustic triggers. It is also worth considering that storage and analysis technologies will likely improve in the future, so the financial and logistical constraints that encourage subsampling today may become less relevant, and it could eventually be desirable to have the most complete archive possible of our contemporary soundscapes. Subdividing also decreases the duration of each recording, increasing the influence of whatever short-term sound event is recorded. Despite these drawbacks, it does yield increased temporal resolution, and it increases the chances of capturing segments of longer sound events that might be otherwise missed (e.g., a 2-minute period of avian alert calls following a predator detection that begins in the 42nd minute of an hour would be missed if one was recording 10 minutes every 30 minutes).

In a recent paper on the topic of PAM study design, Bradfer-Lawrence et al. (2019) argued in favor of continuous recording, but their hypothetical use case seems to center around infrequent studies designed to characterize the soundscape of a given location as rapidly as possible, rather than long-term monitoring. While they considered seasonality a potential complication, it may well be the topic of interest in a different type of study. PAM can be employed to address an impressive diversity of ecological questions, some of which, like phenology or population dynamics, require long-term monitoring. While there seems to be a fairly universal desire for standardization of PAM methods, the diverse tools in the PAM jackknife often require different techniques in order to carve out an answer to the question at hand.

2.4 Conclusions

The vast diversity of Earth's soundscapes makes them a fascinating topic of study and a compelling motivator for global conservation. While the findings of this study have revealed some consistency in their short-term temporal variability, this consistency lends support to the case for using soundscapes as ecological indicators. Differences in temporal variability between times of day and sites are of largely secondary importance to the fact that based on acoustic index values, substantial subsampling is still highly representative of full-duration recordings, at least when quantifying soundscapes through the limited set of fairly general metrics we employed. While the big data concerns associated with PAM remain (Gasc et al. 2017)—and are of especial importance in political and economic climates that are not supportive of scientific research—the findings of this study suggest that judiciously applied subsampling can still yield valid results while minimizing the physical and financial restraints associated with big data storage and processing. The utility of soundscape-based research is greatly enhanced through global involvement and the potential for biogeographically important findings, and optimized subsampling may help promote such involvement and discovery.

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CHAPTER 3—SENTINELS FOR SENTINELS: PASSIVE ACOUSTIC AND CAMERA TRAP MONITORING OF SENSITIVE PENGUIN POPULATIONS

Dante Francomano, Andrea N. Raya Rey, Benjamin L. Gottesman, and Bryan C. Pijanowski

Abstract

Only five of eighteen penguin species are considered species of “least concern” by the IUCN, and the sensitivity of penguins to ecological disturbances makes them useful indicators of ecosystem dynamics. In some respects, penguins are easy to monitor since they regularly congregate in dense breeding colonies and are visually and aurally conspicuous animals. *In situ* observations and visual remote sensing monitoring methods (i.e. camera traps, unmanned aerial vehicles, and satellite imagery) currently provide incredibly valuable information on penguin behavior and population dynamics, but these methods have a number of shortcomings. Several rely on human presence in remote areas, some require clean lines of sight with no visual obstructions, and some offer limited spatial and temporal resolution. In this study we propose the use of passive acoustic monitoring (PAM) as a complementary remote sensing method to monitor penguin behavior and populations at high spatial and temporal resolution without visual constraints or the need for human presence. We conducted observations of acoustic behavior and placed automated acoustic recorders in colonies of Magellanic (*Spheniscus magellanicus*) and southern rockhopper penguins (*Eudyptes chrysocome*) in conjunction with camera traps. We found positive relationships between acoustic activity and counts of Magellanic penguins in camera trap photos. We also identified clear diel patterns of acoustic activity that differed between breeding stages, and we found positive correlations between acoustic activity and estimates of colony density for various times of day and radii around recorders. While much work remains to perfect this method and refine interpretation, PAM holds great promise as a complementary tool for monitoring the relative abundance and behavioral dynamics of penguin species—particularly for species that burrow or nest in dense vegetation that impairs visual monitoring techniques.

3.1 Introduction

Biodiversity loss is one of the principal environmental crises of our era (Rockström et al. 2009). The recent vertebrate extinction rate is up to 53 times greater than the historical background rate (Ceballos et al. 2015), and given the important role of biodiversity in generating ecosystem services, maintaining or augmenting this present rate could threaten the sustainability of social-ecological systems (Chapin III et al. 2000).

Despite this cause for concern, our limited knowledge of biodiversity and ecosystem dynamics restricts our ability to make nuanced management decisions to promote social-ecological sustainability. It is estimated that we have only identified a small minority of extant species, and even for species that are documented, our knowledge of the spatial and temporal dynamics of their behavior and life histories is often minimal (Hortal et al. 2015). Advancing this knowledge is critical to better understand and mitigate current anthropogenic ecological disturbances while actively avoiding such disturbances in the future (Sala et al. 2000). We will never have perfect knowledge of biodiversity and its dynamics unless we embed sensors in every individual organism—a dubious, unrealistic aspiration. We can, however, make targeted efforts to improve our knowledge of species that are a) indicative of broader ecosystem dynamics and/or b) at risk of extirpation or extinction (Caro and O’Doherty 1999).

Many penguin species (Spheniscidae) fit both of the above categorizations. The IUCN only lists five of eighteen penguin species as “least concern” (IUCN 2020), and penguins occupy marine and coastal terrestrial habitats, making them susceptible to an array of anthropogenic disturbances including overfishing, bycatch, petroleum pollution, invasive species, and various consequences of climate change (Boersma 2008). Despite the fact that penguins spend much of their lives at sea, they congregate in colonies to breed and raise young, presenting a valuable opportunity for population monitoring with minimal spatial sampling effort. Boersma (2008) highlighted the need for more frequent and consistent monitoring of these colonies to better document population dynamics. Given the remote nature of many penguin colonies, such advances may be more viable through increased development and application of technological solutions, as opposed to increased human effort.

Previous monitoring of individual penguins has employed *in situ* observations, banding, radio frequency identification tagging, body-mounted data loggers, and camera traps (Sherley et al. 2010; Scioscia et al. 2016; Dodino et al. 2018; Raya Rey et al. 2007); population-level monitoring has employed *in situ* counts, camera traps, unmanned aerial vehicles (UAVs), and satellite imagery (e.g., Raya Rey et al. 2014; Boersma 2008; Black et al. 2017; Sherley et al. 2010; Ratcliffe et al. 2015; Fretwell et al. 2012). All of these methods have yielded a wealth of important information and complement each other well, but they do have some shortcomings, especially for population-level monitoring (see Edney and Wood 2020 for an extensive review). *In situ* methods require human presence, which is often logistically challenging and time consuming. Camera traps, UAVs, and satellite imagery generally require daylight with minimal precipitation, and are dependent on clear lines of sight. The field of view from a single camera trap is often quite limited (Black et al. 2017). Satellite imagery is optimal for situations in which penguin bodies or guano contrast sharply with the background substrate, but penguins in burrows or blocked by vegetation present a challenge for all visual methods of remote sensing. The temporal resolution of UAV and satellite imagery also tends to be quite low (Ratcliffe et al. 2015; Fretwell et al. 2012).

In this study we investigated the suitability of passive acoustic monitoring (PAM) to provide complementary information on spatial and temporal patterns of relative penguin abundance for two species with different nesting behavior: burrow- and shrub-nesting Magellanic penguins (*Spheniscus magellanicus*; hereafter “Magellanics”) and surface-nesting southern rockhopper penguins (*Eudyptes chrysocome*; hereafter “rockhoppers”). These species are respectively listed as “near-threatened” and “vulnerable” by the IUCN (IUCN 2018b; 2018a). While the bioacoustics (*sensu* Penar et al. 2020) of these and other penguin species has been extensively studied (e.g., Clark et al. 2006; Searby and Jouventin 2005; Jouventin and Aubin 2002), and PAM has been applied to other seabirds (e.g., Buxton and Jones 2012; Oppel et al. 2014; Borker et al. 2019; Orben et al. 2019), we believe this study to be the first formal application of passive acoustics to penguin monitoring.

As with camera traps, acoustic recorders can be programmed to optimize either temporal resolution or battery life and data storage, and they can be installed and retrieved with months or

possibly years between minimally invasive colony visits. Upon retrieval, acoustic data can then be analyzed using detection of specific sound types or more general measures of acoustic characteristics (e.g., Orben et al. 2019; Borker et al. 2019). This method does have some shortcomings, and we would not consider it a replacement for the methods described above. It requires some degree of ground truthing, could be biased by non-focal sound events, and is unlikely to be as spatially comprehensive as drone or satellite imagery (though the emergence of more economical equipment may ameliorate that deficit). On the positive side, PAM can reduce human effort relative to *in situ* techniques. It also enables one to easily capture nighttime data, and visual barriers like burrows and vegetation are only partial obstacles to the propagation of sound that is detected by omnidirectional microphones. To enhance monitoring of the spatial and temporal dynamics of penguin populations, PAM represents a potentially powerful tool.

To assess this potential, we documented individual rates of sound production, compared PAM data with camera trap data and *in situ* count data across space and time, and assessed the diel dynamics of acoustic activity during various breeding stages. Given that penguins are highly vocal animals (Aubin 2004), we expected to encounter high vocalization rates, and we hypothesized that acoustic activity would have a positive relationship with relative abundance in camera trap photos and *in situ* counts, particularly during periods of high vocal activity (i.e. pair formation and chick rearing; ARR personal observations). We also hypothesized that these relationships would be strongest when considering camera trap and *in situ* metrics over intermediate distances around acoustic sampling points; for small areas of only a few square meters, many acoustically relevant individuals would not be counted, while for large areas on the order of hectares, the sounds of more distant counted individuals would only reach the recorder at very low amplitudes. During our *in situ* field experiences, we noted that groups of rockhoppers seemed to produce a more constant stream of sound than their Magellanic counterparts, so we further hypothesized that we would find stronger relationships for Magellanic colonies due to their less saturated soundscapes.

3.2 Methods

3.2.1 Study locations

We collected data from three colonies on two islands: a Magellanic colony on Martillo Island in the Beagle Channel (54.90° S, 67.38° W), a Magellanic colony at Franklin Bay on Staten Island east of Tierra del Fuego (54.88° S, 64.64° W), and a rockhopper colony at Franklin Bay on Staten Island (54.87° S, 64.66° W). Martillo Island is home to about 4,000 breeding pairs of Magellanics (Scioscia and Raya Rey, unpublished data), while the studied colonies on Staten Island have about 1,600 pairs of Magellanics and 127,300 pairs of rockhoppers (Raya Rey et al. 2014). Locations of colonies and the camera traps and acoustic recorders within each colony are shown in Figure 3.1. Martillo Island features a mix of bare soil and herbaceous, shrubby, and short forest land cover, with Magellanic nests spread across the majority of the island at varying densities (Quiroga et al. 2020). The Magellanic colony on Staten Island is dominated by herbaceous land cover and features nest densities that are generally lower than those on Martillo Island (DF, personal observations). Rockhopper nests generally occur in higher densities (relative to Magellanic nests) in well-defined patches in a tussock grass matrix (Quiroga et al. 2020; Schiavini 2000). A grid with 50-meter spacing was overlaid over the full extent of each colony and used to define points for acoustic behavior observations and population density estimates. This grid had been physically established on Martillo Island for previous studies, and it was implemented via GPS for Staten Island.

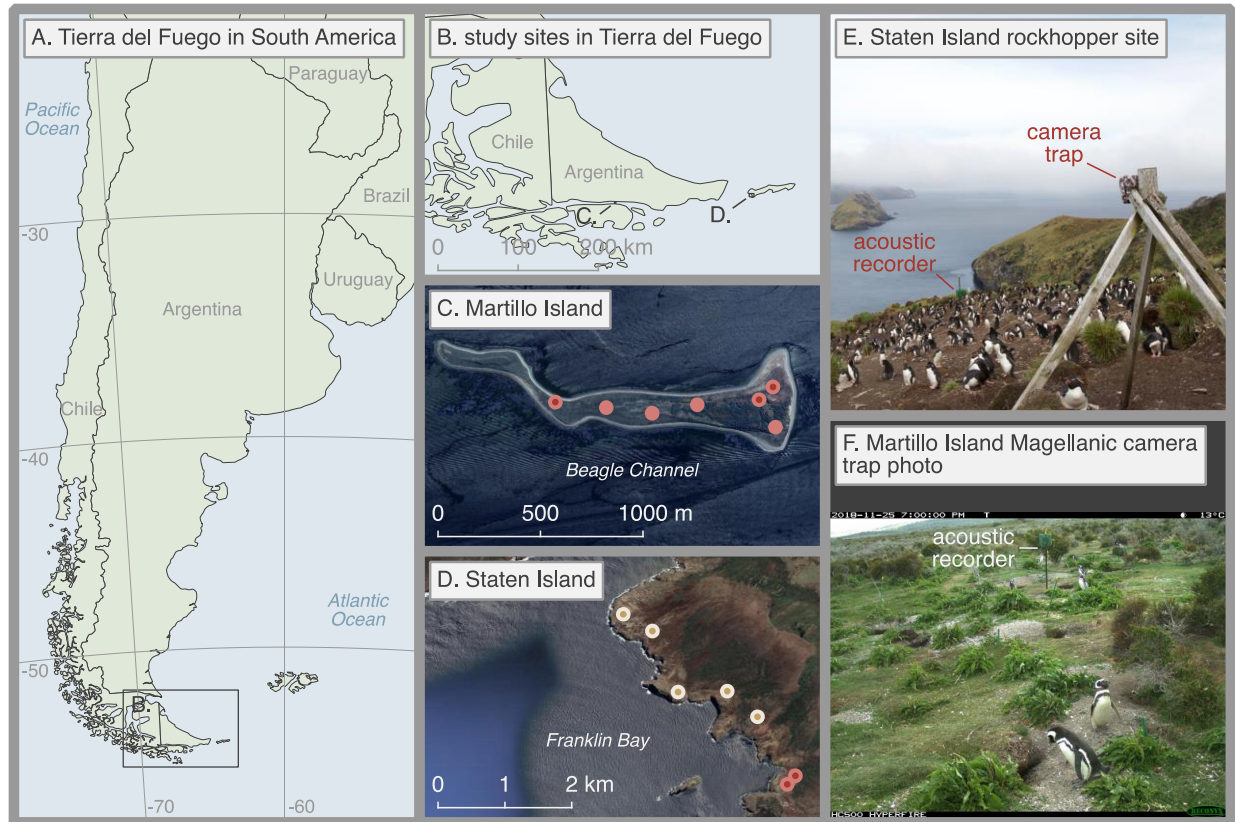


Figure 3.1. A – D) locations of Martillo Island and Staten Island and their study sites. Red circles indicate Magellanic study sites, while tan circles indicate rockhopper study sites. Sites without an associated camera trap lack an inner circle. E) A rockhopper study site on Staten Island illustrating the camera trap and acoustic recorder orientation. F) A sample camera trap photo from Martillo Island showing an acoustic recorder and Magellanics. Maps were produced in QGIS (QGIS.org 2020) using Google Maps satellite imagery.

3.2.2 Data collection and processing

All data were collected during the 2018-2019 breeding season (October – April). Due to the logistical difficulty of accessing Staten Island, data from its colonies are limited to 8 days of the early chick rearing breeding stage in December (Table 3.1).

Table 3.1. Numbers of observations/sites and date ranges for data used within each breeding stage. Breeding stage dates are approximated from Dodino (2020).

species	island	breeding stage	approximate Magellanic breeding stage date range	acoustic behavior observations		acoustic activity-camera trap		acoustic activity- population density	
				number of observations	observation dates	number of sites (photos)	data selection date range	number of sites	data selection date range
Magellanic	Martillo	pair formation	10-01 – 10-20	—	—	2 (64)	10-13 – 10-20	—	—
Magellanic	Martillo	incubation	10-21 – 11-20	—	—	3 (59)	10-27 – 10-31	—	—
Magellanic	Martillo	early chick rearing	12-01 – 12-31	57	11-28; 12-07; 12-08	3 (96)	12-09 – 12-16	3	12-09 – 12-16
Magellanic	Staten	early chick rearing	12-01 – 12-31	—	—	2 (64)	12-09 – 12-16	2	12-09 – 12-16
rockhopper	Staten	early chick rearing	12-01 – 12-31	47	12-12; 12-13; 12-14; 12-16	5 (159)	12-09 – 12-16	5	12-09 – 12-16
Magellanic	Martillo	late chick rearing	01-01 – 02-14	56	01-26; 01-27	3 (84)	01-01 – 01-07	7	01-27 – 02-05
Magellanic	Martillo	pre-molt feeding	02-15 – 03-10	41	02-25	—	—	—	—
Magellanic	Martillo	molting	03-11 – 04-10	20	03-20	2 (87)	03-21 – 03-31	7	03-21 – 03-31

Acoustic behavior observations

To better understand the acoustic behavior of individual penguins, we conducted *in situ* observations for which we observed a randomly selected individual for 5 minutes and counted and classified all the sounds it produced. Sound classifications were based on published literature, previous observations, and discussion with individuals familiar with each species (Clark et al. 2006; Searby and Jouventin 2005). For both species, the following categories were used: ecstatic display call, mutual display call, exhalation, defecation, running, beak clacking, and flipper hitting. Additional categories were used for each species: incomplete “huff” series (Magellanic), grunt (rockhopper), and squeal (rockhopper).

Observations began at the grid points referenced above, and were conducted during daylight hours. When selecting the next grid point for an observation, the point was selected to compromise between spatial comprehensiveness and logistical convenience. Upon arrival at each point, a spinner was used to select a random direction, and the first observed adult penguin within ~20 meters and closest to the chosen direction of the spinner was selected for observation. If moving, the penguin was followed as discreetly as possible. In some cases, visual contact was lost due to elusive penguins moving over rises, behind tussocks, into burrows, below water, or into a visually indistinguishable cluster of conspecifics; only complete 5-minute observations were considered in analysis. Weather data were collected during or after each observation period. Observations were conducted on the dates listed in Table 3.1. Due to low rates of observed sound production, data were consolidated by excluding non-vocal sounds, and categorizing the number of vocalizations as zero, one, or more than one.

Camera trap photos

Reconyx Hyperfire and Bushnell Trophy Cam HD camera traps had been installed at most sites shown in Figure 3.1 for previous studies. Cameras were focused on fairly dense clusters of Magellanic nests and patches of rockhopper nests. For the duration of this study, the cameras were programmed to take hourly photos from sunrise to sunset, except during pair formation and incubation when they were active from 07:00 to 20:00. The date ranges for data selection listed in Table 3.1 were chosen to avoid periods with unrecorded acoustic or camera trap data. Given

this constraint, we also tried to maximize discretization of the breeding stages (by selecting 5- to 11-day periods as close to the center of each stage as possible). Four random photos were selected at each site for each day within the date ranges. Several selected photos were not taken due to a camera programming error, and they were thus excluded from analysis. One photo with a human in it and another blocked by the tail of a perching raptor were also excluded. The numbers of used photos by species, island, and breeding stage are shown in Table 3.1.

Acoustic recorders were installed within the field of view of each camera. In order to approximate the distance of photographed penguins from the recorders, two to four stakes were placed at 0°, 90°, 180°, and 270° positions around the recorder relative to the view of the camera. Stakes were placed 1 – 4 meters from the recorders, and the distance to each stake was recorded. The field of view differed between cameras and was fairly small on some of the pre-installed cameras, so we limited our counts of adult penguins to fixed distances around each recorder: 2 and 4 meters for Magellanics (2 meters at all sites and 4 meters on only Martillo Island) and 1 meter for rockhoppers. A small portion of the 4-meter distance was cut out of some Martillo Island photos, but the missing area was considered negligible. We drew ovals in each photo at the given distances using the curvature pen tool in Adobe Illustrator. We marked the four points where appropriate stakes met the ground or visually estimated the appropriate points based on known stake distances. Then for each photo, we counted the number of adult penguins contacting the ground within each oval.

Passive acoustic recordings

Passive acoustic recordings were made using Wildlife Acoustics Song Meter SM4s programmed to record for 1 minute every 5 minutes with a sample rate of 44,100 Hertz, bit depth of 16, gain of 6 decibels, and a high-pass filter at 220 Hertz. Recorders were installed on metal posts at a height of 1.5 meters, and they were enclosed in a plastic mesh to protect the windscreens from inquisitive perching birds. Magellanic recorders were separated by at least 195 meters (except for two Martillo Island recorders just over 100 meters apart due to camera trap constraints), and rockhopper recorders were separated by at least 500 meters. Due to the camera trap orientations, rockhopper recorders were installed within colony patches near their edges. Recordings were made across the dates listed in Table 3.1.

Acoustic metrics were selected based on a structured listening exercise featuring manual aural and visual examination of a random sample of files for each species stratified by site, time of year, and time of day (200 files for Magellanics and 40 files for rockhoppers). For each file, we noted sound sources, estimated frequency ranges and temporal occupancy percentages, and categorized the approximate amplitude for each of the following sound source categories: geophony, adult penguins, penguin chicks, other biophony, and technophony.

Based on these observations, we calculated several acoustic metrics for each species using a limited frequency band (1,000 – 3,000 Hertz for Magellanics and 1,000 – 6,000 Hertz for rockhoppers). These bands were chosen to maximally isolate the sounds of adult penguins relative to other sounds in the soundscapes (e.g., wind noise, penguin chick sounds, and passerines). We then examined the dimensionality of each set of metrics using inter-metric correlations and principal components analysis. Unless otherwise noted, all analyses were conducted using R versions 3.6.3 – 4.0.2 (R Core Team 2020). Code referencing the packages used is available at: https://github.itap.purdue.edu/PijanowskiGroup/Francomano_et_al_2021_PAM_of_Penguins_in_TDF. Microphone sensitivity measurements were obtained before and after each recorder deployment, and the channel with the least change in sensitivity was used for analysis. The mean of the pre- and post-deployment values was used for calibration following Merchant et al. (2015). A 4096-length Hann window with 50% overlap was used when applicable.

For each species, we calculated broadband sound pressure level (Merchant et al. 2015), a measure of the background sound level, and a novel metric that we term “harmonicity”. The background sound level was intended to reduce the influence of loud local individuals and capture sounds of more distant penguins, and it was measured as the mean of amplitude values below a given quantile (20% for Magellanics and 10% for rockhoppers) of the distribution of maximum amplitude values from a windowed waveform (Towsey 2017). Harmonicity was based on the acoustic complexity index (Pieretti et al. 2011), but intensity differences were calculated between adjacent frequency bands as opposed to adjacent temporal windows in order to highlight the harmonic nature of penguin sounds (especially those of Magellanics). This metric was calculated on a linear power spectral density spectrogram, and the sum of each window value

was divided by the number of windows to generate a value that would not be dependent on the length of the file or the number of windows. We also calculated measures of temporal occupancy and events per minute for Magellanic penguins only, as these measures would not have provided much meaningful information about rockhopper activity, given the near constancy of their sounds in the soundscape (Towsey 2017). Thresholds for these two metrics were selected by employing a wide range of potential values at 1-decibel intervals for the files used in the structured listening exercise. The threshold value that yielded the highest Spearman correlation between each metric and the manually estimated temporal occupancy of adult penguin sounds was used in further analysis. The inter-metric correlations and principal components analyses led us to extract the first principal component for each species, which we termed “acoustic activity”. Sample video spectrograms of recordings from a colony of each species are provided at the above GitHub link.

Population density estimates

Different methods were used to estimate the local population density of each species, given their differences in nest density and structure (i.e. burrows and surface nests). For the Magellanics on Martillo Island, point-transect counts of active nests within 20 meters of each grid point were conducted between the incubation and early chick rearing stages as part of an annual colony census (Figure 3.2A). A nest was considered active if occupied by at least one penguin. These counts were supplemented with similar counts around each recorder conducted during the late chick rearing stage for Magellanic sites on Martillo Island and during the early chick rearing stage on Staten Island. Potential differences between penguin presence during these breeding stages were assumed to be negligible. For each recorder-centered count, the distance to each active nest was recorded, allowing us to precisely determine the number of active nests within increasing radii at 1-meter resolution out to 20 meters around each recorder. To extend the analyzable radii beyond this limit on Martillo Island, we used the grid-based counts to generate Voronoi polygons (Nelson and Boots 2008), in which the area closest to each grid point was assumed to have the same active nest density as the 20-meter-radius circle around each grid point (Figure 3.2B). The 20-meter-radius areas around each recorder were cropped out of the Voronoi layer and assigned the 20-meter density found in the recorder-focused counts. Circles of increasing radii (from 21 – 125 meters at 1-meter resolution) were then intersected with this

density layer, and active nest density estimates were obtained based on the area and nest density of the polygons included in each intersection (Figure 3.2C – D).

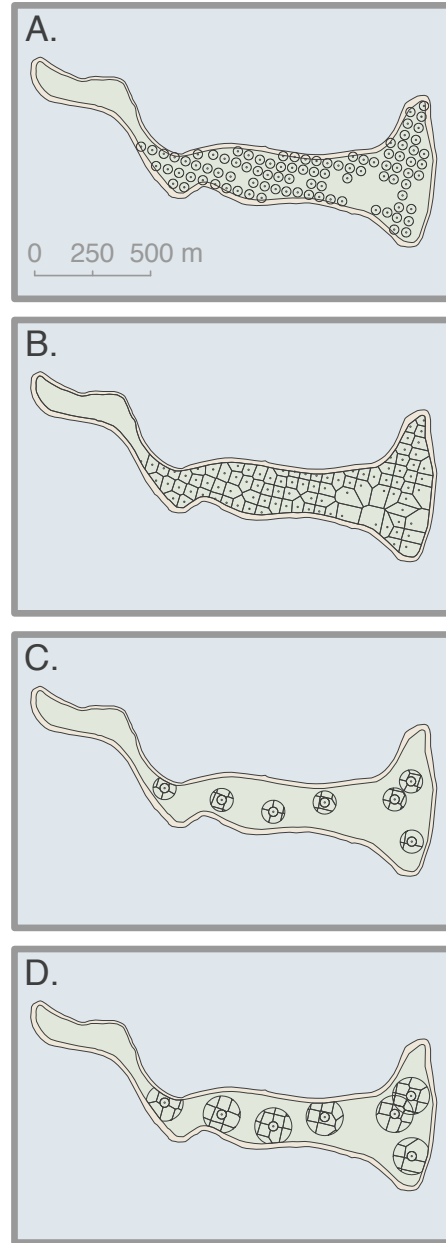


Figure 3.2. Spatial data processing for nest density estimates on Martillo Island. A) 20-meter radius count zones around grid points spaced at 50-meter intervals. B) Voronoi polygons constructed around each count point. Beach areas (in tan) were excluded since they do not contain nests. C) Polygons around each acoustic recorder used for the 30-meter-radius density estimate. D) Polygons around each acoustic recorder used for the 60-meter-radius density estimate. The specific radii in C and D are shown for illustrative purposes.

A similar Voronoi polygon-based method was used for rockhoppers, but the initial counts were conducted differently due to the much higher density of rockhopper nests and the lack of burrows. Counts were conducted at each recorder and at the 25 50-meter grid points closest to each recorder, though if a point was more than 20 meters from a previously mapped colony patch (Raya Rey unpublished data), it was assumed to have a density value of 0. At each sampled point, a spherical photograph was taken using a Ricoh Theta 2013 camera held up on a tripod with the lens around 3.4 meters off the ground. Twenty similar photos were subsequently taken on a flat surface with two marked points at 20 meters from the photo point perpendicular to each other. These calibration photos were adjusted to vertical orientation in the Ricoh Theta application, and then the average pixel height of the 20-meter points was assessed. After vertical adjustment to all photos, a line was drawn on the photos at this height and manually adjusted using the curvature pen tool in Adobe Photoshop to account for varying topography. We then counted the total number of adult penguins contacting the ground below this mark in each photograph, and that number divided by the area of the 20-meter radius circle was used as an index of the rockhopper penguin density for the associated Voronoi polygon. Density estimates for 21- to 125-meter radii were calculated as described for Magellanic above.

3.2.3 Analysis

Acoustic behavior

We initially intended to model individual sound production rates as a function of breeding stage, time of day, and weather conditions, but the low numbers of observed vocalizations precluded statistical testing with an array of independent variables. Instead, we categorized the number of vocalizations as zero, one, or more than one and calculated the percent of vocalization categories observed in each breeding stage.

Relationships between acoustic activity and camera trap data

We constructed separate linear mixed-effects models for each species and photo count radius, combining data across breeding periods for the Magellanic. Acoustic activity was treated as the dependent variable with number of penguins as an independent fixed effect and date as a random effect. While theoretically a random variable, site was also included as a fixed effect due to its

having only five levels (Bates 2010). Normality of error, homogeneity of variance, and linearity were visually assessed. To account for potential statistical noise in the acoustic activity of the single recording taken concurrently with the photo, we also created separate models using the mean of acoustic activity across the three and five recordings temporally closest to the time of the photo. These models generally displayed similar but weaker relationships than the models considering the acoustic activity of a single recording, so they were not considered further. The initial mixed-effect rockhopper model yielded singular fit, so date was treated as a fixed effect to obtain a more reliable model fit (Bates et al. 2015). All models were evaluated through examination of their semi-partial R^2 s and comparison against a null model that dropped the number of penguins variable.

To evaluate potential differences between breeding stages for the strongest acoustic activity-camera trap count relationship we found (Magellanics with 4-meter radius), we split the data by breeding stage (combining Magellanic early chick rearing from both islands), conducted 1,000 iterations of bootstrap resampling for each subset of data, and ran linear models on each resampled subset. Acoustic activity was modeled as a function of penguins in photo, site, and date. Site and date were treated as fixed effects due to their low numbers of levels within each subset of data. We obtained semi-partial R^2 s and F-statistics by comparison against null models as described above, and we used these results as the dependent variables in two permutational ANOVAs with breeding stage as the independent variable. Pairwise contrasts were evaluated with a Tukey HSD test.

Relationships between acoustic activity and population density data

For each breeding stage in which five or more acoustic recorder sites were used for each species, we calculated Pearson and Spearman correlations between the average acoustic activity at each site for each time of day and the density of active nests or penguins at the varying radii described above. Magellanic early chick rearing data from both islands were used together. Given the low number of sites and potential for non-linear relationships, we calculated Spearman correlations to obtain a measure of significance, but also used Pearson correlations to provide more continuous correlation coefficients. We then created a visualization of these findings to show how

relationships vary over time and space. To better contextualize our findings, we plotted the daily dynamics of acoustic activity for each breeding stage.

3.3 Results

3.3.1 Acoustic behavior

Numbers and percentages of vocalization class occurrences from individual penguin observations are shown in Figure 3.3.

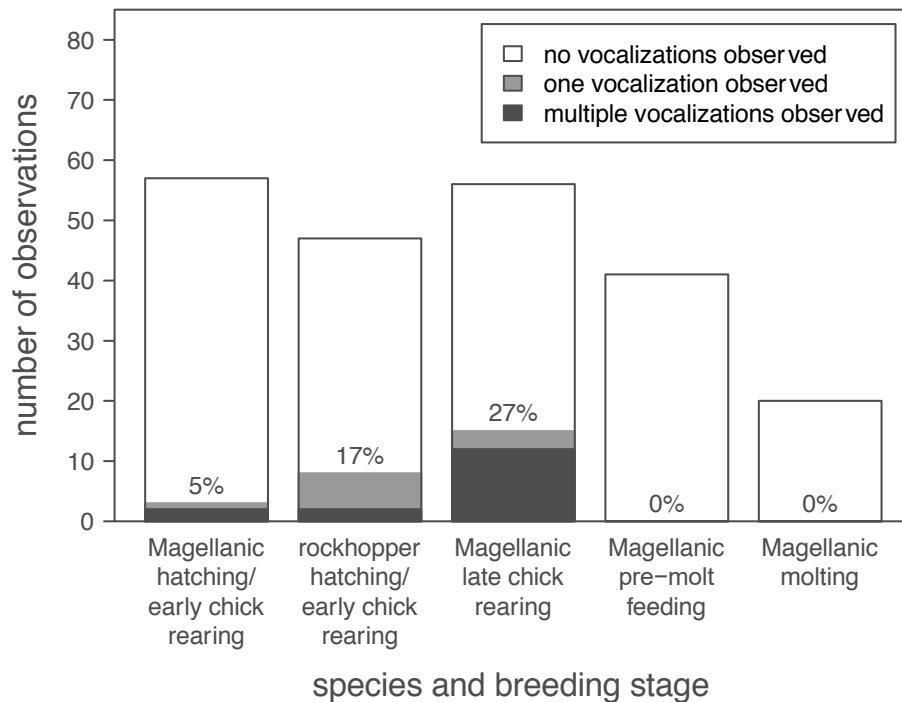


Figure 3.3. Numbers and percentages of vocalization class occurrences from individual penguin observations. Percentages refer to the occurrence of one or more vocalizations.

3.3.2 Relationships between acoustic activity and camera trap data

Significant positive relationships between the number of penguins observed in a camera trap photo and the acoustic activity from the corresponding time were found for Magellanics for both 2-meter (all sites) and 4-meter (just Martillo Island sites) radii (respectively: $\chi^2 = 20.65$, d.f. = 1, $p < 0.001$, semi-partial $R^2 = 0.06$ and $\chi^2 = 55.30$, d.f. = 1, $p < 0.001$, semi-partial $R^2 = 0.20$). A significant relationship was not found for rockhoppers ($F = 0.52$; d.f. = 1, 146; $p = 0.473$; semi-

partial $R^2 < 0.01$). Based on the comparisons of bootstrap-generated F-statistics and semi-partial R^2 s, the Magellanic 4-meter radius relationships differed significantly by breeding stage ($p < 0.001$ for both metrics), with significant contrasts between most breeding stages (Figure 3.4).

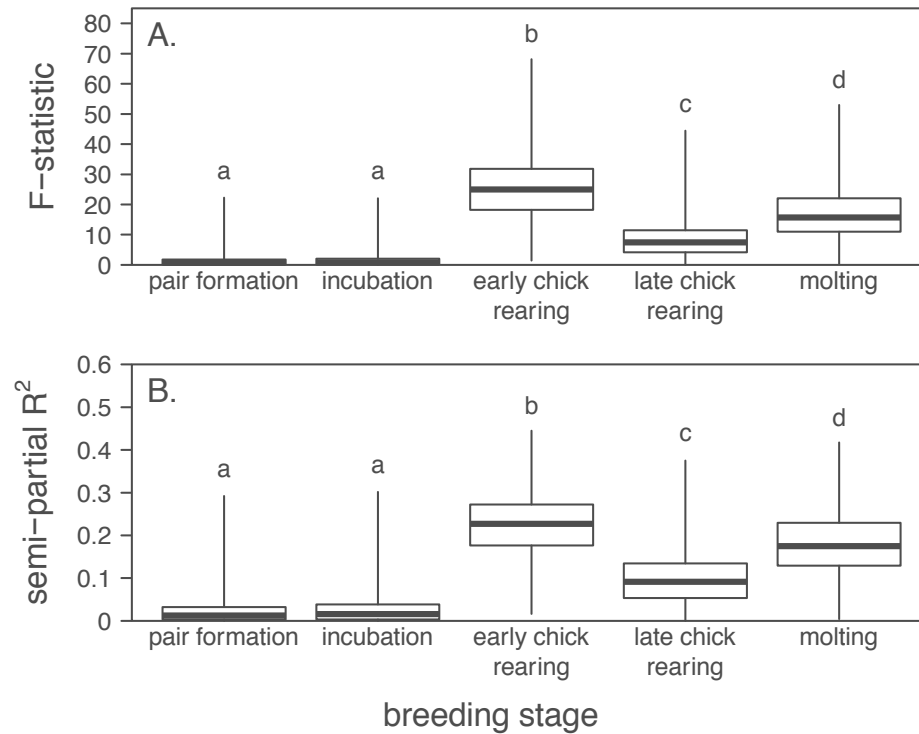


Figure 3.4. F-statistics (A) and semi-partial R^2 s (B) generated via bootstrapping to compare acoustic activity-photo count relationships between breeding stages. Thick horizontal lines represent medians, boxes represent first and third quartiles, and whiskers represent minima and maxima. Differing letters indicate significantly different pairwise contrasts.

3.3.3 Relationships between acoustic activity and population density data

Correlations between acoustic activity and penguin (rockhopper) or active nest (Magellanic) density are presented in Figure 3.5. This visualization shows that for rockhoppers, positive significant correlations were most prevalent between 52 and 74 meters shortly after midnight and in the late afternoon. Occurrence of significant positive relationships for Magellanics varied between breeding periods. For early chick rearing, such relationships occurred from 9 to at least 20 meters from late evening to early morning. For late chick rearing and molting, such relationships became more consistent at radii above ~12 meters and often extended out to at least 125 meters. During late chick rearing these relationships predominated from 15:30 to 20:30 and

from 23:00 to 04:30, while during molting they were common from 04:00 to 06:00 and 10:30 to 20:00.

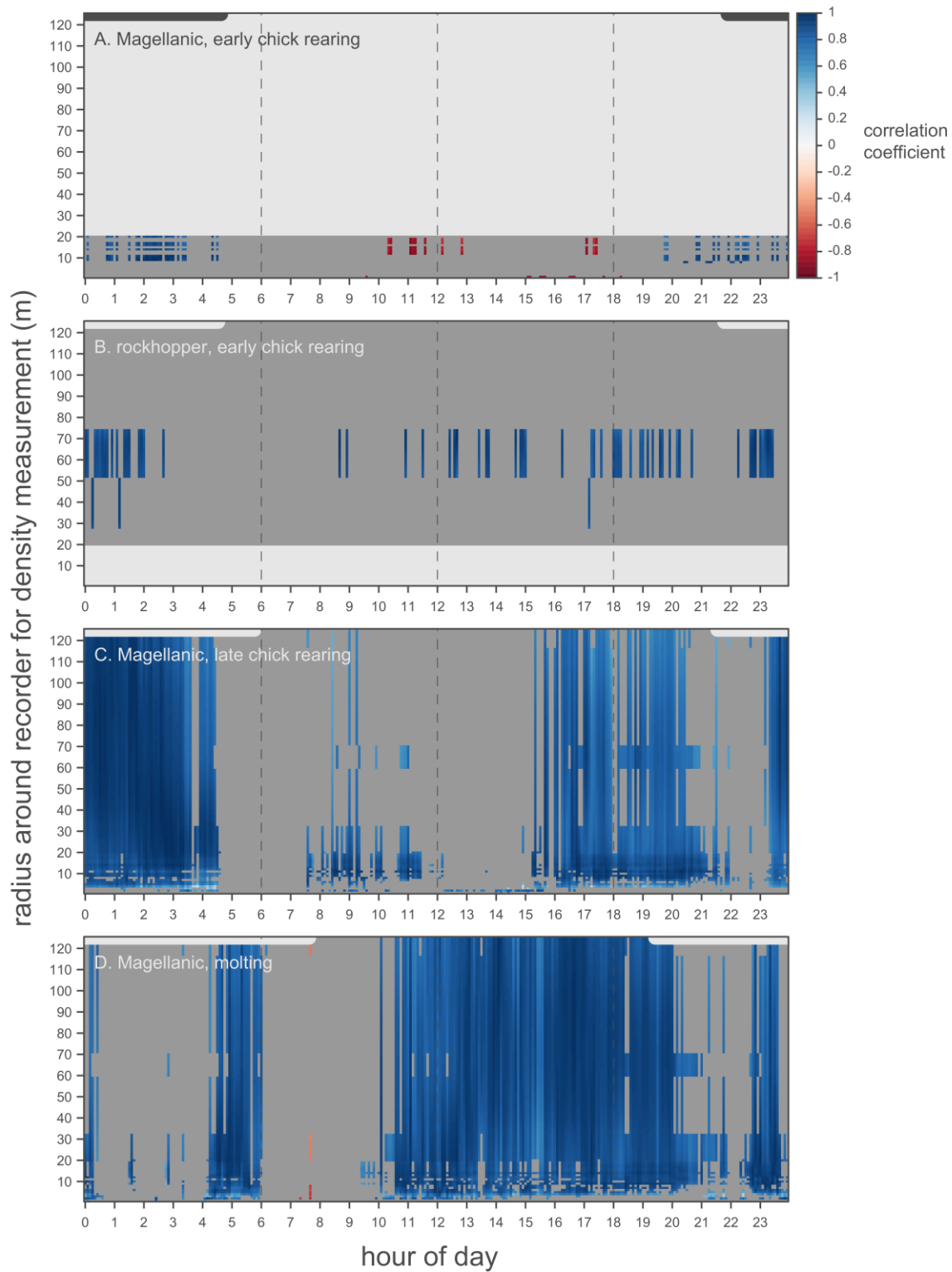


Figure 3.5. Correlations between acoustic activity and active nest (Magellanic) or penguin (rockhopper) density. The color gradient indicates Pearson correlation coefficients. Dark grey covers values with non-significant Spearman correlations, while light grey covers areas with no meaningful data. Lines at the top of each panel indicate periods of darkness.

Diel dynamics of acoustic activity varied between species and breeding stages, while generally following a pattern of peaks near dawn and dusk (Figure 3.6). These peaks were least prevalent during Magellanic incubation, a generally quiet period with little inter-site variability. Inter-site variability was high for both Magellanics and rockhoppers during early chick rearing, and this stage exhibited more moderate peaks for both species. The dawn and dusk peaks were most prevalent for Magellanic pair formation, late chick rearing, and molting.

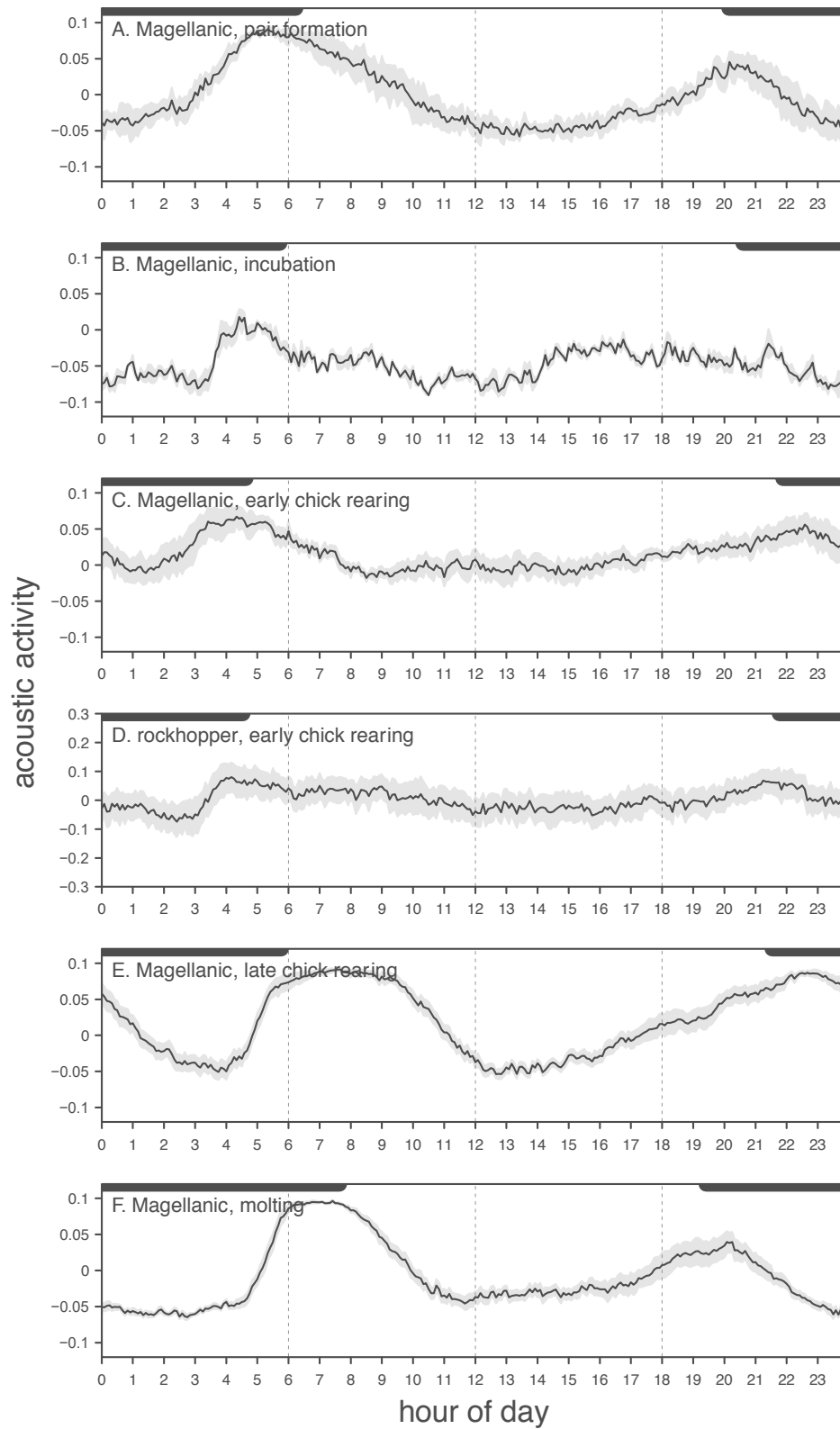


Figure 3.6. Diel dynamics of acoustic activity during different breeding stages (late chick rearing dates corresponding to those used for population density analysis). Lines represent inter-site means of within-site means, while shading extends to site means \pm standard errors. Lines at the top of each panel indicate periods of darkness.

3.4 Discussion

Our findings suggest that PAM is indeed an informative complement to previous methods of penguin monitoring. Questions of temporal and spatial variability and scale are pervasive in PAM and ecology more broadly (Francomano et al. 2020; Pijanowski et al. 2011a; Pijanowski et al. 2011b; Levin 1992). Our results have cast some light on these issues in the context of PAM for penguins, while also highlighting opportunities for further study. Given the importance of time and space to ecological monitoring, we structure the following discussion around these themes and the importance of the ecological differences between the two studied species.

3.4.1 Time

Penguin acoustic activity exhibited variability by time of day (for both species) and breeding stage (at least for Magellanics, given available data; Figure 3.6). The dawn and dusk peaks in activity generally corresponded with penguin arrival and departure times at the studied colonies (Scioscia et al. 2009; Raya Rey et al. 2007). Arrival and departure times often vary between colonies, so this observed association may not hold for other colonies, but it seems likely that these situations would elicit more vocal activity since penguins use vocalizations to identify their mates and chicks (Aubin 2004).

It should be noted that acoustic activity is a product of both the number of present penguins and the vocalization rates of the present individuals. Based on the diel acoustic activity patterns and the fact that we conducted our acoustic behavior observations exclusively during daylight hours, the vocalization rates we found might be biased by the times at which they were observed. At Martillo Island, nighttime and midday lows in acoustic activity were approximately equal, but Scioscia et al. (2009) found the percentage of penguins in the colony at those times to be near 100% and 50%, respectively. Together, these findings suggest higher individual vocalization rates during daytime. Our observed peaks of acoustic activity corresponded with times of intermediate attendance, also highlighting likely diel variability in vocalization rates. Discrepancies between colony attendance and acoustic activity suggest diel variation in vocalization rates that could be of critical importance in monitoring. Additionally, we only conducted a single day of acoustic behavior observations for pre-molt feeding and molting, so

the lack of vocalizations observed during those breeding stages may be due to inter-day variability. More extensive sampling would enable modeling by breeding stage, time of day, and weather conditions, potentially helping to define optimal sampling times and conditions for long-term monitoring.

Our reliance on daylight hours for our acoustic activity-camera trap count comparisons may have similarly limited the variability we encountered in both variables, possibly contributing to the weak to moderate relationships we found. The fact that these relationships weakened when using averages of acoustic activity over longer time periods (in place of direct measurements from single one-minute recordings) suggests that acoustic data do indeed provide information on Magellanic presence at fine temporal resolutions. A concurrent 1-minute recording better represents the number of penguins in a photo than the average of acoustic activity from that recording and its temporal neighbors from 5 minutes before and after the photo. Differences in Magellanic acoustic activity-camera trap count relationships between breeding stages showed mixed correspondence with our hypothesis about stronger relationships during periods of high acoustic activity (i.e. pair formation and chick rearing). The relationship was indeed strongest during early chick rearing, but it was more moderate during late chick rearing and very weak during pair formation (Figure 3.4).

The relationships between acoustic activity and active nest/penguin density exhibited variability at diel and breeding stage timescales. The diel patterns did not support our hypothesis about stronger relationships at times of higher acoustic activity with the possible exception of Magellanic early chick rearing (Figures 3.5A and 3.6C). For the other species-breeding stage combination, relationships were temporally clustered, but not in any way that seemed related to diel trends in acoustic activity. The clustering could merely be a result of temporal autocorrelation in acoustic activity (Francomano et al. 2020). The negative correlations found for Magellanic early chick rearing are illogical, but they could be due to greater wind noise at the Staten Island sites with lower nest densities (included for that breeding stage but not for late chick rearing or molting). As for rockhoppers, it actually appears that stronger relationships occurred during times of relatively low acoustic activity (Figures 3.5B and 3.6D).

3.4.2 Space

The relationship between acoustic activity and camera trap counts for Magellanics and rockhoppers was weak and/or non-significant when considering counts within a 1- or 2-meter radius, but moderate and significant for Magellanics within a 4-meter radius. This difference and our *in situ* observations of penguin vocalization propagation lead us to believe that penguins outside these radii likely exerted substantial influence on our measurements of acoustic activity. The acoustic influence of penguins in the 0- to 2- meter range was likely quite similar to that of penguins in the 2- to 4- meter range, whereas the larger radius allowed for greater variability in count numbers. In short, the radius over which acoustic activity is best predicted by short-term penguin presence almost certainly exceeds 4 meters.

The above conclusion is supported by our findings concerning acoustic activity-density relationships over larger spatial extents, with relationships becoming more consistent with radii above ~12 meters (Figure 3.5). For rockhoppers, the spatial band of positive significant correlations had a clearly defined maximum radius (74 meters), but this was not the case for Magellanics. While we sampled densities using radii at 1-meter intervals, the effective resolution of our data beyond the 20-meter radii was likely coarser due to our use of Voronoi polygons (i.e. densities were assumed to be constant within fairly large areas). This coarseness is likely responsible for the horizontally banded nature of Figure 3.5. To more robustly ascertain the spatial extent over which acoustic activity conveys information on long-term nest/penguin density, it would be necessary to mark the point of each individual nest or penguin within the largest radius of interest. This task would be challenging but may be attainable through GPS point marking (for species with concealed nests) or UAVs (for species with no nests or uncovered surface nests; Ratcliffe et al. 2015). Such an effort would be immensely valuable in revealing the spatial extent over which acoustic data are relevant.

3.4.3 Species ecology

The world's eighteen penguin species inhabit diverse habitats ranging from Antarctic ice shelves to the Galapagos Islands, and they exhibit diverse nesting habits, with some building small raised structures, some digging out burrows or hollows under bushes, and others simply keeping eggs

and chicks on their feet. These habitats and habits all have the potential to influence the strategies that should be employed for effective PAM.

For the Magellanics and rockhoppers that we considered in this study, the spatial distribution and structure of their nests both influenced our methods and findings. The spatial distribution of nests had several important implications. For Magellanics, our recorders with camera traps were generally in areas of higher nest density, while those without camera traps on Martillo Island were spread throughout the remainder of the colony without regard for nest density. For rockhoppers, their spatial distribution led us to place our recorders near the edges of colony patches where camera traps were focused to avoid excessive disturbance during servicing. Penguins at the edge of a colony patch could exhibit distinct acoustic behavior, and this location may have led to artificial homogeneity in the penguin density we observed for the 20 meters around each recorder. We also were forced to select different density count methodologies for each species. Nest structure could have influenced our camera trap counts because Magellanics could enter their burrows and remain hidden while still occupying the relevant radius around the recorder and potentially vocalizing. We observed few individuals vocalizing while in their burrows, so we suspect that any confounding effects would be minor. Lacking burrows, rockhoppers could do no such thing, possibly making them more likely to be visible and silent.

3.5 Conclusions

PAM holds great promise as a complementary tool for monitoring the relative abundance and behavioral dynamics of penguin species, particularly for species that burrow or nest in dense vegetation that impairs visual monitoring techniques. While much work remains to perfect this method, our work has revealed relationships between acoustic metrics and local, short-term presence as well as longer-term density over larger spatial extents by integrating acoustic recordings, camera trap data, and *in situ* counts of nests or penguins. Future efforts should focus on refining our knowledge of the temporal and spatial scales at which PAM is best equipped to provide meaningful complementary information. While we have highlighted some important considerations for the application of PAM to two distinct penguin species, further testing should also consider additional species in different environments. With careful development we hope that PAM will provide valuable insights that promote penguin conservation.

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CHAPTER 4—ACOUSTIC MONITORING SHOWS INVASIVE BEAVERS (*CASTOR CANADENSIS*) INCREASE AVIAN DIVERSITY IN TIERRA DEL FUEGO

Dante Francomano, Alejandro E. J. Valenzuela, Benjamin L. Gottesman, Alvaro González-Calderón, Christopher B. Anderson, Brady S. Hardiman, and Bryan C. Pijanowski

Abstract

1. The North American beaver *Castor canadensis* is an invasive species in Tierra del Fuego. In response to this biological invasion, Argentina and Chile signed a binational agreement to eradicate it and restore affected ecosystems. In southern Patagonia, the beaver's ecological impacts are quite well studied, but there is a relative lack of information on how its invasion (and potential removal) could affect bird communities.
2. In the southern portion of Tierra del Fuego Island, we conducted passive acoustic monitoring (PAM) and avian point counts in intact riparian forests, beaver ponds, and drained beaver meadows to assess differences in acoustic activity, avian abundance, species diversity, and functional diversity.
3. During spring and summer, acoustic activity was significantly higher at meadow sites than at forest sites, with pond sites exhibiting intermediate values.
4. Abundance and species diversity exhibited similar patterns, largely due to resident passerines, while functional diversity tended to be highest in pond sites, largely due to ducks and raptors. Effects were weaker in fall and winter.
5. Acoustic metrics exhibited moderate to strong correlations with all point-count-derived metrics.
6. Synthesis and applications: At the patch-level, the Fuegian avian community was more abundant and diverse in beaver-modified habitats than in intact riparian forests. Dam breaching and pond drainage did not yield a return to an intact forest bird community, indicating that more active reforestation measures may be necessary to restore local avian communities in the short to medium term. Given the immense challenges of eradication and restoration, its social-ecological costs and benefits—including those related to avifauna—ought to be thoroughly considered.

4.1 Introduction

One hallmark of the anthropocene is that humans have both deliberately and accidentally created novel biotic assemblages—and potentially novel ecosystems—through the extirpation and introduction of species (Chapin III et al. 2000; Hobbs et al. 2009; Morse et al. 2014). These novel assemblages can exhibit unexpected or unknown dynamics that threaten ecosystem services (*sensu* Millennium Ecosystem Assessment 2003) and the sustainability and resilience of social-ecological systems (Evers et al. 2018; Folke 2006; Hobbs et al. 2009).

Beavers *Castor spp.* have been eradicated, introduced, and/or reintroduced in Eurasia, North America, and South America, and the manipulation of their presence is especially interesting and ecologically impactful, given their status as quintessential ecosystem engineers that dam watercourses and fell trees (Anderson et al. 2009; Johnson and van Riper III 2014). Through these actions, beavers are capable of drastically altering hydrology, nutrient fluxes, landscape structure, aquatic and terrestrial plant and animal communities, and related ecosystem services (Anderson et al. 2009; Stringer and Gaywood 2016).

While the North American beaver *C. canadensis* has also been introduced as an exotic species in Eurasia (Busher and Dzieciółowski 1999; Halley et al. 2020), beavers have only once been introduced where the genus did not previously exist: in 1946, 20 North American beavers were released in Argentine Tierra del Fuego to initiate a fur trapping industry that never materialized (Pietrek and Fasola 2014). Without natural predators, they rapidly spread across the Fuegian Archipelago and have advanced onto the South American mainland (Anderson et al. 2009; Graells et al. 2015b; 2015a; Valenzuela et al. 2014). Recent studies have highlighted the extent of beaver impacts in this wilderness area (*sensu* Mittermeier et al. 2003): There are over 200,000 beaver dams in the Fuegian Archipelago (Herrera et al. 2020), and dams in the Argentine portion of Tierra del Fuego Island are as dense as 123 per square kilometer, extend for over 2,300 kilometers, and have flooded at least 87 square kilometers (Eljall et al. 2019). 84% of land is now within 1 kilometer of a beaver dam (Eljall et al. 2019). Beavers have some of the most diverse ecosystem impacts of the exotic species in Tierra del Fuego (Valenzuela et al. 2014).

This exotic species is considered a successful invader, and given its extensive ecological and economic impacts, a binational effort to eradicate beavers from South America is in development (Menvielle et al. 2010; Parkes et al. 2008). Aquatically, Fuegian beavers have been shown to modify the hydrogeomorphology of water courses (Westbrook et al. 2017), to increase the organic proportion of benthic material in impounded areas (Anderson and Rosemond 2010; 2007), to increase macroinvertebrate biomass while decreasing macroinvertebrate diversity in impounded areas (Anderson and Rosemond 2007), and to increase native fish abundance below beaver dams (Moorman et al. 2009). Terrestrially, once dams breach and impoundments drain due to abandonment or beaver removal, a successional process begins. In forested regions of Tierra del Fuego, this process does not yield a return to riparian forest, at least in the medium term (Martínez Pastur et al. 2006; Wallem et al. 2010). The most prominent tree species (*Nothofagus pumilio* and *N. betuloides*) regenerate from a seedling bank that is drowned or buried by beavers, and establishment after reseedling is hindered by residually wet soil and dense growth of early successional plants (sometimes including exotics; Anderson et al. 2006; Henn et al. 2014; Martínez Pastur et al. 2006).

Much is known about Fuegian beaver impacts on streams and riparian vegetation, but despite a call for research, knowledge about beaver impacts is lacking for the most diverse vertebrate class of the region: birds (Rozzi and Jiménez 2014). Evidence from beavers' native range in the northern hemisphere suggests that their landscape modifications increase avian abundance and diversity (see Stringer and Gaywood 2016 and references therein), but documentation of this effect in their invaded range in Tierra del Fuego is much more limited. In one of the earliest beaver impact studies from Tierra del Fuego, Venegas and Sieldfeld (1980) suggested that beavers might create useful habitat for aquatic birds and those with edge habitat preferences (Parkes et al. 2008), while Lizarralde (1993) observed that beaver-impacted sites were used for nesting by migratory birds. Vergara and Schlatter (2004, 2006) also found that the abundances of several avian species including the Magellanic woodpecker *Campephilus magellanicus* increased with proximity to wetlands (including peatlands and beaver ponds). However, none of these studies explicitly addressed the question of how beavers affect the structure and function of Fuegian bird communities.

Given this knowledge gap and the potential for future restoration efforts, we conducted passive acoustic monitoring (PAM) and avian point counts to determine how beaver habitat modification affects bird communities in Magellanic forests of Tierra del Fuego. The aforementioned evidence led us to expect greater acoustic activity at beaver-impacted sites as a result of increased avian abundance and diversity. We employed PAM to: a) reduce researcher-induced bias and error, b) enable long-term, synchronous, high-temporal-resolution data collection (Gasc et al. 2017; Sueur and Farina 2015), and c) further test PAM's utility as a scalable biodiversity proxy through comparison against count-derived metrics of avian abundance, species diversity, and functional diversity (e.g., Buxton et al. 2018; Depraetere et al. 2012; Gasc et al. 2015; Zhao et al. 2019). Tierra del Fuego is an auspicious locale for field-based comparison between classical diversity metrics and PAM due to its lack of potentially confounding sounds from human technologies and non-avian taxa (DF, personal observations; Rozzi and Jiménez 2014). PAM has been promoted as a tool for evaluating disturbance impacts (e.g., Gasc et al. 2017), and it is increasingly applied in this context (e.g., Borker et al. 2019; Fuller et al. 2015; Gasc et al. 2018). This study addresses the continuing need for biogeographically and situationally diverse applied PAM trials, while also providing important insights into a previously neglected dimension of beaver impacts in Tierra del Fuego.

4.2 Materials and methods

For brevity, methods are summarized in this section with full details provided in Appendix 4A.

4.2.1 Site selection

We selected five watersheds around the city of Ushuaia, each of which contained three sites with distinct patch-level beaver impact states: intact riparian forest (hereafter “forest”), ponds created by beaver dams (hereafter “pond”), and meadows formed after beaver pond drainage featuring fallen logs, snags, and herbaceous and shrubby vegetation (hereafter “meadow”; Figure 4.1 and Table 4A.1).

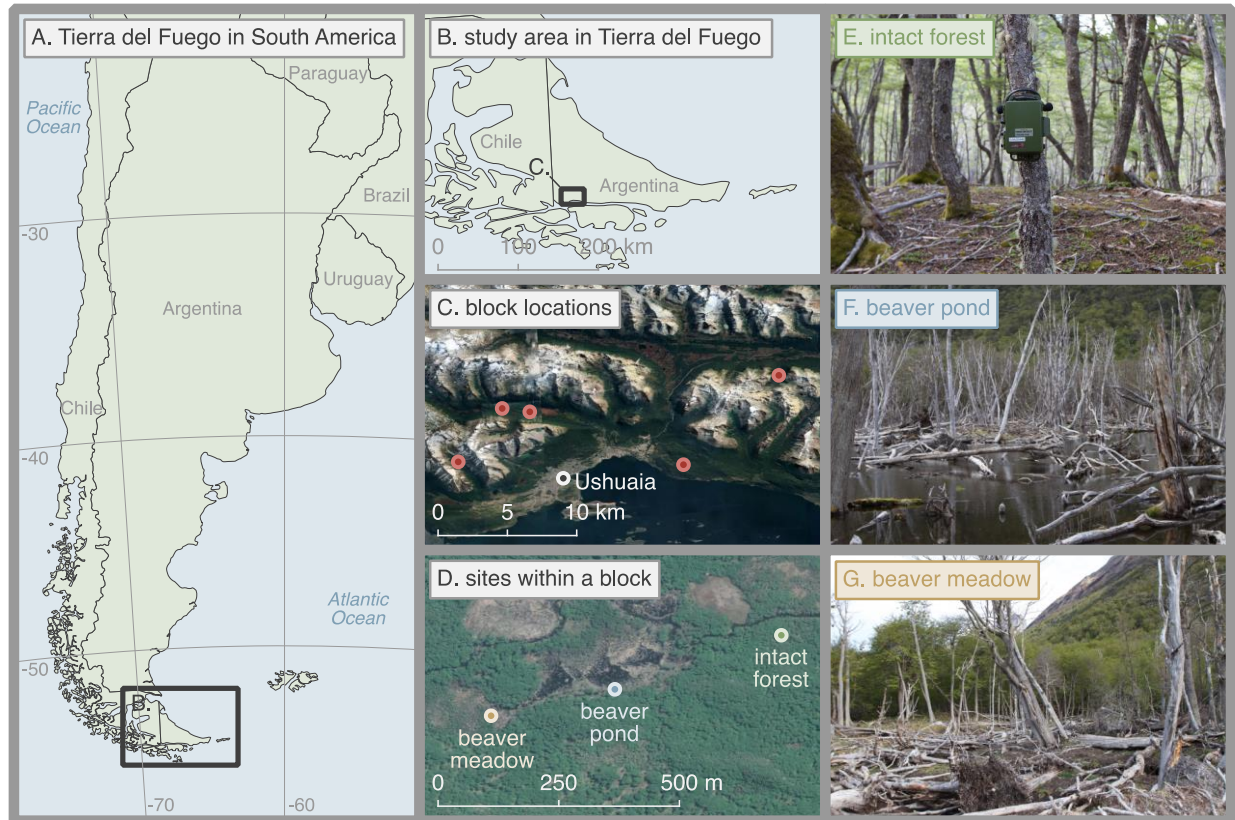


Figure 4.1. Map and images of study sites. Maps were produced in QGIS (QGIS.org 2020) using Google Maps satellite imagery.

4.2.2 Acoustic data collection and analysis

To measure avian acoustic activity, a Wildlife Acoustics Song Meter SM4 recorder was installed at each site and recorded 1 minute every 10 minutes (spring 2018 – winter 2019 for four blocks and summer 2018/2019 – winter 2019 for one block). Recordings made between 0.5 hour before and 5 hours after sunrise were used in analysis. From denoised data that were band-pass filtered between 1.4 and 10.4 kilohertz, we calculated five acoustic metrics with slight modifications from their original descriptions: temporal occupancy (adapted from Towsey’s “activity”; Towsey 2017), events per minute (Towsey 2017), broadband sound pressure level (Merchant et al. 2015), the acoustic complexity index (Pieretti et al. 2011), and the acoustic diversity index (Villanueva-Rivera et al. 2011). Due to unidimensionality, these metrics were reduced to a single measure of acoustic activity by extracting the first axis of a principal components analysis. An average measure of acoustic activity was obtained for each site within each of the four meteorological

seasons, considering November as spring, December – February as summer, March – May as fall, and June – August as winter (Trenberth 1983).

4.2.3 Point counts, abundance adjustments, and diversity metrics

To obtain more direct measures of abundance, species diversity, and functional diversity, seven 10-minute point counts were conducted at each site between January and August 2019 following standard methods and adjusting counts based on detectability (Miller et al. 2017). We calculated species and functional diversity metrics based on adjusted point counts. Data were combined within each season as defined above. Two to three counts were conducted per season at each site, and the highest number of individuals of each species in any single count within a season was treated as the seasonal abundance for that species at that site. From these seasonal data, we estimated abundance, species richness, and Shannon diversity for each site. To quantify functional diversity, we compiled and processed functional trait data as described in Appendix 4A. We then calculated Rao’s quadratic entropy (Rao 1982), defined functional groups via hierarchical agglomerative clustering, calculated functional group richness, and calculated Shannon diversity using those groups. From 20 species, four functional groups were defined (Table 4.1).

Table 4.1. Functional groups for observed species. Mixed migration trait information for some members of resident passerines et al. suggests that group may include partial migrants.

functional group name	scientific name	common name
1. ducks and ibis	<i>Specularnas specularis</i>	spectacled duck
	<i>Anas flavirostris</i>	yellow-billed teal
	<i>Theristicus melanopis</i>	black-faced ibis
2. raptors	<i>Caracara plancus</i>	southern caracara
	<i>Milvago chimango</i>	chimango caracara
3. resident passerines et al.	<i>Campephilus magellanicus</i>	Magellanic woodpecker
	<i>Enicognathus ferrugineus</i>	austral parakeet
	<i>Pygarrhichas albogularis</i>	white-throated treerunner
	<i>Cinclodes patagonicus</i>	dark-bellied cinclodes
	<i>Aphrastura spinicauda</i>	thorn-tailed rayadito
	<i>Troglodytes aedon</i>	house wren
	<i>Turdus falcklandii</i>	austral thrush
	<i>Spinus barbatus</i>	black-chinned siskin
	<i>Zonotrichia capensis</i>	rufous-collared sparrow
	<i>Curaeus curaeus</i>	austral blackbird
	<i>Phrygilus patagonicus</i>	Patagonian sierra-finch
4. migrant passerines	<i>Elaenia albiceps</i>	white-crested elaenia
	<i>Muscisaxicola maclovianus</i>	dark-faced ground-tyrant
	<i>Colorhamphus parvirostris</i>	Patagonian tyrant
	<i>Tachycineta leucopyga</i>	Chilean swallow

4.2.4 Statistical analyses

To assess differences in distinct aspects of avian communities between impact states within each season, we employed variations of linear mixed models for each of the following dependent variables: acoustic activity, each of the six count-based metrics mentioned above, resident passerine et al. abundance, and migrant passerine abundance (Table 4A.4). Due to low numbers of observations for the ducks and ibis and raptors functional groups, we did not statistically evaluate their differences in abundances. Impact state, season, and their interaction were treated as fixed effects, and block was considered a random effect. Model structures were progressively simplified to address convergence issues, and model significance was assessed through comparison against null models containing only the block effect. Pairwise contrasts between impact states within seasons were employed when the effect of impact state was significant.

Differences in community species composition were analyzed using partial canonical correspondence analysis with the same independent variables as above, treating block as a covariate. Significance of the model, terms, and axes were evaluated via permutation tests (Legendre and Legendre 1998). The interaction term was insignificant, so it was excluded to

create a more parsimonious model and facilitate interpretation. Model fit was assessed by adjusted R^2 value and variance inflation factors (Borcard et al. 2011).

To compare between the acoustic and count-based data, the direct relationships between all seasonal diversity metrics, seasonal acoustic metrics, and the seasonal acoustic activity composite were also evaluated using Spearman correlations (most metrics were non-normally distributed, even after transformations). P-values were not adjusted due to the deliberately exploratory nature of this analysis (McDonald 2009).

4.3 Results

4.3.1 Acoustic activity

Acoustic activity differed across impact states and seasons (Figure 4.2 and Table 4A.5). Within each impact state, acoustic activity declined from spring to winter. Activity was similar across impact states in fall and winter, but higher at meadow sites relative to forest sites in spring and summer.

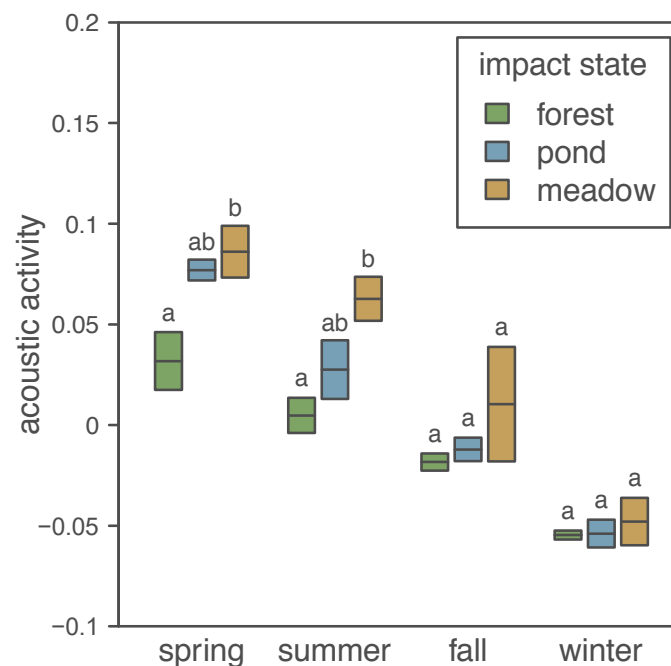


Figure 4.2. Impact state- and season-based differences in acoustic activity. Lines represent means, and bars represent means \pm standard error. Significantly different contrasts are indicated by differing letters within each season.

4.3.2 Abundance and diversity metrics

Complete abundance and diversity model results are presented in Figure 4.3 and Table 4A.5. All full models were significantly different from their null counterparts, and season was a significant predictor in all models. Within each impact state, there were almost universal declines in all variables from summer to winter. Impact state was a significant predictor in models for species abundance, richness, and functional group richness, while the impact state-season interaction was only significant for functional group richness. The number of significant contrasts declined from summer to winter. In significant contrasts, forest sites only once scored higher than pond or meadow sites (winter functional group richness). Pond and meadow sites had variable relationships: they did not statistically differ in terms of species richness, but meadow sites featured higher fall abundance, while pond sites featured higher summer and winter functional group richness.

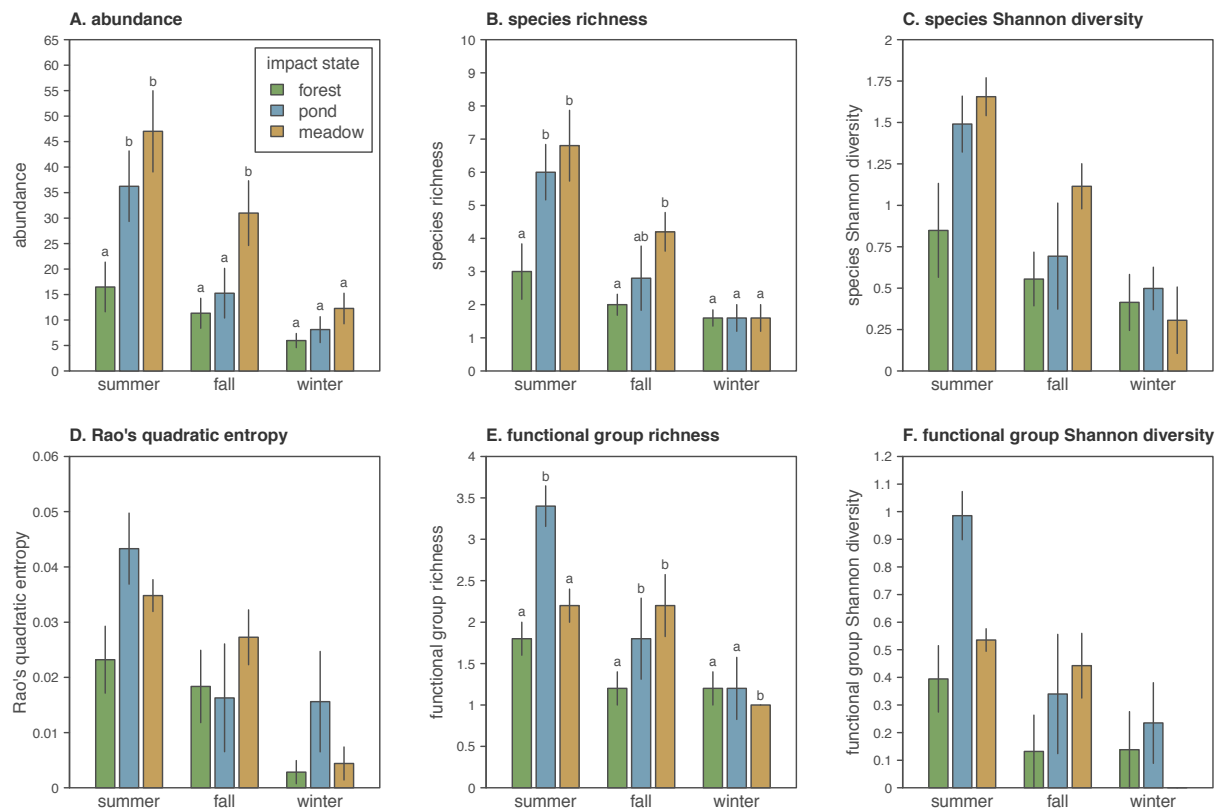


Figure 4.3. Count-based characteristics of bird communities by impact state and season. Bars represent means, and lines represent means \pm standard error. Significantly different contrasts are indicated as in Figure 4.2 for models in which impact state was a significant factor.

4.3.3 Functional group abundance

The ducks and ibis were only observed at pond sites in the summer and fall, while raptors were only observed at pond (in all seasons) and meadow (in fall) sites (Figure 4.4A and 4.4B). Abundances for resident passerines et al. and migrant passerines exhibited significant effects of impact state and season (Figure 4.4C and 4.4D; Table 4A.5). Resident passerines et al. were similarly abundant at forest and pond sites in all seasons, but they were more abundant in meadow sites in summer and fall. Impact state contrasts were all insignificant for migrant passerines, but abundance was somewhat higher at pond and meadow sites in summer and fall.

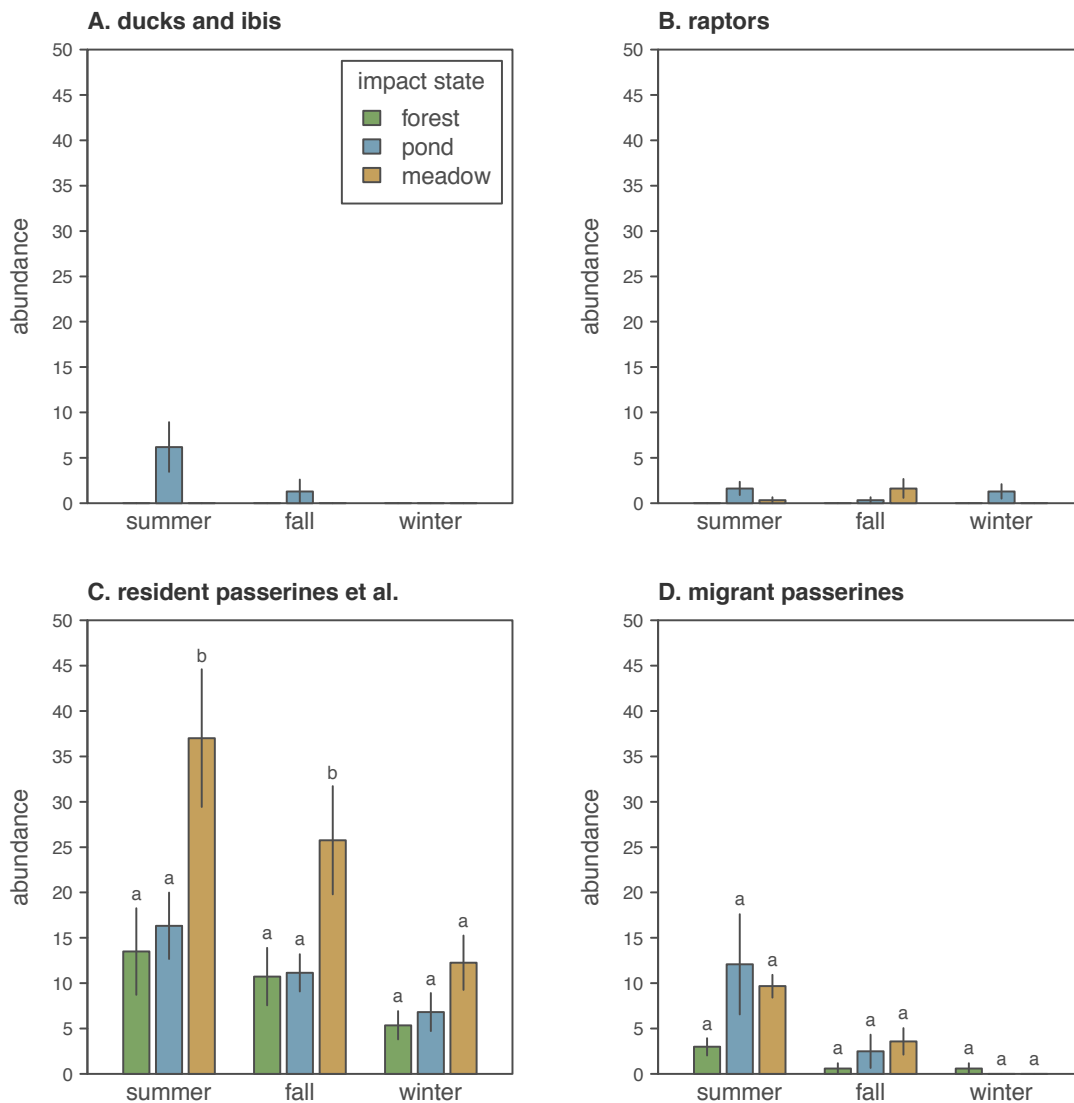


Figure 4.4. Impact state- and season-based differences in abundance for each functional group. Bars represent means, and lines represent means \pm standard error. Significantly different contrasts in C and D are indicated as in Figure 4.2.

4.3.4 Community species composition

The canonical correspondence analysis revealed significant differences in species composition (Figure 4.5; pseudo-F = 2.38; d.f. = 4, 35; $p = 0.005$). The first two axes were significant and accounted for 86% of the explained variance, but the adjusted R^2 was only 0.11. Impact state and season both significantly affected species composition (respectively: pseudo-F = 2.34; d.f. = 2, 35; $p = 0.005$ and pseudo-F = 2.42; d.f. = 2, 35; $p = 0.005$). Differentiation of the avian communities by impact state and season is evident in Figure 4.5, with only minor overlap between the forest and meadow confidence ellipses and minimal overlap between any of the season ellipses. In addition to the ducks and ibis mentioned above, southern caracaras *Caracara plancus* were also observed solely at pond sites. Dark-bellied cinclodes *Cinclodes patagonicus*, dark-faced ground-tyrants *Muscisaxicola maclovianus*, and austral blackbirds *Curaeus curaeus* were exclusively observed at meadow sites, while no species were observed exclusively at forest sites. Other notable species that principally occurred within sites of a single impact state include: Magellanic woodpeckers *Campephilus magellanicus* and Chilean swallows *Tachycineta leucopyga* (pond sites) and house wrens *Troglodytes aedon*, austral thrushes *Turdus falcklandii*, black-chinned siskins *Spinus barbatus*, and rufous-collared sparrows *Zonotrichia capensis* (meadow sites).

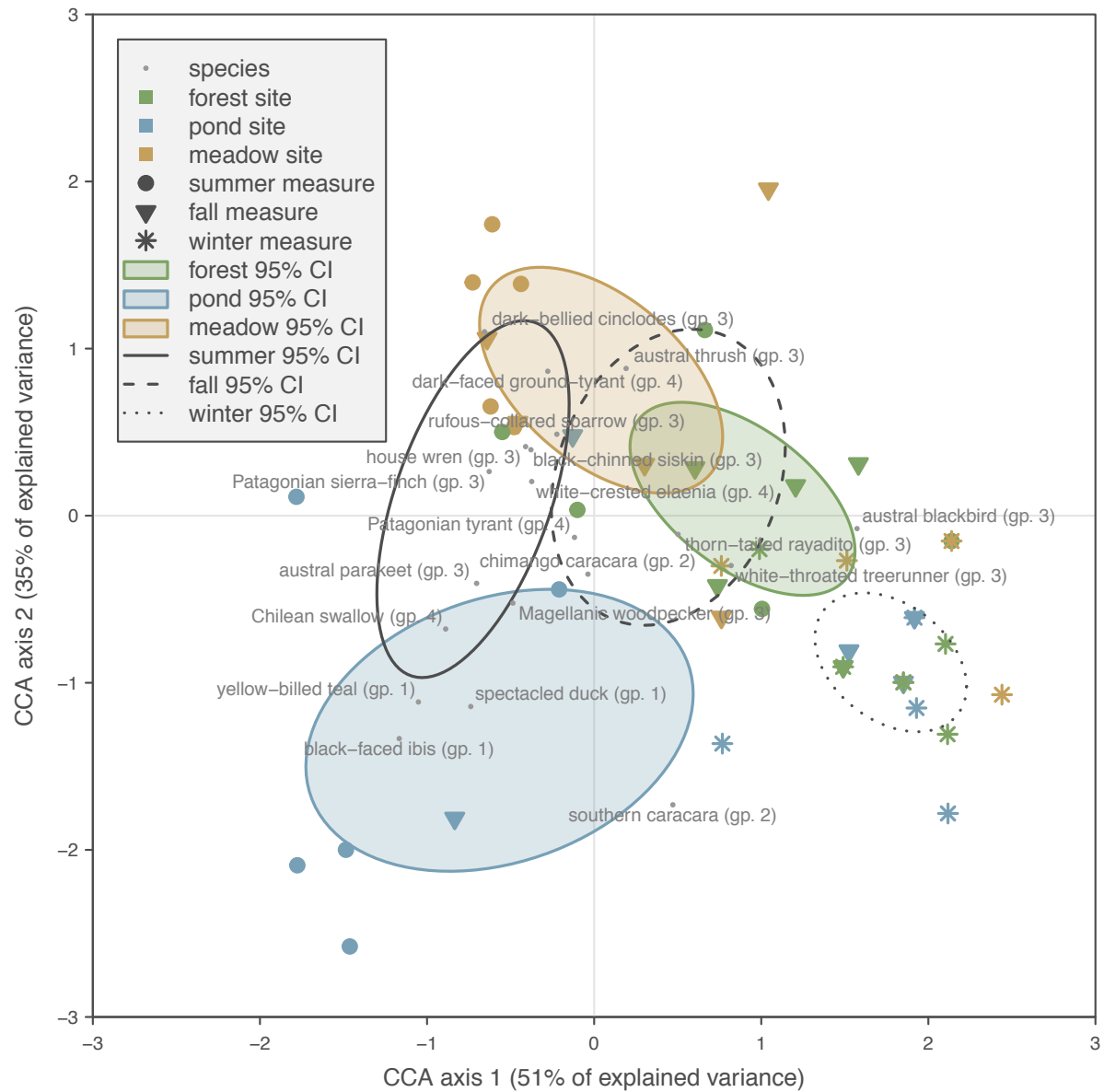


Figure 4.5. Correlation triplot for canonical correspondence analysis of community species composition. Seasonal measurements for each site are represented by each colored point, with the color representing the impact state and the shape representing the season. Ellipses represent 95% confidence intervals around impact state and season centroids, and grey points represent species.

4.3.5 Metric correlations

All metrics were highly and positively intercorrelated (Figure 4.6). Correlations within count-based and acoustic-based metrics were generally stronger than those between the two types of metrics, likely due to some degree of inherent autocorrelation. The strong relationships between

acoustic activity and abundance, species richness, and functional group richness are especially meaningful for consideration of acoustic activity as a proxy for those variables.

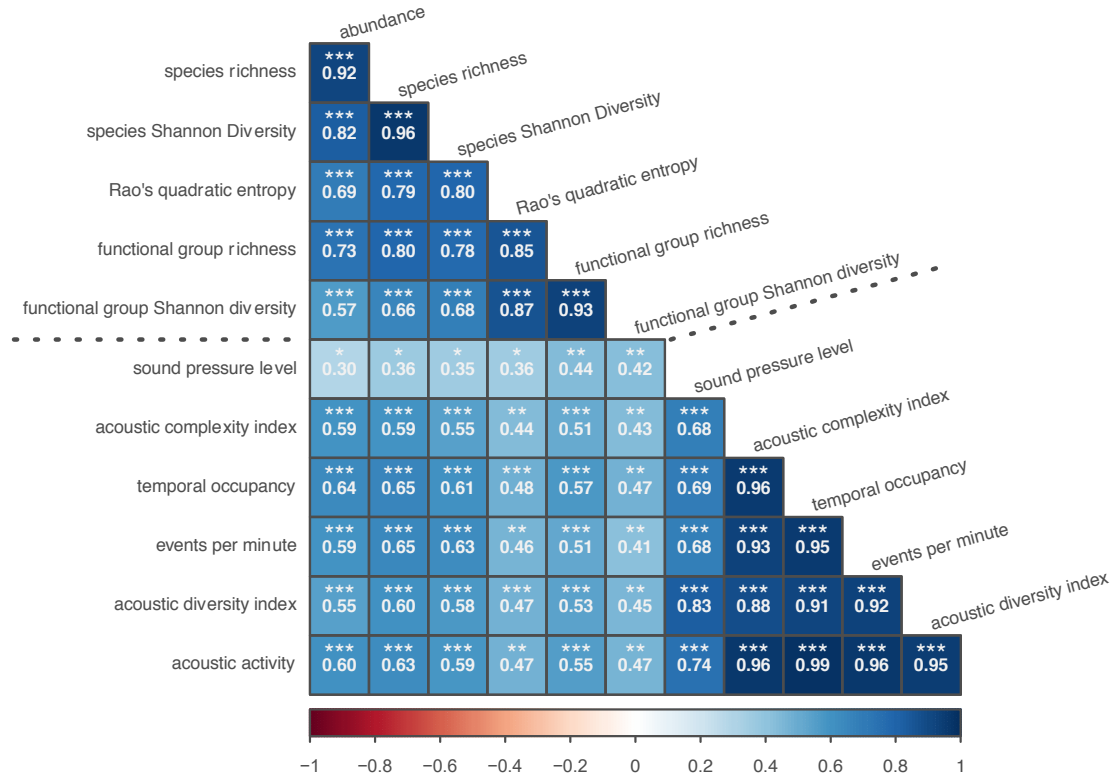


Figure 4.6. Spearman correlations between all metrics. Colors and numbers represent correlation coefficients. * signifies $0.05 \geq p > 0.01$, ** signifies $0.01 \geq p > 0.001$, and *** signifies $p \leq 0.001$. Dotted lines separate count-based and acoustic-based metrics.

4.4 Discussion

Our PAM findings revealed greater acoustic activity at beaver-generated pond and meadow sites relative to intact forest sites, and our count-based results indicate that these acoustic differences were due to increased avian abundance and/or diversity at the beaver-altered sites. Collectively, these outcomes have important implications for 1) the use of PAM as a proxy for abundance and diversity, 2) the global study of beaver-bird relationships, and 3) beaver management in Tierra del Fuego.

4.4.1 Implications and contextualization of acoustic findings

Our acoustic findings compensated for a number of the shortcomings of *in situ* counts (i.e. short-duration, non-simultaneous data collection, researcher influence on avian behavior, and researcher error in data collection), and still exhibited convincing correspondence with our count-based results. The spatial and temporal patterns in acoustic activity mirrored those of avian abundance, species richness, and species Shannon diversity (Figures 2 and 3A – 3C), and correlations with metrics of functional diversity were slightly lower than those for abundance and species diversity metrics, but still positive and significant (Figure 4.6).

Of the growing number of studies comparing PAM results to more classical measures of abundance and diversity (Depraetere et al. 2012; Fuller et al. 2015; Zhao et al. 2019), our correlations are most comparable in terms of methods and statistics with those reported by Eldridge et al. (2018) and Mammides et al. (2017). Our results for individual acoustic metrics and the acoustic activity composite generally fall within the range of positive correlations Eldridge et al. presented for sites in southern England, and they are towards the higher end of the range found by Mammides et al. in southern China. Eldridge et al. suggested that acoustic metrics may best serve as a proxy for avian species richness in temperate ecosystems due to the general absence of sounds from herpetofauna and insects that have the potential to bias acoustic metrics designed to reflect avian acoustic activity. With soundscapes almost entirely devoid of sounds from non-avian taxa, our positive, moderately strong correlations provide support for the temperate aspect of this hypothesis and for the use of PAM in Tierra del Fuego.

While our acoustic results echoed those from our point counts, the counts were superior in the level of detail they provided. The positive, strong correlations we found between our count-based metrics preclude us from saying which of those metrics was or were driving acoustic activity. Soundscape simulations studies such as those by Gasc et al. (Gasc et al. 2015) and Zhao et al. (Zhao et al. 2019) could help to clarify this uncertainty. Count-like detail is potentially obtainable from PAM data through manual listening (e.g., Eldridge et al. 2018; Tucker et al. 2014) or automated sound detection and classification (e.g., Zhang et al. 2018), but those methods obviously lack the ability of an *in situ* count to detect individuals that are silent. In the case of our study, we did not find these acoustic methods necessary since we could conduct *in*

situ counts at all sites, but they may become imperative depending on the scale of data collection and the level of detail required in analysis. We sampled a small portion of just one of several beaver-impacted habitat types in Tierra del Fuego, and further study of beaver-bird relationships should consider the full diversity of habitats, environmental conditions, and beaver impact conditions across the archipelago (Herrera et al. 2020). Such scaling will render *in situ* counts impractical, which may necessitate automated detection and classification to deliver more detailed information that can better inform management decisions.

4.4.2 Contextualization of beaver-bird relationships

Our findings related to certain functional groups and species were largely coherent with the *ad hoc* documentation that we found for Tierra del Fuego (Lizarralde 1993; Parkes et al. 2008; Venegas and Sielfeld 1980; Vergara and Schlatter 2004, 2006) and the more extensive literature on beaver-bird relationships in the northern hemisphere (references in Stringer and Gaywood 2016).

Our observation of the ducks and ibis functional group solely at pond sites supported the informal observations by Venegas and Sielfeld (1980) of spectacled ducks *Specularnas specularis* and yellow-billed teals *Anas flavirostris* using beaver ponds. We did not, however, observe several other species that Venegas and Sielfeld found associated with pond sites—a discrepancy that could have arisen because they considered a greater number of pond sites in more diverse habitat types than we did. Grover and Baldassarre (1995) in New York, USA (native range) and Nummi and Holopainen (2014) in Finland (exotic range) also found North American beavers to promote duck, wader, and goose abundance relative to non-beaver wetlands and ponds. Nummi and Holopainen suggested that increased invertebrate biomass in beaver ponds drives this difference as a food source for ducks. We did not compare beaver ponds against non-beaver ponds or wetlands in the Fuegian landscape, but heightened macroinvertebrate biomass in local beaver ponds and the diets of our observed ducks suggest that this difference could exist in Tierra del Fuego as well (Anderson et al. 2009; BirdLife International 2020; Canevari and Manzione 2017; Couve and Vidal 2003).

We observed a small number of raptors in exclusively pond and meadow sites (Figure 4.4B), and higher raptor density and biomass were also observed at open-canopy, as opposed to closed-canopy, sites in Tierra del Fuego by Pastur et al. (2015). Grover and Baldassarre (1995) specifically mentioned the potential importance of beaver-created snags to raptors as perching sites. While Grover and Baldassarre's data did not appear to support an overall raptor preference for pond or meadow sites, Stringer and Greenwood (2016) made a similar suggestion, and Glinski et al. (1983) provided several examples of raptors that use snags for nesting, foraging, and resting.

For members of our resident passerines et al. functional group (which included Magellanic woodpeckers and austral parakeets *Enicognathus ferrugineus*), research in Tierra del Fuego has shown variable habitat type associations, and our findings are no exception. Vergara and Schlatter (2006) found that white-throated treerunners *Pygarrhichas albogularis* and house wrens *Troglodytes aedon* were attracted to wetlands. The former was the only species we found most abundant at forest sites, and we found the latter associated with meadow sites, which often retain some wetland characteristics (Figure 4.5). In a comparison of avian habitat usage in open and closed *Nothofagus* forests of varying composition, Pastur et al. (2015) also noted that dark-bellied cinclodes were only recorded in open areas, corresponding with our observations of that species exclusively in meadows (Figure 4.5). They observed thorn-tailed rayaditos using various habitats, but preferring closed canopies (present in intact forests); we observed high rayadito abundances for all impact states, but observed the most individuals in meadow sites. Vergara and Schlatter (2004) suggested an association of Magellanic woodpeckers with wetland areas including beaver ponds, and we found stronger evidence for an association between this species and pond sites (Figure 4.5). Woodpecker association with beaver impacts likely results from beavers creating an abundance of snags that serve as woodpecker foraging substrates (Grover and Baldassarre 1995; Vergara and Schlatter 2004). These associations have also been documented in Poland (Sikora and Rys 2004; Tumiel 2008), Québec, Canada (Aznar and Desrochers 2008), Arizona, USA (Johnson and van Riper III 2014), and Georgia, USA (Lochmiller 1979).

The slightly elevated abundance of migrant passerines at pond and meadow sites also reflects Lizzarralde's (1993) observation of migratory birds using beaver-impacted sites (Figure 4.4D), although the contrasts we considered were statistically insignificant (Table 4A.5). As in the case of resident species, Lencinas et al. (2018) observed a preference among migrants for edge and harvested habitats, relative to interior forest remnants. Pastur et al. (2015) also noted an open area preference for dark-faced ground-tyrants and Chilean swallows, which we found to be associated with meadow and pond sites, respectively (Figure 4.5). Chilean swallows are known to aerially forage for insects over bodies of water and to nest in tree or snag cavities (Rozzi and Jiménez 2014).

4.4.3 Management implications

In the context of beaver invasion and potential restoration projects in Tierra del Fuego, it is important to consider effects on birds at landscape, patch, community, species, and individual levels. While we observed heightened acoustic activity, avian abundance, and avian diversity at beaver-altered sites, it is important to note that these patch-level changes should be contextualized in the regional landscape.

From our study alone, we cannot say whether beaver impacts led to novel avian communities or similar communities to those found in natural analogue habitat patches within the landscape (e.g., natural ponds, bogs, and windthrow gaps). Studying avian communities and resource use in such habitat types would help to more fully understand beaver impacts and predict avian responses to habitat restoration. In terms of restoration, however, we can say that pond drainage without active reforestation measures would not reset the avian community to an intact forest state (at least not in the short term). A two-stage approach might be needed: beaver removal, dam breaching, and pond drainage could lead to a fairly rapid patch-level reduction in duck abundance, and reforestation could decrease abundances of other pond- and meadow-associated species on a more decadal time scale.

For species-level avian conservation in Tierra del Fuego, the implications of beaver invasion and potential restoration efforts are uncertain. Of our observed species, the IUCN only lists the spectacled duck as near threatened (IUCN 2020; 2016), but the Argentine Ministry of the

Environment and Sustainable Development (MAyDS) lists that species as vulnerable and the Magellanic woodpecker as near threatened (here stated in IUCN-equivalent categories; MAyDS and AA 2017). Both species are, however, considered regionally abundant (Christopher B. Anderson, personal communication). While species abundances at beaver-altered sites could be reduced at the patch level by restoration efforts, landscape-level effects are unknown.

For individual birds, direct removal of beavers would likely be inconsequential, and seedling planting would probably have limited short-term effects. Dam breaching, however, would lead to an immediate loss of aquatic resources that could impact some individuals (e.g., spectacled ducks). Breaching dams in the fall or winter may help minimize effects on reproduction of any water-dependent species.

4.5 Conclusions

In diverse social-ecological contexts, beavers are both a tool for, and an object of, management efforts. It is thus important that we fully understand the ecological effects of their engineering to take full advantage of their unique habitat modification abilities and avoid unforeseen consequences and. In Tierra del Fuego, further study of avian habitat and resource use at a landscape level will help elucidate potential avian responses to restoration of beaver-altered habitats. The present study has confirmed the utility of PAM for avian biodiversity research in Tierra del Fuego, and while further study will enhance its utility and extensibility, PAM represents a scalable solution to conduct robust avian monitoring in Tierra del Fuego and beyond.

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CHAPTER 5—HUMAN-NATURE CONNECTION AND SOUNDSCAPE PERCEPTION: INSIGHTS FROM TIERRA DEL FUEGO, ARGENTINA

Dante Francomano, Mayra L. Rodríguez González, Alejandro E. J. Valenzuela*, Zhao Ma, Andrea N. Raya Rey*, Christopher B. Anderson, and Bryan C. Pijanowski*

* authors should be considered joint senior authors

Abstract

Human disconnection from nature is thought to have contributed to the environmental crises we currently face, and increasing connection with nature has been proposed as one way of promoting pro-environmental behavior and social-ecological sustainability. Some efforts to increase connection with nature (hereafter “nature relatedness”) have centered on exploring the social-ecological importance of soundscapes, but there is a paucity of empirical evidence supporting the theoretical linkage between soundscape perception and nature relatedness. Using prerecorded and *in situ* soundscape prompts, we conducted a street intercept survey in Ushuaia, Tierra del Fuego, Argentina to assess 1) the relative importance of senses in experiences of nature, 2) the relationship between nature relatedness and soundscape perception, 3) differences in soundscape perception between various soundscapes, and 4) possible demographic influences on sense importance, nature relatedness, and soundscape perception. Participants reported that hearing was of secondary importance to vision in experiences of nature. We also found that nature relatedness was positively correlated with the valuation of soundscapes—particularly more natural ones—but not with the discernment of soundscapes or identification of where soundscapes were recorded. Valuation of more natural soundscapes was higher than valuation of more technophonically-dominated soundscapes, while soundscape discernment and location identification were higher for soundscapes that were likely more familiar to listeners. Demographic influences on these variables were minor, but women reported higher sense importance, and having a nature-based occupation was associated with higher nature relatedness and valuation of a soundscape from a penguin colony. Our study highlighted a number of potential research areas concerning soundscape perception, including differences between prerecorded and *in situ* soundscape prompts, defining various aspects of soundscape perception, and the relative influences of sound sources and quantitative acoustic parameters on soundscape

perception. Further research is certainly needed to account for global diversity in cultures and soundscapes, but we found promising empirical support for the use of natural soundscape-focused programming in efforts to promote nature relatedness.

5.1 Introduction

Our planet is facing anthropogenic crises including biodiversity loss, climate change, and pollution, and resolutions to these problems will require massive societal restructuring (Rockström et al. 2009; Sala et al. 2000; IPCC 2014; Kates et al. 2001). While governmental responsibilities cannot be ignored (Caldwell 1970; Nilhlén Fahlquist 2009), individuals still have important bottom-up roles in catalyzing and implementing change (John et al. 2006; Folke et al. 2005; Folke 2019). In part, governmental inaction and ineffectiveness are products of insufficient popular pressure (Howlett and Kemmerling 2017), and various factors likely influence this shortage of grassroots activism. It is commonly hypothesized, however, that humans lack recognition of and concern for environmental issues because we have become physically and psychologically disconnected from the natural world, not least due to increasing urbanization and technological advancement (Ives et al. 2018; Miller 2005). This disconnected condition, popularized by Louv (2008) as Nature Deficit Disorder, is thought to cause a lack of familiarity with natural systems, a lack of awareness of human impacts on those systems, and limited appreciation for human reliance on ecosystem services (*sensu* Millennium Ecosystem Assessment 2003). Increasing human connection with nature may represent a step toward alleviating the global environmental crises we have created (Whitburn et al. 2020).

To test the above hypothesis, one must operationalize the concepts of “nature” and (dis)connection from it. Ives et al. (2017) have provided a useful review of attempts at the latter, while noting that these efforts have often left “nature” undefined. Largely following Ives et al.’s generalized conception of “nature” as derived from the studies they reviewed, we here consider “nature” and “natural” to refer to a) non-human organisms, species, and communities and b) places, environments, and ecosystems with low human presence or influence, relative to other such entities.

A theoretical framework around the measurement and implications of “connection with nature” has developed at the intersection of environmental psychology, environmental planning and management, and sustainability science (Restall and Conrad 2015; Ives et al. 2017). Numerous attempts to operationalize the construct of “connection with nature” have primarily come from environmental psychology (Tam 2013; but see Ives et al. 2017 and Restall and Conrad 2015). A

review by Tam found nine measures of connection to nature to be “markers of the same underlying construct”, while exhibiting “subtle” divergence (Tam 2013). This divergence and the explicit multidimensionality of two of the considered metrics—“environmental identity” (Clayton 2003) and “nature relatedness” (Nisbet et al. 2009; Nisbet and Zelenski 2013)—led Tam to conclude that, “it may be useful to consider connection to nature to be multidimensional”. A review by Restall and Conrad (2015) echoed these findings, and both Tam (2013) and Restall and Conrad (2015) highlighted positive correlations between this construct and pro-environmental behavior. Supporting the idea of a multidimensional, yet coherent, construct in a broader review, Ives et al. (2017) clustered 475 publications into three groups that considered “human-nature connection” as “mind”, “experience”, and “place”, respectively. They also manually differentiated five classes of human-nature connection: “material”, “experiential”, “cognitive”, “emotional”, and “philosophical”. Later work further emphasized these five classes and discussed their relative importance in terms of affecting change for social-ecological sustainability (Ives et al. 2018). Ives et al. asserted that the classes as listed above range from “external” to “internal” and increase in their “leverage” to induce system change. They also highlighted some overlap and the likelihood of positive interactions between the classes. Collectively, these studies suggest that an individual’s connection with nature is measurable and meaningful (Tam 2013; Ives et al. 2017) and that augmenting connection with nature at internal emotional and philosophical levels would be most effective at promoting social-ecological sustainability (Ives et al. 2018).

There are certainly many approaches that could be applied to increase our connection with nature as prescribed by the theoretical framework described above. One such paradigm focuses on our auditory senses and the concept of a “soundscape”, defined as the entire collection of sounds occurring in a given place over a given timeframe, which may include geophysical, biological, and technological sounds (Gasc et al. 2017; Pijanowski et al. 2011a, 2011b; Schafer 1993). We posit here that humans connect to ecosystems and nature through soundscapes and may do so at material, experiential, cognitive, emotional, and philosophical levels (Dumyahn and Pijanowski 2011; Feld 2012; Francis et al. 2017; Rodaway 2002).

The manners in which we have connected to nature through soundscapes have evolved over time. Experiential and cognitive connections have existed since the dawn of our species, as we have inhabited myriad ecosystems replete with biophony (sounds from organisms) and geophony (sounds from geophysical processes), and we have cognitively processed those sounds as cues that provide us with information about our surroundings (e.g., Filippi et al. 2017). Our emotional and philosophical connections to nature through soundscapes may have come later, but they were at least present by ancient times; for example, both positive and negative reactions to bird sounds and interpretations of those sounds' meanings are found in numerous ancient writings (Mynott 2018). More recently, urbanization and industrialization have reduced our opportunities for experiential connection to nature through sound (Francis et al. 2017). This reduced exposure might yield divergent results: on one hand, a lack of exposure to natural soundscapes can impair the development of emotional and philosophical connections to nature through soundscapes (Francis et al. 2017); alternatively, the scarcity of natural soundscapes could lead to their increased valuation by some individuals, motivating them to experience nature while seeking out natural soundscapes (Marin et al. 2011).

The advent of acoustic recording and reproduction technologies has also led to material connections to nature through soundscapes, as natural recordings have been commoditized. This same technology has played a role in promoting novel cognitive connections to nature through audio recordings. Recording and playback of sounds has greatly facilitated the study of animal sounds (i.e. bioacoustics; Penar et al. 2020) and, more recently, analysis of biodiversity trends and the ecological implications of soundscapes (i.e. soundscape ecology and/or ecoacoustics; Pijanowski et al. 2011a, 2011b; Riede 1993; Sueur and Farina 2015). Much of this work has captured the public imagination outside of academia and has fostered emotional and philosophical connections to nature as well (Rothenberg 2008; Krause 2012; Ghadiri Khanaposhtani et al. 2018a). Awareness of the troublesome ecological implications of reduced biophony and acoustic masking caused by non-biological human sounds (technophony) will often generate feelings of loss, sadness, frustration, or anger (Carson 2002; Krause 2012). It may also cause one to question the justice of global human domination that comes at the expense of non-human animal communication and survival (Pepper 2017).

The abovementioned manners of natural connection through soundscapes seem intuitively valid, and they have inspired an array of efforts to promote such connections through the soundscape paradigm. These efforts range from soundwalks—dedicated excursions to observe the spatially varying sounds of a given area (Behrendt 2018; Westerkamp 2007; Williams 2017)—to more expansive soundscape-based curricula and human-nature connection initiatives (US National Park Service 2018a, 2018b; Ghadiri Khanaposhtani et al. 2018a, 2018b; Barclay 2014). Unfortunately, despite the intuitive appeal of such efforts, there is a paucity of empirical evidence supporting the hypothetical underpinnings of natural connection through soundscapes.

To investigate this theoretical linkage between connection with nature and the soundscape paradigm, we sought to quantify and compare individual connection with nature, importance of senses in experiences of nature, and perceptions of various soundscapes. For the purposes of this study, we considered soundscape perception to be composed of three aspects: 1) soundscape discernment (the accuracy and precision with which one can remember recently heard soundscapes and list and describe their component sounds), 2) soundscape valuation (appreciation of the personal, social, and ecological significance of a soundscape), and 3) soundscape location identification (the accuracy and precision with which one can identify the location in which a soundscape was recorded). We designed and conducted a survey to address several broad hypotheses concerning the above concepts, while also exploring potential demographic influences on them. Our general hypotheses and predictions were as follows:

1. Hearing will be rated as the second most important sense for experiences of nature because a) vision has primacy in nature-based media, b) vision is exceptionally useful in navigating through natural environments, and c) natural soundscapes are popularly conceptualized as beautiful and relaxing, while touch, smell, and taste are generally neglected in descriptions of natural places and phenomena. While there is evidence supporting intercultural variability in sensory importance (Hutmacher 2019; Majid et al. 2018), in a modern Western cultural context, linguistic and survey-based evidence supports the primacy of vision and the secondary role of hearing outside of any specific situation (Roque et al. 2015; Schifferstein 2006).
2. Connection with nature or “nature relatedness” will be positively correlated with soundscape discernment, valuation, and location identification. These relationships were

predicted because individuals that are highly nature related tend to spend more time outdoors (Nisbet et al. 2009; Mayer and Frantz 2004) and are likely to: a) be very aware of their environments and capable of accurately recalling and describing soundscapes in detail, b) understand the ecological importance of soundscapes and actively consider the sounds around them, and c) have a greater awareness of places' characteristic soundscapes.

3. Soundscape discernment, valuation, and location identification will be positively correlated for a given soundscape, but not necessarily across different soundscapes. Better recognition of what one is hearing (discernment) would lead to more authoritative assessments of a soundscape's personal, social, and ecological importance and more accurate and precise recognition of a soundscape's location.
4. Soundscape discernment and location identification will be higher for soundscapes that are more familiar to listeners, given previous experiences with similar soundscapes. Axelsson et al. (2010) found familiarity to be an important dimension of soundscape perception, and it is easier to name and describe sounds that one has heard before, as opposed to novel sounds. Increasing familiarity should increase descriptive ability. Recognition of a more numerous set of sounds should then enhance one's ability to accurately and precisely identify the location where a recording was made.

5.2 Methods

5.2.1 Study area

We conducted our study in the city of Ushuaia, located on the northern coast of the Beagle Channel in Tierra del Fuego, Argentina (Figure 5.1). Soundscapes differ vastly between the sharply defined urban core of Ushuaia, its forested surroundings, and the congregations of seabirds and marine mammals that occur in the Beagle Channel (Raya Rey et al. 2017). In addition to its diverse soundscapes, the social dynamics of this city make it an interesting place to explore the potential demographic influences on nature relatedness and soundscape perception. Around 400,000 tourists visit Ushuaia annually, and many of Ushuaia's 70,000 residents are employed directly or indirectly by tourism (Instituto Fueguino de Turismo 2017; Secretaria de Turismo de Ushuaia, Departamento Estadísticas y Econometría 2011). Spurred on by both

growing tourism and Argentine efforts to reinforce their local sovereignty, the urban population of Tierra del Fuego, Antártida e Islas del Atlántico Sur Province increased by 419% between 1980 and 2010 compared to a national urban increase of 57% (Instituto Nacional de Estadística y Censos 2017; Herbert 2014). Social tensions over resources and the wilderness- and nature-based identity of the city have resulted from these rapid changes and have led to the identification of three distinctive social groups: long-term residents, amenity or lifestyle migrants, and economic migrants (Herbert 2014). The potential to observe differences between these groups in terms of their nature relatedness and soundscape perception was an additional factor that motivated our choice of this study site.

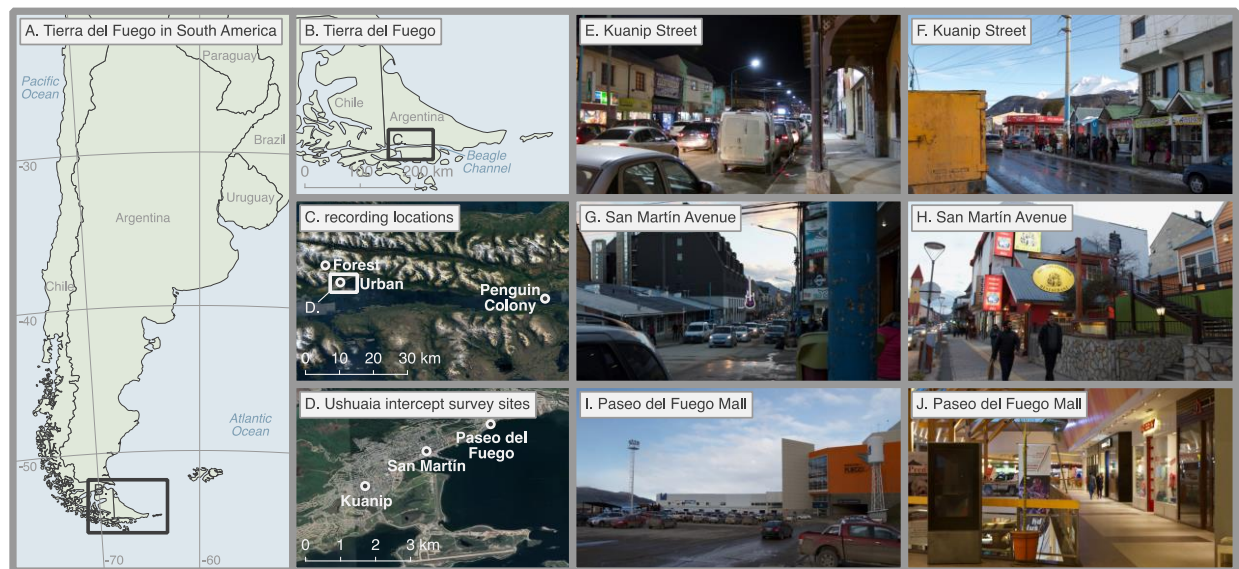


Figure 5.1. Maps and photographs showing Tierra del Fuego in southern South America, the locations at which soundscape prompts were recorded, and the sites at which surveys were conducted. Maps were produced in QGIS (QGIS.org 2020) using satellite imagery from Google Maps, and photographs were taken by the first author.

5.2.2 Survey design

To test the above hypotheses, we designed a street intercept survey. Intercept surveys originated in consumer research (Blair et al. 2013; Rookey et al. 2012) and have been adopted as a common data collection method in leisure and recreation research (Rickard et al. 2011; Campbell 2013; Loomis 2007). These surveys allow the gathering of *in situ* feedback to assess locally salient topics, measure sense of place, and reach out to people who might be hard to contact otherwise (Flint et al. 2016; McKenzie and Mistiaen 2007; Troped et al. 2009). Our survey contained

questions about participant: 1) demographics, 2) nature relatedness, 3) use of senses in experiences of nature, and 4) perception of Fuegian soundscapes. The full texts of English and Spanish versions of the survey are presented in Appendix 5A. All variables employed in analyses that were generated directly or indirectly from survey responses are described in Table 5.1.

Table 5.1. Analysis-form variables employed in this study.

organizational category	name	type	levels or observed and theoretical range	description/derivation
nature relatedness	nature relatedness	interval	observed: 2.5 – 5; theoretical: 1 – 5	the mean of the six nature relatedness scale items (averaged due to unidimensionality; see Appendix 5B)
sense importance	sense	categorical	vision, hearing, touch, smell, taste	the names of the five senses
	sense importance	ordinal	of no importance, of little importance, of moderate importance, of high importance	the self-reported importance of each sense
	mean sensory importance	interval	observed: 1.8 – 4; theoretical: 1 – 4	the average of the five sense importance values
	relative hearing importance	ratio	observed: -2 – 1.4; theoretical: -2.4 – 2.4	the sense importance for hearing minus the mean sensory importance
soundscape prompt	soundscape prompt	categorical	Forest, <i>In Situ</i> , Penguin Colony, Urban	the names of the four soundscape prompts
soundscape discernment	soundscape discernment	interval	observed: 0 – 0.75; theoretical: 0 – 1	the weighted average of the scaled accuracy (weight = 0.5), precision (weight = 0.25), and description detail (weight = 0.25) scores for each soundscape description (see Appendix 5B and the GitHub link provided below for details)
	Forest soundscape discernment	interval	observed: 0.08 – 0.75; theoretical: 0 – 1	the weighted average of the scaled accuracy (weight = 0.5), precision (weight = 0.25), and description detail (weight = 0.25) scores for the description of the Forest soundscape (see Appendix 5B and the GitHub link provided below for details)
	<i>In Situ</i> soundscape discernment	interval	observed: 0 – 0.73; theoretical: 0 – 1	the weighted average of the scaled accuracy (weight = 0.5), precision (weight = 0.25), and description detail (weight = 0.25) scores for the description of the <i>In Situ</i> soundscapes (see Appendix 5B and the GitHub link provided below for details)
	Penguin Colony soundscape discernment	interval	observed: 0 – 0.61; theoretical: 0 – 1	the weighted average of the scaled accuracy (weight = 0.5), precision (weight = 0.25), and description detail (weight = 0.25) scores for the description of the Penguin Colony soundscape (see Appendix 5B and the GitHub link provided below for details)
	Urban soundscape discernment	interval	observed: 0.13 – 0.73; theoretical: 0 – 1	the weighted average of the scaled accuracy (weight = 0.5), precision (weight = 0.25), and description detail (weight = 0.25) scores for the description of the Urban soundscape (see Appendix 5B and the GitHub link provided below for details)

Table 5.1. (continued).

organizational category	name	type	levels or observed and theoretical range	description/derivation
soundscape valuation	soundscape valuation	interval	observed: 1 – 5; theoretical: 1 – 5	the mean of the five soundscape valuation scale items for each soundscape prompt (averaged due to moderate unidimensionality; see Appendix 5B)
	Forest soundscape valuation	interval	observed: 2 – 5; theoretical: 1 – 5	the mean of the five soundscape valuation scale items for the Forest soundscape (averaged due to moderate unidimensionality; see Appendix 5B)
	<i>In Situ</i> soundscape valuation	interval	observed: 1 – 5; theoretical: 1 – 5	the mean of the five soundscape valuation scale items for the <i>In Situ</i> soundscapes (averaged due to moderate unidimensionality; see Appendix 5B)
	Penguin Colony soundscape valuation	interval	observed: 2 – 5; theoretical: 1 – 5	the mean of the five soundscape valuation scale items for the Penguin Colony soundscape (averaged due to moderate unidimensionality; see Appendix 5B)
	Urban soundscape valuation	interval	observed: 1 – 5; theoretical: 1 – 5	the mean of the five soundscape valuation scale items for the Urban soundscape (averaged due to moderate unidimensionality; see Appendix 5B)
soundscape location identification	soundscape location identification	interval	observed: 0 – 1; theoretical: 0 – 1	the mean of the scaled accuracy and precision scores for each soundscape location identification
	Forest location identification	interval	observed: 0 – 1; theoretical: 0 – 1	the mean of the scaled accuracy and precision scores for the Forest soundscape location identification
	Penguin Colony location identification	interval	observed: 0 – 1; theoretical: 0 – 1	the mean of the scaled accuracy and precision scores for the Penguin Colony soundscape location identification
	Urban location identification	interval	observed: 0 – 1; theoretical: 0 – 1	the mean of the scaled accuracy and precision scores for the Urban soundscape location identification

Table 5.1. (continued).

organizational category	name	type	levels or observed and theoretical range	description/derivation
demographics	occupation	binary	related, unrelated	whether or not the participant's primary occupation is related to nature or nature-based tourism (self-reported)
	education	ordinal	elementary, secondary, some post-secondary, bachelor's degree, graduate degree	the participant's highest level of education (self-reported)
	gender	binary	male, female	the surveyor's perception of the participant's gender
	age	ratio	observed: 18 – 69; theoretical: 18 – 122	the participant's age (self-reported)
	country	binary	Argentina, other	the participant's country of current residence with all but Argentina grouped as "other" (self-reported)
	years of residence	ratio	observed: 0 – 69; theoretical: 0 – 122	the participant's number of years lived in Tierra del Fuego (self-reported)
	reason for residence	categorical	visitor, original resident, economic reasons, lifestyle reasons, family reasons	the coded free responses as to why the participant had moved to Tierra del Fuego (if they had indeed moved there; self-reported)
potentially confounding covariates	survey number	interval	observed: 0 – 233	the number referring to the order in which the surveys were completed
	day of surveying	interval	observed: 0 – 21	the day of the survey period, not counting days on which no surveys were conducted
	minute of surveying	interval	observed: 4.6 – 524.9; theoretical: 0 – 545.6	the minute of the day at which the survey began, relative to the first overall time at which a potential participant was asked
	survey duration	ratio	observed: 469 – 1,701 (07:49 – 28:21)	the duration of the survey in seconds
	survey site	categorical	Kuanip, San Martín, Paseo del Fuego	the site of the survey

The nature relatedness survey section was closely modeled on the NR-6 scale of Nisbet and Zelenski (2013) in which participants rate their agreement with six statements about their relationship with the natural world on five-point scales. We slightly modified the phrasing of several original NR-6 statements to adapt to the cultural context and to increase participant understanding (see Appendix 5A).

In the section about sensory experiences of nature, participants rated the importance of each of their five senses (vision, hearing, touch, smell, and taste) in their experiences of nature using a four-point scale.

For the section on soundscape discernment, valuation, and location identification, participants responded to the same instructions for each of a sequence of the following four randomly ordered prompts: 1) the sounds they had heard in approximately the half-minute preceding the survey (sounds generally included those of vehicles, people walking, and people talking; hereafter, *In Situ*), 2) a 20-second recording from a Fuegian forest near a North American beaver (*Castor canadensis*) pond in Andorra Valley just outside of Ushuaia featuring sounds of wind, passerine vocalizations, and a beaver entering the pond (hereafter, *Forest*), 3) a 20-second recording from a Magellanic penguin (*Spheniscus magellanicus*) colony on Martillo Island featuring sounds of wind, waves, and vocalizations from Magellanic penguin chicks and adults (hereafter, *Penguin Colony*), and 4) a 20-second recording from the city of Ushuaia featuring sounds of passing cars, a stationary motor, a ship horn, and passerine calls (hereafter, *Urban*). Recording locations are shown in Figure 5.1C, and the three sound files are accessible via GitHub at https://github.itap.purdue.edu/PijanowskiGroup/Francomano_et_al_2021_Soundscape_Perception_in_TDF. Audio files were played to participants from a tablet at maximum volume through Audio-Technica QuietPoint 50 active noise-cancelling headphones (Audio-Technica 2019). This method of obtaining responses to audio prompts is similar to that employed by Marin et al. (2011).

To quantify soundscape discernment, participants were first asked to list and describe the sounds they heard in the prompt. The survey administrator wrote down the reported sounds and noted whether or not participant descriptions of each sound contained each of the following

characteristics: amplitude, frequency, timbre, imitation, spatial reference, timing, and comparison (see the aforementioned GitHub link for definitions and examples). The survey administrator coded each listed sound for its accuracy and precision (see the above link for details).

We considered soundscape valuation to be a participant's appreciation of the personal, social, and ecological significance of a given soundscape. To measure this variable, we developed the soundscape valuation scale—a five-item agreement-based scale containing the following items:

1. I liked the sounds I heard.
2. The sounds I heard triggered memories.
3. The sounds I heard provided me with information about the place in which they occurred.
4. The sounds I heard have an effect (either positive or negative) on the animals living where the sounds occurred.
5. The sounds I heard made me feel emotions.

These statements were chosen to allow a participant to express their view of a soundscape's importance from several different personal and ecological perspectives and were inspired in part by the “soundscape values” proposed by Dumyahn and Pijanowski (2011).

Finally, for location identification of the three recordings, participants were asked where they thought the recording was made, and the survey administrator scored each response for its accuracy and precision (on three- and four-point scales, respectively). In addition, the surveyor wrote down any qualitative observations about the participants' actions or the nature of their responses that could not have been otherwise captured in the survey data.

5.2.3 Data collection

Street intercept surveys were administered on 21 separate days between 16 July 2019 and 15 August 2019 between 11:30 and 21:00. Surveys were conducted in three sites within the city of Ushuaia: Kuanip Street (one of the city's principal commercial streets with minimal tourist traffic), San Martín Avenue (the city's main street with much tourist traffic), and Paseo del Fuego Shopping Mall (a mall featuring a gym, movie theater, and supermarket; Figure 5.1D – 5.1J). We chose these three sites because they are Ushuaia's three principal public commercial

centers, geographically distributed across the city, and frequented by different social groups. Surveying alternated daily between the two outdoor sites (12 total days split evenly between Kuanip and San Martín) except for days with inclement weather, when surveying was conducted in the entrance of Paseo del Fuego (9 days). Survey administration and sampling techniques were similar to those described by Flint et al. (2016) and Buschmann (2019), and they are presented in further detail in Appendix 5B. Additional information on dates, times, and sites of surveys is also available in Figures 5B.2 to 5B.5.

5.2.4 Analysis

Preparatory data transformation and evaluation

Incomplete survey responses were discarded, and raw data were transformed into analysis-form variables (listed in Table 5.1) as indicated in a spreadsheet available at the above GitHub link. All analyses were conducted in R 4.0.2 (R Core Team 2020) with packages “car”, “corrplot”, “dendextend”, “dplyr”, “emmeans”, “Hmisc”, “lmerTest”, “MASS”, “multilevel”, “openxlsx”, “ordinal”, “reshape”, and “vegan” (Fox and Weisberg 2019; Wei and Simko 2017; Galili 2015; Wickham et al. 2019; Lenth 2019; Harrell Jr. 2018; Kuznetsova et al. 2017; Venables and Ripley 2002; Bliese 2016; Walker 2018; Christensen 2019; Wickham 2007; Oksanen et al. 2018). Code is available at the aforementioned GitHub link. To evaluate the dimensionality of the composite scales employed in this study (nature relatedness and soundscape valuation for each of the four soundscape prompts), we calculated Cronbach’s alpha and plotted the first two principal components of principal components analyses (PCAs; Bernard 2011); results are provided in Appendix 5B (Figure 5B.1).

Statistical tests

To evaluate the importance of hearing relative to other senses in experiences of nature, we performed a mixed-effects ordinal logistic regression with sense importance as the dependent variable, sense as a fixed independent variable, and survey number as a random independent variable. The proportional odds assumption was tested (Harrell 2015; Christensen 2018), and the significance of the model was evaluated through comparison against a null model. Our prediction

that hearing is of secondary importance was tested using two *a priori* contrasts comparing vision against hearing and hearing against touch, smell, and taste.

We employed three linear mixed-effects models to examine the influence of the various soundscape prompts on soundscape discernment, valuation, and location identification. Each of the three soundscape perception variables was treated as the dependent variable in a distinct model with soundscape prompt as a fixed independent variable and survey number as a random independent variable. Assumptions of linearity, homogeneity of variance, and normality of error were graphically verified for each model. Pairwise contrasts were evaluated using a Tukey HSD test.

To explore the relationships between nature relatedness, mean sensory importance, the relative importance of hearing, and the discernment, valuation, and location identification of the four soundscape prompts (excluding location identification for the *In Situ* soundscape prompt), we applied nonparametric Spearman correlations (since Shapiro tests indicated that all but one variable failed to meet the assumption of normality, even following \log_{10} transforms). Given the exploratory nature of this investigation and the relative inconsequentialness of committing Type I Error, we chose not to adjust p-values, as recommended by McDonald (2009).

The influence of demographic factors on the importance of the five senses in experiences of nature was examined through a redundancy analysis that treated the five sense importance variables as dependent variables and all demographic variables and covariates listed in Table 5.1 as independent variables (in the full possible model). Covariates were included in the model to account for any confounding effects they could have induced. We fit a full and null model, using the natural log transformations of age and survey duration to improve their distributional symmetry. We examined bivariate plots of all pairs of ordinal, interval, or ratio variables to ensure that none seemed particularly correlated, which led us to remove day of surveying in favor of survey number. We then performed forward and backward additions and subtractions of non-conditioning independent variables and chose the best fitting model based on permutational p-values and AIC (Borcard et al. 2011). The resultant model was checked for collinearity using

variance inflation factors, and its explanatory power and significance were respectively evaluated considering the adjusted R^2 value and permutational p-value.

The redundancy analysis revealed that only gender and survey duration were significant predictors, so as a follow-up test, we performed a mixed-effects ordinal logistic regression with sense importance as the dependent variable, sense, gender, and their interaction as fixed independent variables, and survey number as a random independent variable. The model was fitted and checked as described above, employing pairwise comparisons between genders for each sense.

To broadly assess the influence of demographics on nature relatedness, mean sensory importance, relative importance of hearing, and discernment, valuation, and location identification (when applicable) of each of the four soundscape prompts, we conducted another redundancy analysis as described above. Age, survey duration, and Forest and Urban discernment were natural log transformed. As demographic and covariate variables both remained after the model selection procedure, we conditioned the covariates in a partial redundancy analysis, that was evaluated as described above.

In addition to our general hypotheses and predictions described in the Introduction, we had several specific predictions and hypotheses related to the three identified social groups of Ushuaia (long-term residents, amenity or lifestyle migrants, and economic migrants; Herbert 2014). Therefore, regardless of the redundancy analysis outcome, we tested them directly using general linear models. If models contained multiple independent variables, bidirectional, AIC-based model selection was performed. Assumptions of linearity, normality of error, and homogeneity of variance were then evaluated graphically, and if they were not met, the independent variable was square root transformed. Specific demographic-related hypotheses, predictions, and model formulae are presented in Table 5B.1.

5.3 Results

We obtained 233 complete responses from 1,008 survey requests (23% response rate; Figures 5B.2 – 5B.5). Six surveys were conducted in English (primarily with tourists), while the rest

were conducted in Spanish. Participants were 48% male and 52% female (Figure 5B.5). Maximum education levels were 9% primary school, 34% secondary school, 13% some post-secondary education, 42% bachelor's degree, and 2% graduate degree (Figure 5B.6), and 24% reported having a nature-related occupation. Non-residents of Tierra del Fuego composed 19% of our participants, 6% of participants were from six countries other than Argentina, and 19% had lived in Tierra del Fuego for their whole lives (Figure 5B.7). Our sample skewed more educated and slightly younger than the provincial population (Dirección General de Estadística y Censos 2013). Mean, median, and mode nature relatedness were all around 4 on the 0 – 5 NR-6 scale, with higher values representing greater nature relatedness.

Self-reported importance of senses in experiences of nature differed between senses (likelihood ratio statistic = 223.15; d.f. = 4; $p < 0.001$; Figure 5.2). In our *a priori* contrasts, vision was rated as more important than hearing (z-ratio = 6.34; $p < 0.001$), and hearing was rated as more important than the remaining three senses (z-ratio = 6.49; $p < 0.001$). Many individuals stated that all senses were of high importance, but others tended to follow the pattern indicated by the above tests (Figure 5B.9).

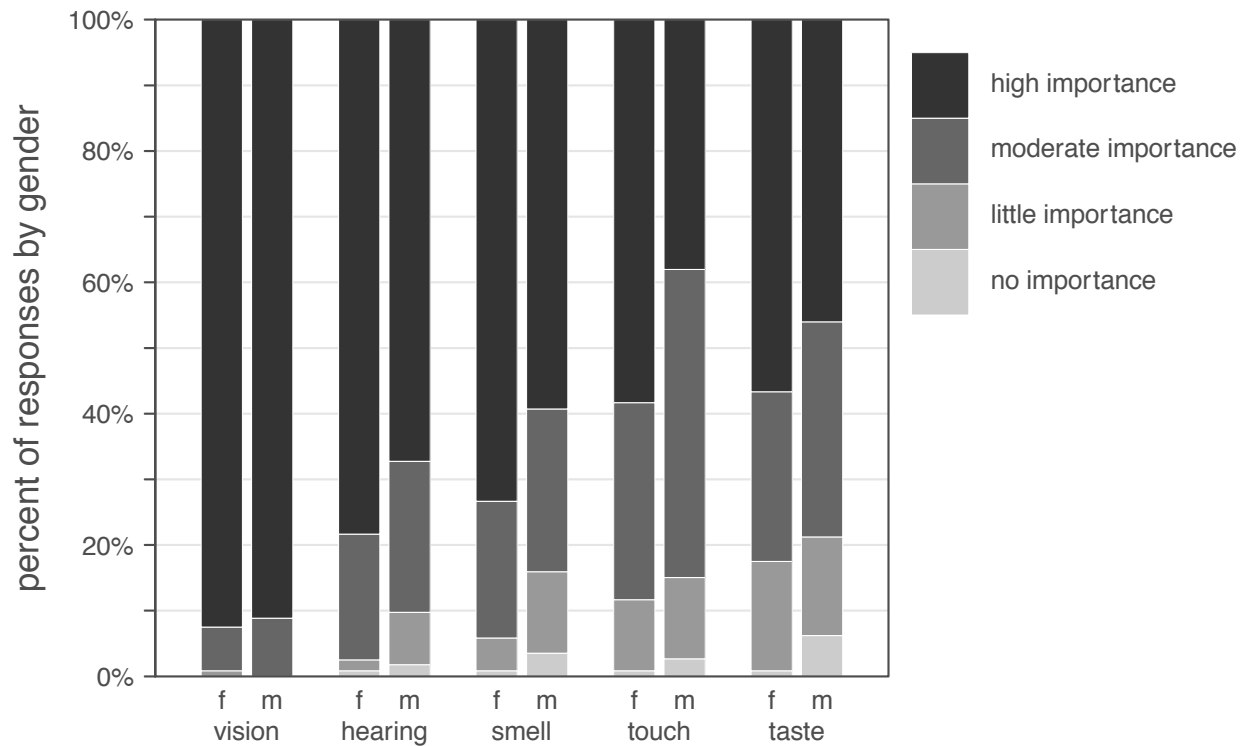


Figure 5.2. Reported importance of the five senses in experiences of nature. Stacked bars represent the percent of participants of each gender who rated each sense with the degree of importance specified by the scale on the right (f = female; m = male).

Soundscape discernment differed between prompts ($F = 23.24$; d.f. = 3, 696; $p < 0.001$; Figure 5.3A; see Table 5B.2 for all contrast statistics); it was highest for *In Situ*, followed by Forest, and then followed by approximately equal means for Penguin Colony and Urban. Soundscape valuation differed between all four prompts ($F = 142.14$; d.f. = 3, 696; $p < 0.001$; Figure 5.3B) with that of Forest being highest, followed in descending order by Penguin Colony, Urban, and *In Situ*. Soundscape location identification differed as well ($F = 4.28$; d.f. = 2, 464; $p = 0.014$; Figure 5.3C). Location identification was highest for Urban, but it did not differ substantially between Forest and Penguin Colony.

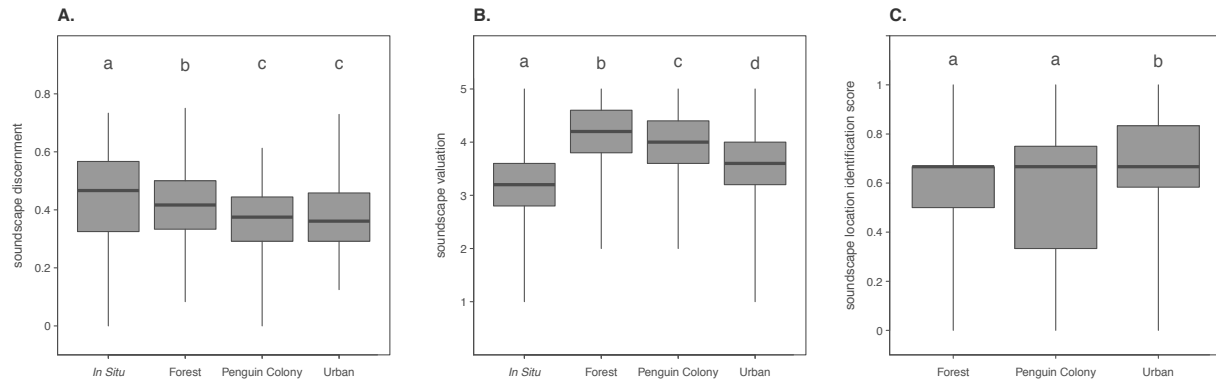


Figure 5.3. Differences in soundscape A) discernment, B) valuation, and C) location identification by soundscape prompt. Horizontal lines in boxes represent medians, and boxes extend from the first to third quartile. Whiskers extend to minima and maxima. Differing letters between prompts signify contrasts with $p \leq 0.05$.

Correlations of interest are presented in Figure 5.4. Nature relatedness and mean sensory importance were positively correlated, as were nature relatedness and soundscape valuation for all soundscapes except *In Situ*. Nature relatedness did not, however, exhibit correlations with soundscape discernment or location identification for any soundscape. Soundscape valuation was positively correlated with both soundscape discernment and location identification, but only for the two more natural soundscapes—Forest and Penguin Colony. Soundscape discernment and location identification of a given soundscape were positively correlated in all three cases.

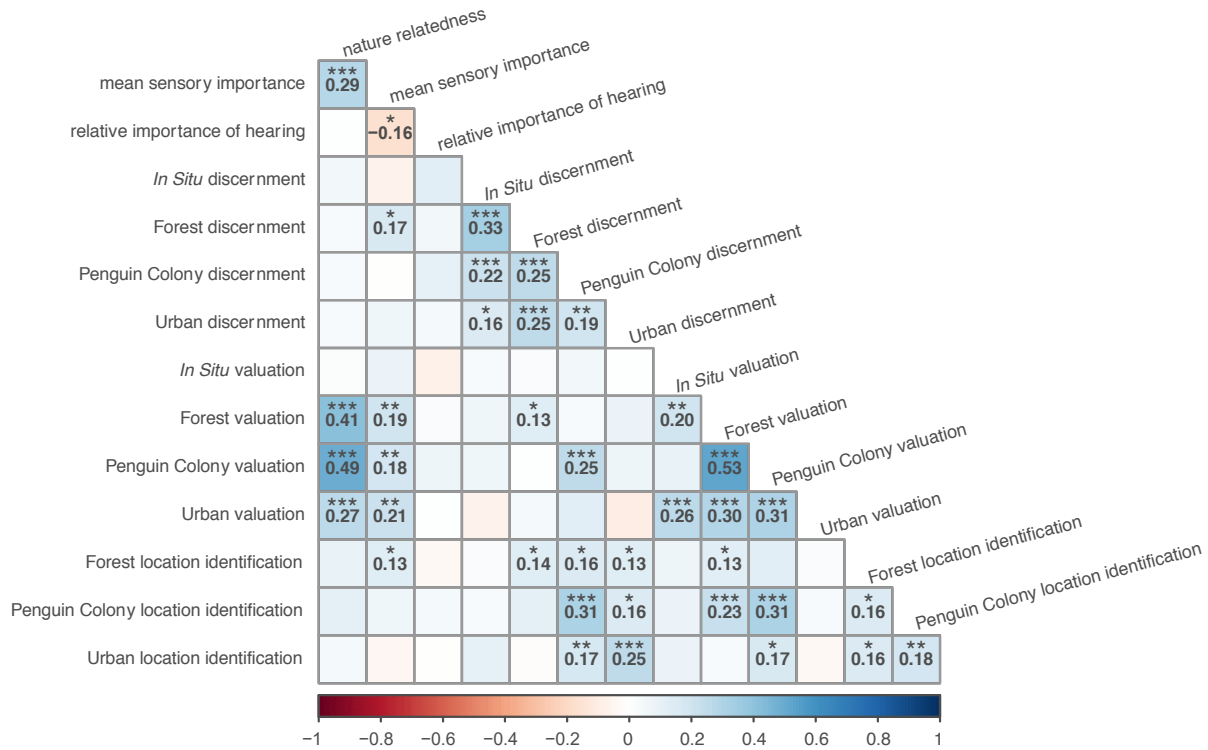


Figure 5.4. Spearman correlations between dependent variables considered in this study. Correlation coefficients are indicated by the colors presented in the scale at the bottom of the figure, and coefficients with p-values ≤ 0.05 are printed in their corresponding boxes. P-values are indicated as follows: * signifies $0.05 \geq p > 0.01$, ** signifies $0.01 \geq p > 0.001$, and *** signifies $p \leq 0.001$.

Model selection yielded a redundancy analysis with a single demographic variable—gender—and survey duration as meaningful predictors of sensory importance (adjusted $R^2 = 0.03$; pseudo- $F = 4.25$; d.f. = 2, 230; $p = 0.001$). The generalized ordinal logistic regression employed as a follow-up test produced an overall likelihood ratio statistic of 235.69 with 9 degrees of freedom and $p < 0.001$. The pairwise contrasts revealed that women reported higher importance than men within smell (z-ratio = 2.80; $p = 0.005$), touch (z-ratio = 2.60; $p = 0.009$), and hearing (z-ratio = 2.55; $p = 0.011$; Figure 5.2). Results for taste and vision, respectively, were: z-ratio = 1.92, $p = 0.055$ and z-ratio = 0.41, $p = 0.682$.

The second redundancy analysis revealed that age, gender, and occupation influence the suite of dependent variables employed: nature relatedness, mean sensory importance, relative importance of hearing, and discernment, valuation, and location identification (when applicable) of each of the four soundscape prompts (adjusted $R^2 = 0.02$; pseudo- $F = 2.95$; d.f. = 3, 226; $p = 0.001$). The

correlation triplot (Figure 5.5) indicates that having a nature-based occupation and being older appear to positively influence nature relatedness and soundscape valuation while negatively influencing soundscape discernment and location identification for most prompts other than Penguin Colony. Being female appears to relate to higher mean sensory importance and perception of the Forest soundscape, while being male appears linked to *In Situ* valuation, Penguin Colony discernment and location identification, and Urban location identification.

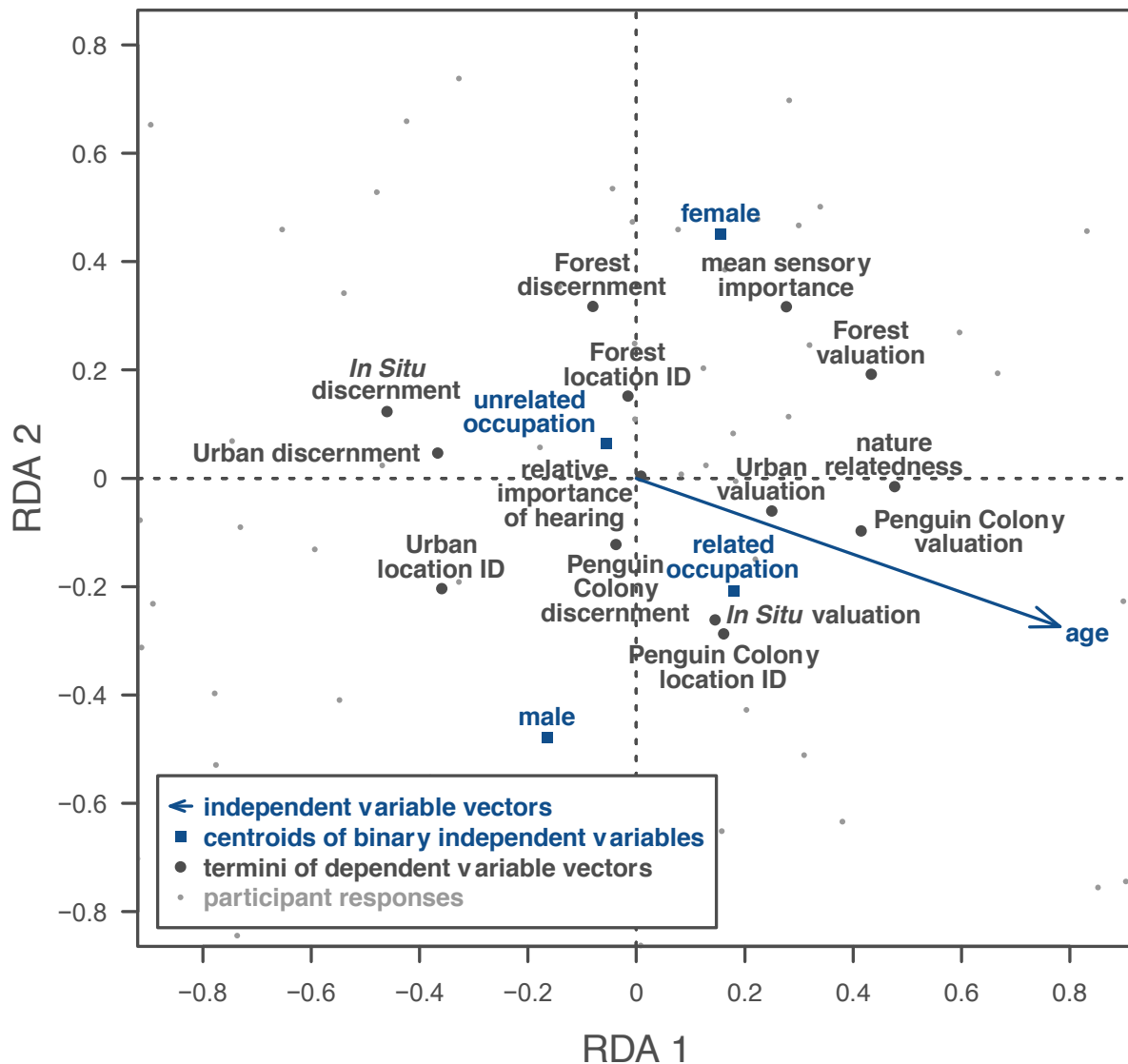


Figure 5.5. Correlation triplot showing the influence of demographic variables on nature relatedness, mean sensory importance, the relative importance of hearing, and soundscape discernment, valuation, and location identification (when applicable) for each soundscape prompt.

Attempts to tests the specific demographic-related hypotheses outlined in Table 5B.1 generally yielded insignificant ($p > 0.05$) or null (due to AIC-based elimination of all independent variables) models, with two exceptions: having a nature-based occupation was found to yield higher nature relatedness ($F = 5.59$; d.f. = 1, 231; $p = 0.019$) and Penguin Colony soundscape valuation ($F = 7.03$; d.f. = 1, 231; $p = 0.008$).

5.4 Discussion

The appeal of using the soundscape paradigm to promote nature relatedness partially rests on the idea that hearing can convey a great deal of information and is generally a familiar sense, but is often an afterthought (Dumyahn and Pijanowski 2011)—a “passive” sense in the terms of Yang and Kang (2005). Indeed, participants in our survey reported that hearing was of secondary importance to vision in their experiences of nature (Figure 5.2), echoing findings from Roque et al. (2015) and Schifferstein (2006). It is important to note that sensory importance may vary across cultures (Hutmacher 2019; Majid et al. 2018), and it may depend on situational context (e.g., Schifferstein 2006). In experiences of nature, the relative importance of senses could vary based on habitat, time of day, or season. For example, vision is not very useful at night in the rainforest, while hearing and smell might be hyper-stimulated in a raucous, stinky penguin colony. Overall, however, in the cultural and situational contexts we considered, hearing was of secondary importance in experiences of nature—a ranking that might be amenable to improvement through interventions like soundscape-based educational programs.

We also found partial support for the hypothesized relationship between nature relatedness and the three aspects of soundscape perception that we considered. Nature relatedness was positively correlated with Forest, Penguin Colony, and Urban soundscape valuation, but not with soundscape discernment or location identification (Figure 5.4). This limited relationship suggests that soundscape perception may be linked to nature relatedness primarily at emotional and philosophical levels, as opposed to experiential and cognitive levels (*sensu* Ives et al. 2018). Soundscape valuation may represent a deeper, more internal human-soundscape relationship than soundscape discernment and location identification, which could be considered more superficial. As the emotional and philosophical levels of nature relatedness provide greater leverage for affecting positive change in social-ecological systems (Ives et al. 2018), this partial support for

our hypothesis still offers a favorable outlook on the use of the soundscape paradigm to promote positive social-ecological change. More generally, this finding also hints at how affective, as opposed to cognitive, aspects of nature relatedness may be more meaningful in terms of promoting pro-environmental behavior (Ives et al. 2018).

Some distinctions can be drawn between our findings for the two more natural soundscapes (Forest and Penguin Colony) and those for the two soundscapes that were more technophonically-dominated (*In Situ* and Urban). Correlation coefficients between nature relatedness and soundscape valuation were highest for the two more natural soundscapes, indicating that valuation of natural soundscapes may be especially linked to nature relatedness. Ample evidence suggests a human preference for more natural, as opposed to technophonically-dominated, soundscapes (Axelsson et al. 2010; Yang and Kang 2005; Payne 2013; Hall et al. 2013; Arras et al. 2003; Carles et al. 1999; Pilcher et al. 2009; Benfield et al. 2018). Most of the above studies, however, considered preference or pleasantness, as opposed to our more complex construct of valuation. Our soundscape valuation scale considered pleasure (“I liked the sounds I heard”, was the first item), but it also sought to measure one’s appreciation for the personal, social, and ecological importance of a given soundscape. By our measure, one could still highly value a soundscape, even if they did not like it.

Another finding related to soundscape “naturalness” concerned the predicted positive correlations between the three aspects of soundscape perception within each soundscape prompt (e.g., between Forest discernment, Forest valuation, and Forest location identification). This prediction was fully validated for just the two more natural soundscapes. Considered together, this finding and the high correlations between natural soundscape valuation and nature relatedness, suggest that nature relatedness may be promoted through the three aspects of soundscape perception, but with a couple of caveats: 1) Emphasizing soundscape valuation is likely a more direct approach to foster nature relatedness than emphasizing soundscape discernment and/or location identification. A focus on the latter two concepts might be reliant on a chain reaction (i.e. soundscape discernment and/or location identification promoting soundscape valuation, which in turn promotes nature relatedness). 2) These relationships might only be dependable when considering natural soundscapes.

Furthermore, given the inclusion of the raucous but natural Penguin Colony soundscape in our study, these results suggest that the classes of dominant sound sources (i.e. natural or technological) may influence soundscape perception more strongly than psychoacoustic parameters. Axelson et al. (2010) previously found an effect of sound sources on soundscape pleasantness, even after controlling for loudness. Much work remains to ascertain the relative extent to which sound source identity/classification and a full suite of psychoacoustic parameters influence soundscape perception. This topic merits future study in field and laboratory conditions for a greater diversity of soundscapes and a wider array of cultural contexts.

Our familiarity-based hypothesis concerning soundscape discernment found weak support. We expected a descending ranking from *In Situ* to Urban, Forest, and then Penguin Colony. The *In Situ* soundscape had just been heard in its environmental context, and given the survey sites in Ushuaia, the Urban soundscape from the city would likely be familiar as well. For the other two prompts, it is much more likely that one would have experienced a forest with passerine song than a penguin colony, so Penguin Colony was expected to follow Forest. *In Situ* did rank highest, but it was followed by Forest and then Urban and Penguin Colony, which were statistically similar. The flipping of Forest and Urban from our expected order may be due to the fact that the sounds in the Forest soundscape were slightly less ambiguous and potentially less misleading than those in the Urban soundscape. Especially if study participants had previously heard the Penguin Colony soundscape and interpreted it as “marine” to some extent, the ship horn at the beginning of the Urban soundscape seems to have misled some participants who subsequently thought that the passing cars were waves and the motor sound (from an idling truck or generator) was a boat engine. The difference in discernment between the Urban and *In Situ* prompts (which generally represented the two most qualitatively similar prompts) raises the question of whether similar, or even identical, soundscapes will always be discerned better *in situ* (relative to a recording) due to better audio quality, enhanced spatial awareness of audio sources, and additional sensory inputs (especially vision). In limited studies comparing perception of *in situ* and prerecorded soundscapes, playback methods and perceptual measures have largely differed from those we employed, precluding useful comparisons (e.g., Sudarsono et al. 2016; Guastavino et al. 2005). Nonetheless, this potential difference has important implications for the design of programs based on the soundscape paradigm. The implementation and results of such

programs may differ vastly if structured around experiences of *in situ* or prerecorded soundscapes.

We expected to find differences in nature relatedness and soundscape perception between the social groups in Ushuaia that were distinguished by Herbert (2014). Generally, we had predicted that lifetime/long-term Fuegian residents, lifestyle migrants, and individuals with occupations related to nature or nature-based tourism would score higher on nature relatedness and most soundscape perception variables (see Table 5B.1 for specific demographic-related hypotheses and predictions). However, we found only minor differences that were primarily limited to general variables like gender and age—not years of residence or reason for residence.

One important exception is that those with nature-related occupations exhibited higher nature relatedness and valuation of the Penguin Colony soundscape. The former finding likely represents a positive feedback loop (i.e. someone who is highly nature related could seek out a nature-related occupation, which further increases their nature relatedness and encourages them to stay in that field of work; Rosa and Collado 2019; Zavestoski 2003). Higher valuation of the Penguin Colony soundscape among those with nature-related occupations may reflect the higher probability that they had previously visited the colony where the recording was made and developed an experiential connection with the place and its sounds; positive environmental attitudes have been broadly linked with experiences of nature (Rosa and Collado 2019). More generally, our findings suggest that social divisions in Ushuaia around nature relatedness may be defined more by occupation than by years of residence or reason for residence. In this context, any local soundscape-based programming to promote nature relatedness and social-ecological sustainability might be most appropriately targeted to those without nature-related occupations. To facilitate this programming, the robust system of nature-based tourism in Ushuaia (Raya Rey et al. 2017) could be leveraged to serve the local population through targeted community outreach. One source of tension highlighted by Herbert (2014) is that tourism benefits are not equitably shared amongst Ushuaians. Many of the nature-based touristic activities in Ushuaia are expensive, so reduced-cost natural excursions offered to locals could improve the public image of the tourism industry while simultaneously promoting public nature relatedness by allowing locals to experience the natural places and soundscapes that lie just outside their city.

Our results concerning the influence of gender on sensory importance, soundscape perception, and nature relatedness exhibited limited similarities with previous research. Our finding of women reporting higher sense importance corresponds with Schifferstein's (2006) finding that women reported slightly higher importance of senses in product evaluations. Yang and Kang (2005) noted that women responded more favorably toward several sounds including the sound of water, but the low R^2 value of our redundancy analysis and lack of clear general relationships between gender and soundscape perception in Figure 5.5 preclude any conclusions. More broadly, work by Clayton (2003), Eisler et al. (2003), Kollmuss and Agyeman (2002), and Zelezny et al. (2000) suggested that women tend to exhibit slightly more pro-environmental attitudes and behaviors, perhaps due to social promotion (in certain cultural contexts) of greater empathy and social responsibility in women (Zelezny et al. 2000). We did not explicitly test for the direct influence of gender on nature relatedness, but a clear relationship was not evident in Figure 5.5. This disparate previous research suggests that women may connect to nature through soundscape valuation more easily or strongly than men. Our findings did not provide strong support for this hypothesis, but they also did not refute it. Potential gender differences remain an important consideration in determining how to best leverage the soundscape paradigm to promote nature relatedness and social-ecological sustainability.

Our findings related to the influence of age on soundscape perception and nature relatedness are generally coherent with previous research. The negative relationships between age and soundscape discernment/location identification may be a product of the fact that human hearing often deteriorates with increasing age (Bowl and Dawson 2019). Regarding soundscape valuation, Yang and Kang (2005) found that preference for natural sounds was higher for older individuals, while preference for technophonic sounds was higher for younger individuals. In our results, age was positively related to valuation of all soundscape prompts. This discrepancy between our findings for technophonic sounds and those of Yang and Kang (2005) may be related to our differing definitions of preference and valuation. As for nature relatedness, Colléony et al. (2017) also found older individuals to exhibit higher nature relatedness, but in their study and ours, it is unclear if this finding is due to a generational or aging-related effect. With a non-longitudinal study, it is impossible to tell if presently young people will become more nature related as they age or if presently old people were already less nature related when

they were younger. Soundscape-based educational programming has largely been targeted at youth (Ghadiri Khanaposhtani et al. 2018a, 2018b; US National Park Service 2018b; but see Barclay 2014); longitudinal investigation of nature relatedness and soundscape perception would help to determine the relative value of such programming at various ages and the longevity of its efficacy.

Beyond our contribution to the understanding of soundscape perception and nature relatedness, the soundscape valuation scale we developed may also be applicable in other contexts. Due to the nature of street-intercept surveys, we had to be judicious with the length of our survey questions and the number of questions included in the survey. We think the internal consistency and comprehensiveness of our soundscape valuation scale might be further improved by adding additional scale items. Particularly, recognition of the ecological importance of soundscapes could be probed further and may emerge as a clearly defined second dimension of soundscape valuation (in addition to recognition of personal importance). In addition, we used headphone-administered soundscape prompts in public spaces, which represented a compromise between representative sampling and acoustic quality/noise interference. Future large-scale studies seeking generalizability may wish to use an acoustically insulated booth in a public space to provide a more controlled acoustic and visual environment, while still allowing for random sampling of passersby (e.g., Marin et al. 2011).

We also recommend the testing of a more geographically and acoustically diverse set of audio prompts, more direct comparison of *in situ* versus prerecorded prompts, and deeper investigation of the role of “naturalness” in soundscape perception. For example, the *in situ* versus prerecorded distinction could be probed by replicating this study at the other recording locations we used outside of Ushuaia. Audio-based surveys are unfortunately time consuming—our average survey duration was over 12 minutes (Figure E.8), and participants in a study by Hall et al. (2013) took about 5 hours to respond to 219 audio prompts. Despite this logistical hurdle, the diversity of global soundscapes necessitates testing of diverse audio prompts with explicit consideration of sound source composition and a comprehensive analysis of acoustic parameters. Moreover, given the potential cultural variability in the relative importance of hearing (Hutmacher 2019; Majid et al. 2018), nature relatedness (Eisler et al. 2003; Colléony et al. 2017), and soundscape

perception (Yang and Kang 2005), it is important to include more socio-demographically diverse participants.

5.5 Conclusions

This study provided important empirical evidence supporting the notion that nature relatedness can be promoted through a soundscape paradigm, as we identified positive correlations between nature relatedness and the valuation of soundscapes—particularly natural ones. The lack of correlations between nature relatedness and soundscape discernment or location identification indicates that the soundscape paradigm may promote nature relatedness more successfully at emotional and philosophical levels. These deep, affective human-nature connections are well suited to meaningfully impact social-ecological systems (Ives et al. 2018). For a given soundscape prompt, positive correlations between aspects of soundscape perception were generally only found for natural soundscapes as well. The “naturalness” of soundscapes thus appears to be an important factor in individual development of linkages between 1) extracting information from a soundscape, 2) valuing that soundscape, and 3) feeling a connection with the natural world represented by that soundscape. Our results show that enabling experiences of natural soundscapes may represent one way to promote nature relatedness, pro-environmental behavior, and social-ecological sustainability. We hope further work will elucidate this relationship in greater detail with an emphasis on global social and acoustic diversity, further exploration of soundscape valuation, and consideration of the relative importance of soundscape sources, informational content, and acoustic parameters.

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CHAPTER 6—CONCLUSION

Even after structuring a social-ecological research project with geographic boundaries and a theoretical or methodological framework, the questions one could ask and the approaches one could employ are nearly limitless. This dissertation has merely scratched the surface of the vast body of knowledge we could acquire by considering the role of sound and soundscapes in the social-ecological systems of Tierra del Fuego. Despite the necessarily limited nature of this work I believe that its depth has provided several important insights while its breadth has hinted at the potential of comprehensive, multi-method, sound-based studies of social-ecological systems.

Chapter 2, “Biogeographical and analytical implications of temporal variability in geographically diverse soundscapes”, laid some important groundwork for passive acoustic monitoring (PAM) by: 1) providing a framework for measuring temporal variability in soundscapes, 2) comparing temporal soundscape variability across times of day and geographically diverse sites, and 3) showing how different temporal sampling schemes can affect the representativeness of acoustic data. While geographically diverse, our site selection was not biogeographically comprehensive, so future work could seek greater generalizability. We also used a small subset of the universe of possible acoustic metrics, so further exploration of different metrics and sound type detection in the context of temporal variability could offer guidance for more diverse applications of PAM.

Chapter 3, “Sentinels for sentinels: passive acoustic and camera trap monitoring of sensitive penguin populations”, showed the promise of PAM for penguins through the revelation of clear diel and breeding stage dynamics and the presence of positive relationships between acoustic metrics and both small-spatial-extent camera trap data and large-spatial-extent colony density estimates. While our findings were encouraging, further ground truthing of relationships between acoustic metrics and penguin behavior and relative abundance will be needed before implementing PAM as a robust monitoring tool with unambiguous results. Our integration of acoustic studies with preexisting penguin research proved advantageous in terms of convenience, mutual benefit, and continuation of long-term data collection, but more specialized comparative data sources would allow for more robust conclusions. Namely, wider-angle camera trap photos and comprehensive nest or penguin counts around randomly located acoustic recorders would

yield more easily interpretable findings, particularly in terms of the spatial extent over which PAM provides the most meaningful data. Study of Magellanic (*Spheniscus magellanicus*) and southern rockhopper penguins (*Eudyptes chrysocome*) provided excellent contrast in terms of spatial distribution and nesting ecology, and study of additional species would allow for greater generalizability of findings. It would be especially interesting to include *Aptenodytes* spp. that do not use nests and to compare findings between different species with similar colony density and nesting ecology.

Chapter 4, “Acoustic monitoring shows invasive beavers (*Castor canadensis*) promote avian diversity in Tierra del Fuego”, revealed higher avian acoustic activity at post-beaver meadow sites relative to intact riparian forest sites in the spring and summer. That finding was supported by avian point counts that showed higher species richness, abundance, and functional group richness at the beaver pond and meadow sites. The counts also showed that ducks and raptors were associated with pond sites. Scaling up from these patch-level findings, a landscape-level study incorporating natural analog habitats (e.g., windthrow gaps and natural ponds) and beaver impacted areas in non-forest areas of Tierra del Fuego (i.e. peat bog, ecotone, and steppe habitats) would provide more complete information on the nature of beaver impacts throughout their invaded range. To fully understand the potential impacts of beaver eradication and forest restoration, it would also be valuable to compare sites with beaver eradication and no additional restoration efforts against sites with beaver eradication and various forms of active restoration techniques.

Chapter 5, “Human-nature connection and soundscape perception: insights from Tierra del Fuego, Argentina”, highlighted a positive correlation between nature relatedness and the valuation of natural soundscapes, while indicating that valuation of more natural soundscapes was higher than valuation of more technologically dominated soundscapes. These findings suggest that outreach programming focused on natural soundscapes may promote nature relatedness, though interventional studies would obviously be needed to support this hypothesis. Additional opportunities for further research include deeper exploration of the concept of soundscape valuation, incorporation of more diverse soundscape prompts, and further comparison of *in situ* and prerecorded prompts in more diverse locations. Insight into soundscape

perception could also be gained by evaluating the relative influence on perception of the quantitative acoustic characteristics and the semantic content of a given soundscape prompt.

Sound is certainly not the only lens through which we can view social-ecological systems, and it very well may not be the most appropriate or useful lens depending on the circumstances. However, in a noisy world where environmental crises are a dime a dozen, thinking a bit more about sound may just make us stop for a moment and listen—to nature, to people, to data, and to the needs of a wondrous planet being trampled by one of its luckiest species.

APPENDIX 2A—SUPPLEMENTARY FIGURES FOR CHAPTER 2

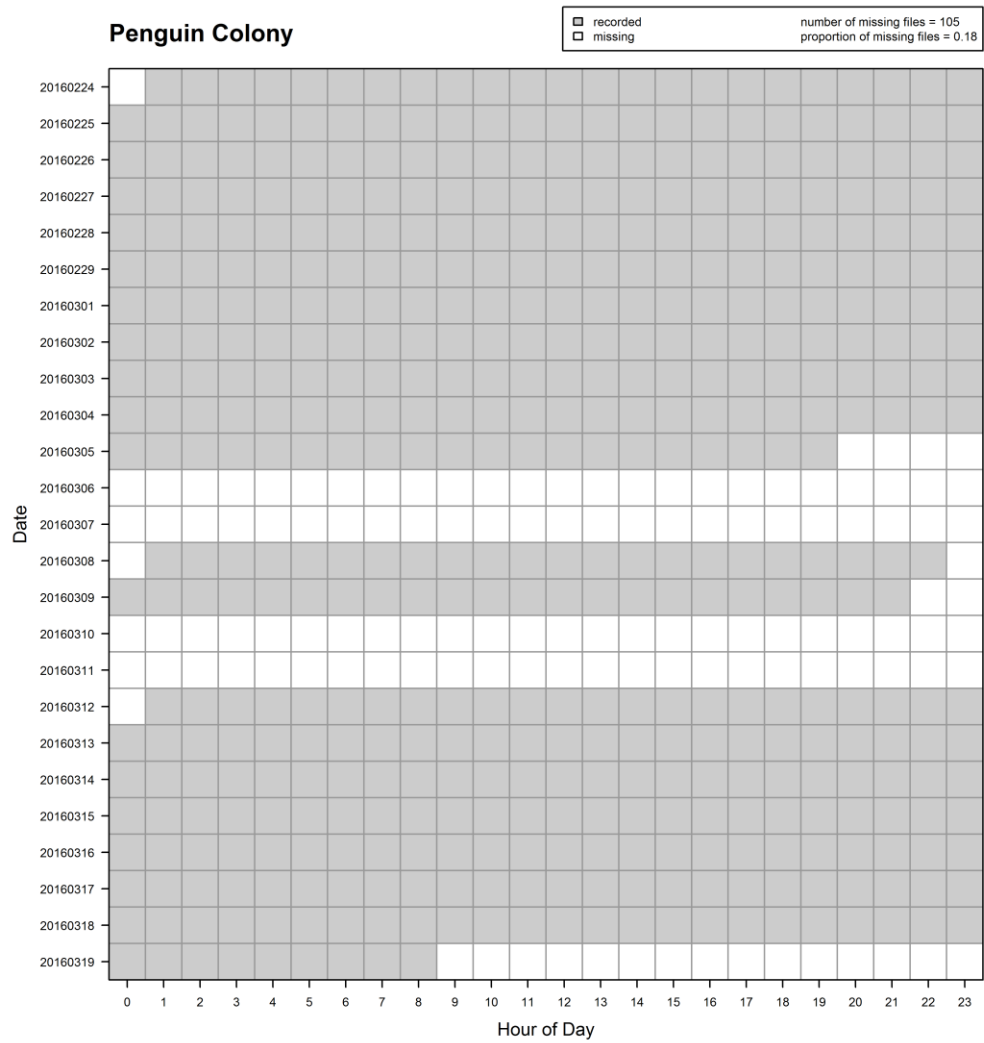


Figure 2A.1. Temporal data coverage for Penguin Colony.

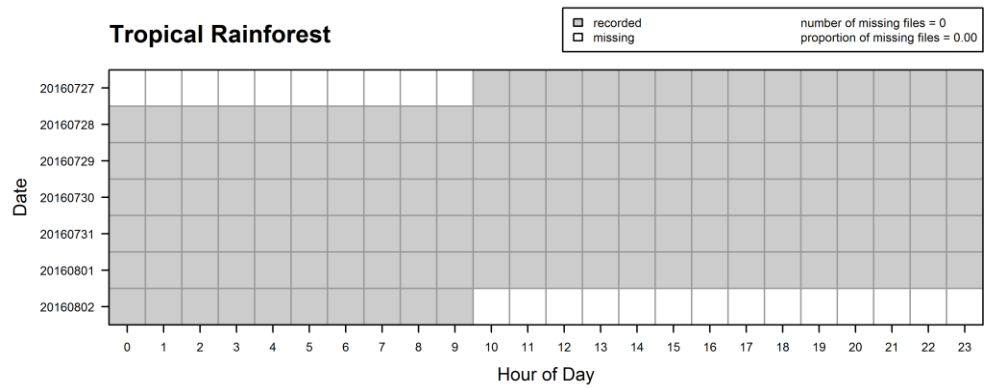


Figure 2A.2. Temporal data coverage for Tropical Rainforest.

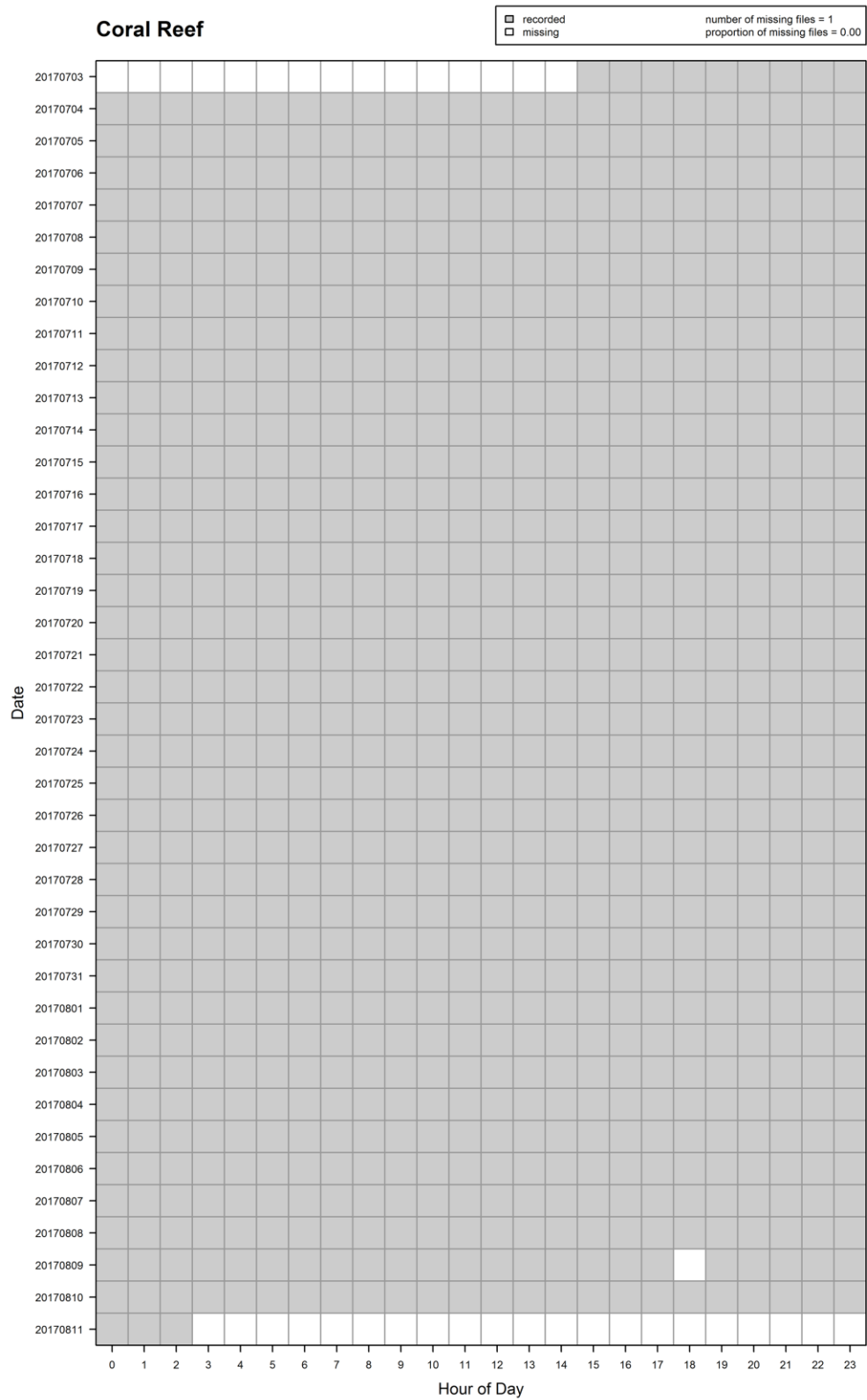


Figure 2A.4. Temporal data coverage for Coral Reef.

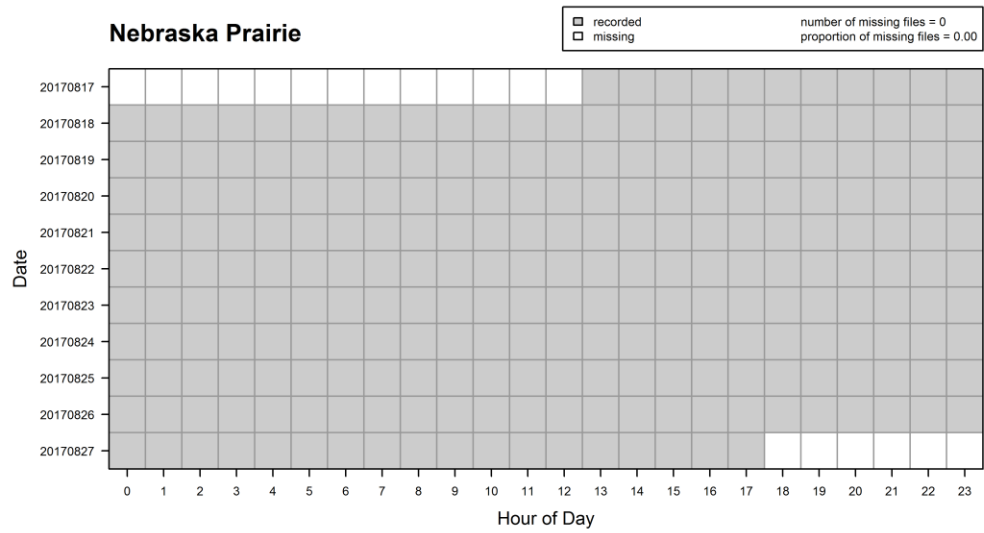


Figure 2A.6. Temporal data coverage for Nebraska Prairie.

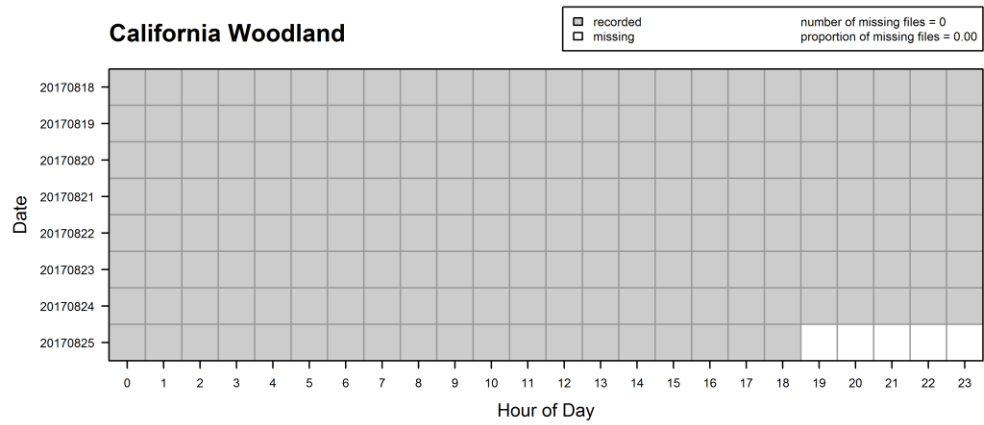


Figure 2A.7. Temporal data coverage for California Woodland.



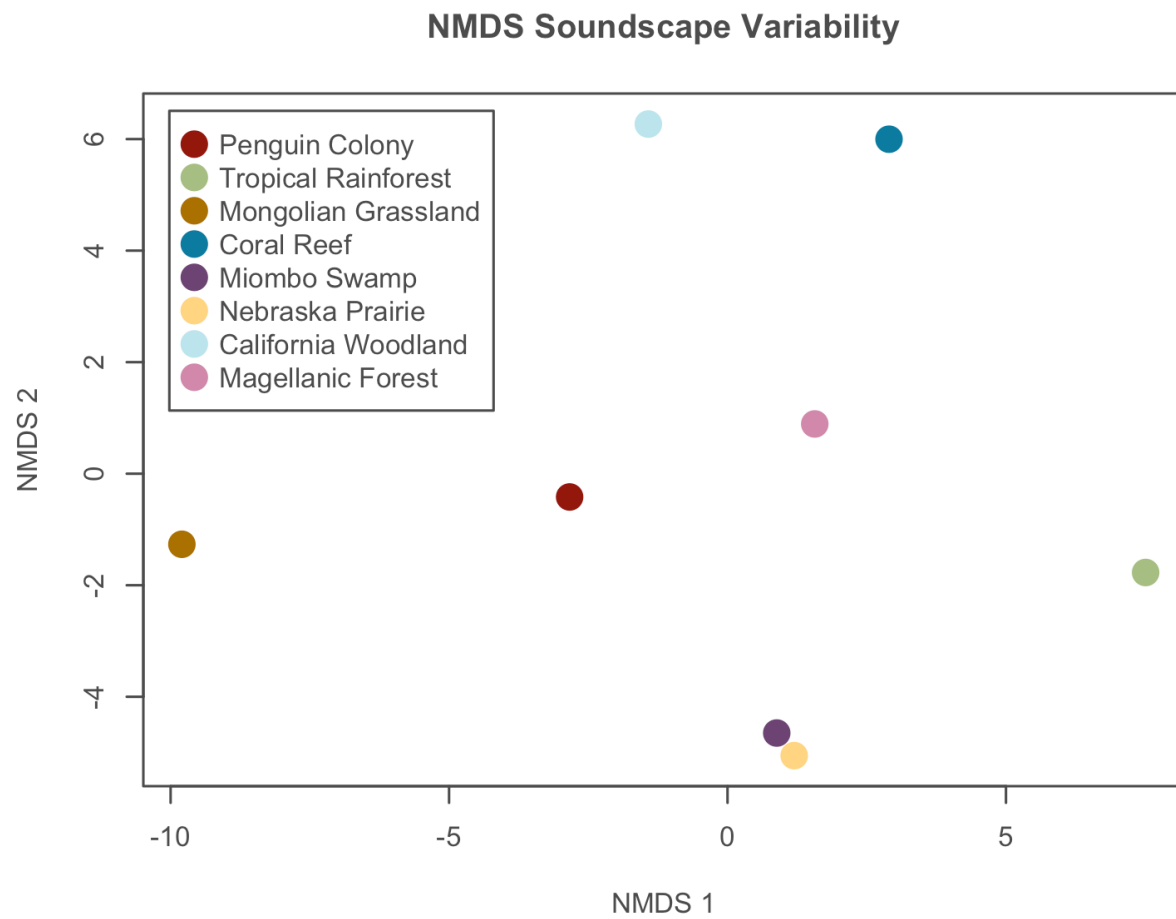


Figure 2A.9. Plot of non-metric multidimensional scaling (NMDS) using multi-scale temporal variability values for each site.

APPENDIX 4A—SUPPORTING INFORMATION FOR CHAPTER 4

4A.1 Site selection

Our choice of 15 sites was based on our number of available acoustic monitoring units and our desire to collect simultaneous acoustic data across all sites. While we needed sites to be human-accessible for point counts and acoustic recorder servicing, we also wanted to exclude potentially confounding technophonic sounds from our recordings. Given these conflicting impetuses, we chose sites within a 2-hour hike from a trailhead within a 0.5-hour drive from Ushuaia, but topographically isolated from the city and its major national road. Sites—at which acoustic recorders were installed and point counts were conducted—were separated from each other by at least 270 meters to reduce the chances of a) two devices recording sounds from a common source and b) double counting of individual birds (Ralph et al. 1995). No two sites within a single block were spaced more than 1,125 meters apart to maintain relative environmental homogeneity (aside from beaver impact states) within each block. The maximum elevation difference between sites in a block was 50 meters, and the ordering of sites by elevation was inconsistent between blocks. Recorders were installed on thin trees or snags at about 1.3 meters above ground level. In forest sites they were installed about 10 – 50 meters from the stream edge to reduce acoustic masking from water flow; in pond sites they were installed as close to the pond edge as possible while avoiding flow sounds; in meadow sites they were installed as close to the center of the deforested patch as possible. Coordinates of each site are provided in Table 4A.1. While edge habitats were included in the sampling radii of recorders and point counts, the existence of these habitats was considered a relevant effect of beaver presence.

Table 4A.1. Study site locations.

block	site name	impact state	latitude	longitude	elevation (masl)
Valle de Andorra 1	Andorra 1 Sin	forest	-54.75626	-68.35801	254
Valle de Andorra 1	Andorra 1 Con	pond	-54.75666	-68.34868	225
Valle de Andorra 1	Andorra 1 Post	meadow	-54.75411	-68.35452	204
Valle de Andorra 2	Andorra 2 Sin	forest	-54.74880	-68.37986	230
Valle de Andorra 2	Andorra 2 Con	pond	-54.74990	-68.38530	232
Valle de Andorra 2	Andorra 2 Post	meadow	-54.75038	-68.38932	235
Cañadon de la Oveja	Oveja Sin	forest	-54.79355	-68.43786	428
Cañadon de la Oveja	Oveja Con	pond	-54.79095	-68.43900	449
Cañadon de la Oveja	Oveja Post	meadow	-54.79855	-68.42978	399
Arroyo Submarino	Submarino Sin	forest	-54.73199	-68.07294	327
Arroyo Submarino	Submarino Con	pond	-54.73872	-68.07481	377
Arroyo Submarino	Submarino Post	meadow	-54.73445	-68.07343	365
Arroyo Tunel	Túnel Sin	forest	-54.81161	-68.17568	124
Arroyo Tunel	Túnel Con	pond	-54.80656	-68.18565	153
Arroyo Tunel	Túnel Post	meadow	-54.80467	-68.18835	152

4A.2 Code and R packages used in analysis

All analyses were conducted in R versions 3.6.3 – 4.0.2 (R Core Team 2020). All code used in analyzing the data and producing graphics for this study is available at https://github.itap.purdue.edu/PijanowskiGroup/Francomano_et_al_2021_Beavers_and_Birds_in_TDF. It employed the following R packages:

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 UL: Department of Statistics, California Polytechnic State University, San Luis Obispo, California, USA.
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4A.3 Acoustic data collection and exploration details

We used Wildlife Acoustics Song Meter SM4 recorders programmed to record 1 minute every 10 minutes with a sample rate of 44.1 kilohertz, a bit depth of 16, 26 decibels of preamplifier gain, 6 decibels of programmed gain, and a high-pass filter at 220 Hertz. Two blocks of recorders were installed on 06 November 2018, followed by two more blocks on 11 November 2018, and the last on 18 January 2019. All recorders were recovered between 29 July and 02 August 2019. More than a week of non-recordings due to battery failures only occurred at two sites (see data coverage figures provided at the above GitHub link). The mounting snag for one recorder broke at one point, but the recorder did not hit the ground, and no change in data quality was immediately evident. Microphone sensitivity of all recorders was measured immediately before and after deployment with a REED R8090 calibrator.

Qualitative visual and aural assessment of acoustic data is an important step to guide targeted quantitative analysis (Gottesman et al. 2018). To this end, we produced long-term spectrograms (provided at the above GitHub link) and listened to a spatially and temporally stratified random sample of 216 files while viewing their spectrograms in Audacity (Audacity Team 2018). We identified sound sources and classified them as geophony, technophony, bird sounds, or other biophony. We then estimated the frequency range and amplitude of each category in each recording. This structured listening exercise revealed that technophony and other biophony were very rare and unlikely to confound quantitative analysis. Geophony—primarily distant wind and flowing water—was common, and while it did not seem to differ substantially by impact state, we cautiously decided to denoise files before calculating acoustic metrics. The long-term spectrograms revealed a dawn increase in bird sounds that did not rapidly decline, so we chose to use a daily temporal analysis window matching that of the point counts. Frequency-related analysis parameters were determined through consideration of long-term spectrograms, and an examination of the spectral vocalization profiles for relevant species (see below).

4A.4 Examination of spectral vocalization profiles for relevant species

To examine the spectral distribution of sounds produced by the species we observed in point counts, we generated average spectra for each observed species and overlaid them to produce Figure 4A.1. We downloaded recordings from xeno-canto (Xeno-canto Foundation 2020) and Narosky and Yzurieta (2010) for each observed species. For each species, we selected the ten foreground recordings (if available) from xeno-canto that were geographically closest to the study area (excluding the Falkland/Malvinas Islands) along with one recording from Narosky and Yzurieta. Recordings are individually referenced below. We then denoised these files in Audacity, and deleted portions that did not contain the sounds of interest. We then generated and plotted average spectra from these recordings for each species to assess the distribution of spectral energy and peaks for the observed species (Figure 4A.1).

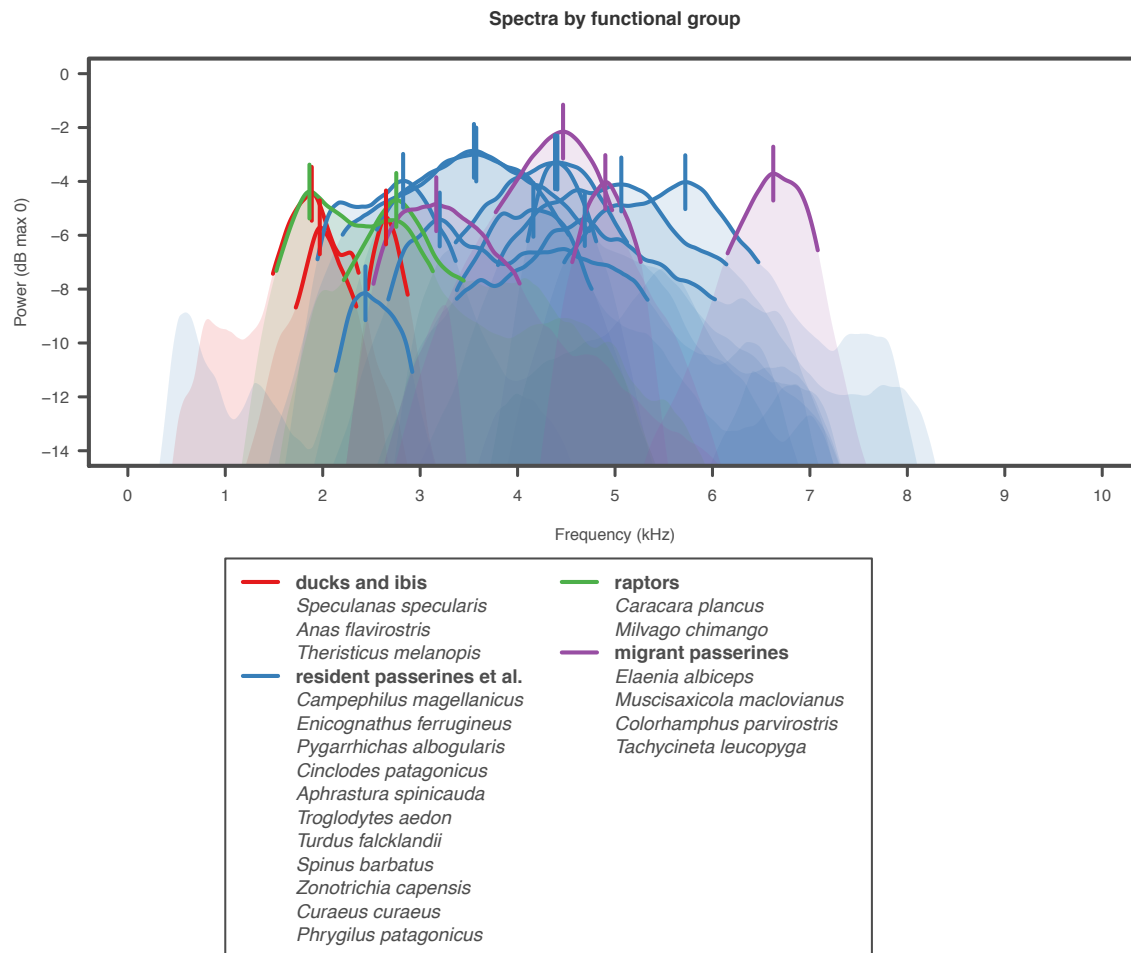


Figure 4A.1. Average spectra of observed species. Colors are assigned by functional group (see group determination details below).

The following are the individual recordings used to generate Figure 4A.1:

- Benner, Lance A. M. 2017a. XC370045 · *Thorn-Tailed Rayadito* · *Aphrastura Spinicauda*. Mp3. Natales, Ultima Esperanza, Región de Magallanes y de la Antártica Chilena, Chile. xeno-canto. <https://www.xeno-canto.org/370045>.
- . 2017b. XC370046 · *Austral Blackbird* · *Curaeus Curaeus*. Mp3. Natales, Ultima Esperanza, Región de Magallanes y de la Antártica Chilena, Chile. xeno-canto. <https://www.xeno-canto.org/370046>.
- . 2017c. XC370037 · *Austral Parakeet* · *Enicognathus Ferrugineus*. Mp3. Torres de Paine (near Estancia Pudeto), Ultima Esperanza, Región de Magallanes y de la Antártica Chilena, Chile. xeno-canto. <https://www.xeno-canto.org/370037>.
- . 2017d. XC370038 · *Austral Parakeet* · *Enicognathus Ferrugineus*. Mp3. Torres de Paine (near Estancia Pudeto), Ultima Esperanza, Región de Magallanes y de la Antártica Chilena, Chile. xeno-canto. <https://www.xeno-canto.org/370038>.

- . 2017e. XC370039 · *Thorn-Tailed Rayadito* · *Aphrastura Spinicauda*. Mp3. Torres de Paine (near Estancia Pudeto), Ultima Esperanza, Región de Magallanes y de la Antártica Chilena, Chile. xeno-canto. <https://www.xeno-canto.org/370039>.
- . 2017f. XC370040 · *Thorn-Tailed Rayadito* · *Aphrastura Spinicauda*. Mp3. Hotel Lago de Grey, Torres de Paine, Ultima Esperanza, Región de Magallanes y de la Antártica Chilena, Chile. xeno-canto. <https://www.xeno-canto.org/370042>.
- . 2017g. XC370041 · *Thorn-Tailed Rayadito* · *Aphrastura Spinicauda*. Mp3. Hotel Lago de Grey, Torres de Paine, Ultima Esperanza, Región de Magallanes y de la Antártica Chilena, Chile. xeno-canto. <https://www.xeno-canto.org/370041>.
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- Boesman, Peter. 2013a. XC273169 · *Southern Crested Caracara* · *Caracara Plancus*. Mp3. Miramar west side, Córdoba, Argentina. xeno-canto. <https://www.xeno-canto.org/273169>.
- . 2013b. XC273170 · *Southern Crested Caracara* · *Caracara Plancus*. Mp3. Miramar east side, Córdoba, Argentina. xeno-canto. <https://www.xeno-canto.org/273170>.
- . 2013c. XC273171 · *Southern Crested Caracara* · *Caracara Plancus*. Mp3. Miramar east side, Córdoba, Argentina. xeno-canto. <https://www.xeno-canto.org/273171>.
- . 2018a. XC449885 · *Patagonian Tyrant* · *Colorhamphus Parvirostris*. Mp3. PN Puyehue-Aguas Calientes, X Región, Chile. xeno-canto. <https://www.xeno-canto.org/449885>.
- . 2018b. XC450173 · *Chilean Swallow* · *Tachycineta Leucopyga*. Mp3. PN Puyehue-Aguas Calientes, X Región, Chile. xeno-canto. <https://www.xeno-canto.org/450173>.
- . 2018c. XC449806 · *Yellow-Billed Teal* · *Anas Flavirostris*. Mp3. Chacao, Chiloé, X Región, Chile. xeno-canto. <https://www.xeno-canto.org/449806>.
- . 2018d. XC449886 · *Patagonian Tyrant* · *Colorhamphus Parvirostris*. Mp3. PN Puyehue-Aguas Calientes, X Región, Chile. xeno-canto. <https://www.xeno-canto.org/449886>.
- . 2018e. XC449887 · *Patagonian Tyrant* · *Colorhamphus Parvirostris*. Mp3. PN Puyehue-Aguas Calientes, X Región, Chile. xeno-canto. <https://www.xeno-canto.org/449887>.
- . 2018f. XC449875 · *Dark-Bellied Cinclodes* · *Cinclodes Patagonicus*. Mp3. Quetalmahue, Chiloé, X Región, Chile. xeno-canto. <https://www.xeno-canto.org/449875>.
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- . 2010d. 196 *Caracara Plancus*. Mp3. Buenos Aires. Aves de Argentina y Uruguay: guía de indentificación.
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- . 2010g. 496 *Campephilus Magellanicus*. Mp3. Buenos Aires. Aves de Argentina y Uruguay: guía de indentificación.
- . 2010h. 516 *Cinclodes Patagonicus*. Mp3. Buenos Aires. Aves de Argentina y Uruguay: guía de indentificación.
- . 2010i. 535 *Pygarrhichas Albogularis*. Mp3. Buenos Aires. Aves de Argentina y Uruguay: guía de indentificación.
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4A.5 Acoustic processing, denoising, and metric modifications

For each site, the audio channel with the least change between pre- and post-deployment sensitivity measurements was used for all analysis. Acoustic recordings were transformed into the time-frequency domain with a 4,096-sample Hann window with 50% overlap. Amplitude values below 1,400 and above 10,400 Hertz were then set to zero, and we performed spectral denoising using methods adapted from Towsey (2017). In a modification to Towsey’s methods, we added a constant coefficient of 1.6 that we multiplied by the modal amplitude in order to remove a greater amount of noise. This parameter is similar to the N used by Towsey in waveform denoising, but we did not incorporate the standard deviation of the amplitude vector, as it led to horizontal banding on the spectrograms. We selected this parameter and Towsey’s θ (0.011) through an iterative process using the random files from the structured listening exercise. We sought to remove the maximum amount of non-avian sound while maintaining almost all avian sound. Figure 4A.2 shows the filtering and denoising process applied to a single file. While many recordings were not as replete with bird sounds or as precisely denoised, this example is illustrative of the way in which we were able to isolate foreground sounds from background noise. We were not concerned about potentially removing sounds from distant birds, as they would not have been actively using the habitat of interest.

Denoising Test Results: Part_1 12_S4A03801_20181210_062000

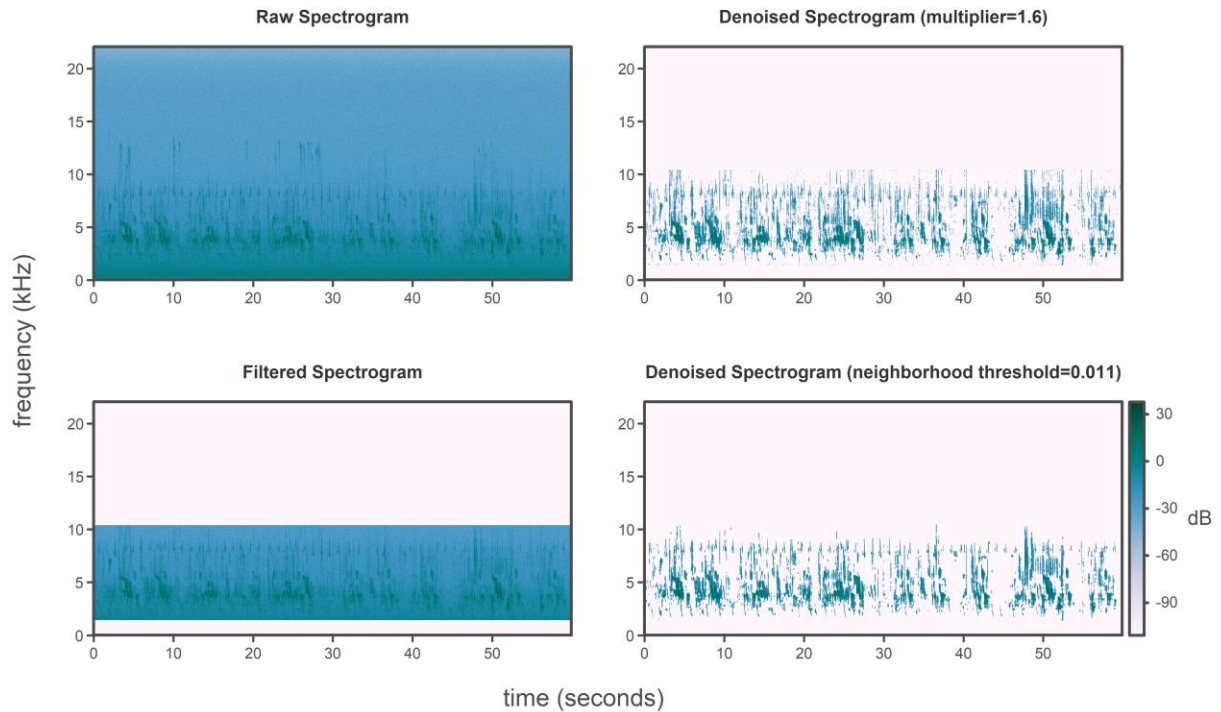


Figure 4A.2. Sample spectrograms showing successful noise removal through filtering and two denoising steps.

From denoised, filtered data, we calculated five acoustic metrics: temporal occupancy (adapted from Towsey’s “activity”; Towsey 2017), events per minute (Towsey 2017), broadband sound pressure level (Merchant et al. 2015), the acoustic complexity index (Pieretti et al. 2011), and the acoustic diversity index (Villanueva-Rivera et al. 2011). We used a 4,096-sample window length when applicable, and all signals were calibrated using the mean of the pre- and post-deployment calibration measurements (following Merchant et al. 2015), leading us to adjust published thresholds for temporal occupancy, events per minute, and the acoustic diversity index. To select thresholds, we visually evaluated post-denoising spectrograms for each of the structured listening files, and we estimated the percent of temporal and spectral-temporal occupancy of bird sounds. We then calculated the above metrics with a wide range of thresholds at 1-decibel intervals and ran correlations with temporal bird sound occupancy (for temporal occupancy and events per minute) and spectral-temporal bird sound occupancy (for the acoustic diversity index), selecting thresholds for each metric that yielded the highest correlation coefficients. The acoustic complexity index was calculated on a linear power spectral density spectrogram, and it was time-

standardized by dividing by the number of windows in the recording. The acoustic diversity index was calculated on a decibel power spectral density spectrogram using 500-Hertz frequency bins. Acoustic measurements were assigned to seasons as for point counts, with November recordings considered as spring data and December recordings considered as summer data.

4A.6 Point counts and abundance adjustments

Point counts were conducted between a 0.5 hours before sunrise and 5 hours after sunrise with negligible precipitation and average wind speeds below 12 kilometers per hour (Ralph et al. 1995). Counts were conducted at all randomly ordered sites within a given block on the same morning, and the full set of blocks was always counted within a period of 9 days, with at least 6 days separating a set of counts. DF paused for 2 minutes upon arrival at each site before conducting a 10-minute, unlimited-radius count in which he estimated distances to aurally or visually observed birds using a Leica Rangemaster CRF 1000 (Buckland et al. 2008). After each count he measured the sound level (L_{eq}), temperature, average wind speed, maximum wind speed, humidity, and atmospheric pressure over a 30-second period using a Larson Davis 824 sound level meter and Kestrel 5500 Weather Meter. He also estimated wind direction and cloud cover and provided a categorical assessment of precipitation. Birds flying over the site were recorded, but their status as flyovers was noted. Distance estimates were made for all individuals except on several occasions when flocks of Chilean swallows *Tachycineta leucopyga* were too numerous and mobile for individual measurements. For these cases, DF estimated the number of individuals and the minimum and maximum distances at which they were observed, and they were assumed to be evenly distributed throughout that bounded area. 84% of 564 qualifying observations were identified to species level, and unidentified observations were not considered in further analysis. Flyovers and observations beyond 100 meters were also excluded from further analysis.

Point count detectability functions were generated for three species with sufficiently high numbers of observations (thorn-tailed rayaditos *Aphrastura spinicauda*, Chilean swallows, and house wrens *Troglodytes aedon*) and two species groups (other passerines and non-passerines), for which there were too few species-level detections to generate reliable species-specific functions. Possible detection functions were generated using all possible combinations of cosine

adjustment terms, half-normal, hazard-rate, and uniform key functions, and the following covariates (which did not exhibit correlations greater than 0.75): impact state, hours from sunrise, average wind speed, temperature, atmospheric pressure, and cloud cover. Models within each key function family were sorted by QAIC, and the best model from each family was assessed for goodness of fit via Kolmogorov-Smirnov tests. Of the top models from each family, the best fitting model was chosen for all cases except house wrens, and no models included covariates (Table 4A.2). For house wrens, the most conservative key function was selected, but even this model yielded unrealistically high adjusted values, so the adjustment coefficient was averaged with that of the thorn-tailed rayaditos (a relatively similar species in terms of size, color, and behavior) to produce a more realistic adjustment. Counts were adjusted based on these chosen models.

Table 4A.2. Detection functions used for point count adjustments.

observation group	model family	covariates or adjustment terms	notes
thorn-tailed rayaditos	half-normal	cosine terms of order 2 and 3	
Chilean swallows	uniform	cosine term of order 1	
house wrens	uniform	cosine terms of order 1, 2, and 3	coefficient averaged with that of thorn-tailed rayaditos for more realistic adjustment
other passerines	uniform	cosine term of order 1	
non-passerines	hazard-rate	none	

4A.7 Functional diversity quantification

To quantify functional diversity, we first compiled functional trait data on body size, diet, feeding habitats, nesting habitats, reproduction, and migration from Povedano and Bisheimer (2016), Rozzi and Jiménez (2014), Narosky and Yzurieta (2010), Couve and Vidal (2003), de la Peña and Rumboll (1998), Canevari and Manzione (2017), and BirdLife International (2020). Variables presented in Table 4A.3 were gleaned from as many of these sources as possible. Mean body size and reproduction variables were averaged across sources, while a qualitative assessment of source consensus was provided for ordinal variables. A functional distance matrix was calculated on these traits using Gower's distance. From this distance matrix, we calculated Rao's quadratic entropy (Rao 1982), defined functional groups via hierarchical agglomerative UPGMA clustering, and calculated Shannon diversity on those functional groups.

Table 4A.3. Variables used to quantify functional diversity.

category	trait	measurement units	weighting for distance matrix
body size	mass	grams	0.5
	length	centimeters	0.5
diet	buds/flowers	ordinal importance rating (0 – 3)	0.0625
	nectar	ordinal importance rating (0 – 3)	0.0625
	seeds/grains	ordinal importance rating (0 – 3)	0.0625
	fruits	ordinal importance rating (0 – 3)	0.0625
	other vegetation	ordinal importance rating (0 – 3)	0.0625
	invertebrates	ordinal importance rating (0 – 3)	0.0625
	vertebrates	ordinal importance rating (0 – 3)	0.0625
	carrion	ordinal importance rating (0 – 3)	0.0625
	number of diet items	count of non-zero-rated items	0.5
foraging habitats	water	ordinal importance rating (0 – 3)	0.0714
	ground	ordinal importance rating (0 – 3)	0.0714
	bushes	ordinal importance rating (0 – 3)	0.0714
	trunks	ordinal importance rating (0 – 3)	0.0714
	tree foliage	ordinal importance rating (0 – 3)	0.0714
	high exposed perches	ordinal importance rating (0 – 3)	0.0714
	air	ordinal importance rating (0 – 3)	0.0714
	number of foraging habitats	count of non-zero-rated habitats	0.5
nesting habitats	ground	ordinal importance rating (0 – 3)	0.0714
	tree cavities	ordinal importance rating (0 – 3)	0.0714
	cavities other than trees	ordinal importance rating (0 – 3)	0.0714
	bushes	ordinal importance rating (0 – 3)	0.0714
	tree branches	ordinal importance rating (0 – 3)	0.0714
	cliffs	ordinal importance rating (0 – 3)	0.0714
	human constructions	ordinal importance rating (0 – 3)	0.0714
	number of nesting habitats	count of non-zero-rated habitats	0.5
reproduction	clutch size	eggs per year	0.5
	generation length	years	0.5
migration status	migration status	ordinal (resident = 0, partial migrant = 0.5, migrant = 1)	1

4A.8 Statistical analysis details

Adjusted abundance data were first rounded and modeled with Poisson generalized linear mixed models (GLMMs), and then switched to generalized Poisson or negative binomial models in case of under- and over-dispersion, respectively (Consul and Famoye 1992). Tobit models were employed for the other dependent variables due to the censoring of data at zero by each of the metric formulae (Peterson 2005). The logistic distribution was used for the functional group Shannon diversity model, as the non-zero data were not normally distributed, and the logistic

distribution yielded the lowest AIC of all possible distributions. Residual distributions were visually assessed for all models by plotting them against fitted values and each of the three categorical independent variables. Model significance was evaluated by comparing full models against block-only models by analysis of deviance, and the terms of significant models were evaluated with analysis of deviance as well. When impact state was significant, within-season, between-impact-state contrasts were examined with a pairwise Tukey HSD test between the three values for each season. A summary of univariate models used in this study is provided in Table 4A.4.

Table 4A.4. Univariate model overview.

dependent variable	modifications to dependent variable	modifications to independent variables	type of model
acoustic activity	square-root transformed	treated block as a fixed effect due to singularity	general linear model
abundance	rounded non-integer values resulting from count adjustment	none	negative binomial linear mixed model
species Shannon diversity	none	none	mixed Gaussian tobit model
functional group richness	none	none	generalized Poisson linear mixed model
Rao's quadratic entropy	none	none	mixed Gaussian tobit model
functional group Shannon diversity	none	eliminated interaction due to singularities	mixed logistic tobit model
resident passerines et al. abundance	rounded non-integer values resulting from count adjustment	none	negative binomial linear mixed model
migrant passerines abundance	rounded non-integer values resulting from count adjustment	none	negative binomial linear mixed model

Acoustic metrics were averaged within days at each site, and days were randomly selected such that no site had more days than the site with the fewest days. The acoustic metric dimensionality was reduced by principal components analysis on all (non-averaged) metrics that fell within the temporal analysis window. All original metrics loaded on the first principal component in the same direction. That component accounted for 74% of variability, and comparison against a broken stick model revealed it to be the sole significant component. We considered this component to represent acoustic activity. We calculated averages of acoustic activity for each site-season combination and treated these values as the dependent variable in a linear mixed model as described above. Model fit was singular, so we treated block as a fixed effect in an

ANOVA. Assumptions of normality of error and homogeneity of variance were evaluated visually, and a Shapiro-Wilk test was also used to evaluate normality of error. Acoustic activity was square-root-transformed to allow residuals to approach normality. Given ANOVA's robustness to violations of residual normality under balanced designs and our modest sample size, we proceeded with analysis despite a significant Shapiro-Wilk test and one clearly outlying point in a qq-plot (Gotelli and Ellison 2013).

4A.9 Statistical results for univariate models

Table 4A.5. Univariate model test result.

full model					terms				impact state contrasts													
dependent variable	Δ AIC	test statistic	d.f.	p-value	term	test statistic	d.f.	p-value	season	contrast	t-ratio	d.f.	p-value									
acoustic activity	-68.00	$F = 14.35$	11, 41	< 0.001	impact state	$F = 7.41$	2, 41	0.002	spring	forest – pond	2.20	41	0.083									
					season	$F = 45.54$	3, 41	< 0.001		forest – meadow	2.63	41	0.032									
					block	$F = 0.26$	4, 41	0.903		pond – meadow	-0.42	41	0.906									
					interaction	$F = 1.07$	6, 41	0.398	summer	forest – pond	1.27	41	0.421									
										forest – meadow	3.20	41	0.007									
										pond – meadow	-1.93	41	0.142									
									fall	forest – pond	0.36	41	0.930									
										forest – meadow	1.57	41	0.272									
										pond – meadow	-1.20	41	0.459									
									winter	forest – pond	0.03	41	0.999									
										forest – meadow	0.39	41	0.921									
										pond – meadow	-0.36	41	0.933									
									species richness	-32.93	$\chi^2 = 48.93$	8	< 0.001	impact state	$\chi^2 = 23.79$	2	< 0.001	summer	forest – pond	3.18	34	0.009
														season	$\chi^2 = 69.07$	2	< 0.001		forest – meadow	4.01	34	< 0.001
interaction	$\chi^2 = 3.46$	4	0.485		pond – meadow	-0.86	34	0.671														
				fall	forest – pond	1.97	34	0.135														
					forest – meadow	3.18	34	0.009														
					pond – meadow	-1.40	34	0.353														
				winter	forest – pond	0.14	34	0.990														
					forest – meadow	0.58	34	0.834														
					pond – meadow	-0.44	34	0.900														

Table 4A.5. (continued).

full model					terms				impact state contrasts				
dependent variable	Δ AIC	test statistic	d.f.	p-value	term	test statistic	d.f.	p-value	season	contrast	t-ratio	d.f.	p-value
abundance	-39.17	$\chi^2 = 55.17$	8	< 0.001	impact state	$\chi^2 = 43.94$	2	< 0.001	summer	forest – pond	3.88	34	0.001
					season	$\chi^2 = 68.33$	2	< 0.001		forest – meadow	5.15	34	< 0.001
					interaction	$\chi^2 = 5.45$	4	0.244		pond – meadow	-1.55	34	0.281
									fall	forest – pond	0.98	34	0.593
										forest – meadow	3.92	34	0.001
										pond – meadow	-3.08	34	0.011
									winter	forest – pond	0.46	34	0.889
										forest – meadow	1.76	34	0.200
										pond – meadow	-1.29	34	0.412
species Shannon diversity	-16.47	$\chi^2 = 34.97$	9.25	< 0.001	impact state	$\chi^2 = 5.54$	2	0.063	summer	forest – pond	—	—	—
					season	$\chi^2 = 23.67$	2	< 0.001		forest – meadow	—	—	—
					interaction	$\chi^2 = 5.22$	4	0.266		pond – meadow	—	—	—
									fall	forest – pond	—	—	—
										forest – meadow	—	—	—
										pond – meadow	—	—	—
									winter	forest – pond	—	—	—
										forest – meadow	—	—	—
										pond – meadow	—	—	—
functional group richness	-33.14	$\chi^2 = 49.14$	8	< 0.001	impact state	$\chi^2 = 30.15$	2	< 0.001	summer	forest – pond	4.61	34	< 0.001
					season	$\chi^2 = 29.97$	2	< 0.001		forest – meadow	1.79	34	0.189
					interaction	$\chi^2 = 26.40$	4	< 0.001		pond – meadow	3.22	34	0.008
									fall	forest – pond	4.23	34	< 0.001
										forest – meadow	4.23	34	< 0.001
										pond – meadow	-0.28	34	0.959
									winter	forest – pond	0.51	34	0.867
										forest – meadow	-2.51	34	0.044
										pond – meadow	2.65	34	0.032

Table 4A.5. (continued).

full model					terms				impact state contrasts				
dependent variable	Δ AIC	test statistic	d.f.	p-value	term	test statistic	d.f.	p-value	season	contrast	t-ratio	d.f.	p-value
Rao's quadratic entropy	-12.81	$\chi^2 = 29.01$	8.10	< 0.001	impact state	$\chi^2 = 3.61$	2	0.164	summer	forest – pond	—	—	—
					season	$\chi^2 = 20.21$	2	< 0.001		forest – meadow	—	—	—
					interaction	$\chi^2 = 6.52$	4	0.163		pond – meadow	—	—	—
									fall	forest – pond	—	—	—
										forest – meadow	—	—	—
										pond – meadow	—	—	—
									winter	forest – pond	—	—	—
										forest – meadow	—	—	—
										pond – meadow	—	—	—
functional group Shannon diversity	-18.87	$\chi^2 = 27.05$	4.09	< 0.001	impact state	$\chi^2 = 4.09$	2	0.130	summer	forest – pond	—	—	—
					season	$\chi^2 = 22.03$	2	< 0.001		forest – meadow	—	—	—
					interaction	—	—	—		pond – meadow	—	—	—
									fall	forest – pond	—	—	—
										forest – meadow	—	—	—
										pond – meadow	—	—	—
									winter	forest – pond	—	—	—
										forest – meadow	—	—	—
										pond – meadow	—	—	—
resident passerines et al. abundance	-24.26	$\chi^2 = 40.26$	8	< 0.001	impact state	$\chi^2 = 44.88$	2	< 0.001	summer	forest – pond	1.15	34	0.489
					season	$\chi^2 = 30.12$	2	< 0.001		forest – meadow	4.49	34	< 0.001
					interaction	$\chi^2 = 1.02$	4	0.906		pond – meadow	-3.62	34	0.003
									fall	forest – pond	0.36	34	0.932
										forest – meadow	3.22	34	0.008
										pond – meadow	-2.93	34	0.016
									winter	forest – pond	0.32	34	0.947
										forest – meadow	2.05	34	0.117
										pond – meadow	-1.72	34	0.211

Table 4A.5. (continued).

full model					terms				impact state contrasts				
dependent variable	Δ AIC	test statistic	d.f.	p-value	term	test statistic	d.f.	p-value	season	contrast	t-ratio	d.f.	p-value
migrant passerines abundance	-32.75	$\chi^2 = 48.75$	8	< 0.001	impact state	$\chi^2 = 8.34$	2	0.015	summer	forest – pond	2.20	34	0.086
					season	$\chi^2 = 15.80$	2	< 0.001		forest – meadow	2.21	34	0.083
					interaction	$\chi^2 = 1.44$	4	0.837		pond – meadow	0.01	34	1
									fall	forest – pond	0.92	34	0.630
										forest – meadow	1.87	34	0.164
										pond – meadow	-1.18	34	0.474
									winter	forest – pond	0	34	1
										forest – meadow	0	34	1
										pond – meadow	0	34	1

4A.10 Additional note

The data coverage figures and long-term spectrogram video provided via the GitHub link use working site names we used in the field. For impact state designations, “sin” refers to forest, “con” refers to pond, and “post” refers to meadow.

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APPENDIX 5A—FULL BILINGUAL SURVEY

English version of survey

Part 1: Demographic information

Is your primary occupation related to nature or nature-based tourism? _____

[Yes/No/Decline to answer]

What is your level of education? _____

[Primary school/Secondary school/Some post-secondary education/Bachelor's degree/Graduate degree/Decline to answer]

Gender: ___ Male ___ Female

What is your age? _____

[Number/Decline to answer]

In which country do you currently live? _____

[Country/Decline to answer]

Have you ever lived in Tierra del Fuego (currently or previously)? _____

[Yes/No/Decline to answer]

If yes:

How many years have you lived in Tierra del Fuego? _____

[Number/NA/Decline to answer]

Are you currently living in Tierra del Fuego? _____

[Yes/No/NA/Decline to answer]

If age is not equal to the number of years lived in Tierra del Fuego and is currently living in Tierra del Fuego:

Why did you or your family move to Tierra del Fuego? _____

[Reasons/NA/Decline to answer]

Part 2: Connection with nature

Transition to connection with nature.

First, please indicate the extent to which you agree with the following statements:

[Strongly disagree (-2), Disagree (-1), Neither agree or disagree (0), Agree (1), Strongly agree (2), Decline to answer (DA)]

Statement	-2	-1	0	1	2	DA
<i>My ideal vacation spot would be a remote, wilderness area.</i>						
<i>I always think about how my actions affect the environment.</i>						
<i>I feel a spiritual relationship with nature and the environment.</i>						
<i>I take notice of wildlife wherever I am.</i>						
<i>My relationship to nature is an important part of my identity.</i>						
<i>I feel very connected to all living things and the earth.</i>						

Part 3: Sensory experiences of nature

And what is the importance of the following senses for your experiences of nature?

[Of no importance (-2), Of little importance (-1), Of moderate importance (1), Of high importance (2), Decline to answer (DA)]

Sense	-2	-1	1	2	DA
<i>Vision</i>					
<i>Hearing</i>					
<i>Touch</i>					
<i>Smell</i>					
<i>Taste</i>					

Part 4: Soundscape perception and valuation

Finally, I am going to ask some questions about the sounds you heard immediately before this survey and about three 20-second audio recordings from local sites that I will play for you. Ready? [Order of soundscape presentation is randomized, and the same series of questions is repeated for each soundscape.]

Soundscape ID: _____

List each sound you heard, and then describe it.

[Sound or sound source name and check marks for description categories/Decline to answer (DA)]

Sound	Accuracy			Precision				Description						
	-1	0	1	-2	-1	1	2	Amplitude	Frequency	Timbre	Imitation	Location	Temporal	Comparison

Indicate the extent to which you agree with each of the following statements in the context of the sounds you just heard.

[Strongly disagree (-2), Disagree (-1), Neither agree or disagree (0), Agree (1), Strongly agree (2), Decline to answer (DA)]

Statement	-2	-1	0	1	2	DA
<i>I liked the sounds I heard.</i>						
<i>The sounds I heard triggered memories.</i>						
<i>The sounds I heard provided me with information about the place in which they occurred.</i>						
<i>The sounds I heard have an effect (either positive or negative) on the animals living where the sounds occurred.</i>						
<i>The sounds I heard made me feel emotions.</i>						

Where do you think this recording was made? [Not used for *In Situ* soundscape]

Accuracy	-1	0	1

Precision	-2	-1	1	2

Part 5: Optional contact information

Would you be willing to participate in a follow-up interview? Ok, could you please provide your name, email, and phone number? Again, this information will be kept completely confidential.

Name: _____ Email: _____ Phone: _____

Notes:

Spanish version of survey

Parte 1: Información demográfica

¿Su ocupación principal, está relacionada con la naturaleza, o el turismo basado en la naturaleza?

[Sí/No/Declino a contestar]

¿Cuál es su nivel de educación? _____

[Primaria/Secundaria/Alguna educación después de la secundaria/Estudio universitario o terciario/Posgrado/Declino a contestar]

Género: __ Hombre __ Mujer

¿Cuál es su edad? _____

[Numero/Declino a contestar]

¿En qué país vive actualmente? _____

[País/Declino a contestar]

¿Vive o ha vivido en Tierra del Fuego (actualmente o previamente)? _____

[Sí/No/Declino a contestar]

Si sí:

¿Por cuántos años ha vivido en Tierra del Fuego? _____

[Numero/NA/Declino a contestar]

¿Está viviendo en Tierra del Fuego actualmente? _____

[Sí/No/NA/Declino a contestar]

Si la edad no es igual al numero de años vivido en Tierra del Fuego y está viviendo en Tierra del Fuego actualmente:

¿Porqué se mudó, usted o su familia, a Tierra del Fuego?

[Razones/NA/Declino a contestar]

Parte 2: Conexión con la naturaleza

Transición a conexión con la naturaleza.

Primero, indique en qué nivel está de acuerdo con cada de las declaraciones siguientes:

[Fuertemente en desacuerdo (-2), En desacuerdo (-1), Ni acuerdo ni desacuerdo (0), De acuerdo (1), Fuertemente de acuerdo (2), Declino a contestar (DC)]

Declaración	-2	-1	0	1	2	DC
<i>Mi lugar ideal para las vacaciones sería una zona remota, inhóspita, natural.</i>						
<i>Siempre pienso sobre como mis acciones afectan al medio ambiente.</i>						
<i>Siento una relación espiritual con la naturaleza y el medio ambiente.</i>						
<i>Presto atención a la vida salvaje en todos lados.</i>						
<i>Mi relación a la naturaleza es una parte importante de mi identidad.</i>						
<i>Siento muy conectado a todos los seres vivos y al planeta tierra.</i>						

Parte 3: Experiencias sensoriales de la naturaleza

¿Y cuál es la importancia de los siguientes sentidos para vivenciar sus experiencias de la naturaleza?

[De ninguna importancia (-2), De poca importancia (-1), De importancia moderada (1), De alta importancia (2), Declino de contestar (DC)]

Sentido	-2	-1	1	2	DC
<i>Visión</i>					
<i>Oído</i>					
<i>Tacto</i>					
<i>Olfato</i>					
<i>Gusto</i>					

Parte 4: Percepción y valorización de paisajes sonoros

Finalmente, voy a presentarle algunas preguntas sobre grabaciones de audio que le hare escuchar y los sonidos que ha oído inmediatamente antes de esta encuesta. Las grabaciones son de sitios locales y duran 20 segundos. ¿Listo/a?

ID del paisaje sonoro: _____

Enumere cada sonido que oyó, y luego descríbalos.

[Nombre del sonido o del fuente del sonido y marcas para categorías de descripción/Declinó a contestar (DC)]

Sonido	Exactitud			Precisión				Descripción						
	-1	0	1	-2	-1	1	2	Amplitud	Frecuencia	Timbre	Imitación	Ubicación	Temporal	Comparación

Indique cuán de acuerdo está con cada de las siguientes declaraciones en el contexto de los sonidos que acaba de oír.

[Fuertemente en desacuerdo (-2), En desacuerdo (-1), Ni acuerdo ni desacuerdo (0), De acuerdo (1), Fuertemente de acuerdo (2), Declino a contestar (DC)]

Declaración	-2	-1	0	1	2	DC
Me gustaban los sonidos que oí.						
Los sonidos que oí evocaron memorias.						
Los sonidos que oí me dieron información sobre el lugar en que ocurrieron.						
Los sonidos que oí afectan (positivamente o negativamente) a los animales viviendo donde los sonidos ocurrieron.						
Los sonidos que oí me hicieron sentir emociones.						

¿Dónde se realizó esta grabación, piense? [No usado para paisaje sonoro *In Situ*]

Exactitud	-1	0	1

Precisión	-2	-1	1	2

Parte 5: Información de contacto opcional

¿Estaría dispuesto/a a participar en una entrevista de seguimiento? ¿Ok, podría darme su nombre, correo, y teléfono? De nuevo, esta información será completamente confidencial.

Nombre y apellido: _____ Correo: _____ Teléfono: _____

Notas:

APPENDIX 5B—METHODOLOGICAL DETAILS AND ADDITIONAL FIGURES

5B.1 Soundscape discernment definitions and examples

- Amplitude: a description of the loudness or volume of the sound (e.g., “loud”, “quiet”, “soft”)
- Frequency: a description of the perceived pitch of the sound (e.g., “high”, “low”, “bass”)
- Timbre: a description of the acoustic quality of the sound as a result of its frequency content (e.g., “brash”, “noisy”, “tonal”, “smooth”, “dark”)
- Imitation: an attempt to reproduce the sound (e.g., rubbing hands together to produce a sound of light rain, “whoosh”, “squawk squawk squawk”)
- Spatial reference: an indication of where a sound came from relative to the listener (e.g., “passing cars”, “birds above in trees”, “to the left”)
- Timing: an indication of when a sound occurred relative to the recording duration or other sounds in the recording (e.g., “at the beginning”, “after the horn”, “throughout”)
- Comparison: a comparison to other sounds (e.g., “louder”, “higher”, “brighter”)

5B.2 Survey implementation details

While conducting surveys DF wore blue or black jeans and a grey winter jacket along with a bright yellow hat and a nametag, both of which featured the logo of the Centro Austral de Investigaciones Cinéticas (CADIC), the local branch of the Argentine national science organization, the Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET). He carried (or kept near in Paseo del Fuego) a tablet for entering survey data, a folder with study information sheets and visual guides for the Likert-scale survey prompts (provided in Appendix 5C), and a set of headphones. All data were recorded in a Lenovo TAB4 8 tablet using the Qualtrics OfflineSurveys application (Qualtrics Inc. 2018).

For Kuanip and Avenida San Martín, DF walked back and forth along a designated stretch of each street, always on the right sidewalk based on the direction he was walking. He greeted the most physically approachable individual who appeared over 17 years of age in every third group

of people he passed. Groups composed entirely of the following types of people were not counted or approached: people who were clearly working, people in the act of entering or exiting buildings or vehicles, people speaking on their phone or listening to their phone with it up to their ear, people who were engaged in conversations that would be awkward or rude to interrupt, groups containing only individuals who appear to be younger than 18. If the third group of people was encountered while crossing a street or in another dangerous or impractical situation, a person from the following group was selected. Sampling was similar for Paseo del Fuego, but DF remained stationary and selected the most physically approachable person from every third group of people entering the mall.

5B.3 Specific demographic-related hypotheses, predictions, and model formulae

Table 5B.1. Specific demographic-related predictions, hypotheses/justifications, and model formulae.

prediction	hypothesis/justification	model formula(e)
People who have occupations related to nature or nature-based tourism will exhibit higher nature relatedness than those without such occupations.	Occupational choices of those with nature-related occupations may be a result of preexisting affinities for nature or may place them in close proximity with influential nature-related individuals.	nature relatedness ~ occupation
Lifetime Fuegian residents and people who moved to Tierra del Fuego due to lifestyle reasons will exhibit higher nature relatedness than people who moved to Tierra del Fuego due to family or economic reasons (analysis excluding responses from non-Fuegian residents).	Lifetime Fuegian residents have likely had more time to potentially explore their natural surroundings than more recent migrants and may have experienced life in Tierra del Fuego before its recent surge in urbanization. Lifestyle migrants, on the other hand, may not have lived in Tierra del Fuego for a long period of time, but their choice to move to city in a wilderness area (Mittermeier et al. 2003) reflects a desire to be in close proximity to nature.	nature relatedness ~ reason for residence
People who have lived in Tierra del Fuego for longer will discern Urban and <i>In Situ</i> soundscapes better than contrasting demographics.	The identification and description of sounds is easier when one is familiar with them, and longer-term residents are more likely to find urban Ushuaia soundscapes familiar.	Urban discernment ~ years in TDF; <i>In Situ</i> discernment ~ years in TDF
People who have lived in Tierra del Fuego for longer, lifetime Fuegian residents, people who moved to Tierra del Fuego due to lifestyle reasons, and people who have occupations related to nature or nature based tourism will discern Forest and Penguin Colony soundscapes better than contrasting demographics.	The identification and description of sounds is easier when one is familiar with them, and these demographics are more likely to find these soundscapes familiar. Increased time in Tierra del Fuego increases the likelihood that one would have experienced similar soundscapes, and lifetime Fuegian residents, lifestyle migrants, and people with nature-based occupations are more likely to have visited the places where similar soundscapes would be found.	Forest discernment ~ years in TDF + reason for residence + occupation; Martillo discernment ~ years in TDF + reason for residence + occupation
People who have lived in Tierra del Fuego for longer, lifetime Fuegian residents, people who moved to Tierra del Fuego due to lifestyle reasons, and people who have occupations related to nature or nature based tourism will value Urban and <i>In Situ</i> soundscapes less than contrasting demographics.	These demographics are more likely to have experienced, remembered, and/or developed an affinity for soundscapes with little technophony, which are easily contrasted with these human-dominated soundscapes.	Urban valuation ~ years in TDF + reason for residence + occupation; <i>In Situ</i> valuation ~ years in TDF + reason for residence + occupation
People who have lived in Tierra del Fuego for longer, lifetime Fuegian residents, people who moved to Tierra del Fuego due to lifestyle reasons, and people who have occupations related to nature or nature based tourism will value Forest and Penguin Colony soundscapes more than contrasting demographics.	These demographics are more likely to have experienced those soundscapes, learned from them, and associated them with positive memories and emotions.	Forest valuation ~ years in TDF + reason for residence + occupation; Martillo valuation ~ years in TDF + reason for residence + occupation

5B.4 Evaluation of scale dimensionality

Cronbach's alpha for nature relatedness was 0.77, and the first item ("My ideal vacation spot would be a remote, wilderness area.") was slightly separated from the other five items in the principal components analysis (PCA). The soundscape valuation scales were not necessarily assumed to be unidimensional but were tested for exploratory purposes. Cronbach's alpha values for Forest, *In Situ*, Penguin Colony, and Urban were 0.65, 0.54, 0.67, and 0.64 respectively. The item, "The sounds I heard have an effect (either positive or negative) on the animals living where the sounds occurred", was consistently most separated from the other items in the PCAs (Figure 5B.1).

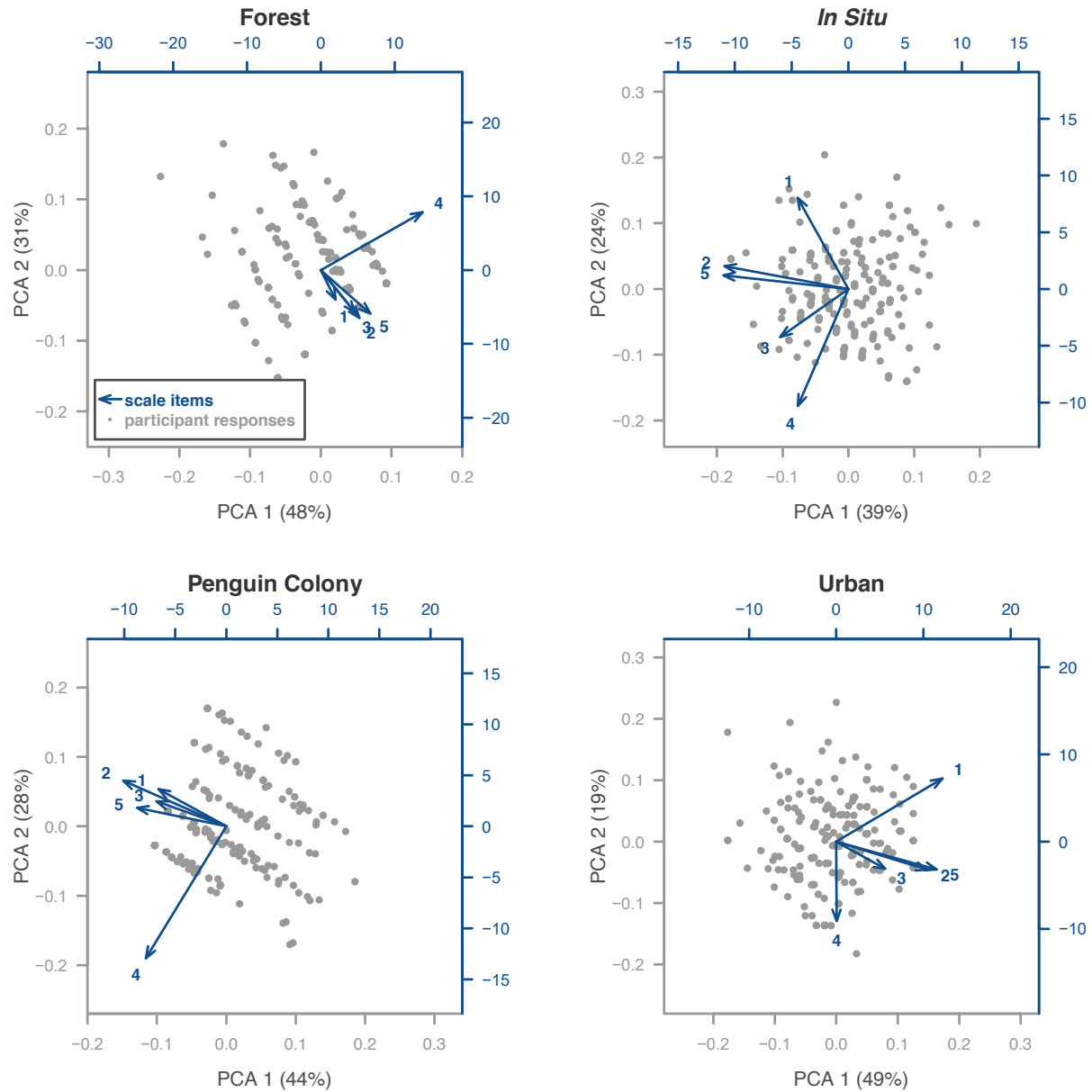


Figure 5B.1. Principal components analyses of items from the soundscape valuation scale. Grey points indicating responses are plotted against the bottom and left axes, while blue vectors indicating scale items are plotted against the top and right axes. Scale item numbers correspond with those in Section 5.2.2.

5B.5 Response rate and descriptive demographic figures

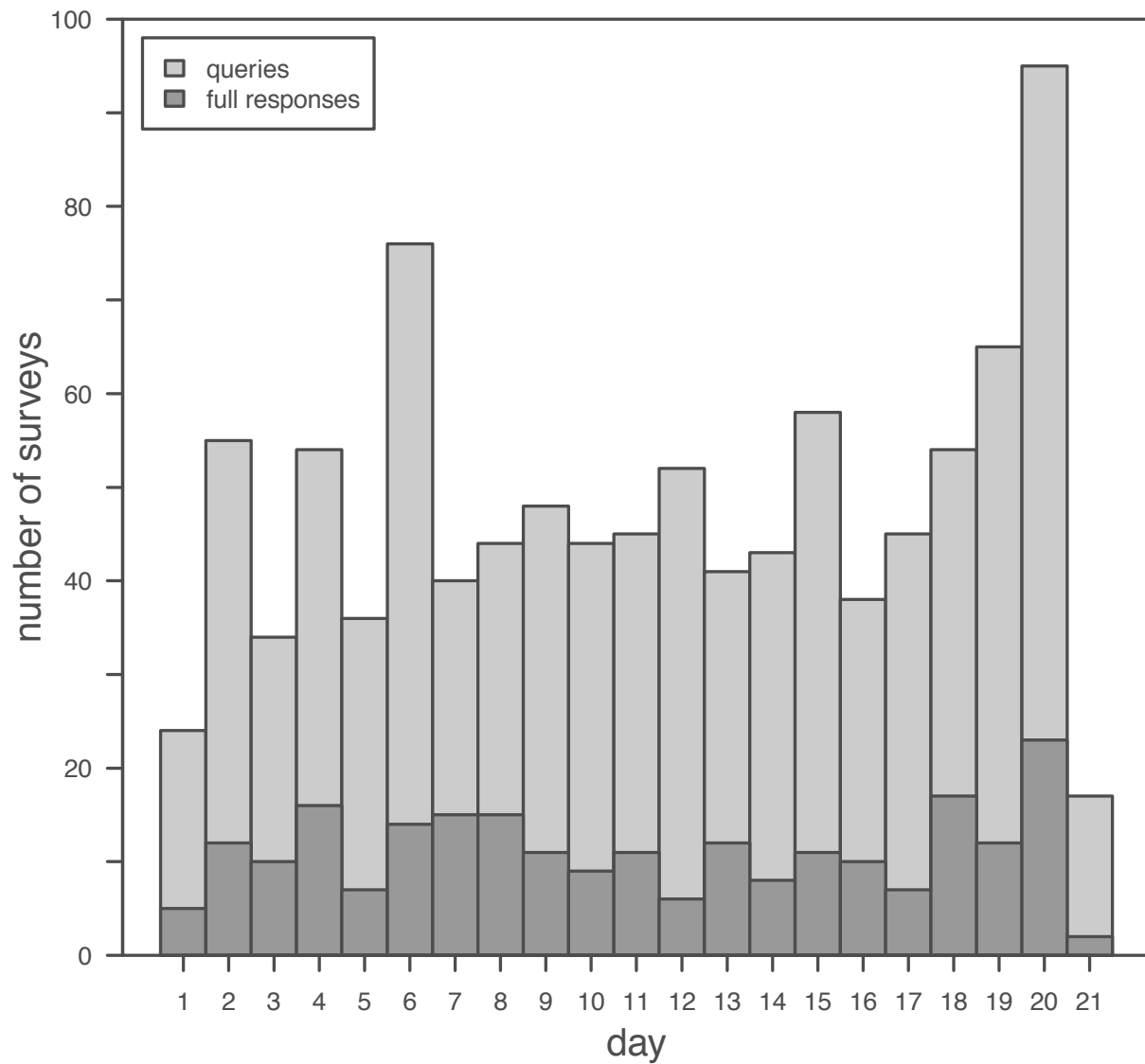


Figure 5B.2. Numbers of survey queries and full responses obtained on each day of surveying.

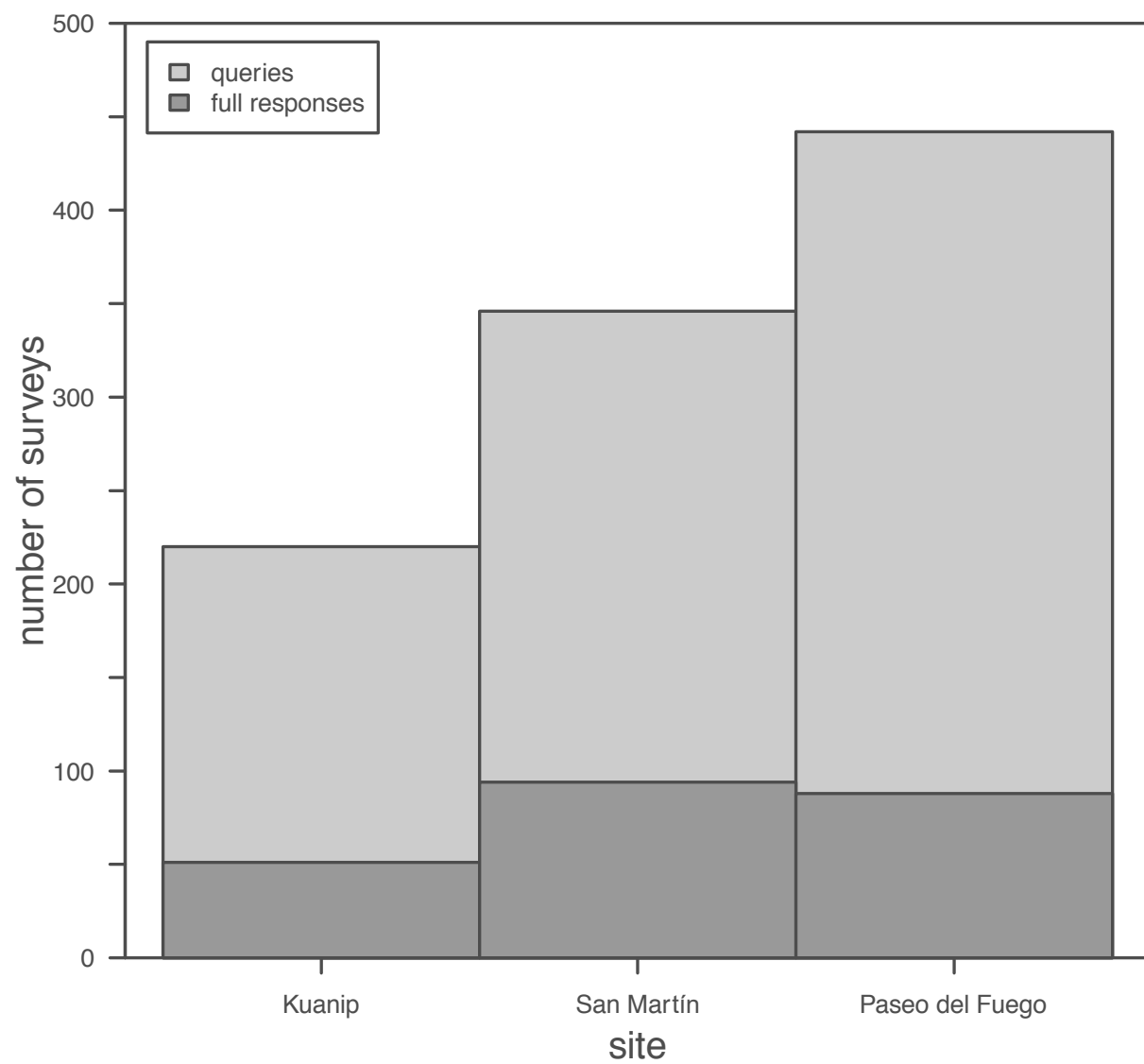


Figure 5B.3. Numbers of survey queries and full responses obtained at each survey site.

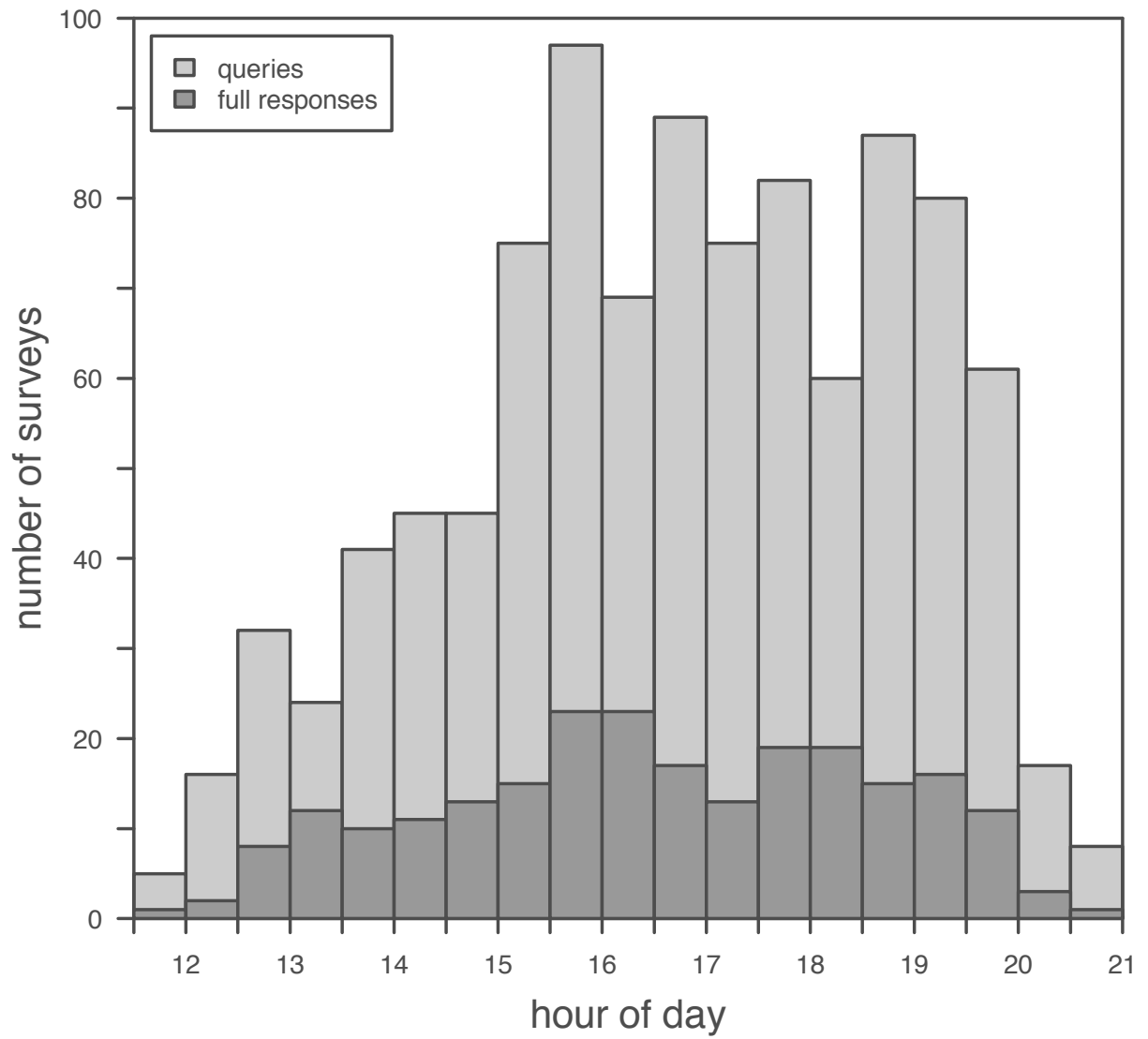


Figure 5B.4 Distribution of survey queries and full responses by time of day.

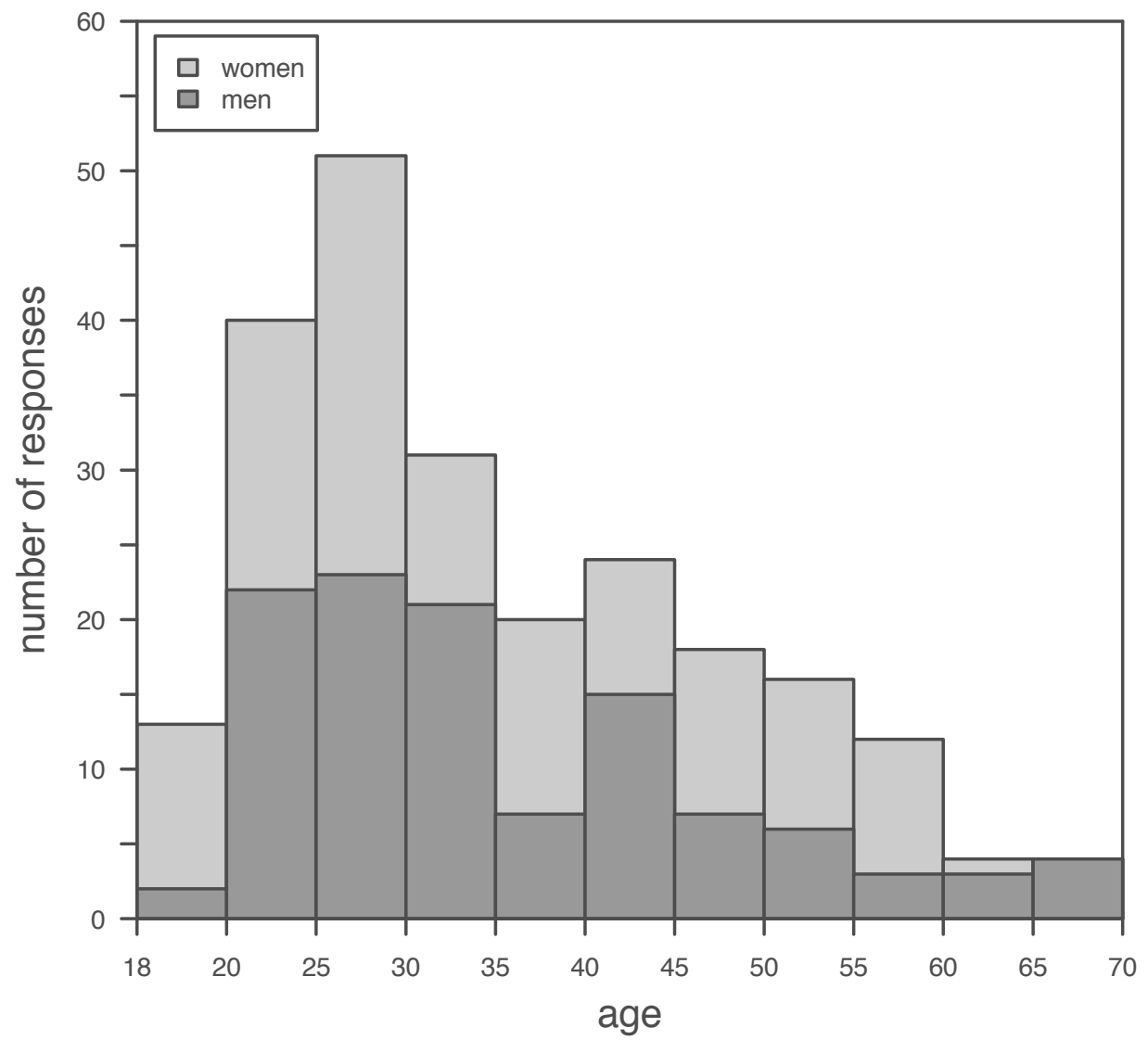


Figure 5B.5. Distribution of participant ages by gender.

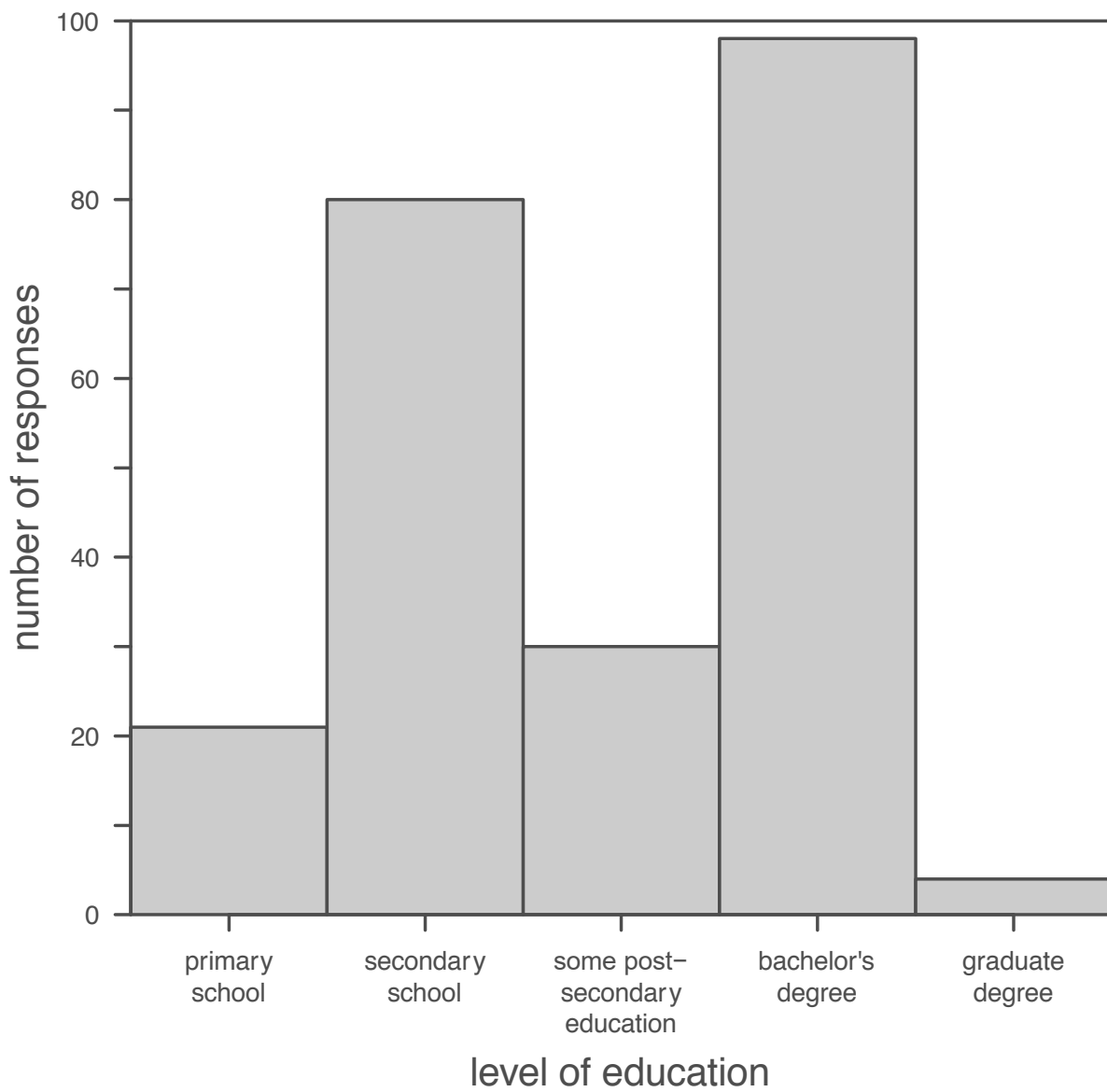


Figure 5B.6. Distribution of participant education.

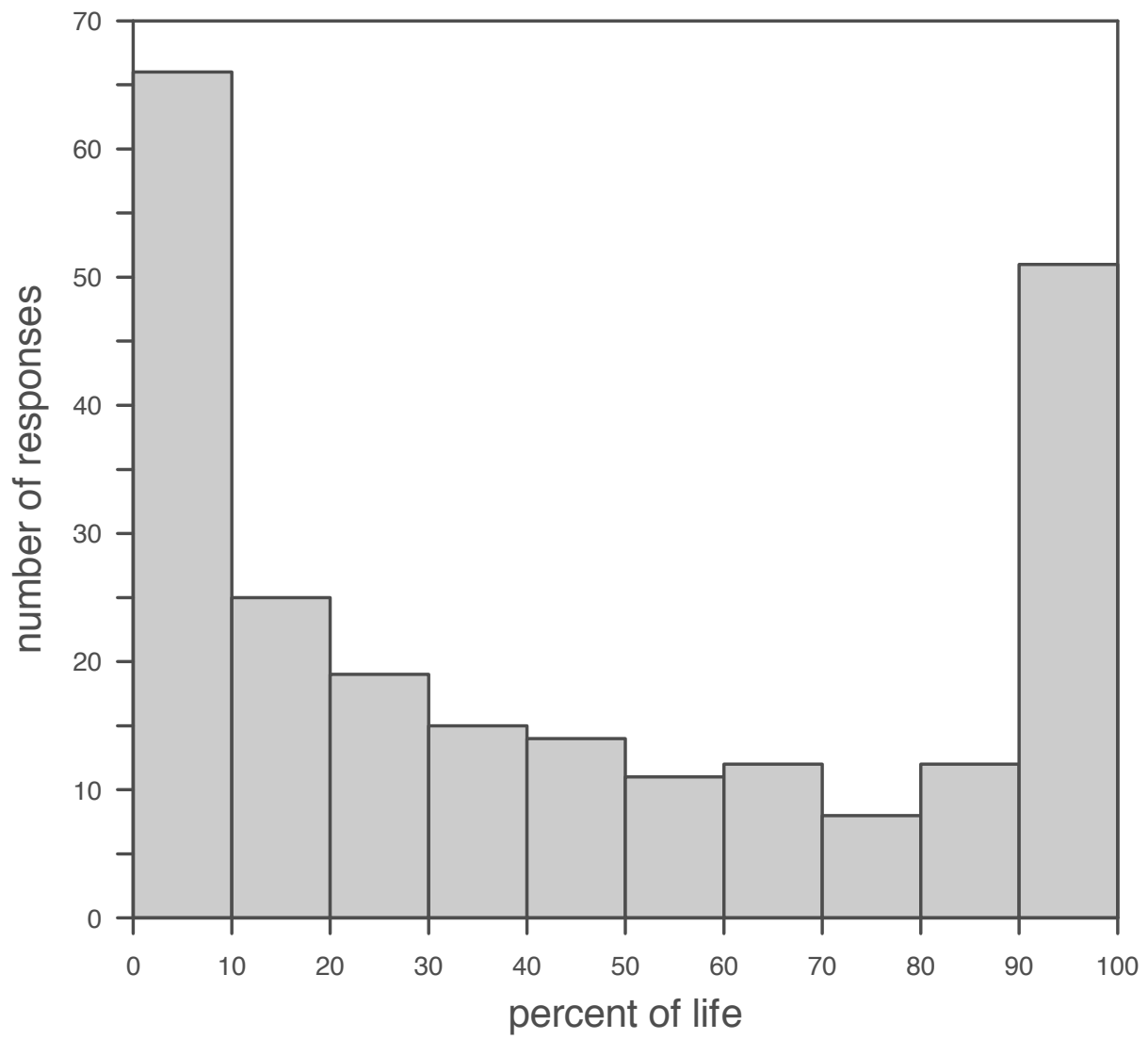


Figure 5B.7. Distribution of participants' percent of life lived in Tierra del Fuego.

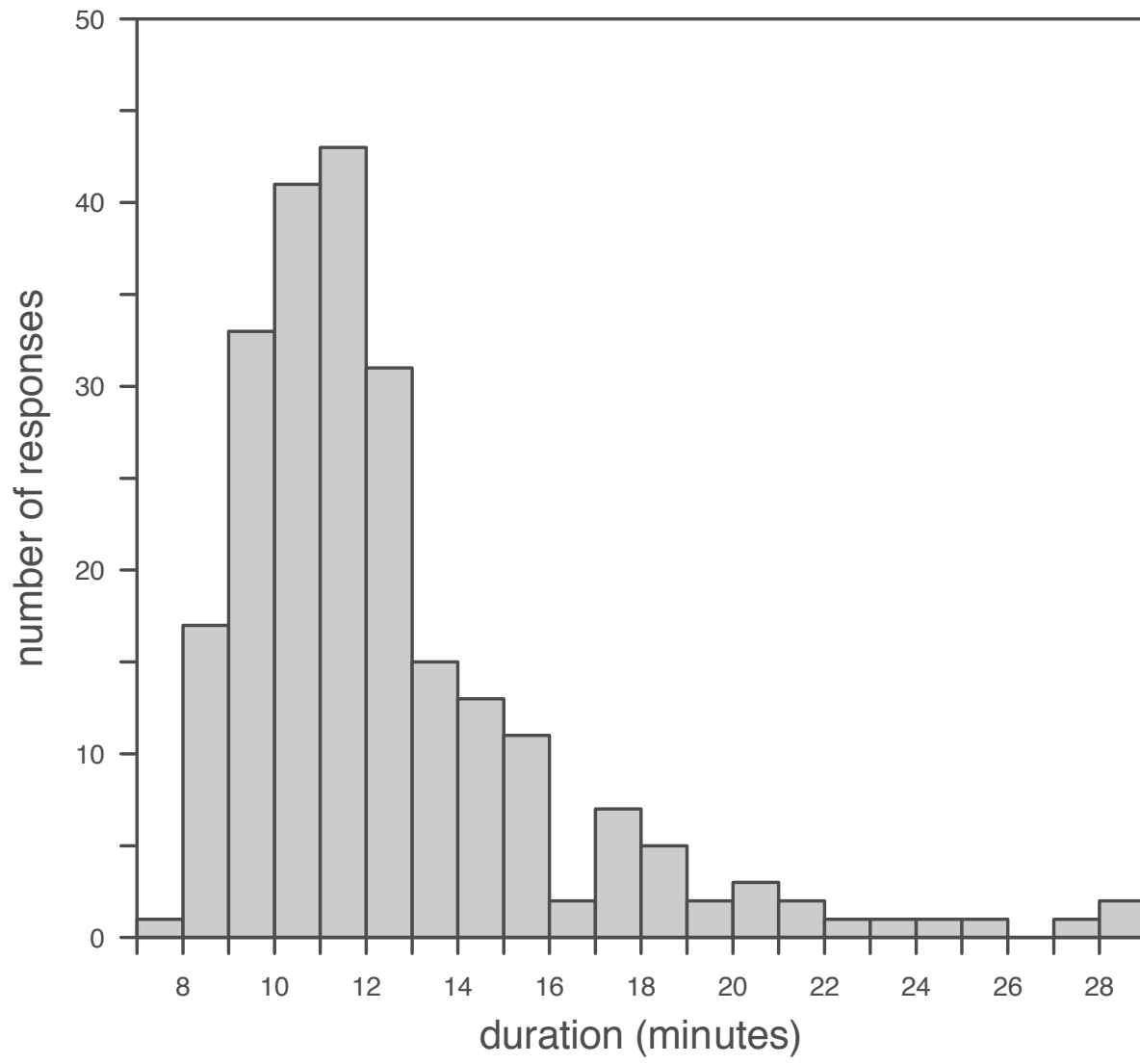


Figure 5B.8. Distribution of survey durations for full responses.

5B.6 Sensory importance response profiles and contrasts

To visualize the patterns of individual responses regarding each of the five senses, we calculated a Euclidean dissimilarity matrix and performed agglomerative clustering to generate response profiles. A scree plot suggested pruning the resultant dendrogram to eight groups, but this pruning was a bit finer than needed, so the dendrogram was pruned back to four groups, yielding a satisfactorily simple classification of typical response profiles.

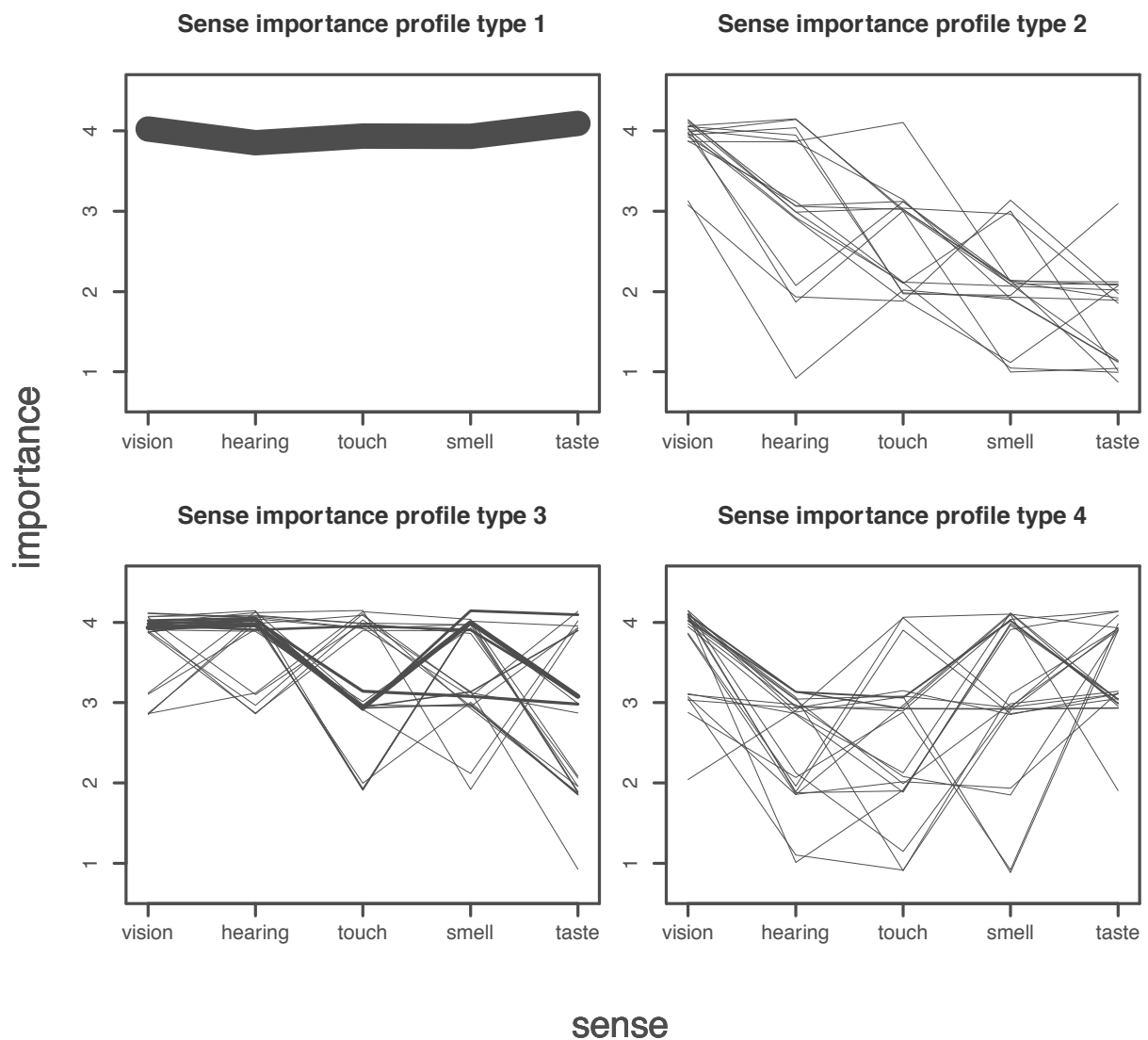


Figure 5B.9. Individual patterns of sense importance. Line thickness reflects the number of individuals who responded following the pattern indicated by that line. For example, profile type 1 represents a response of “high importance” for all senses, while the thickest line in profile type 3 represents a response of “high importance” for vision, hearing, and smell and “moderate importance” for touch and taste. Ordinal responses were assigned random noise to improve legibility.

Contrast statistics for inter-prompt soundscape perception comparisons are provided in Table 5B.2.

Table 5B.2. Contrast statistics for comparison of soundscape discernment, valuation, and location identification based on different soundscape prompts.

prompt pair	discernment			valuation			location identification		
	t-ratio	degrees of freedom	p-value	t-ratio	degrees of freedom	p-value	t-ratio	degrees of freedom	p-value
Forest – <i>In Situ</i>	-2.68	696	0.038	18.92	696	< 0.001	—	—	—
Forest – Penguin Colony	4.71	696	< 0.001	4.24	696	< 0.001	0.08	464	0.996
Forest – Urban	3.70	696	0.001	12.34	696	< 0.001	-2.49	464	0.035
<i>In Situ</i> – Penguin Colony	7.39	696	< 0.001	-14.68	696	< 0.001	—	—	—
<i>In Situ</i> – Urban	6.38	696	< 0.001	-6.59	696	< 0.001	—	—	—
Penguin Colony – Urban	-1.01	696	0.745	8.10	696	< 0.001	-2.57	464	0.028

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APPENDIX 5C—RESPONSE GUIDE SHEETS

Strogly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
-----------------------------	-----------------	---	--------------	---------------------------

1. My ideal vacation spot would be a remote, wilderness area.
2. I always think about how my actions affect the environment.
3. I feel a spiritual relationship with nature and the environment.
4. I take notice of wildlife wherever I am.
5. My relationship with nature is an important part of my identity.
6. I feel very connected to all living things and the earth.

Of no importance	Of little importance	Of moderate importance	Of high importance
-----------------------------	---------------------------------	-----------------------------------	-------------------------------

What is the importance of the following senses for your experience of nature?

1. Vision

2. Hearing

3. Touch

4. Smell

5. Taste

Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly agree
------------------------------	-----------------	---	--------------	---------------------------

1. I liked the sounds I heard.

2. The sounds I heard triggered memories.

3. The sounds I heard provided me with information about the place in which they occurred.

4. The sounds I heard have an effect (either positive or negative) on the animals living where the sounds occurred.

5. The sounds I heard made me feel emotions.

Fuertemente en desacuerdo	En desacuerdo	Ni acuerdo ni desacuerdo	De acuerdo	Fuertemente de acuerdo
--	--------------------------	---	-------------------	-----------------------------------

1. Mi lugar ideal para las vacaciones sería una zona remota, inhóspita, natural.
2. Siempre pienso sobre como mis acciones afectan al medio ambiente.
3. Siento una relación espiritual con la naturaleza y el medio ambiente.
4. Presto atención a la vida salvaje en todos lados.
5. Mi relación con la naturaleza es una parte importante de mi identidad.
6. Me siento muy conectado a todos los seres vivos y al planeta tierra.

De ninguna importancia	De poca importancia	De importancia moderada	De alta importancia
-----------------------------------	--------------------------------	------------------------------------	--------------------------------

¿Cuál es la importancia de los siguientes sentidos para vivenciar sus experiencias de la naturaleza?

1. Visión

2. Oído

3. Tacto

4. Olfato

5. Gusto

Fuertemente en desacuerdo	En desacuerdo	Ni acuerdo ni desacuerdo	De acuerdo	Fuertemente de acuerdo
--	--------------------------	---	-------------------	-----------------------------------

1. Me gustaban los sonidos que oí.
2. Los sonidos que oí evocaron memorias.
3. Los sonidos que oí me dieron información sobre el lugar en que ocurrieron.
4. Los sonidos que oí afectan (positivamente o negativamente) a los animales
viviendo donde los sonidos ocurrieron.
5. Los sonidos que oí me hicieron sentir emociones.

VITA

Education

PURDUE UNIVERSITY

Doctor of Philosophy Candidate

West Lafayette, IN

Aug. 2015 – present

- Concentration in Interdisciplinary Ecological Sciences and Engineering
- Major in Forestry and Natural Resources
- Advisor: Dr. Bryan Pijanowski, Professor of Landscape and Soundscape Ecology
- GPA: 3.93
- Relevant coursework: Responsible Conduct of Research, Advanced Spatial Ecology and GIS, Sensory Ecology, Ecology of Disturbance, Ecological Statistics, Digital Signal Processing I, Evolution, Analysis of Ecological Data, Theory and Application of Natural Resources Extension Programming, Ecological Engineering and Ecosystem Restoration, Soundscape Ecology, Urban Ecology, Building the Social-ecological Toolkit, Spanish 102, Spanish 201, Spanish 202

MIDDLEBURY COLLEGE

Bachelor of Arts, *summa cum laude*, May 2015

Middlebury, VT

Sep. 2011 – May 2015

- Major in music, minor in French
- Advisor: Dr. Jeffrey Buettner, Christian A. Johnson Professor of Music
- Elected to Phi Beta Kappa (academic honor society)
- College Scholar (Middlebury's highest academic honor) all semesters
- GPA: 3.86
- Relevant coursework: Natural Science and the Environment, Music in World Cultures, Ethnomusicological Research Methods, Ethnomusicological Approaches and Methods, Advanced [Music] Composition I, Electronic Music, Independent Study in Music Composition, French 205, French 210, French 221, French 230

MIDDLEBURY COLLEGE, C. V. STARR SCHOOL IN AFRICA

Completed, January 2014

Yaoundé, Cameroon

Sep. 2013 – Jan. 2014

- French immersion program
- Studied local music and culture through coursework and independent research

Research experience

PURDUE UNIVERSITY, CENTER FOR GLOBAL SOUNDSCAPES

Graduate Research Assistant for Dr. Bryan Pijanowski

West Lafayette, IN

Aug. 2015 – present

- Self-directed projects
 - PhD dissertation—Soundscape dynamics in the social-ecological systems of Tierra del Fuego
 - Temporal variability in biophony: implications for biogeography and ecological monitoring
 - Temporal soundscape dynamics in a Magellanic penguin colony in Tierra del Fuego

Research experience (continued)

- Center for Global Soundscapes Projects
 - Long-term soundscape dynamics in Tippecanoe County, IN
 - Soundscape impacts of a solar eclipse
 - Glacial sound type analysis
 - Impacts of prairie management techniques on bird and soundscape diversity in Nebraska
 - Acoustic monitoring reveals diversity and surprising dynamics in tropical freshwater soundscapes
 - Effects of highways on bird distribution and soundscape diversity around Aldo Leopold's shack in Baraboo, Wisconsin, USA
 - Promoting STEM interest and connections to nature through soundscape ecology camp for students with visual impairments
 - Analysis and projection of urban densification based on the Land Transformation Model: A case study in southeastern Wisconsin, USA
 - Soundscapes reveal disturbance impacts: biophonic response to wildfire in the Sonoran Desert Sky Islands
 - The vanishing soundscapes project: Documenting spatiotemporal soundscape variation around the globe and linking it to social-ecological drivers of change
- Methodologies: passive acoustic monitoring, analysis of soundscape composition and dynamics through sound types and acoustic indices, semi-structured interviews, social surveys, avian point counts, primary source analysis and synthesis
- Focal regions: Tierra del Fuego, Argentina; Tippecanoe County, IN; Wood River, NE; Ainsworth, NE; Sarapiquí, Costa Rica; Baraboo, WI; Chiricahua National Monument, AZ
- Fieldwork sites: Tierra del Fuego, Argentina; Tippecanoe County, IN; Wood River, NE; Ainsworth, NE; Sarapiquí, Costa Rica; Wells, ME; Gatlinburg, TN

MIDDLEBURY COLLEGE, DEPARTMENT OF MUSIC
Undergraduate Research Assistant for Dr. Damascus Kafumbe

Middlebury, VT
Feb. 2012 – May 2015

- Self-directed projects
 - Undergraduate senior thesis—African music performance in the American academy: Capital exchange, institutional dynamics, and the challenges of representation
 - Playing from the same horn: The context and racial politics behind the musics of Louis Armstrong and Hugh Masekela
 - The formation and articulation of musical identity: An examination of Hugh Masekela and his music
- Projects for Professor Kafumbe
 - Tuning the kingdom: Kawuugulu music, politics, and storytelling in Buganda (editing and annotated bibliography development)
- Methodologies: participant-observation, semi-structured interviews, secondary source analysis and synthesis
- Focal regions and institutions: American colleges and universities; New Orleans, LA; Africa (with emphasis on Cameroon, South Africa, and Uganda)
- Fieldwork sites: Yaoundé, Cameroon; Medford, MA; Middlebury, VT; New York, NY

Publications

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- Francomano, Dante**. 2015. “African music performance in the American academy: Capital exchange, institutional dynamics, and the challenges of representation.” Undergraduate, Middlebury, VT: Middlebury College.

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- Francomano, Dante**, Mayra Rodríguez González, Alejandro E. J. Valenzuela, Zhao Ma, Andrea N. Raya Rey, Christopher B. Anderson, and Bryan C. Pijanowski. In preparation. “Human-nature connection and soundscape perception: insights from Tierra del Fuego, Argentina.”
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- Francomano, Dante.** 2020. "Soundscape dynamics in the social-ecological systems of Tierra del Fuego." Doctoral dissertation defense presented remotely, November 23.
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- Francomano, Dante.** 2018. "Estudiando pingüinos a través el sonido [Studying penguins through sound]." presented at a meeting of the Grupo de Ecología y Conservación de la Vida Silvestre, Ushuaia, Argentina, September 18.
- Francomano, Dante,** Benjamin Gottesman, and Bryan Pijanowski. 2017. "Temporal soundscape dynamics in a Magellanic penguin colony in Tierra del Fuego." presented at the Quantitative Ecology Group Meeting, West Lafayette, IN, October 05.
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- Gottesman, Benjamin, **Dante Francomano,** Zhao Zhao, Kristen Bellisario, Taylor Broadhead, Maryam Ghadiri, Amandine Gasc, and Bryan Pijanowski. 2017. "Soundscape diversity and dynamics in a tropical Costa Rican wetland." presented at the International Congress for Conservation Biology, Cartagena, Colombia, July 27.
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- Francomano, Dante.** 2015. "Soundscapes in composition: Theoretical thoughts and practical applications." presented at the Global Sustainable Soundscapes Network Workshop, Brookings, SD, July 16.
- Francomano, Dante.** 2015. "African music performance in the American academy: Capital exchange, institutional dynamics, and the challenges of representation." presented at the Rohatyn Center for Global Affairs Mellon Foundation Study Abroad Research Grant Presentations, Middlebury, VT, May 06.
- Francomano, Dante,** Maryam Ghadiri, Brad Lisle, and Bryan Pijanowski. 2014. "What is a YELL? An introduction to an informal soundscape ecology curriculum." presented at the Global Sustainable Soundscapes Network Workshop, Ogunquit, ME, July 18.
- Francomano, Dante.** 2014. "Playing from the same horn: The context and racial politics behind the musics of Louis Armstrong and Hugh Masekela." presented at the Northeast Chapter of the Society for Ethnomusicology 2014 Chapter Meeting, Norton, MA, April 05.
- Francomano, Dante.** 2013. "The transaction of power in Ugandan musical pedagogy." presented at the Northeast Chapter of the Society for Ethnomusicology 2013 Chapter Meeting, Brunswick, ME, April 20.

* Undergraduate mentee

Teaching, leadership, and professional service

DEPARTMENT OF FORESTRY AND NATURAL RESOURCES Graduate student peer mentor to Recep Yildiz	West Lafayette, IN Aug. 2019 – present
CADIC-CONICET Active member of Grupo SocioEco	Ushuaia, Argentina Sep. 2018 – present
ECOLOGICAL SCIENCES AND ENGINEERING INTERDISCIPLINARY GRADUATE PROGRAM Graduate student peer mentor to Rebecca Nixon	West Lafayette, IN June 2017 – present
DEPARTMENT OF FORESTRY AND NATURAL RESOURCES Active member of Quantitative Ecology Group	West Lafayette, IN Aug. 2015 – present
ADVANCED SPATIAL ECOLOGY AND GIS, PURDUE UNIVERSITY Guest panelist	West Lafayette, IN Oct. 2020
DEPARTMENT OF FORESTRY AND NATURAL RESOURCES Graduate student peer mentor to Patricia Nease	West Lafayette, IN Aug. 2017 – Aug. 2019
ADVANCED SPATIAL ECOLOGY AND GIS, PURDUE UNIVERSITY Teaching assistant	West Lafayette, IN Aug. – Dec. 2019
ECOLOGICAL INFORMATICS Peer reviewer	Ushuaia, Argentina Apr. – July 2019
REMOTE SENSING IN ECOLOGY AND CONSERVATION Peer reviewer	Ushuaia, Argentina Feb. – May 2019
DISSERTATION FIELDWORK Supervisor of undergraduate research assistants Jessica Archibald, Emiliano Arona, Nora Jara, and Elena Schaefer	Ushuaia, Argentina Nov. 2018 – Apr. 2019
ECOLOGÍA DE COMUNIDADES [COMMUNITY ECOLOGY], UNIVERSIDAD NACIONAL DE TIERRA DEL FUEGO Guest lecturer	Ushuaia, Argentina Oct. 2018
DEPARTMENT OF FORESTRY AND NATURAL RESOURCES Graduate student peer mentor to Ben Taylor	West Lafayette, IN Aug. 2016 – May 2018
ADVANCED SPATIAL ECOLOGY AND GIS, PURDUE UNIVERSITY Guest lecturer	West Lafayette, IN Dec. 2017
NATIONAL GEOGRAPHIC SOCIETY COMMITTEE FOR RESEARCH AND EXPLORATION External grant application reviewer	West Lafayette, IN Aug. 2017
PURDUE SUMMER UNDERGRADUATE RESEARCH FELLOWSHIP Graduate student mentor to Sheryl Vanessa Amoroch	West Lafayette, IN May 2017 – Aug. 2017
CENTER FOR GLOBAL SOUNDSCAPES Acoustic monitoring fieldwork leader for undergraduate students	West Lafayette, IN Oct. 2015 – Aug. 2017
ADVANCED SPATIAL ECOLOGY AND GIS, PURDUE UNIVERSITY Guest lab instructor	West Lafayette, IN Sep. 2016

Teaching, leadership, and professional service (continued)

ECOLOGICAL SCIENCES AND ENGINEERING INTERDISCIPLINARY GRADUATE PROGRAM SYMPOSIUM

West Lafayette, IN
Dec. 2015 – Sep. 2016

Chair

- Led twenty graduate students to run a multi-day symposium entitled “Polarization: A Forum on Extreme and Radical Thought in our Environment, Society, and Technology”; Symposium events included lectures, a panel, discussion sessions, a poster session, an art gallery, an art workshop, a film screening, and social meals

Outreach and extension

TDF SOUNDSCAPES WEBSITE, BLOG, AND SOCIAL MEDIA PAGES

Ushuaia, Argentina
Sep. 2018 – present

- Created a bilingual website (tdfsoundscapes.org), blog, and social media pages (@tdfsoundscapes) to share project updates, stories, and findings with a broader academic and nonacademic audience

YOUR ECOSYSTEM LISTENING LABS (YELLs)

West Lafayette, IN
Apr. 2014 – present

- Helped develop, design, and edit an informal environmental learning curriculum about soundscape ecology for middle school students

PURDUE CLIMATE STRIKE

West Lafayette, IN
Sep. 2019

- Gave a talk at a public teach-in on using passive acoustics to monitor disturbance impacts on penguins

LECTURE FOR TOUR GUIDES—USHUAIA

Ushuaia, Argentina
Apr. 2019

- Delivered a lecture in Spanish to a group of Ushuaia tour guides about my research in Tierra del Fuego

LECTURE FOR CLUB DE OBSERVADORES DE AVES—USHUAIA

Ushuaia, Argentina
Nov. 2018

- Delivered a lecture in Spanish to a club of Ushuaia birdwatchers about the potentials for integration between soundscape ecology and ornithology

NATIONAL SCIENCE TEACHERS ASSOCIATION (NSTA) VIDEO

West Lafayette, IN
Feb. 2017

- Spoke and acted in a video about Center for Global Soundscapes extension materials
- Video was screened at the 2017 National Science Teachers Association National Conference

INDIANAPOLIS SYMPHONY ORCHESTRA MUSIC OF THE EARTH

Indianapolis, IN
Jan. 2017

- Discussed soundscape ecology and Center for Global Soundscapes activities with concertgoers

PURDUE UNIVERSITY DISCOVERY PARK OPEN HOUSE

West Lafayette, IN
Sep. 2016

- Helped set up, staff, and take down a set of displays showcasing the Center for Global Soundscapes

SPECTROGRAM YOUTUBE VIDEO

West Lafayette, IN
May 2016

- Scripted and acted in a short, publicly available educational video about spectrograms and their use in soundscape analysis

GLOBAL SOUNDSCAPES: A MISSION TO RECORD THE EARTH

North Attleboro, MA
June 2014 – May 2015

- Helped script and produce this interactive IMAX film on soundscape ecology

Outreach and extension (continued)

PERKINS SCHOOL FOR THE BLIND YELLS DEVELOPMENT

- Worked with students at Perkins School for the Blind to begin development of the Your Ecosystem Listening Labs curriculum (see above)

Watertown, MA
Apr. 2014

Selective opportunities, grants, awards, and honors

SEAWORLD & BUSCH GARDENS CONSERVATION FUND Grant Recipient—\$10,000

Orlando, FL
July 2018

PURDUE UNIVERSITY CLIMATE CHANGE RESEARCH CENTER Graduate Student Travel Grant Recipient—\$1,000

West Lafayette, IN
May 2018

D. WOODS THOMAS MEMORIAL FUND TO SUPPORT INTERNATIONAL STUDIES Grant Recipient—\$1,000

West Lafayette, IN
Apr. 2018

MYSTIC SEAPORT

38th Voyager aboard the Charles W. Morgan

- Recorded soundscapes while sailing on the Charles W. Morgan's 38th voyage
- Commissioned to compose a musical piece inspired by these soundscapes that was premiered aboard the Charles W. Morgan (the world's oldest wooden whaling ship) in June 2015

Mystic, CT
July 2014 – June 2015

PURDUE UNIVERSITY Purdue Doctoral Fellowship Recipient

West Lafayette, IN
Apr. 2015

THE NORTHEAST CHAPTER OF THE SOCIETY FOR ETHNOMUSICOLOGY Lise Waxer Prize

- "The Transaction of Power in Ugandan Musical Pedagogy" selected as best undergraduate paper at the 2013 conference of the Northeast Chapter of the Society for Ethnomusicology

Brunswick, ME
Apr. 2013

MIDDLEBURY COLLEGE; MELLON FOUNDATION Research Grant Recipient

- Researched intercultural musical pedagogy in preparation for my thesis while studying abroad in Cameroon

Middlebury, VT
Mar. 2013

BOY SCOUTS OF AMERICA Eagle Scout

- My deep respect for nature and my concern for sustainability are in part inspired by my time in scouting
- Eagle Project was the installation of a shed to collect recyclable bottles and cans to benefit my high school music association
- Secured school board approval for the installation of the shed on school grounds
- Organized over 50 volunteers for a three-town bottle and can drive that collected over 40,000 bottles and cans and raised over \$2,000 for the new shed

Foxboro, MA
Dec. 2010

Work experience

FOXFIRE INTERACTIVE

Production Assistant

North Attleboro, MA
June 2014 – May 2015

- Worked in partnership with Purdue University's Center for Global Soundscapes (CGS) to produce an interactive IMAX film, summer camp program, and apps that introduce soundscape ecology to middle school students
- Designed extracurricular content based on national educational standards
- Helped script and produce an interactive IMAX film
- Served as a liaison between Foxfire and Purdue for certain aspects of the project

STATE STREET BANK

Intern

Boston, MA
Jun. 2012 – Aug. 2012

- Maintained the back end of a digital platform for high-volume foreign exchange trading
- Manipulated databases in Microsoft Excel
- Collaborated with colleagues to provide technical assistance to clients

Language skills

ENGLISH

- Native speaker

FRENCH

- Proficient in French following eight years of formal study and exclusive use of French while studying and conducting research in Cameroon
- Maintain proficiency through communication with French and Cameroonian colleagues and friends

SPANISH

- Proficient in Spanish through formal study and exclusive use of Spanish while conducting research in Argentina
- Maintain proficiency through communication with Spanish-speaking colleagues and friends

Technological skills

OPERATING SYSTEMS

- Macintosh (intermediate/advanced)
- PC (intermediate/advanced)
- Linux (intermediate)
- iOS (intermediate/advanced)

PROGRAMMING LANGUAGES

- R (intermediate/advanced)
- Bash (beginner/intermediate)
- MATLAB (beginner)
- LaTeX (beginner)

Technological skills (continued)

SOFTWARE

- Microsoft Word (advanced)
- Microsoft PowerPoint (advanced)
- Microsoft Excel (advanced)
- Zotero (advanced)
- GitHub (intermediate)
- ESRI ArcGIS Pro (beginner/intermediate)
- QGIS (beginner/intermediate)
- Google Earth Pro (intermediate/advanced)
- Wildlife Acoustics smconfig (intermediate/advanced)
- Wildlife Acoustics sm3config (intermediate/advanced)
- Wildlife Acoustics sm4config (intermediate/advanced)
- Adobe InDesign (beginner/intermediate)
- Adobe Illustrator (beginner/intermediate)
- Audacity (intermediate/advanced)
- Finale (intermediate/advanced)

AUDIOVISUAL HARDWARE

- Wildlife Acoustics SongMeter SM2 (advanced)
- Wildlife Acoustics SongMeter SM2BAT (intermediate)
- Wildlife Acoustics SongMeter SM3 (advanced)
- Wildlife Acoustics SongMeter SM3BAT (intermediate)
- Wildlife Acoustics SongMeter SM4 (advanced)
- Zoom H2n (advanced)
- Zoom H4n (advanced)
- Zoom H5 (intermediate)
- Zoom H6 (intermediate)
- Stage audio and live sound (intermediate)
- Cannon EOS 7D (intermediate)
- Panasonic Lumix DMC-LF1 (intermediate)
- Sony Handycam (beginner)
- GoPro Hero 4 (beginner)
- Brinno TLC 200 Pro (beginner)